

Hydroclimatic Assessment and Integrated Modeling of Climate Change,
Permafrost Thaw, and Wildfire Impacts on River Discharge in a
Discontinuous Permafrost Watershed

by

Abigail R. Baran

A thesis submitted to the Graduate Program in Civil Engineering
in conformity with the requirements for the
Degree of Master of Applied Science

Queen's University
Kingston, Ontario, Canada

December 2025

Copyright © Abigail R. Baran, 2025

Abstract

Rapid climate warming across the (sub-)Arctic is reshaping northern river systems, yet the combined impacts of changing meteorological conditions, permafrost thaw, and wildfire on watershed hydrology remain poorly understood, partly due to sparse meteorological data. This thesis examines the climatic and landscape drivers of recent hydrological change in the discontinuous permafrost La Martre River watershed of the central Northwest Territories, guided by two objectives: (1) identifying watershed-scale hydroclimatic trends and assessing whether long-term precipitation changes explain observed increases in streamflow, and (2) quantifying the individual and cumulative influences of precipitation, permafrost thaw, and wildfire on discharge magnitude and timing.

ERA5-Land reanalysis data were evaluated for their ability to detect long-term climatic trends in a region with limited in situ observations. Analysis of both the full ERA5-Land record (1950–2023) and the period overlapping discharge data (1977–2023) revealed statistically significant increases in temperature and precipitation across the watershed, with ERA5-Land effectively capturing spatial and temporal variability. However, increasing precipitation alone cannot fully explain observed increases in annual and winter discharge. These results highlight challenges in resolving robust climate trends in highly variable northern environments and underscore the need for enhanced monitoring networks to better characterize climate–hydrology interactions in discontinuous permafrost systems.

Hydrological modeling was then used to assess the relative contributions of climate change, permafrost thaw, and wildfire to past, present, and future streamflow under a

high-emissions scenario. Model results indicate that increased precipitation is the dominant driver of rising discharge in the La Martre River, while permafrost thaw contributes additional increases by enhancing subsurface flow pathways. Wildfire has limited direct influence on discharge but accelerates permafrost thaw–related streamflow increases. Together, these processes produce cumulative increases in annual and winter flows that exceed their individual effects, with projections indicating continued discharge intensification under future climate conditions.

Collectively, this research demonstrates that hydrological change in La Martre River watershed is driven primarily by increasing precipitation and shaped by climate- and wildfire-induced permafrost thaw. The findings advance understanding of hydroclimatic drivers in northern permafrost systems and inform water management, ecosystem protection, and climate adaptation planning in vulnerable sub-Arctic regions.

Acknowledgements

First and foremost, I would like to express my sincere gratitude to my supervisors, Dr. Élise Devoie and Dr. Stephanie Wright, for their unwavering support throughout this journey, from inviting me to join the project, through several exciting field trips to Whatì, and ultimately helping me navigate the complexities of modeling. I am particularly grateful to Dr. Wright for her thoughtful feedback, her enthusiasm and expertise during fieldwork, and her meticulous pursuit of perfect figures. I am also deeply thankful to Dr. Devoie for her exceptional support with modeling, her encouragement and guidance through difficult tasks, and her camaraderie in knitting. I'm excited to continue our collaboration as I move into the next chapter of my career.

I would also like to thank my friends for providing the perfect balance of distraction and support throughout this process. And a special mention to my plants, that reminded me of the passing of time and offered comfort during long days of work.

To my parents, thank you for always valuing my education and for your excitement at each step of the process. And to my brother, who shared in this journey with me as he pursued his own master's.

Finally, my heartfelt thank you to Matthew, for your patience, balanced perspective, and countless hugs. I truly could not have done this without you.

This research was supported by the Northwest Territories Cumulative Impact Monitoring Program (CIMP), and I am grateful to TD for their generous support through the TD Fellowship in Arctic Environmental Issues.

Table of Contents

Abstract.....	ii
Acknowledgements	iv
List of Tables	viii
List of Figures	ix
List of Abbreviations and Symbols	xiv
Chapter 1 Introduction	1
1.1 Arctic Climate Change	1
1.2 Drivers of Hydrological Change	3
1.3 Research Objectives	7
1.4 Organization of Thesis	7
1.5 Literature Cited	9
Chapter 2 Assessing Climate-Hydrology Interactions in La Martre River Watershed Using ERA5-Land Reanalysis	15
Abstract	15
2.1 Introduction	16
2.2 Methods	20
2.2.1 Study Site.....	20
2.2.2 Observational Data Gap-Filling.....	23
2.2.3 Reanalysis Data Bias Correction	23
2.2.4 Anomaly Calculation.....	24
2.2.5 Discharge Data	25
2.2.6 Trend Analysis	25
2.3 Results and Discussion	27
2.3.1 Comparison of ERA5-Land	27
2.3.2 Effect of Time Window on Trend Analysis.....	34
2.3.3 Assessment of Spatial Variability in Trends.....	38
2.3.4 Hydrometric Analysis	41
2.4 Conclusions	47
2.5 Literature Cited	49
Chapter 3 Hydrological Modeling of Climate Change, Permafrost Thaw, and Wildfire Impacts on River Discharge in a Discontinuous Permafrost Watershed.....	56
Abstract	56

3.1 Introduction	57
3.2 Study Site	63
3.3 Methods.....	66
3.3.1 Climate Forcing Data	66
3.3.2 Model Discretization.....	68
3.3.3 Permafrost and Wetland Representation.....	70
3.3.4 Model Processes.....	72
3.3.5 Model Calibration and Validation	74
3.3.6 Model Simulations.....	75
3.3.7 Test Cases	76
3.3.8 Simulation Evaluation	79
3.4 Results and Discussion	80
3.4.1 Evaluation of the Base Period Model.....	80
3.4.2 Individual Driver Response.....	81
3.4.3 Relative Importance of Driving Factors	87
3.4.4 Cumulative Impact of Driving Factors	90
3.4.5 Implications	94
3.4.6 Limitations.....	95
3.5 Conclusions	96
3.6 Literature Cited.....	98
Chapter 4 Conclusions	109
4.1 Summary of Results	109
4.2 Contributions	110
4.3 Recommendations	112
Appendix A Meteorological Data Preparation.....	115
A.1 Observational Data Gap-Filling.....	115
A.2 Complete Results of ERA5-Land Anomaly Comparison	116
A.3 ERA5-Land Bias Correction	117
Appendix B Model Discretization	118
B.1 Watershed and Sub-Basin Delineation	118
B.2 Land Cover Classification Details	122
Appendix C Field Data Analysis for Model Parameterization.....	124
C.1 Soil Properties	124

C.2 Slug Test Analysis	125
C.3 Freeze/Thaw Timing	126
Appendix D Model Processes	128
D.1 Raven Hydrological Processes Input File (.rvi)	128
D.2 Raven Parameters Input File (.rvp)	131
D.3 Description of Wetland Processes in Raven Manual.....	134
Appendix E Model Calibration.....	136
E.1 Calibration Ranges	136
E.2 Calibrated Base Period Model	139
Appendix F Model Test Cases	140
F.1 Simulations Case Details.....	140
F.2 HRU Generation Table	141
F.3 Meteorological Forcing Simulation Details.....	141
F.4 Wildfire Simulation Details	143
F.5 Wildfire Sensitivity Analysis.....	144

List of Tables

Table 2.1 Meteorological stations within and near La Martre River watershed. Site ID refers to the Environment and Climate Change Canada Climate ID, with * indicating a Canadian Air and Precipitation Monitoring Network (CAPMoN) site. Start and end years represent the period of continuous daily data with at least 10 complete months. The Snare Rapids CAPMoN site does not report temperature data.	22
Table 2.2 Comparison of annual, seasonal, monthly, and daily temperature and precipitation anomalies between observational, ERA5-Land, and bias-corrected ERA5-Land datasets. The comparison period corresponds to the available observational record for each meteorological station. Anomalies were computed relative to observational data for the period 1990–2019.....	28
Table 3.1 Table of base period model soil profile properties informed by field investigations. Detailed soil profiles in Appendix C. Note, Org: Organic, Min: Mineral, PF: Permafrost, FB: Fractured bedrock.	70
Table 3.2. Hydraulic conductivity ranges from slug tests. Calibrated porosity, M_{base} and M_{perc} values based on hydraulic conductivity and assumed gradient and anisotropy ranges.	71
Table 3.3. Description of changes made in each simulation case. Changes are relative to the base case, where == means that there is no change from the base case. Note, PF: permafrost, PP: peat plateau.....	78
Table B.1 Description of HWL land cover classes and classification within model land cover scheme. Modified from EOSD Land Cover Classification Legend Report (Wulder & Nelson, 2003).....	123
Table E.1 Table of automatic calibration variables, range, and calibrated values. The calibrated values can be found in place in the .rvp file in Appendix D.	136
Table F.1 Detailed description of changes made to model for each simulation case.	140

List of Figures

Figure 2.1 Location of La Martre River watershed and study sites. The map shows meteorological stations, discharge gauging stations, and the watershed boundary. The Whatì meteorological station (orange circle) is the only long-term station located within La Martre River watershed. La Martre River flows from Lac La Martre to Great Slave Lake.

..... 21

Figure 2.2. Comparison of monthly temperature (a, b) and monthly precipitation (c, d) among observational data, ERA5-Land, and bias-corrected ERA5-Land. Shading in panels (a) and (b) indicates the mean $\pm$ standard deviation. Box plots in panels (c) and (d) show the interquartile range (25th–75th percentiles), with outliers represented by points. The analysis period for each meteorological station corresponds to its available record; the Snare Rapids record includes only data from the CAPMoN station (1988–2023).

.....28

Figure 2.3. Comparison of trends in air temperature and total precipitation derived from observational, ERA5-Land, and bias-corrected ERA5-Land datasets. Panels (a–c) show mean annual temperature, and panels (j–l) show total annual precipitation. Points represent mean annual values, solid lines indicate the trend over the available observational period, and shaded areas denote the 95% confidence interval of the slope for each meteorological station. Panels (d–f) and (g–i) show annual trends in seasonal and monthly mean air temperature, respectively, while panels (m–n) and (o–p) show annual trends in seasonal and monthly total precipitation. Points represent the estimated trend, and error bars indicate the 95% confidence interval. Statistically significant trends are shown in bold and marked with an asterisk.

.....32

Figure 2.4. Trends in (a) mean annual air temperature and (b) total annual precipitation derived from ERA5-Land data for Whatì (63.1°N, 117.2°W) during 1951–2023. Each cell represents the slope of the annual trend for the period defined by its Start Year and End Year. Black points denote statistically significant trends at the 95% confidence level. All trends are reported in $^{\circ}\text{C decade}^{-1}$ or mm decade^{-1} . Time windows longer than 30 years (40 years) are located above the black (grey) diagonal line. Insets show the corresponding ERA5-Land records of (c) mean annual air temperature (MAAT) and (d) total annual precipitation. Panel (e) highlights the 1985–2001 (17-year) temperature trend; the color of the selected cell indicates the trend magnitude for the period with the given start and end year.

..... 35

Figure 2.5. Spatial distribution of (a) mean annual air temperature and (b) total annual precipitation for the full record 1951–2022, and trends in (c–d) annual and seasonal (e, g, i) temperature and (f, h, k) precipitation, respectively, based on ERA5-Land. Each cell in panels (c–k) represents the trend magnitude in mean annual or seasonal temperature or precipitation at that grid location. Black points denote statistically significant trends at the 95% confidence level. La Martre River watershed boundary is shown in white. Color scales differ among panels to emphasize spatial variability: in (a–b) white indicates the mean value, while in (c–k) white corresponds to a trend magnitude of zero.

.....39

Figure 2.6. Daily mean discharge ($\text{m}^3 \text{s}^{-1}$) over the hydrological year at La Martre River below outlet of Lac La Martre Water Survey of Canada (WSC) gauging station, shown for four time periods. Shaded envelopes denote the mean $\pm$ standard error for each day. Dashed vertical lines indicate seasonal boundaries. 42

Figure 2.7. Annual, seasonal, and monthly trends in ERA5-Land precipitation at Whatì (63.1°N, 117.2°W; red) and La Martre River discharge (blue) for 1977–2023. Trend significance is indicated by symbol style: dark squares for $p < 0.05$, light circles for $0.05 \leq p < 0.10$, and open circles for $p \geq 0.10$. Error bars denote 95% confidence intervals. Trends are expressed as $\% \text{yr}^{-1}$, relative to the predicted value in the initial year (1977). A horizontal dashed line marks zero trend, and solid vertical lines separate annual, seasonal, and monthly groupings. 44

Figure 2.8. Annual and winter (January–March) specific discharge at La Martre River gauging station (1977–2022) for the $\sim 14,500 \text{ km}^2$ watershed. Dashed lines indicate linear trends of $10.1 \text{ mm decade}^{-1}$ (annual) and $2.6 \text{ mm decade}^{-1}$ (winter), both significant at the 95% confidence level. The proportion of annual discharge occurring in winter is shown by red squares, with its trend also indicated by a dashed line, also significant (right axis). 46

Figure 3.1. Map of field sites and virtual meteorological stations. Map (a) of La Martre River watershed boundary, the Thçhç lands boundary, and the location within the Northwest Territories (inset), and the locations used for downloading ERA5-Land meteorological data (virtual meteorological stations). Map (b) of field sites within burned and unburned wetland and upland land-cover types, as well as the locations of drilled deep wells. 64

Figure 3.2. Representation of sub-basins and land-cover types in the model. Map (a) shows sub-basins 1–14 within the watershed. Major lakes that were modeled as lake-type reservoirs (Lac La Martre in sub-basin 10, Grandin Lake in sub-basin 4, and Bartlett Lake in sub-basin 12) are shown in dark blue, while all other lakes and rivers are shown in light blue. Elevation is displayed in the background. (b) The total area and land-cover composition are displayed by sub-basin. 69

Figure 3.3. Simulated (blue) and observed (black) mean annual specific discharge (mm) in La Martre River in hydrological years 1977–2023. The dashed line represents the end of the base period (1977–1984). 81

Figure 3.4. Daily hydrographs for all simulations. Rows 1–3 present hydrographs for the isolated component-driver simulations: Meteorological, Permafrost Thaw, and Wildfire, respectively. Row 4 presents the comparison of the driving factors for each period. Columns 1–3 present hydrographs for each period: past, present, and future. Column 4 presents the comparison of the period for each driving factor. The lower-right panel summarizes the cumulative influence of all three driving factors across the three time periods. 82

Figure 3.5. Percent change in annual discharge (columns 1–3), winter discharge (columns 4–6), and peak discharge (columns 7–9) for all simulations relative to the base case. Each

row reports the percent change for a single component driver within one of the three driving factors: meteorological forcing (rows 1–5), permafrost thaw (rows 6–10), and wildfire (rows 11–14). The net effect of all component drivers within each driving factor is shown below the dashed line. Columns corresponding to the past (1, 4, 7), present (2, 5, 8), and future (3, 6, 9) periods follow the same order across each discharge metric. 84

Figure 3.6. Relative importance of present and future period seasonalized precipitation (rows 1 and 3) and combined permafrost thaw and wildfire (rows 2 and 4) on annual, winter, and peak discharge and the runoff ratio (columns 1, 2, 3, and 4, respectively) compared to the base case.....89

Figure 3.7. Percent change in annual, winter, and peak discharge (columns 1, 2, and 3) and runoff ratio (column 4) for the cumulative-impact simulations that combine all three component drivers. Rows represent the past (1), present (2), and future (3) periods. ... 91

Figure A.1 Number of months of complete observation temperature (rows 1-3), and precipitation (rows 4-6) for Yellowknife (YT), Whatì (WT), and Snare Rapids (SR) meteorological stations. Precipitation data for Snare Rapids after 1986 is provided by the CAPMoN station. Grey indicates that no data is available in that year, and black indicates that there are no gaps in that year. The number in colored cells indicates the number of complete months available for that year..... 115

Figure A.2 Plot of Whatì daily temperature (black) with gap filling from linear comparison with Yellowknife (red) and long-term daily mean temperature at Whatì (blue).....116

Figure A.3 Plot of RMSE (points) and R^2 (line) for each month for Yellowknife (grey), Whatì (blue), Snare Rapids (black). Note, R^2 axis is on the right. 116

Figure B.1 Comparison of WSC watershed delineation (black outline), NALRRP delineation (yellow) and additional Bartlett sub-watershed (pink), and major lakes (blue) and rivers. 118

Figure B.2 ArcticDEM watershed delineation and elevation of region surrounding Bartlett Lake. 119

Figure B.3 Aerial photo of boulder field landscape on eastern shore of Lac La Martre.120

Figure B.4 Photo of ground cover in burned exposed bedrock forest land cover type of the eastern shore of Lac La Martre. The boulders are interpreted to be highly weathered exposed bedrock. 120

Figure B.5 Tested discretization schemes.....121

Figure B.6 Hydrograph output of early model simulation using discretization schemes described in Figure B.4. Case 3 (purple) was found to best represent the observed hydrograph (black).....121

Figure B.7 Comparison of HWL and DUC land cover classifications. The values represent the percentage of the HWL land cover classification that is present within each DUC classification for the overlapping area. Green indicates greater agreement between the two land cover classification schemes, and red represents no agreement. Note that the sparse coniferous forest land cover is highly correlated to the DUC WETLAND land cover.	122
Figure C.1 Mean composition of soil samples for each field site (left), and USGS soil classification (right).	124
Figure C.2 Range of hydraulic conductivity for each piezometer/well, color identified the soil type that each is taken to represent.....	125
Figure C.3 Fitted slug test to early (left) and late (right) time response using Bouwer Rice Unconfined method for well BC-W1.	126
Figure C.4 Ground temperature at 5 cm depth (a) and 30 cm depth (b) for temperature sensors in Whatì. Minimum (blue), mean (black), and maximum (red) daily temperature in a. Burned coniferous (red) and unburned coniferous (black) in b. Dashed line represents the onset of freeze-up (a), and summer thaw (b).	127
Figure D.1 Land use representation of sub-basin 5 in the present period net permafrost thaw simulation case (left). The wetland fraction break-down for this case (right).....	134
Figure D.2 Representation of 20ths of peat plateau by soil profile type (top left), randomization (top right), and connection to bog (bottom left) and fen (bottom right) land use classes.....	135
Figure E.1 Calibrated base period model (blue) compared to observed discharge (black) during the base period. The selected year, hydrological year 1982, is between the dashed lines.....	139
Figure F.1 Representation of input parameter for generating the HRUs used in simulation cases.....	141
Figure F.2 Mean annual temperature in each hydrological year (points), 8-year running average temperature (thin line), selected mean annual 8-year running average temperature (thick horizontal lines) for each model period, separated by dashed vertical lines.....	142
Figure F. 3 Selected modeled temperature for each period: base case (0), past (1), present (2), and future (3) for each of the virtual meteorological stations.	142
Figure F.4 Historical percentage of forest land cover type burned by wildfire. The remaining percentage is wetland and all other land cover types are excluded. The HWL layer is based on 2009 imagery, represented as the vertical black line. The percentage of forest changes after this year.	143

Figure F.5 Wildfire simulation sub-basins North, East, and West. 144

Figure F.6 Results of the wildfire sensitivity analysis. Percent change in annual discharge relative to the base case for all combinations of wildfire burn characteristics. Rows are grouped by burn location (North in rows 1–3, East in rows 4–6, and West in rows 7–9) and, within each location, by burn area (5% in rows 1, 4, and 7; 8% in rows 2, 5, and 8; and 11% in rows 3, 6, and 9). Columns represent burn-thaw severity for the past (1), present (2), and future (3) periods. 145

List of Abbreviations and Symbols

AHCCD	Adjusted and Homogenized Canadian Climate Data
ALT	Active Layer Thickness
CAPMoN	Canadian Air and Precipitation Monitoring Network
CMIP	Coupled Model Intercomparison Project
CIMP	Cumulative Impact Monitoring Program
CRHM	Cold Regions Hydrological Model
DDS	Dynamically Dimensioned Search
DEM	Digital Elevation Model
DU	Ducks Unlimited Canada
ECCC	Environment and Climate Change Canada
ECMWF	European Centre for Medium-Range Weather Forecasts
ET	Evapotranspiration
HRU	Hydrological Response Unit
HWL	Hybrid Wetland Layer
JFM	January, February, March
KGE	Kling-Gupta Efficiency
LAI	Leaf Area Index
MAAT	Mean annual air temperature
NALRRP	North American Lake-River Routing Product
NSE	Nash-Sutcliffe Efficiency
NWT	Northwest Territories
R^2	Coefficient of determination
RCP	Representative Concentration Pathway
RMSE	Root mean square error
SLT	Supra-permafrost Layer Thickness
SWAT	Soil Water Assessment Tool
SWE	Snow water equivalent
VIC	Variable Infiltration Capacity model
WMO	World Meteorological Organization
WSC	Water Survey of Canada

Chapter 1 Introduction

1.1 Arctic Climate Change

Climate change has increased the global annual average air temperature by 1.1°C above pre-industrial levels to date, with significant impacts across the globe (Bilgili et al., 2024). The rate and magnitude of these changes are especially profound at high latitudes (Rantanen et al., 2022; Serreze & Barry, 2011). Arctic amplification refers to the accelerated increase in Arctic and sub-Arctic temperatures, driven by feedback mechanisms such as declining sea ice extent, increased atmospheric moisture, and the prevalence of temperature inversions that trap heat in the lower atmosphere (Bintanja, 2018; Dai et al., 2019; Screen & Simmonds, 2010; Serreze & Barry, 2011). Winters are warming faster than summers (Box et al., 2019), which is further driving rapid changes to Arctic and sub-Arctic landscapes that rely on cold temperatures for stability (Connon et al., 2014; Kelsey et al., 2021; Pascual & Johansson, 2022). Amplified warming trends are expected to persist regardless of near-term emission reductions, although the eventual rate and extent of warming remain sensitive to mitigation efforts (Overland et al., 2019). Improving our understanding of the impacts of climate warming is essential for supporting northern communities as they adapt to ongoing and future environmental changes.

Amplified warming at high latitudes has initiated a cascade of interconnected climate responses. The number of extreme temperature days has increased (Vincent et al., 2018; Zhang et al., 2025), along with more frequent mid-winter warming and rain-on-snow events (Foster et al., 2013). Earlier snowmelt (Musselman et al., 2017; Semmens et al., 2013) and reductions in snow cover extent and duration have also been

observed (Brown et al., 2019; Mudryk et al., 2018). Increased precipitation is linked to warming because warmer air can hold more atmospheric moisture (Bintanja et al., 2020), and changing atmospheric circulation patterns transport additional moisture toward the poles (Vihma et al., 2016). Shifts in the volume, timing, and phase of precipitation have been documented (Bintanja & Selten, 2014; Walsh et al., 2023), although the direction and magnitude of these trends vary across space, time, and season (Bintanja, 2018; Box et al., 2019). Higher temperatures have contributed to a longer and sometimes drier fire season, resulting in more frequent and severe wildfires (Hanes et al., 2025). These warming and wetting trends pose significant risks to northern landscapes that are sensitive to small climatic shifts (Shur & Jorgenson, 2007). However, sparse and discontinuous observational networks across northern regions complicate the detection and attribution of temperature and precipitation trends (Ahmed et al., 2020; Vincent et al., 2018).

Northern landscapes are not only experiencing rapid climate warming but are also uniquely vulnerable to disturbance because they contain permafrost and climate-sensitive ecosystems (Chasmer et al., 2011). Permafrost is ground that remains below 0°C for at least two consecutive years. Across the Arctic and sub-Arctic, permafrost occurs in continuous, extensive discontinuous, sporadic discontinuous, and isolated zones, with more than 90%, 50 to 90%, 10 to 50%, and less than 10% areal permafrost coverage, respectively (Woo, 2012). In the warming Canadian sub-Arctic, discontinuous permafrost is particularly susceptible to thaw (Gibson et al., 2021; Quinton et al., 2019) because mean annual ground surface temperatures are often close to 0°C (Obu et al., 2019). Much of this permafrost is considered *climate-driven and ecosystem-protected*, meaning that it formed under cooler climatic conditions and is now maintained

primarily by insulating vegetation, snow, and organic soils, such as peat (Shur & Jorgenson, 2007). This dependence on ecosystem conditions introduces an additional layer of vulnerability because climatic or ecological disturbances that reduce surface insulation can trigger rapid destabilization of the permafrost-landscape system. Disturbances such as wildfire, infrastructure development, and land use change accelerate the loss of these protective ecosystems (Gibson et al., 2018; Lemieux et al., 2024). Continued warming and the degradation of insulating vegetation create a feedback that accelerates thaw and drives widespread landscape change with significant hydrological consequences.

1.2 Drivers of Hydrological Change

Hydrological impacts of climate warming and permafrost thaw have been identified across the pan-Arctic. In northern Europe and Siberia, increasing streamflow and rising Arctic Ocean discharge have been documented since the early 2000s (McClelland et al., 2004; Peterson et al., 2002). In contrast, the direction and magnitude of discharge trends in North America have been more uncertain and vary with the datasets and periods examined (Déry et al., 2009; Déry & Wood, 2005). More recent work has identified statistically significant increases in winter and annual discharge in large basins such as the Mackenzie and Yukon Rivers (Liu et al., 2022; Yang et al., 2015; Brabets and Walvoord, 2009), as well as in smaller catchments across northern Canada (Bennet et al., 2023; Déry et al., 2016). These increases are often most pronounced in winter (St. Jacques and Sauchyn, 2009), while concurrent declines in peak flow magnitude (Yang et al., 2015) and shifts in peak flow timing have also been observed (Overeem and Syvitski, 2010). Overall, increasing discharge across the pan-

Arctic and northern Canada has been attributed to climatic change and to alterations in the hydrological landscape (Déry et al., 2016).

Increasing precipitation has been identified as a dominant driver of hydrological change in Arctic and sub-Arctic regions. Streamflow increases are frequently interpreted as evidence of hydrological intensification, which is characterized by greater streamflow and more frequent positive precipitation anomalies (Rawlins et al., 2009). In some basins, increases in snow water equivalent (SWE) have supported higher peak and annual discharge (Troy et al., 2021). However, SWE in northern Canada has generally declined over recent decades (Liston and Hiemstra, 2011; Brown et al., 2019) as warming temperatures have shifted precipitation from snowfall to rainfall during the shoulder seasons (Bitanja et al., 2019). Within North America, summer precipitation has emerged as an especially influential control on streamflow. Increases in discharge in the Yukon and Mackenzie Rivers have been linked to enhanced summer rainfall (Liu et al., 2022), and in smaller Canadian catchments, trends in summer precipitation often explain more streamflow variability than trends in annual totals (Bennet et al., 2023). The increasing frequency of intense summer rainfall events has also been associated with dual-peak hydrographs and long-term increases in winter baseflow (Déry et al., 2016; Spence et al., 2014). These findings indicate that both the amount and timing of precipitation are critical for understanding discharge trends. Yet some regions, such as the Taiga Plains ecoregion, exhibit significant increases in annual and winter discharge have been observed despite the absence of clear precipitation trends (Mack et al., 2021). This spatial and temporal inconsistency in wetting trends suggests that precipitation alone cannot fully explain recent hydrological change.

Permafrost thaw processes also influence streamflow by increasing lateral and vertical hydrological connectivity (Lamontagne-Halle, 2018). In discontinuous permafrost, warming temperatures cause an increase in the active layer thickness (ALT; Walvoord and Kuryluk, 2016). As summer warming drives deeper thaw, winter freeze-back does not reach the permafrost table, resulting in the development of lateral taliks (Connon et al., 2018; Devoie et al., 2019). Increases in the supra-permafrost layer thickness (SLT), defined as the maximum depth of summer thaw or the depth to permafrost (Devoie et al., 2024), and the development and expansion of taliks (Lamontagne-Halle et al., 2019), enlarge the subsurface domain that is thawed and able to transmit water. Taliks, in particular, allow perennial subsurface flow. Thaw-driven landscape change also links previously isolated hydrological units, creating a more integrated drainage network that promotes enhanced runoff and altered flow routing (Connon et al., 2014). Permafrost thaw may also reopen or expand deep flow pathways and reactivate regional groundwater flow systems (Evans et al., 2020). Disturbances such as wildfire further accelerate thaw by increasing SLT and promoting the formation of collapse-scar wetlands (Gibson et al., 2018), which intensify hydrological connectivity.

Peatlands are key ecosystems in discontinuous permafrost zone, where frozen ground restricts drainage and promotes the accumulation of surface water (Woo, 2012). In the Taiga Plains ecoregion of the central Canadian sub-Arctic, the flat, low-lying landscape is dominated by extensive peatland complexes that cover nearly half of the region (Tarnocai et al., 2000). Permafrost in this region is typically thin, ranging from roughly 1.5 to 17 meters (Smith et al., 2010), and is commonly found beneath tree-covered peat plateaus (Wright et al., 2022). Adjacent to plateaus, collapse-scar wetlands

(Quinton et al., 2003) include fens, which are groundwater-fed, nutrient rich, and often hydrologically connected to channel outlets, and bogs, which are ombrotrophic, nutrient poor, and often hydrologically isolated (Gilvear and Bradley, 2009; Clymo, 1964). As climate warming intensifies, the stability of these permafrost-peatland systems is increasingly vulnerable to thaw. Permafrost thaw processes are altering how water enters, moves through, and is stored in northern environments, with significant implications for hydrology (Bring et al., 2016).

Climate change, permafrost thaw, and increasing wildfire activity are all well established as drivers of northern hydrological change. However, relatively few studies have compared the roles of these drivers directly. McClelland et al. (2004) evaluated the influence of increases in precipitation, permafrost thaw, wildfire, and regulation on Eurasian Arctic Ocean discharge, and found that precipitation exerted the strongest influence. Their assessment, however, represented permafrost thaw only through direct ground-ice meltwater contributions, which have since been shown to be a relatively minor component of thaw-induced hydrological change (Connon et al., 2014; Spence et al., 2014). The study also applied a simplified approach to estimate the effects of wildfire and precipitation across a very large region, rather than examining the physical processes that govern streamflow generation. Other studies have considered a subset of these drivers (for example, Mack et al., 2021; Gibson et al., 2018). Yet the individual and cumulative roles of precipitation, permafrost thaw, and wildfire on discharge have not been fully established.

1.3 Research Objectives

Many recent studies have investigated the processes and consequences of rapid permafrost thaw, particularly in the southern Northwest Territories (e.g. Scotty Creek, Ackley et al., 2021; Cannon et al., 2015; Haynes et al., 2018). By contrast, the slightly cooler and drier central Northwest Territories, where hydrological impacts may be even more pronounced, remains comparatively understudied (St. Jacques & Sauchyn, 2009). In response, La Martre River watershed, located within the Taiga Plains and covering approximately 14,500 km², includes the Northwest Territories' third-largest lake (Lac La Martre) and the community of Whatì, and serves as the study area for this thesis.

To address these knowledge gaps, this thesis is structured around two interconnected research objectives that examine the drivers of hydrological change in the peatland-dominated, discontinuous permafrost La Martre River watershed:

1. Identify watershed-scale trends in precipitation and temperature and assess whether long-term hydroclimatic trends can account for recent increases in streamflow.
2. Quantify the individual and cumulative influence of precipitation, permafrost thaw, and wildfire disturbance on streamflow variability, with a particular focus on their relative contributions to observed changes in discharge magnitude and timing.

1.4 Organization of Thesis

This thesis is organized in a manuscript format. The body of the thesis is composed of two chapters (Chapters 2 and 3), which will be submitted to the Journal of

Hydrology, a peer-reviewed academic journal. Each chapter includes a separate introduction and literature review that motivates the objectives within the context of relevant research.

Chapter 2 addresses objective 1 by evaluating long-term climate and hydrological observations to determine whether temperature and precipitation trends are sufficient to explain observed increases in discharge. Special attention is given to assessing the suitability of reanalysis datasets as substitutes for sparse and low-resolution observational records. Chapter 3 addresses objective 2 by employing a hydrological model to quantify the individual and combined influences of increased temperature and precipitation, enhanced permafrost thaw, and wildfire disturbance on the volume and timing of discharge.

Together, these chapters contribute to the interpretation of observed hydrological shifts in northern watersheds and to broader efforts to assess the vulnerability of discontinuous permafrost systems. This thesis supports improved forecasting of water resource availability, enhanced predictions of landscape responses to continued warming, and informs adaptation strategies for northern communities and ecosystems. In doing so, this work responds to concerns identified by residents of Whatì and aligns with the Government of the Northwest Territories directive to evaluate cumulative impacts of climate change.

1.5 Literature Cited

- Ahmed, R., Prowse, T., Dibike, Y., Bonsal, B., & O'Neil, H. (2020). Recent Trends in Freshwater Influx to the Arctic Ocean from Four Major Arctic-Draining Rivers. *Water*, 12(4), 1189. <https://doi.org/10.3390/w12041189>
- Bennett, K. E., Schwenk, J., Bachand, C., Gasarch, E., Stachelek, J., Bolton, W. R., & Rowland, J. C. (2023). Recent streamflow trends across permafrost basins of North America. *Frontiers in Water*, 5. <https://www.frontiersin.org/articles/10.3389/frwa.2023.1099660>
- Bilgili, M., Tumse, S., & Nar, S. (2024). Comprehensive Overview on the Present State and Evolution of Global Warming, Climate Change, Greenhouse Gasses and Renewable Energy. *Arabian Journal for Science and Engineering*, 49(11), 14503–14531. <https://doi.org/10.1007/s13369-024-09390-y>
- Bintanja, R., & Selten, F. M. (2014). Future increases in Arctic precipitation linked to local evaporation and sea-ice retreat. *Nature*, 509(7501), 479–482. <https://doi.org/10.1038/nature13259>
- Bintanja, R., van der Wiel, K., van der Linden, E. C., Reusen, J., Bogerd, L., Krikken, F., & Selten, F. M. (2020). Strong future increases in Arctic precipitation variability linked to poleward moisture transport. *Science Advances*, 6(7), eaax6869. <https://doi.org/10.1126/sciadv.aax6869>
- Box, J. E., Colgan, W. T., Christensen, T. R., Schmidt, N. M., Lund, M., Parmentier, F.-J. W., Brown, R., Bhatt, U. S., Euskirchen, E. S., Romanovsky, V. E., Walsh, J. E., Overland, J. E., Wang, M., Corell, R. W., Meier, W. N., Wouters, B., Mernild, S., Mård, J., Pawlak, J., & Olsen, M. S. (2019). Key indicators of Arctic climate change: 1971–2017. *Environmental Research Letters*, 14(4), 45010. <https://doi.org/10.1088/1748-9326/aafc1b>
- Brabets, T. P., & Walvoord, M. A. (2009). Trends in streamflow in the Yukon River Basin from 1944 to 2005 and the influence of the Pacific Decadal Oscillation. *Journal of Hydrology*, 371(1), 108–119. <https://doi.org/10.1016/j.jhydrol.2009.03.018>
- Bring, A., Fedorova, I., Dibike, Y., Hinzman, L., Mård, J., Mernild, S. H., Prowse, T., Semenova, O., Stuefer, S. L., & Woo, M.-K. (2016). Arctic terrestrial hydrology: A synthesis of processes, regional effects, and research challenges. *Journal of Geophysical Research: Biogeosciences*, 121(3), 621–649. <https://doi.org/10.1002/2015JG003131>
- Brown, R. D., Fang, B., & Mudryk, L. (2019). Update of Canadian Historical Snow Survey Data and Analysis of Snow Water Equivalent Trends, 1967–2016. *Atmosphere-Ocean*, 57(2), 149–156. <https://doi.org/10.1080/07055900.2019.1598843>
- Chasmer, L., Quinton, W., Hopkinson, C., Petrone, R., & Whittington, P. (2011). Vegetation Canopy and Radiation Controls on Permafrost Plateau Evolution within the Discontinuous Permafrost Zone, Northwest Territories, Canada.

- Permafrost and Periglacial Processes*, 22(3), 199–213.
<https://doi.org/10.1002/ppp.724>
- Clymo, R. S. (1964). The Origin of Acidity in Sphagnum Bogs. *The Bryologist*, 67(4), 427. <https://doi.org/10.2307/3240768>
- Connon, R., Devoie, É., Hayashi, M., Veness, T., & Quinton, W. (2018). The Influence of Shallow Taliks on Permafrost Thaw and Active Layer Dynamics in Subarctic Canada. *Journal of Geophysical Research: Earth Surface*, 123(2), 281–297. <https://doi.org/10.1002/2017JF004469>
- Connon, R., Quinton, W. L., Craig, J. R., & Hayashi, M. (2014). Changing hydrologic connectivity due to permafrost thaw in the lower Liard River valley, NWT, Canada. *Hydrological Processes*, 28(14), 4163–4178. <https://doi.org/10.1002/hyp.10206>
- Connon, R., Quinton, W. L., Craig, J. R., Hanisch, J., & Sonnentag, O. (2015). The hydrology of interconnected bog complexes in discontinuous permafrost terrains. *Hydrological Processes*, 29(18), 3831–3847. <https://doi.org/10.1002/hyp.10604>
- Dai, A., Luo, D., Song, M., & Liu, J. (2019). Arctic amplification is caused by sea-ice loss under increasing CO₂. *Nature Communications* 2019 10:1, 10(1), 121-. <https://doi.org/10.1038/s41467-018-07954-9>
- Déry, S. J., & Wood, E. F. (2005). Decreasing river discharge in northern Canada. *Geophysical Research Letters*, 32(10). <https://doi.org/10.1029/2005GL022845>
- Déry, S. J., Hernández-Henríquez, M. A., Burford, J. E., & Wood, E. F. (2009). Observational evidence of an intensifying hydrological cycle in northern Canada. *Geophysical Research Letters*, 36(13). <https://doi.org/10.1029/2009GL038852>
- Déry, S. J., Stadnyk, T. A., MacDonald, M. K., & Gauli-Sharma, B. (2016). Recent trends and variability in river discharge across northern Canada. *Hydrology and Earth System Sciences*, 20(12), 4801–4818. <https://doi.org/10.5194/hess-20-4801-2016>
- Devoie, É. G., Craig, J. R., Connon, R. F., & Quinton, W. L. (2019). Taliks: A Tipping Point in Discontinuous Permafrost Degradation in Peatlands. *Water Resources Research*, 55(11), 9838–9857. <https://doi.org/10.1029/2018WR024488>
- Devoie, É., Connon, R. F., Beddoe, R., Goordial, J., Quinton, W. L., & Craig, J. R. (2024). Disconnected active layers and unfrozen permafrost: A discussion of permafrost-related terms and definitions. *Science of The Total Environment*, 912, 169017. <https://doi.org/10.1016/j.scitotenv.2023.169017>
- Evans, S. G., Yokeley, B., Stephens, C., & Brewer, B. (2020). Potential mechanistic causes of increased baseflow across northern Eurasia catchments underlain by permafrost. *Hydrological Processes*, 34(11), 2676–2690. <https://doi.org/10.1002/hyp.13759>

- Foster, J. L., Cohen, J., Robinson, D. A., & Estilow, T. W. (2013). A look at the date of snowmelt and correlations with the Arctic Oscillation. *Annals of Glaciology*, 54(62), 196–204. <https://doi.org/10.3189/2013AoG62A090>
- Gibson, C. M., Chasmer, L. E., Thompson, D. K., Quinton, W. L., Flannigan, M. D., & Olefeldt, D. (2018). Wildfire as a major driver of recent permafrost thaw in boreal peatlands. *Nature Communications*, 9(1), 3041. <https://doi.org/10.1038/s41467-018-05457-1>
- Gibson, C., Cottenie, K., Gingras-Hill, T., Kokelj, S. v, Baltzer, J. L., Chasmer, L., & Turetsky, M. R. (2021). Mapping and understanding the vulnerability of northern peatlands to permafrost thaw at scales relevant to community adaptation planning. *Environmental Research Letters*, 16(5), 55022. <https://doi.org/10.1088/1748-9326/abe74b>
- Gilvear, D. J., & Bradley, C. (2009). Hydrological Dynamics II: Groundwater and Hydrological Connectivity. In *The Wetlands Handbook* (pp. 169–193). John Wiley & Sons, Ltd. <https://doi.org/10.1002/9781444315813.ch7>
- Hanes, C., Jain, P., Wang, W., Wang, X., Parisien, M.-A., Little, J., & Flannigan, M. D. (2025). Fire regime changes in Canada: an update. *Canadian Journal of Forest Research*. <https://doi.org/10.1139/CJFR-2025-0209>
- Haynes, K. M., Connon, R. F., & Quinton, W. L. (2018). Permafrost thaw induced drying of wetlands at Scotty Creek, NWT, Canada. *Environmental Research Letters*, 13(11), 114001. <https://doi.org/10.1088/1748-9326/aae46c>
- Kelsey, K. C., Pedersen, S. H., Leffler, A. J., Sexton, J. O., Feng, M., & Welker, J. M. (2021). Winter snow and spring temperature have differential effects on vegetation phenology and productivity across Arctic plant communities. *Global Change Biology*, 27(8), 1572–1586. <https://doi.org/10.1111/gcb.15505>
- Lamontagne-Hallé, P., McKenzie, J. M., Kurylyk, B. L., & Zipper, S. C. (2018). Changing groundwater discharge dynamics in permafrost regions. *Environmental Research Letters*, 13(8), 84017. <https://doi.org/10.1088/1748-9326/aad404>
- Lemieux, J.-M., Frampton, A., & Fortier, P. (2024). Recent Advances (2018–2023) and Research Opportunities in the Study of Groundwater in Cold Regions. *Permafrost and Periglacial Processes*, n/a(n/a). <https://doi.org/10.1002/ppp.2255>
- Liston, G. E., & Hiemstra, C. A. (2011). The Changing Cryosphere: Pan-Arctic Snow Trends (1979–2009). *Journal of Climate*, 24(21), 5691–5712. <https://doi.org/10.1175/JCLI-D-11-00081.1>
- Liu, S., Wang, P., Yu, J., Wang, T., Cai, H., Huang, Q., Pozdniakov, S. P., Zhang, Y., & Kazak, E. S. (2022). Mechanisms behind the uneven increases in early, mid- and late winter streamflow across four Arctic river basins. *Journal of Hydrology*, 606, 127425. <https://doi.org/10.1016/j.jhydrol.2021.127425>
- Mack, M., Connon, R., Makarieva, O., McLaughlin, J., Nesterova, N., & Quinton, W. (2021). Heterogenous runoff trends in peatland-dominated basins throughout

- the circumpolar North. *Environmental Research Communications*, 3(7), 75006. <https://doi.org/10.1088/2515-7620/ac11ed>
- Musselman, K. N., Clark, M. P., Liu, C., Ikeda, K., & Rasmussen, R. (2017). Slower snowmelt in a warmer world. *Nature Climate Change* 2017 7:3, 7(3), 214–219. <https://doi.org/10.1038/nclimate3225>
- Obu, J., Westermann, S., Bartsch, A., Berdnikov, N., Christiansen, H. H., Dashtseren, A., Delaloye, R., Elberling, B., Etzelmüller, B., Kholodov, A., Khomutov, A., Kääb, A., Leibman, M. O., Lewkowicz, A. G., Panda, S. K., Romanovsky, V., Way, R. G., Westergaard-Nielsen, A., Wu, T., ... Zou, D. (2019). Northern Hemisphere permafrost map based on TTOP modelling for 2000–2016 at 1 km² scale. *Earth-Science Reviews*, 193, 299–316. <https://doi.org/10.1016/j.earscirev.2019.04.023>
- Overeem, I., & Syvitski, J. P. M. (2010). Shifting Discharge Peaks in Arctic Rivers, 1977–2007. *Geografiska Annaler: Series A, Physical Geography*, 92(2), 285–296. <https://doi.org/10.1111/j.1468-0459.2010.00395.x>
- Overland, J., Dunlea, E., Box, J. E., Corell, R., Forsius, M., Kattsov, V., Olsen, M. S., Pawlak, J., Reiersen, L.-O., & Wang, M. (2019). The urgency of Arctic change. *Polar Science*, 21, 6–13. <https://doi.org/10.1016/j.polar.2018.11.008>
- Pascual, D., & Johansson, M. (2022). Increasing impacts of extreme winter warming events on permafrost. *Weather and Climate Extremes*, 36, 100450. <https://doi.org/10.1016/j.wace.2022.100450>
- Peterson, B. J., Holmes, R. M., McClelland, J. W., Vörösmarty, C. J., Lammers, R. B., Shiklomanov, A. I., Shiklomanov, I. A., & Rahmstorf, S. (2002). Increasing River Discharge to the Arctic Ocean. *Science*, 298(5601), 2171–2173. <https://doi.org/10.1126/science.1077445>
- Quinton, W. L., Hayashi, M., & Pietroniro, A. (2003). Connectivity and storage functions of channel fens and flat bogs in northern basins. *Hydrological Processes*, 17(18), 3665–3684. <https://doi.org/10.1002/hyp.1369>
- Quinton, W., Berg, A., Braverman, M., Carpino, O., Chasmer, L., Connon, R., Craig, J., Devoie, É., Hayashi, M., Haynes, K., Olefeldt, D., Pietroniro, A., Rezanezhad, F., Schincariol, R., & Sonnentag, O. (2019). A synthesis of three decades of hydrological research at Scotty Creek, NWT, Canada. *Hydrology and Earth System Sciences*, 23(4), 2015–2039. <https://doi.org/10.5194/hess-23-2015-2019>
- Rantanen, M., Karpechko, A. Y., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., Vihma, T., & Laaksonen, A. (2022). The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth & Environment*, 3(1), <https://doi.org/10.1038/s43247-022-00498-3>
- Rawlins, M. A., Serreze, M. C., Schroeder, R., Zhang, X., & McDonald, K. C. (2009). Diagnosis of the record discharge of Arctic-draining Eurasian rivers in 2007. *Environmental Research Letters*, 4(4), 45011. <https://doi.org/10.1088/1748-9326/4/4/045011>

- Screen, J. A., & Simmonds, I. (2010). The central role of diminishing sea ice in recent Arctic temperature amplification. *Nature*, 464(7293), 1334–1337. <https://doi.org/10.1038/nature09051>
- Semmens, K. A., Ramage, J., Bartsch, A., & Liston, G. E. (2013). Early snowmelt events: detection, distribution, and significance in a major sub-arctic watershed. *Environmental Research Letters*, 8(1), 14020. <https://doi.org/10.1088/1748-9326/8/1/014020>
- Serreze, M. C., & Barry, R. G. (2011). Processes and impacts of Arctic amplification: A research synthesis. *Global and Planetary Change*, 77(1), 85–96. <https://doi.org/10.1016/j.gloplacha.2011.03.004>
- Shur, Y. L., & Jorgenson, M. T. (2007). Patterns of permafrost formation and degradation in relation to climate and ecosystems. *Permafrost and Periglacial Processes*, 18(1), 7–19. <https://doi.org/10.1002/ppp.582>
- Smith, S. L., Romanovsky, V. E., Lewkowicz, A. G., Burn, C. R., Allard, M., Clow, G. D., Yoshikawa, K., & Throop, J. (2010). Thermal state of permafrost in North America: a contribution to the international polar year. *Permafrost and Periglacial Processes*, 21(2), 117–135. <https://doi.org/10.1002/ppp.690>
- Spence, C., Kokelj, S. A., Kokelj, S. v, & Hedstrom, N. (2014). The process of winter streamflow generation in a subarctic Precambrian Shield catchment. *Hydrological Processes*, 28(14), 4179–4190. <https://doi.org/10.1002/hyp.10119>
- St. Jacques, J.-M., & Sauchyn, D. J. (2009). Increasing winter baseflow and mean annual streamflow from possible permafrost thawing in the Northwest Territories, Canada. *Geophysical Research Letters*, 36(1). <https://doi.org/10.1029/2008GL035822>
- Tarnocai, C., Kettles, I. M., & Lacelle, B. (2000). *Peatlands of Canada*. <https://doi.org/10.4095/211269>
- Troy, T. J., Sheffield, J., & Wood, E. F. (2012). The role of winter precipitation and temperature on northern Eurasian streamflow trends. *Journal of Geophysical Research: Atmospheres*, 117(D5). <https://doi.org/10.1029/2011JD016208>
- Vihma, T., Screen, J., Tjernström, M., Newton, B., Zhang, X., Popova, V., Deser, C., Holland, M., & Prowse, T. (2016). The atmospheric role in the Arctic water cycle: A review on processes, past and future changes, and their impacts. *Journal of Geophysical Research: Biogeosciences*, 121(3), 586–620. <https://doi.org/10.1002/2015JG003132>
- Vincent, L. A., Zhang, X., Mekis, É., Wan, H., & Bush, E. J. (2018). Changes in Canada's Climate: Trends in Indices Based on Daily Temperature and Precipitation Data. *Atmosphere-Ocean*, 56(5), 332–349. <https://doi.org/10.1080/07055900.2018.1514579>
- Walsh, J. E., Bigalke, S., McAfee, S. A., Lader, R., Serreze, M. C., & Ballinger, T. J. (2023). *NOAA Arctic Report Card 2023 : Precipitation*. <https://doi.org/10.25923/hcm7-az41>

- Walvoord, M. A., & Kurylyk, B. L. (2016). Hydrologic Impacts of Thawing Permafrost—A Review. *Vadose Zone Journal*, 15(6), vzj2016.01.0010. <https://doi.org/10.2136/vzj2016.01.0010>
- Woo, M. (2012). *Permafrost Hydrology*. <https://books.scholarsportal.info/en/read?id=/ebooks/ebooks2/springer/2012-05-29/1/9783642234620#page=15>
- Wright, S. N., Thompson, L. M., Olefeldt, D., Connon, R. F., Carpino, O. A., Beel, C. R., & Quinton, W. L. (2022). Thaw-induced impacts on land and water in discontinuous permafrost: A review of the Taiga Plains and Taiga Shield, northwestern Canada. *Earth-Science Reviews*, 232, 104104. <https://doi.org/10.1016/j.earscirev.2022.104104>
- Yang, D., Shi, X., & Marsh, P. (2015). Variability and extreme of Mackenzie River daily discharge during 1973–2011. *Quaternary International*, 380–381, 159–168. <https://doi.org/10.1016/j.quaint.2014.09.023>
- Zhang, X., Vihma, T., Rinke, A., Moore, G. W. K., Tang, H., Äijälä, C., DuVivier, A., Huang, J., Landrum, L., Li, C., Zhang, J., Boisvert, L., Cheng, B., Cohen, J., Handorf, D., Hanna, E., Hartmuth, K., Jonassen, M. O., Luo, Y., ... Zhang, M. (2025). Weather and climate extremes in a changing Arctic. *Nature Reviews Earth & Environment*, 6(11), 691–711. <https://doi.org/10.1038/s43017-025-00724-4>

Chapter 2 Assessing Climate-Hydrology Interactions in La Martre River Watershed Using ERA5-Land Reanalysis

Abstract

Increases in discharge have been observed across the pan-Arctic, but in the Taiga Plains of northern Canada, these trends have not been linked to rising precipitation due to a lack of significant trends in sparse meteorological data. This study evaluates the potential of ERA5-Land reanalysis to detect long-term climatic trends and explore climate-hydrology interactions in La Martre River watershed in the central Northwest Territories. The three main objectives of the study were to: (1) assess the suitability of ERA5-Land for identifying climate trends in a northern watershed with limited in situ meteorological observations, (2) characterize the spatial and temporal variability of temperature and precipitation trends within the watershed, and (3) examine the influence of climatic variables on discharge timing and volume, and hydrograph shape. The period of study spans 1977–2023, during which significant hydrological changes were observed, including trends in both annual and winter discharge. ERA5-Land was found to reliably capture long-term trends, with statistically significant increases identified in both temperature and precipitation. However, the precipitation trend alone cannot fully explain the observed increase in discharge. The study also underscores how the high variability in temperature and precipitation complicates trend detection. This research highlights the need for improved climate monitoring in northern regions and advances our understanding of climate-hydrology linkages. These insights are critical for supporting adaptation planning in regions vulnerable to climate change and permafrost degradation.

2.1 Introduction

Arctic and sub-arctic regions are warming faster than the global average due to arctic amplification (Screen & Simmonds, 2010; Serreze & Barry, 2011). However, the rate and pattern of temperature and precipitation change vary across latitudes and time scales throughout the pan-Arctic (Rantanen et al., 2022; Serreze & Barry, 2011). In the subarctic regions of northern Canada, these changes are disrupting the energy and water balance, with implications for both terrestrial ecosystems and hydrological processes. Understanding how temperature and precipitation are changing over time is essential for evaluation the hydrological impacts of climate change in northern Canada.

In northern Canada, many studies have reported increasing precipitation and temperature, and especially winter temperature trends (Vincent et al., 2015; Box et al., 2019). In warm discontinuous permafrost zones, high variability in winter air temperatures significantly affect ground thermal regimes, influencing the stability and structure of near-surface permafrost (Fortier et al., 2023; Lemieux et al., 2024). The combined increase in winter temperature and precipitation influences snow accumulation, melt timing, and runoff processes, thereby affecting the timing and magnitude of streamflow (Mudryk et al., 2018). In the sub-arctic, pronounced seasonal and interannual variability in temperature and precipitation complicates the detection of long-term climate trends (Serreze and Barry, 2011). This variability reflects a combination of natural seasonal and synoptic fluctuations and longer-term trends driven by external climatic forcing (Way & Viau, 2015; Deser et al., 2010). However, in many northern catchments, where climate records are short, sparse, or discontinuous, it remains difficult to confidently detect and attribute statistically significant long-term

changes (Woo and Thorne, 2003). These challenges underscore the need for reliable, spatially continuous data sources to improve our ability to monitor and interpret hydroclimatic change in northern environments.

Hydroclimatic trend analysis in northern Canada is challenged by the limited availability and inhomogeneity of observational data. In northern Canada, long-term, homogeneous climate records suitable for trend analysis are rare (Vincent et al., 2012; Way & Bonnaventure, 2015), and the number of stations measuring key variables such as temperature and precipitation has decreased since the early 2000s (Rapać et al., 2015). Even where stations are present, the accuracy of high-latitude winter precipitation measurements is limited by challenges in measuring snow, including persistent under catch, blowing snow, and logistical constraints to accessing sites, which may result in missed or underestimated trends, especially in the winter, an important part of the record (McClelland et al., 2004). Observational datasets are further complicated by inhomogeneities due to changes in instrumentation, station relocations, and other non-climatic influences (Vincent et al., 2012).

Given the limitations in observational weather data, reanalysis products have emerged as a vital alternative for evaluating climate variability and change in data-sparse regions like northern Canada, offering continuous, spatially complete datasets by assimilating available observations into physically based models. Numerous reanalysis products have been applied globally and in Arctic environments for studies involving climate trends, ground temperature and hydrological modeling, and other applications (e.g., Box et al., 2019; Hu et al., 2019; Tarek et al., 2020), including MERRA and MERRA-2, JRA-25, and ERA-Interim, a widely used predecessor to ERA5 (Lindsay et al., 2014). In northeastern Canada, for example, ERA-Interim has been used successfully to

infill sparse observations and analyze climate trends in Labrador (Way & Bonnaventure, 2015). ERA5 and ERA5-Land provide further improvements in spatial and temporal resolution, land-surface representation, and observational assimilation, strengthening their potential for regional-scale climate assessment in Arctic and subarctic environments (Tarek et al., 2020). Despite growing adoption in high-latitude studies (e.g., Boisvert et al., 2023; Box et al., 2019; Yu & Zhong, 2021), evaluations of ERA5-Land performance in northern Canada remain limited. Existing work indicates generally reliable representation of temperature and slight precipitation overestimation in the Canadian prairies (Fatolahzadeh Gheysari et al., 2023; Frank et al., 2022), and the Canadian arctic (Moore, 2024). ERA5-Land has not been evaluated for the suitability for trend analysis in the Canadian sub-arctic. Although reanalysis products may introduce biases, particularly in ungauged areas or under the influence of ocean-atmosphere variability such as El Niño (Cowtan & Way, 2013), they have supported diverse applications from heatwave attribution in western Canada (Whitfield et al., 2024) to land-atmosphere modeling in Alaska and the Yukon River Basin (Cheng et al., 2025). These diverse applications highlight the need for continued evaluation in cold, remote, permafrost-affected basins.

Trends in observational and reanalysis data can be used to better understand the links between climate and the hydrological cycle. Several studies have identified linkages between climate change and shifts in the hydrological cycle in the pan-Arctic (Mack et al., 2021; Overeem & Syvitski, 2010; McClelland et al., 2004). In northern Canada, summer precipitation has been identified as a particularly important control on streamflow (Spence et al., 2014). Increasing early winter discharge in major Arctic watersheds, such as the Yukon and Mackenzie, has been attributed to significant

increases in summer rainfall (Liu et al., 2022), and in smaller Canadian catchments, summer precipitation trends are stronger predictors of streamflow than total annual precipitation (Bennet et al., 2023). Furthermore, in recent years, the increased frequency of intense summer rainfall events has been linked to the development of dual-peak hydrographs and long-term increases in winter baseflow (Déry et al., 2016; Spence et al., 2014). These changes are further modulated by watershed characteristics, such as lakes (Spence et al., 2014), and by permafrost thaw, which enhances subsurface storage and connectivity (Streletskiy et al., 2015).

While hydrological change is often linked to precipitation increases, temperature change has also been identified as a critical driver. Warmer conditions, particularly in winter, have been linked to increased baseflow, especially in discontinuous permafrost regions in Canada (St. Jacques & Sauchyn, 2009; Mack et al., 2021). In contrast, rising summer temperatures and the associated increase in evapotranspiration have likely contributed to a decline in summer baseflow (Murray et al., 2023; Tiwari & Laudon, 2025). These dynamic changes underscore the need for a comprehensive understanding of both temperature and precipitation trends when evaluating streamflow responses, particularly in regions where both variables are subject to high variability.

The objectives of this study are threefold: (1) assess the suitability of ERA5-Land reanalysis data for detecting long-term climatic trends in a northern Canadian watershed, where in situ observations are sparse and discontinuous; (2) characterize the spatial and temporal variability of temperature and precipitation trends within the watershed using ERA5-Land, to better understand how climate change manifests across different locations and timescales in this subarctic environment; and (3) assess the influence of variations in temperature and precipitation on the timing, volume, and

shape of the discharge hydrograph in La Martre River watershed, located in the central Northwest Territories (NWT) and underlain by discontinuous permafrost. By linking reanalysis-based climate indicators with hydrological response, this study contributes to an improved understanding of climate-hydrology interactions in cold regions and the potential for reanalysis data to support hydrological assessments in remote, data-scarce landscapes.

2.2 Methods

2.2.1 Study Site

La Martre River watershed in the Taiga Plains ecoregion of the Northwest Territories (NWT) has a catchment area of approximately 14,500 km² and is underlain by discontinuous permafrost and fractured bedrock (Figure 2.1). This watershed has been monitored continuously by the Water Survey of Canada (WSC) since 1977. During the period of record, discharge has increased dramatically compared to other gauged watersheds in the Canadian sub-arctic and the pan arctic (St. Jacques & Sauchyn, 2009). Within the watershed, there is a single long-term meteorological station located in the community of Whatì. Therefore, this watershed is an excellent study site to test the use of reanalysis data products to understand the linkage between climate change and hydrology.

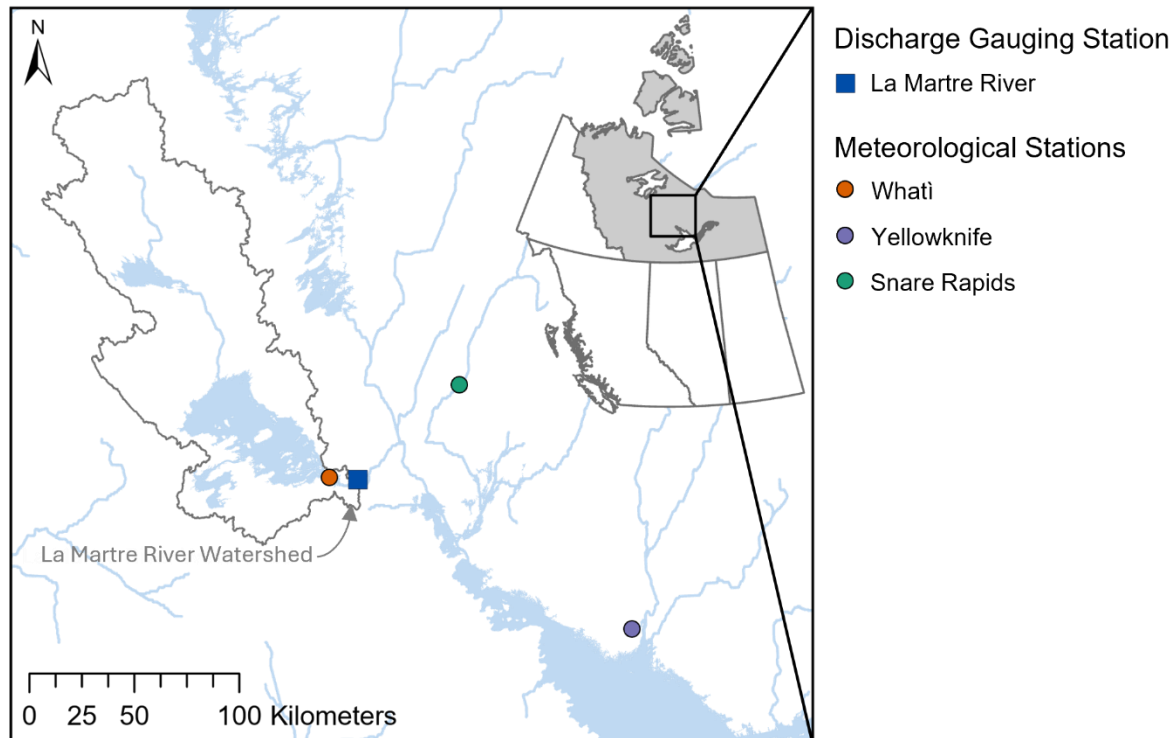


Figure 2.1 Location of La Martre River watershed and study sites. The map shows meteorological stations, discharge gauging stations, and the watershed boundary. The Whatì meteorological station (orange circle) is the only long-term station located within La Martre River watershed. La Martre River flows from Lac La Martre to Great Slave Lake.

Observational and reanalysis data were compared and used to calculate temporal trends. Observational meteorological station data were sourced from the three nearest Environment and Climate Change Canada (ECCC) weather stations to the watershed: Whatì located at the southern extent of La Martre River watershed on the shore of Lac La Martre, and Yellowknife A and Snare Rapids located approximately 150, and 70 km from La Martre River gauging station (Figure 2.1, Table 2.1). Snare Rapids precipitation data were supplemented from ECCC Atmospheric Precipitation Chemistry station at Snare Rapids. Each station provides nearly continuous temperature (precipitation) data for at least 15 (5) years (Table 2.1).

*Table 2.1 Meteorological stations within and near La Martre River watershed. Site ID refers to the Environment and Climate Change Canada Climate ID, with * indicating a Canadian Air and Precipitation Monitoring Network (CAPMoN) site. Start and end years represent the period of continuous daily data with at least 10 complete months. The Snare Rapids CAPMoN site does not report temperature data.*

Station	Site ID	Lat (°)	Lon (°)	Temperature		Precipitation	
				Start	End	Start	End
Whati	2202678	63.13	-117.24	1994	2023	2018	2023
Yellowknife A	2204101	62.46	-114.44	1942	2013	1942	2013
Yellowknife A	2204100	62.46	-114.44	2013	2023	2013	2023
Snare Rapids	2203700	63.52	-116.00	1947	1975	1947	1975
Snare Rapids	CAPMCANT1SNA*	63.51	-116.01	–	–	1988	2023

The suitability of reanalysis data to represent the temporal and spatial variability in temperature, precipitation and climate trends was evaluated in this study. ERA5-Land was selected as it is commonly used in hydrological modeling and has been shown to perform well in other high latitude Canadian regions (Moore, 2024; Walsh et al., 2023). ERA5-Land was developed by the European Centre for Medium-Range Weather Forecasts (ECMWF), and produced using observations from meteorological stations where available, assimilated into a land-surface model and downscaled to a spatial resolution of $0.1^{\circ} \times 0.1^{\circ}$ (Muñoz Sabater, 2019). ERA5-Land offers enhanced spatial resolution that improves the representation of temperature and precipitation of previous ECMWF reanalysis products, while maintaining consistency with the ERA5 model. Throughout this study, findings from other studies from ERA5 and ERA5-Land are both considered as they are derived from the same base model. Hourly 2m air temperature and total precipitation were extracted for the cells containing the selected meteorological stations for the period 1950-2023. All temperature and precipitation data were aggregated to daily values for use in subsequent analyses. ERA5-Land is available at hourly and monthly temporal aggregations. Monthly aggregated ERA5-Land data were retrieved for the entire region of La Martre River watershed ($62.9^{\circ}\text{N}, 117.0^{\circ}\text{W}$ – $64.8^{\circ}\text{N}, 120.1^{\circ}\text{W}$) for the period 1950-2022 to assess the

spatial patterns in temperature and precipitation. The watershed delineation used throughout was derived from the North American Lake-River Routing Product v2.0 (NALRRP; Han et al., 2023), adapted through comparison with an ArcGIS-based watershed delineation of the high resolution ActicDEM (Porter et al., 2023; Appendix B).

2.2.2 Observational Data Gap-Filling

Continuous observational data are essential for trend analysis. Observational records were divided into continuous segments, with breaks defined by short (1–several days) or extended (several months) gaps. Only periods with at least four months of continuous data per hydrological year (October–September) were retained, except for Whatì in 2013 which was retained despite having insufficient data to maintain a sufficiently long continuous record for trend analysis (Appendix A). Linear relationships were established between daily temperatures at Whatì and Yellowknife, and Snare Rapids and Yellowknife. Missing temperature values in Whatì and Snare Rapids were infilled using the linearly adjusted data from Yellowknife, and gaps in Yellowknife data were filled using the mean of linearly adjusted Whatì and Snare Rapids when both were available, or otherwise the available station. Precipitation gaps were infilled directly between stations without adjustment. When all stations were missing data for the same day, values were estimated using the long-term mean for that day based on the full observational record of each station.

2.2.3 Reanalysis Data Bias Correction

Reanalysis data products are produced from physically based models and assimilated station and satellite data. Regardless of the reanalysis product selected,

there are differences between the reanalysis and the observed temperature and precipitation. The systematic difference between the datasets is called the bias. Many bias-correction algorithms have been developed to improve the accuracy of reanalysis data and vary in complexity (Pierce et al., 2015). Despite the availability of more complex techniques a straightforward method was chosen due to the lack of available observational data for comparison and for ease of application. Monthly scaling factors were derived through comparison of ERA5-Land data with Yellowknife ECCC station observations and applied to correct ERA5-Land data for the other two sites (see Appendix A). The scaling factor was applied to the temperature and precipitation data by multiplying the factor by the reanalysis value. Bias correction used the *getBiasFactor* function from the *hyfo* R package (Xu, 2023). For precipitation, a 0.02 mm threshold was used to exclude trace precipitation, as recommended by Xu (2023).

2.2.4 Anomaly Calculation

To compare observational, reanalysis, and bias-corrected reanalysis data, anomalies were calculated against the base period of observational data for each aggregation period of interest (e.g., annual, monthly, seasonal). The 1990–2019 period was selected as the reference base period as it provides the most complete observational coverage (≥ 15 years for all stations and variables). Gap-filled observational data were not used for this analysis; accordingly, years with fewer than 350 days, months with fewer than 28 days, and seasons with more than five missing days were omitted. Agreement between observational and reanalysis datasets, both raw and bias-corrected, was evaluated using the coefficient of determination (R^2) and root mean square error

(RMSE). Monthly and seasonal comparisons included all available months and seasons, with anomalies aggregated at the corresponding temporal scale.

2.2.5 Discharge Data

To link climatic and hydrologic changes in the water balance of La Martre River watershed, a hydrometric analysis was conducted by comparing historical river discharge with precipitation data. Discharge records were obtained from the WSC hydrometric station La Martre River below outlet of Lac La Martre, Station ID 07TA001, (Figure 2.1) for the period 1977-2023. Winter baseflow was taken as the total discharge in the months of January through March. This was considered a proxy for baseflow as the surface is frozen (St. Jacques & Sauchyn, 2009). The winter baseflow percent was calculated as the total winter baseflow divided by the total discharge for each hydrological year.

2.2.6 Trend Analysis

The trends in temperature, precipitation, and discharge were analyzed in R using the non-parametric Mann-Kendall trend test and Sen slope indicator at annual, seasonal, and monthly timescales. A 95% confidence interval (p-value less than or equal to 0.05) was used to identify significance, except where otherwise stated.

The annual period was defined according to the hydrological year, spanning October to September, and labeled by the latter calendar year (e.g., the 1979 hydrological year spans October 1978 to September 1979). Seasons were delineated based on the typical annual hydrograph pattern: winter baseflow (October 1–February 28/29), peak flow (March 1–June 30), and summer recession (July 1–September 30), hereafter referred to as winter, spring, and summer, respectively. Note, the winter season defined here differs from the winter baseflow discharge period (January 1–

March 1). The winter season represents the low flow period during the months with sub-zero average temperatures, excluding March and April which begin to show spring snowmelt-driven discharge increase. Monthly and seasonal trends reflect changes over time in the respective month or season across the specified analysis period.

Trends were calculated for each continuous period of observational temperature and precipitation data at each station, ensuring that only periods with sufficient data coverage were included. To enable direct comparison between observational and reanalysis data, trends in both reanalysis and bias-corrected reanalysis data were computed over the same time periods as the corresponding available observational records. This approach ensures that differences in trend magnitude or direction can be attributed to the data source or correction method, rather than inconsistencies in the analysis period.

To assess the influence of trend period and time window length on temperature and precipitation trends, annual trends based on the hydrological year were calculated using non-bias-corrected reanalysis data for Whatì. Trends were computed for all combinations of start and end years spanning at least 10 years. Spatial patterns in temperature and precipitation and their associated annual and seasonal trends were calculated. Mean annual air temperature (MAAT) and average annual precipitation and long-term trends were then calculated over the full period of available monthly ERA5-Land data for all cells in the watershed, 1950–2022 period. The full 2023 hydrological year was not available at the time of download. Results are expressed in °C or mm per decade.

Trends in discharge and precipitation were analyzed for the period of available discharge 1977–2023. Annual, seasonal, and monthly trends were expressed as percent

change per year, normalized to the predicted discharge or precipitation in the first year of the period, to facilitate comparison with precipitation trends. In addition, trends in total discharge and winter baseflow (JFM discharge) in mm decade⁻¹ and the percent of discharge occurring in the winter flow percent were calculated.

2.3 Results and Discussion

2.3.1 Comparison of ERA5-Land

2.3.1.1 Temperature Means and Anomalies

ERA5-Land captured seasonal temperature patterns at Yellowknife and Whatì but exhibited a cold bias at Yellowknife ($-3.5\text{ }^{\circ}\text{C}$) and a warm bias at Whatì ($+0.85\text{ }^{\circ}\text{C}$) (Figure 2.2). Bias correction improved the representation in Yellowknife but worsened the comparison in Whatì due to the opposing bias directions (Table 2.2), reflecting the spatial variability of ERA5-Land bias. Similar warm biases of up to $2\text{ }^{\circ}\text{C}$ have been reported elsewhere in the Arctic (Tian et al., 2024). While spatially adaptive bias-correction have been shown to effectively reduce bias in heterogeneously represented regions (Voropay et al., 2021), short observational records at Whatì and Snare Rapids, constrain station-specific adjustments. The improvement at Yellowknife indicates that the simple bias-correction method is effective within its applicable range, and seasonal variability in bias supports using monthly rather than static or annual correction factors.

The agreement between ERA5-Land temperature data and observations improves at coarser temporal scales (Table 2.2). Despite this, ERA5-Land effectively captures variability at monthly, seasonal, and annual scales, though daily anomalies are less reliable. These results suggest that while ERA5-Land may not accurately reproduce short-term fluctuations, it is well-suited for analyzing broader temporal trends, particularly at annual scales.

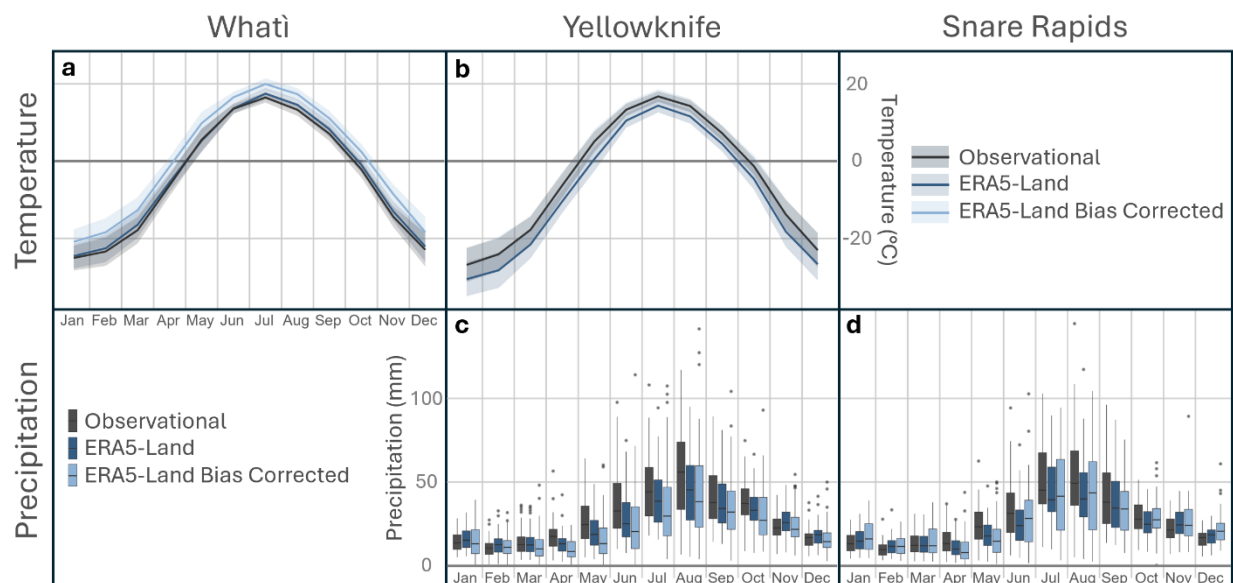


Figure 2.2. Comparison of monthly temperature (a, b) and monthly precipitation (c, d) among observational data, ERA5-Land, and bias-corrected ERA5-Land. Shading in panels (a) and (b) indicates the mean $\pm$ standard deviation. Box plots in panels (c) and (d) show the interquartile range (25th–75th percentiles), with outliers represented by points. The analysis period for each meteorological station corresponds to its available record; the Snare Rapids record includes only data from the CAPMoN station (1988–2023).

Table 2.2 Comparison of annual, seasonal, monthly, and daily temperature and precipitation anomalies between observational, ERA5-Land, and bias-corrected ERA5-Land datasets. The comparison period corresponds to the available observational record for each meteorological station. Anomalies were computed relative to observational data for the period 1990–2019.

	Station	Temporal Aggregation	R ²		RMSE	
			ERA5-Land	ERA5-Land Bias-Corrected	ERA5-Land	ERA5-Land Bias-Corrected
Temperature	Whati	Annual	0.908	0.908	0.942	4.423
	Whati	Seasonal	0.886	0.847	1.029	4.355
	Whati	Monthly	0.904	0.866	1.202	4.514
	Whati	Daily	0.809	0.800	2.656	5.081
	Yellowknife	Annual	0.918	0.918	3.563	0.403
	Yellowknife	Seasonal	0.831	0.898	3.513	0.592
	Yellowknife	Monthly	0.880	0.919	3.701	0.927
	Yellowknife	Daily	0.804	0.814	4.493	2.710
Precipitation	Whati	Daily	0.658	0.658	2.174	2.143
	Yellowknife	Annual	0.106	0.105	93.301	68.863
	Yellowknife	Seasonal	0.112	0.141	42.084	33.409
	Yellowknife	Monthly	0.181	0.209	17.45	15.217
	Yellowknife	Daily	0.097	0.101	2.610	2.474
	Snare Rapids	Annual	0.154	0.157	67.055	54.078
	Snare Rapids	Seasonal	0.242	0.313	33.817	26.513
	Snare Rapids	Monthly	0.377	0.429	13.555	11.781
	Snare Rapids	Daily	0.145	0.145	2.498	2.385

2.3.1.2 Precipitation Means and Anomalies

ERA5-Land simulates precipitation less accurately than temperature (Table 2.2), reflecting the inherently stochastic nature of precipitation (Flato et al., 2013). It slightly overestimates total annual precipitation at Yellowknife and Snare Rapids, consistent with findings from other pan-Arctic regions (Jiang et al., 2021; Lavers et al., 2022; Voropay et al., 2021) (Figure 2.3). Due to limited observational data, performance at Whatì could not be fully assessed. Among the stations analyzed, ERA5-Land shows higher accuracy at Snare Rapids than Yellowknife across temporal scales, possibly reflecting differences in measurement methods between manual and automated gauges (Brown et al., 2021). Despite relatively poor correlation with observations (Table 2.2) the reanalysis captures seasonal precipitation cycles reasonably well at both Yellowknife and Snare Rapids (Figure 2.2).

A known limitation of ERA5-Land and other reanalysis datasets is drizzle bias: the systematic overestimation of light precipitation events and underestimation of high-intensity events (Argüeso et al., 2013; Lazoglou et al., 2024; Xu et al., 2019). Extreme events that are not well captured can skew seasonal averages, particularly during summer when large storms are more frequent. The mismatch between gridded reanalysis and point-based station observations can further contribute to bias, though it is less significant in regions with low topographic variability, such as La Martre River watershed (Benestad et al., 2008; Voropay et al., 2021).

Bias correction improved agreement between ERA5-Land and observations at both Yellowknife and Snare Rapids (Table 2.2). However, its benefit is limited by the complex and variable nature of precipitation. The scaling-based correction method uniformly reduces precipitation values but does not fully resolve the underprediction of

extremes or overprediction of low-intensity events. While daily-scale accuracy remains poor, the bias-corrected approach is appropriate for large, slowly responding basins, such as La Martre River watershed, where cumulative precipitation over longer periods is more relevant than short-term variability. Addressing these biases is essential for improving the reliability of reanalysis data in hydrological and climate impact studies.

2.3.1.3 Comparison of Temperature Trends

The magnitude and significance of mean annual air temperature trends are generally consistent between ERA5-Land and observational datasets across the three stations. However, ERA5-Land shows slightly higher trends (Figure 2.3 a–c). In Yellowknife, a significant warming trend of 0.299 °C/decade was observed and closely mirrored by ERA5-Land (0.304 °C/decade) and bias-corrected ERA5-Land (0.305 °C/decade). In Whatì, a non-significant increasing trend was observed across all datasets, while Snare Rapids showed a slight, non-significant decreasing trend for its period of record (1951–1966).

ERA5-Land also accurately reproduced the seasonal and monthly trends (Figure 2.3 d-i). Wider confidence intervals at stations with shorter records (e.g., Snare Rapids) indicate that longer observational data improve trend detection. Yellowknife exhibited a significant winter warming trend of 0.418 °C/decade, compared with 0.450 °C/decade in both ERA5-Land versions, consistent with accelerated winter warming reported elsewhere. Spring (0.303 °C/decade; 0.193 °C/decade in ERA5-Land) and summer (0.178 °C/decade; 0.184 °C/decade in ERA5-Land) trends were slightly lower ERA5-Land slightly overestimated winter trends and underestimated spring trends. In contrast, non-significant decreasing winter trends were observed at Whatì and Snare Rapids. Interestingly, Yellowknife also showed negative winter trends during the

periods of overlap with those stations (-1.301 °C/decade for 1950–1966; -0.436 °C/decade for 1996–2023), indicating substantial temporal variability in winter temperatures. Overall, these results indicate that ERA5-Land is a reliable dataset for temperature trend analysis, including at seasonal scales.

2.3.1.4 Comparison of Precipitation Trends

Precipitation trends in ERA5-Land generally align in direction with observational data, though the reanalysis tends to show slightly higher annual trends. In Yellowknife, the observed data indicate a non-significant increasing trend of approximately 0.4% decade⁻¹ (relative to the 1991–2000 average), while ERA5-Land shows a greater but still non-significant increase of about 1.4% decade⁻¹. This reanalysis trend closely matches the broader Arctic pattern reported in ERA5 data, which shows an average increase of 1.3% decade⁻¹ (Walsh et al., 2023). In contrast, Snare Rapids exhibited a slight non-significant decreasing trend in annual precipitation over the 1992–2023 period in all datasets. Although ERA5-Land appears to slightly overestimate the rate of change compared to observations, the overall direction and magnitude of trends remain broadly consistent.

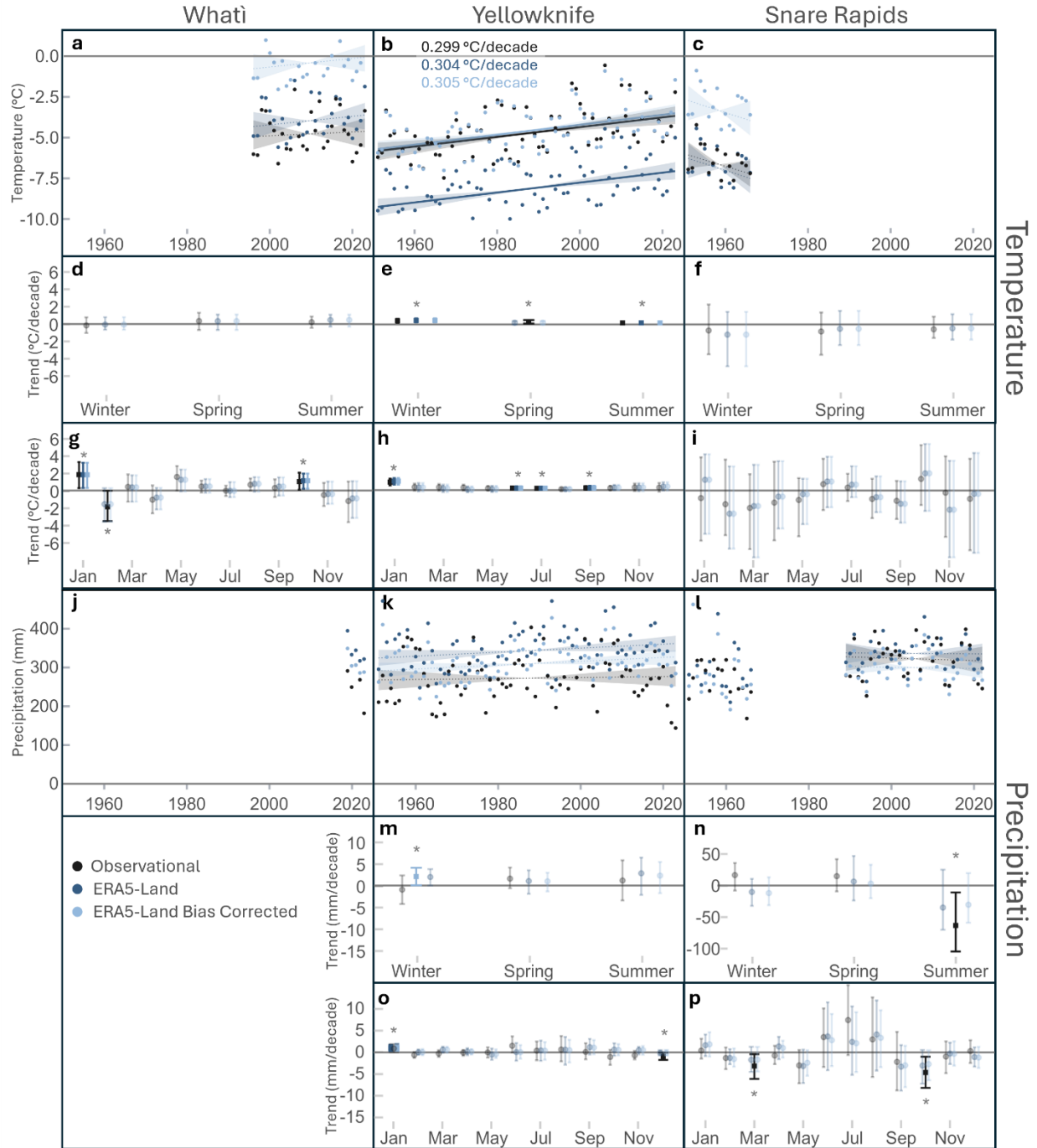


Figure 2.3. Comparison of trends in air temperature and total precipitation derived from observational, ERA5-Land, and bias-corrected ERA5-Land datasets. Panels (a–c) show mean annual temperature, and panels (j–l) show total annual precipitation. Points represent mean annual values, solid lines indicate the trend over the available observational period, and shaded areas denote the 95% confidence interval of the slope for each meteorological station. Panels (d–f) and (g–i) show annual trends in seasonal and monthly mean air temperature, respectively, while panels (m–n) and (o–p) show annual trends in seasonal and monthly total precipitation. Points represent the estimated trend, and error bars indicate the 95% confidence interval. Statistically significant trends are shown in bold and marked with an asterisk.

While individual precipitation events are often poorly captured, ERA5-Land represents broader patterns of interannual variability and extreme event climatology reasonably well, consistent with findings from other regions (Loeb et al., 2022; Frank et al., 2022; Lei et al., 2022). The reanalysis reliably identifies major wet and dry periods, although it tends to underestimate the full range of variability (Figure 2.3 j-l). Notably, ERA5-Land does not fully capture the severity of the recent drying trend observed since 2020 at all three stations, a decline that has had substantial impacts on local hydrology, landscape conditions, and wildfire activity.

Seasonal and monthly precipitation trends in ERA5-Land generally align in direction with observations, though discrepancies exist in magnitude and significance (Figure 2.3 m-p). The only significant observed trend is a decreasing summer trend at Snare Rapids (-63 mm/decade), which contrasts with Spence et al. (2014), who reported increasing late-summer precipitation in a nearby catchment. ERA5-Land does not capture this decline, and it is absent in Yellowknife. Summer precipitation is highly variable at both stations, producing wide confidence intervals for trends between May and September. The largest directional discrepancy occurs in the winter season in Yellowknife, where observations show a slightly negative trend, while ERA5-Land (and its bias-corrected version) shows a significant positive trend (Figure 2.3 m). Given reports of increasing winter precipitation, particularly snowfall, across northern Canada (Mekis & Vincent, 2017), the observed decline at Yellowknife is unexpected and may partly reflect inhomogeneities from a station change in 2013. However, prior studies indicate increasing winter precipitation at Yellowknife before the change (Laing & Binyamin, 2013), supporting ERA5-Land's representation.

Accurate detection of precipitation trends requires homogeneous data, as changes in station quality or measurement methods can affect trend magnitude, significance, and direction (Mudelsee, 2019). In northern Canada, long-term precipitation trends vary by dataset. Homogenized datasets, such as the Adjusted and Homogenized Canadian Climate Data (AHCCD), correct known observational deficiencies and enable robust long-term analyses (Mekis & Vincent, 2017; Vincent et al., 2018; Vincent & Mekis, 2017). AHCCD data are not available for all stations in this study, including Whatì and Snare Rapids. Despite occasional differences in magnitude or significance, ERA5-Land generally captures the direction of seasonal and annual precipitation trends, supporting its use as a proxy where long-term, high-quality observations are lacking.

2.3.2 Effect of Time Window on Trend Analysis

To link hydrological responses to climatic changes in La Martre River watershed, temporal trends in mean temperature and total precipitation for a hydrological year were derived from daily ERA5-Land data in Whatì. However, the direction and magnitude of trends are highly dependent on the length of the time window selected for analysis between 1951 and 2023 (Figure 2.4). The World Meteorological Organization (WMO) recommends a period of 30 or more years to define climate trends or climate conditions, such as climate normals (WMO, 2017). Short-term trends (less than 30 years) showed significant variability in both direction and magnitude, while long-term trends (30+ years) were more stable, though their magnitude still varied, with only a subset being statistically significant, especially for temperature.

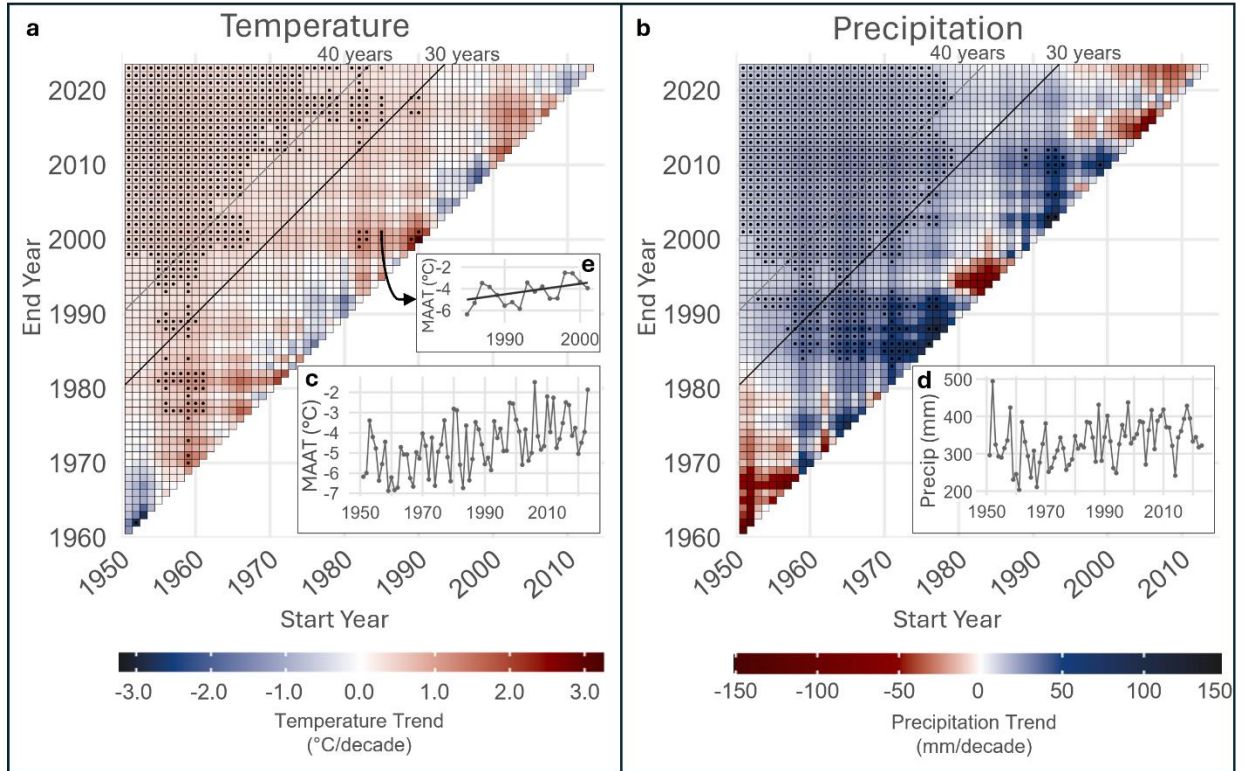


Figure 2.4. Trends in (a) mean annual air temperature and (b) total annual precipitation derived from ERA5-Land data for Whatì (63.1°N, 117.2°W) during 1951–2023. Each cell represents the slope of the annual trend for the period defined by its Start Year and End Year. Black points denote statistically significant trends at the 95% confidence level. All trends are reported in $^{\circ}\text{C decade}^{-1}$ or mm decade^{-1} . Time windows longer than 30 years (40 years) are located above the black (grey) diagonal line. Insets show the corresponding ERA5-Land records of (c) mean annual air temperature (MAAT) and (d) total annual precipitation. Panel (e) highlights the 1985–2001 (17-year) temperature trend; the color of the selected cell indicates the trend magnitude for the period with the given start and end year.

All significant long-term trends in temperature and precipitation indicate increases. For periods of 30 years or more, the average temperature trend was $0.38^{\circ}\text{C decade}^{-1}$ (range: $0.27\text{--}0.63^{\circ}\text{C decade}^{-1}$) and the average precipitation trend was $18.46\text{ mm decade}^{-1}$ (range: $10.09\text{--}33.41\text{ mm decade}^{-1}$) (Figure 2.4). Over 40-year periods, trends were slightly weaker, while the proportion of significant trends increased (temperature: $0.37^{\circ}\text{C decade}^{-1}$, range: $0.27\text{--}0.55^{\circ}\text{C decade}^{-1}$; precipitation: $17.18\text{ mm decade}^{-1}$, range: $10.09\text{--}26.54\text{ mm decade}^{-1}$). The trends for the full 1951–2023 time series were $0.32^{\circ}\text{C decade}^{-1}$ for temperature and $10.91\text{ mm decade}^{-1}$ for precipitation (both significant, $p < 0.0001$). As time windows lengthened, trend magnitudes became

more consistent, highlighting the importance of using the full data set for accurate trend analysis, particularly in future predictions. For example, relying on the maximum magnitude significant long-term trend would overestimate the 2023 predicted mean temperature by 2.23°C and precipitation by 162 mm compared to the 72-year trend.

The selection of the time window length used to define climate trends is crucial for accurately assessing the rate and direction of climate change. In this study, the majority of statistically significant trends were identified in time windows longer than 30 years, consistent with previous research in northern Atlantic Canada that reports sustained increases in temperature and precipitation over multi-decadal scales, with less pronounced trends for shorter periods, particularly for precipitation (Thistle & Caissie, 2013). While some studies argue that shorter time windows may better capture the rapid and non-linear nature of recent climate shifts (Scherrer et al., 2024), our results indicate that significant trends observed in sub-30-year periods often exhibited larger magnitudes than those derived from longer time windows (Figure 2.4). This suggests that shorter datasets may overestimate the rate of warming or wetting relative to long-term trends, emphasizing the importance of using at least 30 years of data for robust climate trend assessments.

The impact of interannual variability also poses a challenge for accurately detecting climate trends, as extreme weather events can distort both short-term and long-term trend analyses. Extreme wet and dry periods, such as those in the 1950s and early 2020s, obscure the long-term trends; 40-year trends that include these anomalous periods often fail to show statistical significance, despite most long-term precipitation trends typically being significant (Figure 2.4). Furthermore, short-term trends that include these periods may show drying patterns, in contrast to the prevailing wetting

trends observed over the entire period, highlighting the vulnerability of short-term climate analyses to extreme events, particularly when such events occur at the beginning or end of the observation period. In the Arctic, where both temperature and precipitation variability are projected to increase by up to 40% by the end of the 21st century (Bitanja et al., 2020; Konapala et al., 2017), such interannual fluctuations can mask underlying trends. This underscores the limitations of relying solely on trends to assess climate change, especially when year-to-year variability can reduce the relevance of these trends for understanding current or future hydrological conditions. For instance, although the long-term trend in Whatì indicates increasing precipitation, a severe drought in 2024-2025 led to the lowest recorded water levels in La Martre River, illustrating how short-term extremes can overshadow long-term trends.

These findings align with broader evidence that the sensitivity of detected climate trends depends strongly on the chosen analysis window. For instance, Rantanen et al. (2022) demonstrated that the rate of Arctic amplification varies with time window length, with the most pronounced acceleration observed over 25-year periods. Similarly, the so-called “global warming hiatus” of the early 2010s, in which global mean temperatures appeared to stabilize (Kosaka & Xie, 2013), was largely an artifact of the temporal window applied; extending the record to include data beyond 2017 revealed a continued upward trend (Meghaud et al., 2017). These examples show that trend magnitude and significance can be highly sensitive to the length of the dataset used, particularly in regions with sparse or discontinuous records such as the NWT, where data limitations can substantially influence the interpretation of climate variability and change.

2.3.3 Assessment of Spatial Variability in Trends

2.3.3.1 Annual Means and Trends

Annual and seasonal trends in mean temperature and total precipitation for the hydrological year were calculated using monthly ERA5-Land data for all grid cells within La Martre River watershed (Figure 2.5). Across the watershed, there is a pronounced spatial gradient in both temperature and precipitation. Mean annual temperature varies by nearly 4°C, ranging from -7.8°C in the northern and higher-elevation areas to -3.9°C in the southwest (Figure 2.5 a). A localized cooling effect is evident over Lac La Martre (see Figure 2.1 for lake location). Precipitation exhibits a more distinct spatial gradient than temperature. Most of the watershed receives between 325 and 395 mm yr⁻¹ of precipitation, while the far northern portion receives considerably more, up to 465 mm yr⁻¹ (Figure 2.5 b). ERA5-Land has been shown to reliably capture such spatial variability in precipitation (McCrystall et al., 2021; Moore, 2024). Despite this variability across the ~14,500 km² watershed, there is only one operational meteorological station (in Whatì). For comparison, a 50km radius area around Kingston, Ontario (~7,900 km²), hosts 34 ECCC weather stations. This stark difference highlights the scarcity of in-situ climate data in the watershed, despite the large variability in temperature and precipitation. This variability likely contributes to spatial differences in hydrological processes such as discharge generation and permafrost vulnerability across the watershed.

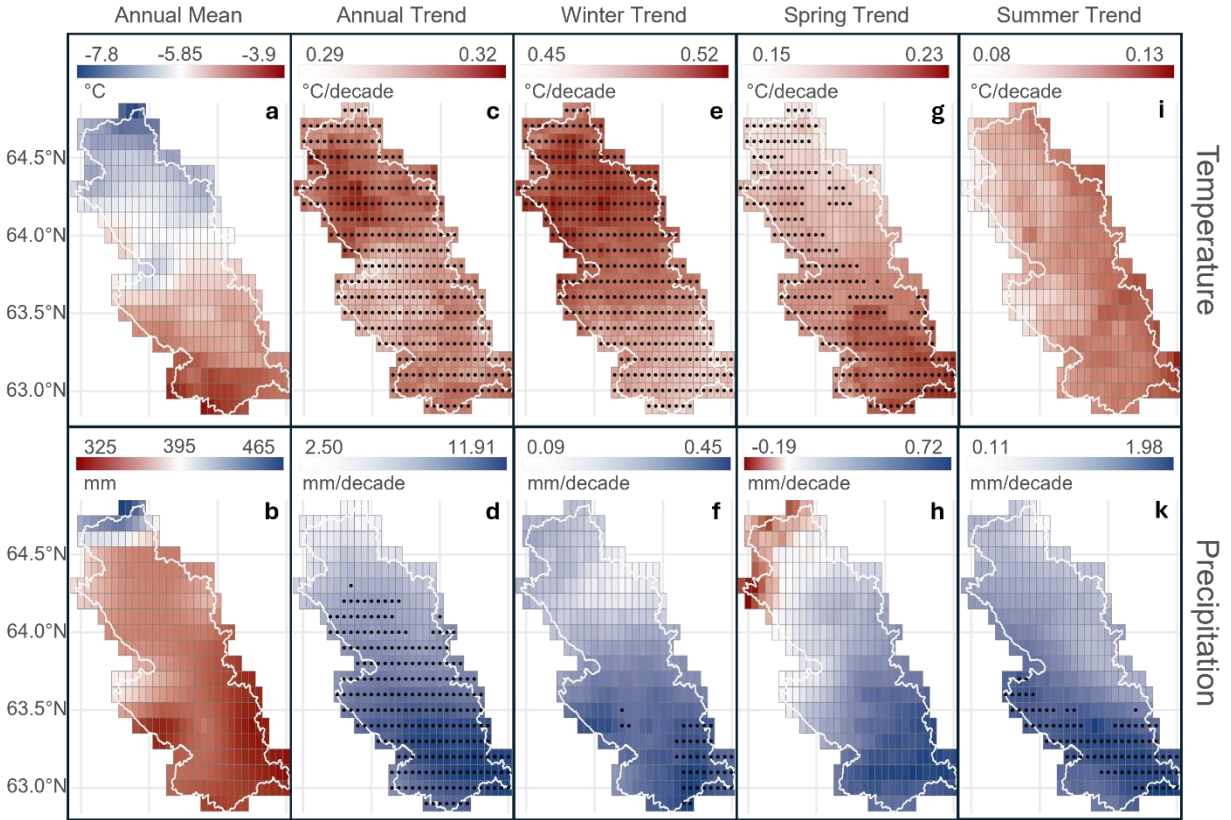


Figure 2.5. Spatial distribution of (a) mean annual air temperature and (b) total annual precipitation for the full record 1951–2022, and trends in (c–d) annual and seasonal (e, g, i) temperature and (f, h, k) precipitation, respectively, based on ERA5–Land. Each cell in panels (c–k) represents the trend magnitude in mean annual or seasonal temperature or precipitation at that grid location. Black points denote statistically significant trends at the 95% confidence level. La Martre River watershed boundary is shown in white. Color scales differ among panels to emphasize spatial variability: in (a–b) white indicates the mean value, while in (c–k) white corresponds to a trend magnitude of zero.

Significant positive trends in annual temperature and precipitation were observed across most of the watershed, except for precipitation in the far north. Temperatures increased at rates of $0.29\text{--}0.32\text{ }^{\circ}\text{C decade}^{-1}$ (Figure 2.5 c), with slightly faster warming in the northern half, consistent with the broader pattern of faster high-latitude warming (Zheng et al., 2019; Rantanen et al., 2022). Precipitation increased by $5.9\text{--}11.9\text{ mm decade}^{-1}$, decreasing from south to north. Areas with lower baseline precipitation, particularly the southeastern region near Whatì, experienced the fastest increases. Assuming that the ERA5–Land pattern is accurate, hydrological projections

based solely on Whatì data overestimate precipitation impacts, emphasizing the need for a denser network to capture spatial variability across large northern watersheds.

2.3.3.2 Seasonal Trends

Seasonal analyses indicate that the overall increase in annual precipitation is primarily driven by summer, while other seasons show smaller or inconsistent changes. Significant summer trends range from 1.25 to 1.98 mm decade⁻¹, concentrated in the southern watershed, particularly near Whatì and along a northwest-oriented band across Lac La Martre (Figure 2.5 i). Winter precipitation trends are weaker but significant in parts of the southern watershed, whereas spring trends are spatially inconsistent and not statistically significant, with modest increases in the south and east and slight decreases in the northwest (Figure 2.5 e,g).

Seasonal temperature trends also vary across the watershed. Winter shows the strongest warming, with significant trends of 0.45–0.52 °C decade⁻¹ and a stable northward-increasing gradient (Figure 2.5 f). Accelerated winter warming has been documented as a dominant feature of Arctic amplification, which is expected to intensify in the coming decades (Cohen et al., 2014; Screen & Simmonds, 2010). Spring and summer temperature trends are smaller, and slightly elevated trends over Lac La Martre (Figure 2.5 h). This pattern suggests that recent warming has been dominated by cold-season temperature increases, whereas summer temperatures have changed little, which may indicate that the increase in summer evapotranspiration is less significant than the winter changes on the hydrological cycle.

2.3.4 Hydrometric Analysis

Alterations to the hydrological cycle have been widely documented across watersheds in the Northwest Territories and the Taiga Plains ecoregion in response to climate change (e.g., Wright et al., 2022; Spence et al., 2014; Wang et al., 2021). La Martre River has experienced particularly pronounced increases. St. Jacques and Sauchyn (2009) reported increases in annual discharge of $3.9\% \text{ yr}^{-1}$ and in winter baseflow (January 1–March 31) of $8.1\% \text{ yr}^{-1}$ for the period 1977–2007, the second largest among the catchments they examined, after the much smaller Jean-Marie River (mean discharge $0.3 \text{ m}^3 \text{ s}^{-1}$). Extending the record to 2023, our analysis indicates an annual discharge increase of $2.1\% \text{ yr}^{-1}$ and a winter discharge increase of $3.4\% \text{ yr}^{-1}$. Although the magnitude of these trends has decreased relative to the earlier study, the continued positive trajectory over a 46-year period demonstrates a persistent intensification of the hydrological regime in La Martre watershed. As previously discussed (Section 2.3.2), extending the temporal window generally diminishes the magnitude of observed precipitation and temperature trends (Figure 2.4). A similar pattern may apply to discharge, such as identified by Déry et al. (2009) in the reversal in the direction of North American Arctic Ocean discharge trends when the analysis period was lengthened (Déry & Wood, 2005).

The total volume of the discharge hydrograph has changed substantially over time (Figure 2.6). However, the rate of hydrological change has not been uniform throughout the 21st century. The hydrograph displays an overall upward shift in discharge between the earliest (1977–1988) and second-most-recent (2000–2012) periods, indicating a general increase in flow across all seasons. Although annual mean

discharge has declined slightly in the most recent period, winter flows remain elevated relative to earlier periods, reflecting a persistent increase in winter baseflow. The mean annual discharge during the most recent period (2013–2023) has decreased to levels comparable to those observed during 1989–2000. Despite their similar volumes, the hydrograph shapes differ: the 2013–2023 period exhibits a steeper summer baseflow recession than 1989–2000, even though both intervals show similar peak discharges, which occur approximately five days earlier in the later period. Variability in discharge has also increased markedly since the early record, as indicated by the widening of the shaded region (representing the standard error), particularly during winter months (Figure 2.6). This enhanced variability suggests that the hydrological regime has become increasingly sensitive to interannual climatic fluctuations.

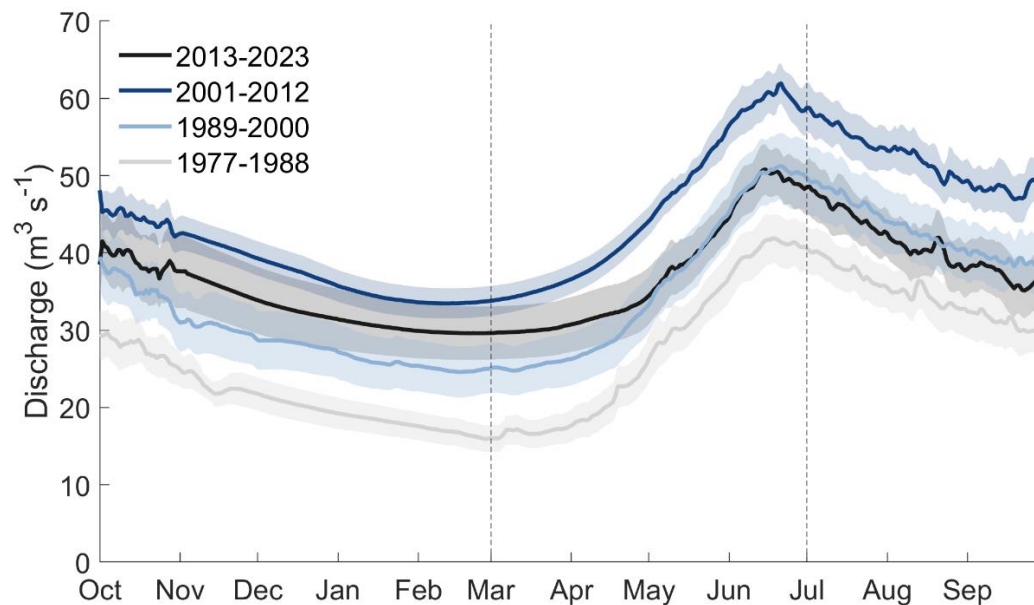


Figure 2.6. Daily mean discharge ($\text{m}^3 \text{s}^{-1}$) over the hydrological year at La Martre River below outlet of Lac La Martre Water Survey of Canada (WSC) gauging station, shown for four time periods. Shaded envelopes denote the mean $\pm$ standard error for each day. Dashed vertical lines indicate seasonal boundaries.

Increased temperature may also contribute to the observed alterations in the hydrological cycle. Air temperature has increased significantly in Whatì during the

discharge record period (1977–2023; Figure 2.4 a). Moreover, the rate of annual temperature increase is greater across most of the watershed than in Whatì (Figure 2.5 c). The majority of this warming is concentrated in winter and spring (Figure 2.5 e,g). Rising temperatures can enhance discharge by accelerating snowmelt, thereby increasing surface runoff while the ground remains frozen (Park et al., 2024; Liu et al., 2022), or indirectly through permafrost degradation (Walvoord & Kurylyk, 2016). These mechanisms may help explain the sustained elevation in winter discharge during the most recent period (2013–2023; Figure 2.6), even as total precipitation has declined since its peak around 2012 (Figure 2.4 b).

Increased precipitation likely accounts for part of the observed discharge rise. Numerous studies have linked enhanced precipitation to higher discharge across Arctic and subarctic basins (McClelland et al., 2004; Rawlins et al., 2009; Bennett et al., 2023, and others). Within La Martre River watershed, the increase in annual precipitation ($11.15 \text{ mm decade}^{-1}$, 1977–2023) slightly exceeds the increase in specific discharge ($10.80 \text{ mm decade}^{-1}$; Figure 2.7, Note, the figure shows the percent increase per year). While the trend in annual precipitation is not significant at the 95% confidence level ($0.05 < p < 0.10$), this is likely driven by the anomalous precipitation in 2023, as all longer trends are significant (Figure 2.4 b). Mack et al. (2021) reported that the Taiga Plains ecoregion was one of the few pan-Arctic regions where discharge increases were not clearly linked to precipitation trends. However, our analysis indicates statistically significant increases in both variables, implying that precipitation has indeed contributed to higher flows in this basin.

The very low discharge observed at the beginning of the record may, in part, reflect the influence of a mid-1970s drought, resulting in anomalously low flows and

giving the appearance of a monotonic increase over time. However, ERA5-Land precipitation data indicate that although the mid-1970s were drier than subsequent decades, they do not represent a significant departure from earlier conditions (Figure 2.4 b). Consequently, the apparent shift from the 1970s to the present is more consistent with a long-term increase in precipitation rather than a short-term recovery from an isolated dry period coinciding with the start of the discharge record. This interpretation supports the conclusion that the observed rise in annual discharge in La Martre River is at least partly driven by a sustained upward trend in precipitation.

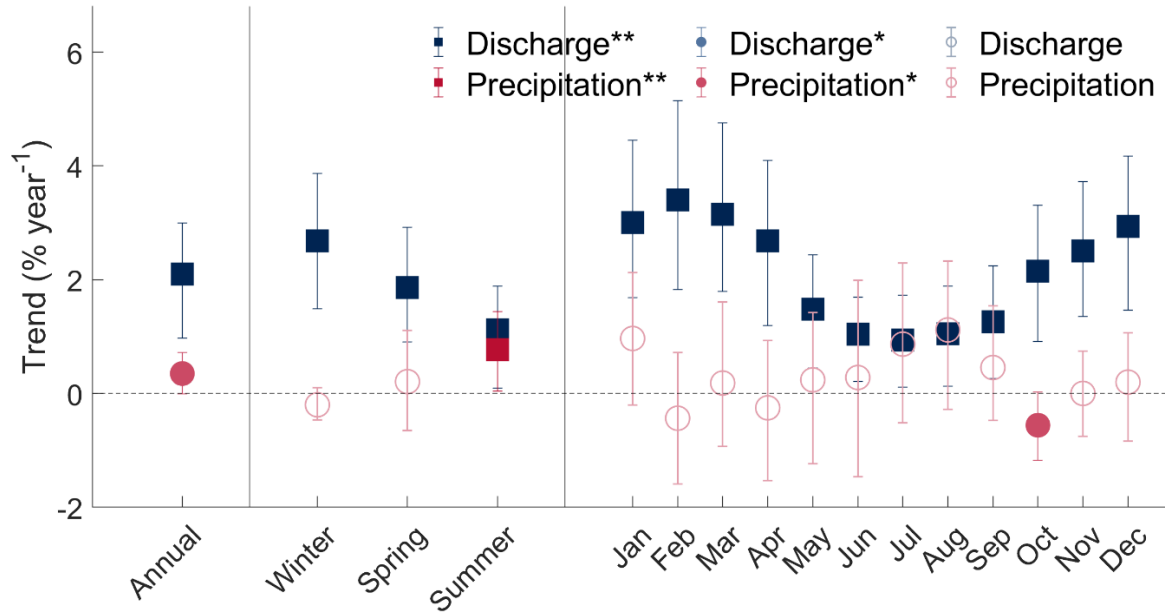


Figure 2.7, Annual, seasonal, and monthly trends in ERA5-Land precipitation at Whatì (63.1°N, 117.2°W; red) and La Martre River discharge (blue) for 1977–2023. Trend significance is indicated by symbol style: dark squares for $p < 0.05$, light circles for $0.05 \leq p < 0.10$, and open circles for $p \geq 0.10$. Error bars denote 95% confidence intervals. Trends are expressed as $\% \text{ yr}^{-1}$, relative to the predicted value in the initial year (1977). A horizontal dashed line marks zero trend, and solid vertical lines separate annual, seasonal, and monthly groupings.

Although the increase in precipitation is nearly equivalent to the increase in specific discharge when expressed in absolute terms (mm decade^{-1}), the relative rate of change is greater for discharge ($2.3 \% \text{ yr}^{-1}$) than for precipitation ($0.4 \% \text{ yr}^{-1}$). This discrepancy suggests that the runoff ratio, the proportion of precipitation that reaches

the watershed outlet, has increased over time. While enhanced precipitation alone may contribute modestly to higher runoff ratios (Zhang et al., 2018), several other processes likely play a more substantial role in the Taiga Plains ecoregion and similar permafrost-affected watersheds. Permafrost thaw has been shown to increase hydrological connectivity in discontinuous permafrost landscapes by thickening the active layer (the seasonally thawed zone) and promoting the development of taliks, or perennially unfrozen layers (Bense et al., 2009; Lamontagne-Hallé et al., 2018). Thawing permafrost may also expand the extent of runoff-generating land cover types, such as fens and hydrologically connected bogs, effectively enlarging the contributing drainage area (Connon et al., 2014). In addition, deeper thaw can reactivate sub-permafrost flow paths, enhancing subsurface drainage and contributing to higher overall discharge (Evans et al., 2020).

The increase in discharge is significant across all temporal aggregations for every season and month, whereas precipitation shows significant upward trends only during summer (Figure 2.7). During winter, when the ground surface is frozen, precipitation accumulates as snow and contributes to spring peak flows upon melt. In contrast, late-summer rainfall can infiltrate the unfrozen active layer and be stored in the subsurface before freeze-up, sustaining elevated winter baseflow (Spence et al., 2014; Liu et al., 2022). This mechanism likely accounts for part of the observed increase in winter discharge. However, the persistence and magnitude of the winter trend, particularly the substantial rise in each of the winter months (Nov.-Mar.; Figure 2.7), may also indicate enhanced subsurface connectivity associated with permafrost thaw. Supporting this interpretation, the proportion of annual discharge occurring as winter baseflow increased statistically significantly from approximately 16% to 22% between 1977 and

2023 (Figure 2.8). While seasonal precipitation contributes to elevated winter flows, the sustained increase in winter baseflow likely reflects long-term shifts in subsurface flow pathways driven by permafrost degradation.

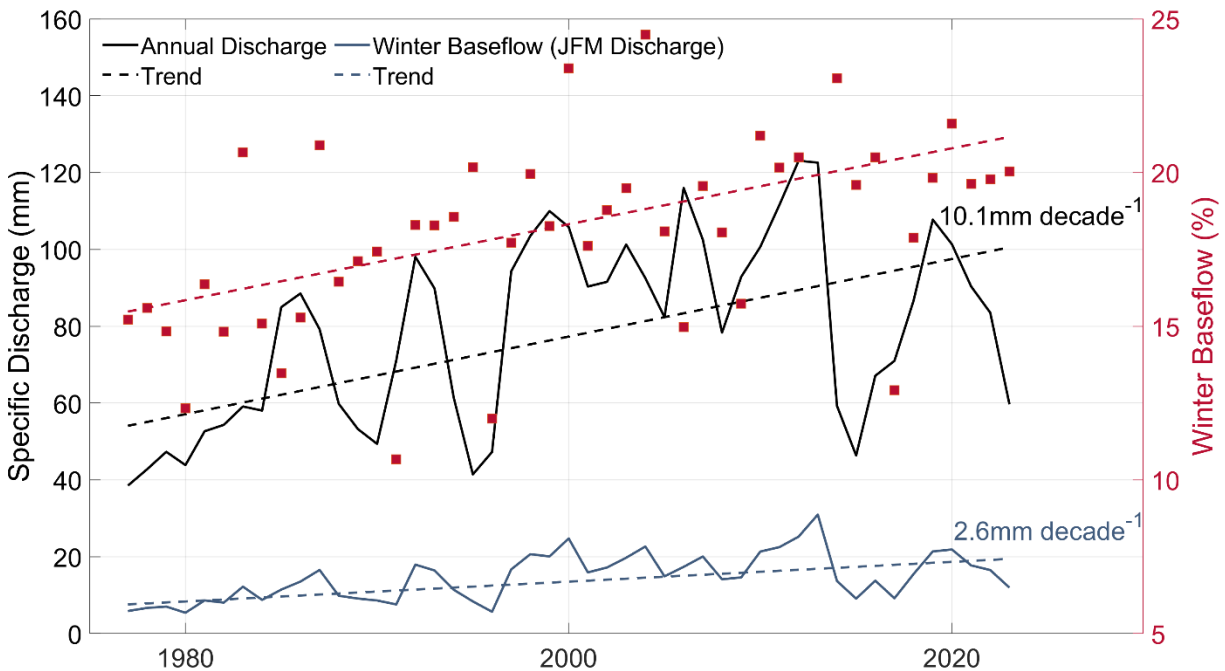


Figure 2.8. Annual and winter (January–March) specific discharge at La Martre River gauging station (1977–2022) for the ~14,500 km² watershed. Dashed lines indicate linear trends of 10.1 mm decade⁻¹ (annual) and 2.6 mm decade⁻¹ (winter), both significant at the 95% confidence level. The proportion of annual discharge occurring in winter is shown by red squares, with its trend also indicated by a dashed line, also significant (right axis).

Overall, La Martre River record demonstrates that both the volume and timing of discharge are linked to increases in precipitation and, to a lesser extent direct temperature increase, but may be increasingly impacted by permafrost thaw processes. Continued warming is likely to enhance subsurface flow contributions and further modify the hydrograph shape, with implications for water availability, sediment transport, and aquatic ecosystems in northern environments.

2.4 Conclusions

Trends in precipitation and temperature are key drivers of changing hydrological regimes in northern Canadian catchments underlain by discontinuous permafrost. The detection of these climate–hydrology linkages remains challenging due to sparse observational coverage, uneven data quality, and high intra- and inter-annual variability. Reanalysis datasets, such as ERA5-Land, are therefore frequently used to fill spatial and temporal gaps. This study focused on La Martre River watershed in the Taiga Plains ecoregion of the Northwest Territories, a region undergoing rapid hydrological change where annual and winter discharge have increased significantly over the 1977–2023 period. The objectives of this study were to: (1) evaluate the performance of ERA5-Land against observations near the watershed (Whatì, Yellowknife, and Snare Rapids); (2) characterize the spatial variability and role of the time window on climate trends in the watershed; and (3) assess how variations in climate forcing influence discharge timing, volume, and hydrograph shape.

Key findings from the study include:

- ERA5-Land accurately represents temperature on annual and seasonal scales, though precision varies, while precipitation is generally overestimated. Improved long-term precipitation monitoring in northern Canada would greatly enhance reanalysis verification and hydrological application.
- Simple scaling bias-correction is suitable for annual temperature adjustment, but spatial variability in bias must be considered. For precipitation, simple scaling exacerbates “drizzle bias” and is not recommended for daily, monthly or seasonal analyses, although it can adjust annual totals to match the observational record.

- ERA5-Land captures annual and seasonal trends in temperature and precipitation, including their direction and magnitude. Monthly trends are more uncertain and spatially inconsistent.
- Strong temporal variability in both climate variables complicates trend detection. When anomalous values occur near the start or end of the record, ≥ 40 -year time windows increase the likelihood of identifying robust climate trends.
- Spatial variability in climate change signals exists across the watershed. Annual and winter temperature trends increase from south to north, while spring and summer trends are weaker and less spatially consistent. Precipitation trends are significant across most of the watershed, particularly in summer, but not in the wetter far north of the watershed.
- Annual discharge in La Martre River has increased (annual: $10.1 \text{ mm decade}^{-1}$, winter baseflow: $2.6 \text{ mm decade}^{-1}$) since 1977. Although annual precipitation increases are slightly larger (11.1 mm yr^{-1}), changes in runoff ratios, flow timing, and hydrograph shape indicate additional control from other factors such as permafrost thaw.

Overall, this work underscores the need for enhanced high-quality, long-term climate observations and improved understanding of hydrological responses to changing climate forcing and permafrost degradation. As northern climates continue to warm and become more variable, the resulting shifts in hydrology will have direct implications for water availability, ecosystem function, and community water security. Quantifying these changes is essential to support climate adaptation in northern regions.

2.5 Literature Cited

- Argüeso, D., Evans, J. P., & Fita, L. (2013). Precipitation bias correction of very high resolution regional climate models. *Hydrology and Earth System Sciences*, 17(11), 4379–4388. <https://doi.org/10.5194/hess-17-4379-2013>
- Benestad, R. E., Hanssen-Bauer, I., & Chen, D. (2008). *Empirical-statistical downscaling*. World Scientific Publ.
- Bennett, K. E., Schwenk, J., Bachand, C., Gasarch, E., Stachelek, J., Bolton, W. R., & Rowland, J. C. (2023). Recent streamflow trends across permafrost basins of North America. *Frontiers in Water*, 5. <https://www.frontiersin.org/articles/10.3389/frwa.2023.1099660>
- Bense, V. F., Ferguson, G., & Kooi, H. (2009). Evolution of shallow groundwater flow systems in areas of degrading permafrost. *Geophysical Research Letters*, 36(22). <https://doi.org/10.1029/2009GL039225>
- Bintanja, R., van der Wiel, K., van der Linden, E. C., Reusen, J., Bogerd, L., Krikken, F., & Selten, F. M. (2020). Strong future increases in Arctic precipitation variability linked to poleward moisture transport. *Science Advances*, 6(7), eaax6869. <https://doi.org/10.1126/sciadv.aax6869>
- Boisvert, L. N., Webster, M. A., Parker, C. L., & Forbes, R. M. (2023). Rainy Days in the Arctic. *Journal of Climate*, 36(19), 6855–6878. <https://doi.org/10.1175/JCLI-D-22-0428.1>
- Box, J. E., Colgan, W. T., Christensen, T. R., Schmidt, N. M., Lund, M., Parmentier, F.-J. W., Brown, R., Bhatt, U. S., Euskirchen, E. S., Romanovsky, V. E., Walsh, J. E., Overland, J. E., Wang, M., Corell, R. W., Meier, W. N., Wouters, B., Mernild, S., Mård, J., Pawlak, J., & Olsen, M. S. (2019). Key indicators of Arctic climate change: 1971–2017. *Environmental Research Letters*, 14(4), 45010. <https://doi.org/10.1088/1748-9326/aafc1b>
- Brown, R., Smith, C., Derksen, C., & Mudryk, L. (2021). Canadian In Situ Snow Cover Trends for 1955–2017 Including an Assessment of the Impact of Automation. *Atmosphere-Ocean*, 59(2), 77–92. <https://doi.org/10.1080/07055900.2021.1911781>
- Cheng, Y., Craig, A., Musselman, K., Bennett, A., Seefeldt, M., Hamman, J., & Newman, A. J. (2025). Coupled High-Resolution Land-Atmosphere Modeling for Hydroclimate and Terrestrial Hydrology in Alaska and the Yukon River Basin (1990–2021). *Journal of Geophysical Research: Atmospheres*, 130(1). <https://doi.org/10.1029/2024JD041185>
- Cohen, J., Screen, J. A., Furtado, J. C., Barlow, M., Whittleston, D., Coumou, D., Francis, J., Dethloff, K., Entekhabi, D., Overland, J., & Jones, J. (2014). Recent Arctic amplification and extreme mid-latitude weather. *Nature Geoscience*, 7(9), 627–637. <https://doi.org/10.1038/ngeo2234>

- Cowtan, K., & Way, R. G. (2014). *Biases in the instrumental temperature record: the policy and communications context*. 2014, GC43G-05. <https://ui.adsabs.harvard.edu/abs/2014AGUFMGC43G..05C>
- Déry, S. J., & Wood, E. F. (2005). Decreasing river discharge in northern Canada. *Geophysical Research Letters*, 32(10). <https://doi.org/10.1029/2005GL022845>
- Déry, S. J., Stadnyk, T. A., MacDonald, M. K., & Gauli-Sharma, B. (2016). Recent trends and variability in river discharge across northern Canada. *Hydrology and Earth System Sciences*, 20(12), 4801–4818. <https://doi.org/10.5194/hess-20-4801-2016>
- Deser, C., Phillips, A., Bourdette, V., & Teng, H. (2012). Uncertainty in climate change projections: the role of internal variability. *Climate Dynamics*, 38(3), 527–546. <https://doi.org/10.1007/s00382-010-0977-x>
- Evans, S. G., Yokeley, B., Stephens, C., & Brewer, B. (2020). Potential mechanistic causes of increased baseflow across northern Eurasia catchments underlain by permafrost. *Hydrological Processes*, 34(11), 2676–2690. <https://doi.org/10.1002/hyp.13759>
- Fatolahzadeh Gheysari, A., Maghoul, P., Ojo, E. R., & Shalaby, A. (2024). Reliability of ERA5 and ERA5-Land reanalysis data in the Canadian Prairies. *Theoretical and Applied Climatology*, 155(4), 3087–3098. <https://doi.org/10.1007/s00704-023-04771-z>
- Fortier, P., Young, N. L., Lemieux, J., Walvoord, M. A., & Fortier, R. (2023). Long-Term, High-Resolution Permafrost Monitoring Reveals Coupled Energy Balance and Hydrogeologic Controls on Talik Dynamics Near Umiujaq (Nunavik, Québec, Canada). *Water Resources Research*, 59(1). <https://doi.org/10.1029/2022WR032456>
- Frank, T., da Silva Junior, C. A., Chutko, K. J., Teodoro, P. E., de Oliveira-Júnior, J. F., & Guo, X. (2022). Is the Gridded Data Accurate? Evaluation of Precipitation and Historical Wet and Dry Periods from ERA5 Data for Canadian Prairies. *Remote Sensing*, 14(24), 6347. <https://doi.org/10.3390/rs14246347>
- Han, M., Shen, H., Tolson, B. A., Craig, J. R., Mai, J., Lin, S. G. M., Basu, N. B., & Awol, F. S. (2023). BasinMaker 3.0: A GIS toolbox for distributed watershed delineation of complex lake-river routing networks. *Environmental Modelling & Software*, 164, 105688. <https://doi.org/10.1016/j.envsoft.2023.105688>
- Hu, G., Zhao, L., Li, R., Wu, X., Wu, T., Xie, C., Zhu, X., & Su, Y. (2019). Variations in soil temperature from 1980 to 2015 in permafrost regions on the Qinghai-Tibetan Plateau based on observed and reanalysis products. *Geoderma*, 337, 893–905. <https://doi.org/10.1016/j.geoderma.2018.10.044>
- Jiang, Y., Yang, K., Shao, C., Zhou, X., Zhao, L., Chen, Y., & Wu, H. (2021). A downscaling approach for constructing high-resolution precipitation dataset over the Tibetan Plateau from ERA5 reanalysis. *Atmospheric Research*, 256, 105574. <https://doi.org/10.1016/j.atmosres.2021.105574>

- Konapala, G., Mishra, A., & Leung, L. R. (2017). Changes in temporal variability of precipitation over land due to anthropogenic forcings. *Environmental Research Letters*, 12(2), 24009. <https://doi.org/10.1088/1748-9326/aa568a>
- Kosaka, Y., & Xie, S.-P. (2013). Recent global-warming hiatus tied to equatorial Pacific surface cooling. *Nature*, 501(7467), 403–407. <https://doi.org/10.1038/nature12534>
- Laing, J., & Binyamin, J. (2013). Climate Change Effect on Winter Temperature and Precipitation of Yellowknife, Northwest Territories, Canada from 1943 to 2011. *American Journal of Climate Change*, 2(4), 275–283. <https://doi.org/10.4236/ajcc.2013.24027>
- Lamontagne-Hallé, P., McKenzie, J. M., Kurylyk, B. L., & Zipper, S. C. (2018). Changing groundwater discharge dynamics in permafrost regions. *Environmental Research Letters*, 13(8), 84017. <https://doi.org/10.1088/1748-9326/aad404>
- Lavers, D. A., Simmons, A., Vamborg, F., & Rodwell, M. J. (2022). An evaluation of ERA5 precipitation for climate monitoring. *Quarterly Journal of the Royal Meteorological Society*, 148(748), 3152–3165. <https://doi.org/10.1002/qj.4351>
- Lazoglou, G., Economou, T., Anagnostopoulou, C., Zittis, G., Tzyrkalli, A., Georgiades, P., & Lelieveld, J. (2024). Multivariate adjustment of drizzle bias using machine learning in European climate projections. *Geoscientific Model Development*, 17(11), 4689–4703. <https://doi.org/10.5194/gmd-17-4689-2024>
- Lei, X., Xu, W., Chen, S., Yu, T., Hu, Z., Zhang, M., Jiang, L., Bao, R., Guan, X., Ma, M., Wei, J., Feng, A., & Gao, L. (2022). How Well Does the ERA5 Reanalysis Capture the Extreme Climate Events Over China? Part I: Extreme Precipitation. *Frontiers in Environmental Science*, 10. <https://doi.org/10.3389/fenvs.2022.921658>
- Lemieux, J.-M., Frampton, A., & Fortier, P. (2024). Recent Advances (2018–2023) and Research Opportunities in the Study of Groundwater in Cold Regions. *Permafrost and Periglacial Processes*, n/a(n/a). <https://doi.org/10.1002/ppp.2255>
- Lindsay, R., Wensnahan, M., Schweiger, A., & Zhang, J. (2014). *Evaluation of Seven Different Atmospheric Reanalysis Products in the Arctic*. <https://doi.org/10.1175/JCLI-D-13-00014.1>
- Liu, S., Wang, P., Yu, J., Wang, T., Cai, H., Huang, Q., Pozdniakov, S. P., Zhang, Y., & Kazak, E. S. (2022). Mechanisms behind the uneven increases in early, mid- and late winter streamflow across four Arctic river basins. *Journal of Hydrology*, 606, 127425. <https://doi.org/10.1016/j.jhydrol.2021.127425>
- Loeb, N. A., Crawford, A., Stroeve, J. C., & Hanesiak, J. (2022). Extreme Precipitation in the Eastern Canadian Arctic and Greenland: An Evaluation of Atmospheric Reanalyses. *Frontiers in Environmental Science*, 10. <https://doi.org/10.3389/fenvs.2022.866929>
- Mack, M., Cannon, R., Makarieva, O., McLaughlin, J., Nesterova, N., & Quinton, W. (2021). Heterogenous runoff trends in peatland-dominated basins throughout

- the circumpolar North. *Environmental Research Communications*, 3(7), 75006. <https://doi.org/10.1088/2515-7620/ac11ed>
- McClelland, J. W., Holmes, R. M., Peterson, B. J., & Stieglitz, M. (2004). Increasing river discharge in the Eurasian Arctic: Consideration of dams, permafrost thaw, and fires as potential agents of change. *Journal of Geophysical Research: Atmospheres*, 109(D18). <https://doi.org/10.1029/2004JD004583>
- McCrystall, M. R., Stroeve, J., Serreze, M., Forbes, B. C., & Screen, J. A. (2021). New climate models reveal faster and larger increases in Arctic precipitation than previously projected. *Nature Communications*, 12(1), 6765. <https://doi.org/10.1038/s41467-021-27031-y>
- Medhaug, I., Stolpe, M. B., Fischer, E. M., & Knutti, R. (2017). Reconciling controversies about the ‘global warming hiatus.’ *Nature*, 545(7652), 41–47. <https://doi.org/10.1038/nature22315>
- Mekis, É., & Vincent, L. A. (2017). An Overview of the Second Generation Adjusted Daily Precipitation Dataset for Trend Analysis in Canada. In *Data, Models and Analysis*. Routledge.
- Moore, R. E. M. (2024). *Evaluation and bias adjustment of daily ERA5 precipitation in the Canadian Arctic*. <https://doi.org/10.14288/1.0444045>
- Mudelsee, M. (2019). Trend analysis of climate time series: A review of methods. *Earth-Science Reviews*, 190, 310–322. <https://doi.org/10.1016/j.earscirev.2018.12.005>
- Mudryk, L. R., Derksen, C., Howell, S., Laliberté, F., Thackeray, C., Sospedra-Alfonso, R., Vionnet, V., Kushner, P. J., & Brown, R. (2018). Canadian snow and sea ice: historical trends and projections. *The Cryosphere*, 12(4), 1157–1176. <https://doi.org/10.5194/tc-12-1157-2018>
- Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D. G., Piles, M., Rodríguez-Fernández, N. J., Zsoter, E., Buontempo, C., & Thépaut, J.-N. (2021). ERA5-Land: a state-of-the-art global reanalysis dataset for land applications. *Earth System Science Data*, 13(9), 4349–4383. <https://doi.org/10.5194/essd-13-4349-2021>
- Murray, J., Ayers, J., & Brookfield, A. (2023). The impact of climate change on monthly baseflow trends across Canada. *Journal of Hydrology*, 618, 129254. <https://doi.org/10.1016/j.jhydrol.2023.129254>
- Overeem, I., & Syvitski, J. P. M. (2010). Shifting Discharge Peaks in Arctic Rivers, 1977–2007. *Geografiska Annaler: Series A, Physical Geography*, 92(2), 285–296. <https://doi.org/10.1111/j.1468-0459.2010.00395.x>
- Park, H., Kim, Y., Suzuki, K., & Hiyama, T. (2024). Influence of snowmelt on increasing Arctic river discharge: numerical evaluation. *Progress in Earth and Planetary Science*, 11(1), 13. <https://doi.org/10.1186/s40645-024-00617-y>

- Pierce, D. W., Cayan, D. R., Maurer, E. P., Abatzoglou, J. T., & Hegewisch, K. C. (2015). *Improved Bias Correction Techniques for Hydrological Simulations of Climate Change*. <https://doi.org/10.1175/JHM-D-14-0236.1>
- Porter, C., Howat, I., Noh, M.-J., Husby, E., Khuvis, S., Danish, E., Tomko, K., Gardiner, J., Negrete, A., Yadav, B., Klassen, J., Kelleher, C., Cloutier, M., Bakker, J., Enos, J., Arnold, G., Bauer, G., Morin, P., & Polar Geospatial Center. (2023). *ArcticDEM - Mosaics, Version 4.1*. Harvard Dataverse. <https://doi.org/10.7910/DVN/3VDC4W>
- Rantanen, M., Karpechko, A. Y., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., Vihma, T., & Laaksonen, A. (2022). The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth & Environment*, 3(1), 1–10. <https://doi.org/10.1038/s43247-022-00498-3>
- Rapačić, M., Brown, R., Markovic, M., & Chaumont, D. (2015). An Evaluation of Temperature and Precipitation Surface-Based and Reanalysis Datasets for the Canadian Arctic, 1950–2010. *Atmosphere-Ocean*, 53(3), 283–303. <https://doi.org/10.1080/07055900.2015.1045825>
- Rawlins, M. A., Serreze, M. C., Schroeder, R., Zhang, X., & McDonald, K. C. (2009). Diagnosis of the record discharge of Arctic-draining Eurasian rivers in 2007. *Environmental Research Letters*, 4(4), 45011. <https://doi.org/10.1088/1748-9326/4/4/045011>
- Scherrer, S. C., de Valk, C., Begert, M., Gubler, S., Kotlarski, S., & Croci-Maspoli, M. (2024). Estimating trends and the current climate mean in a changing climate. *Climate Services*, 33, 100428. <https://doi.org/10.1016/j.cliser.2023.100428>
- Screen, J. A., & Simmonds, I. (2010). The central role of diminishing sea ice in recent Arctic temperature amplification. *Nature*, 464(7293), 1334–1337. <https://doi.org/10.1038/nature09051>
- Serreze, M. C., & Barry, R. G. (2011). Processes and impacts of Arctic amplification: A research synthesis. *Global and Planetary Change*, 77(1), 85–96. <https://doi.org/10.1016/j.gloplacha.2011.03.004>
- Spence, C., Kokelj, S. A., Kokelj, S. v, & Hedstrom, N. (2014). The process of winter streamflow generation in a subarctic Precambrian Shield catchment. *Hydrological Processes*, 28(14), 4179–4190. <https://doi.org/10.1002/hyp.10119>
- St. Jacques, J.-M., & Sauchyn, D. J. (2009). Increasing winter baseflow and mean annual streamflow from possible permafrost thawing in the Northwest Territories, Canada. *Geophysical Research Letters*, 36(1). <https://doi.org/10.1029/2008GL035822>
- Streletskiy, D. A., Tananaev, N. I., Opel, T., Shiklomanov, N. I., Nyland, K. E., Streletskaya, I. D., Tokarev, I., & Shiklomanov, A. I. (2015). Permafrost hydrology in changing climatic conditions: seasonal variability of stable isotope composition in rivers in discontinuous permafrost. *Environmental Research Letters*, 10(9), 095003. <https://doi.org/10.1088/1748-9326/10/9/095003>

- Tarek, M., Brissette, F. P., & Arsenault, R. (2020). Evaluation of the ERA5 reanalysis as a potential reference dataset for hydrological modelling over North America. *Hydrology and Earth System Sciences*, 24(5), 2527–2544. <https://doi.org/10.5194/hess-24-2527-2020>
- Thistle, M. E., & Caissie, D. (2013). *Trends in air temperature, total precipitation, and streamflow characteristics in eastern Canada*.
- Tian, T., Yang, S., Høyer, J. L., Nielsen-Englyst, P., & Singha, S. (2024). Cooler Arctic surface temperatures simulated by climate models are closer to satellite-based data than the ERA5 reanalysis. *Communications Earth & Environment*, 5(1), 111. <https://doi.org/10.1038/s43247-024-01276-z>
- Tiwari, T., & Laudon, H. (2025). Trends in hydroclimate extremes: how changes in winter affect water storage and baseflow. *Hydrology and Earth System Sciences*, 29(17), 4055–4071. <https://doi.org/10.5194/hess-29-4055-2025>
- Vincent, L. A., & Mekis, É. (2017). Changes in Daily and Extreme Temperature and Precipitation Indices for Canada over the Twentieth Century. In *Data, Models and Analysis*. Routledge.
- Vincent, L. A., Wang, X. L., Milewska, E. J., Wan, H., Yang, F., & Swail, V. (2012). A second generation of homogenized Canadian monthly surface air temperature for climate trend analysis. *Journal of Geophysical Research: Atmospheres*, 117(D18). <https://doi.org/10.1029/2012JD017859>
- Vincent, L. A., Zhang, X., Brown, R. D., Feng, Y., Mekis, E., Milewska, E. J., Wan, H., & Wang, X. L. (2015). Observed Trends in Canada's Climate and Influence of Low-Frequency Variability Modes. *Journal of Climate*, 28(11), 4545–4560. <https://doi.org/10.1175/JCLI-D-14-00697.1>
- Vincent, L. A., Zhang, X., Mekis, É., Wan, H., & Bush, E. J. (2018). Changes in Canada's Climate: Trends in Indices Based on Daily Temperature and Precipitation Data. *Atmosphere-Ocean*, 56(5), 332–349. <https://doi.org/10.1080/07055900.2018.1514579>
- Voropay, N., Ryazanova, A., & Dyukarev, E. (2021). High-resolution bias-corrected precipitation data over South Siberia, Russia. *Atmospheric Research*, 254, 105528. <https://doi.org/10.1016/j.atmosres.2021.105528>
- Walsh, J. E., Bigalke, S., McAfee, S. A., Lader, R., Serreze, M. C., & Ballinger, T. J. (2023). *NOAA Arctic Report Card 2023 : Precipitation*. <https://doi.org/10.25923/hcm7-az41>
- Walvoord, M. A., & Kurylyk, B. L. (2016). Hydrologic Impacts of Thawing Permafrost—A Review. *Vadose Zone Journal*, 15(6), vjz2016.01.0010. <https://doi.org/10.2136/vjz2016.01.0010>
- Wang, F., Huang, G. H., Cheng, G. H., & Li, Y. P. (2021). Impacts of climate variations on non-stationarity of streamflow over Canada. *Environmental Research*, 197, 111118. <https://doi.org/10.1016/j.envres.2021.111118>

- Way, R. G., & Viau, A. E. (2015). Natural and forced air temperature variability in the Labrador region of Canada during the past century. *Theoretical and Applied Climatology*, 121(3), 413–424. <https://doi.org/10.1007/s00704-014-1248-2>
- Whitfield, P. H., Abdelmoaty, H., Nerantzaki, S., & Papalexiou, S. M. (2024). The 2021 heatwave results in simultaneous but different hydrological responses over Canada west of 100°W. *Journal of Hydrology*, 632, 130824. <https://doi.org/10.1016/j.jhydrol.2024.130824>
- Woo, M.-K., & Thorne, R. (2003). Streamflow in the Mackenzie Basin, Canada. *Arctic*, 53(4), 328–340.
- World Meteorological Organization (WMO), 2017. *The Climate Normals and the WMO Climate System: Guide to the Calculation of the Standard Normals and Their Use in the Definition of Climatological Normals*, WMO-No. 306. World Meteorological Organization, Geneva, Switzerland.
- Wright, S. N., Thompson, L. M., Olefeldt, D., Connon, R. F., Carpino, O. A., Beel, C. R., & Quinton, W. L. (2022). Thaw-induced impacts on land and water in discontinuous permafrost: A review of the Taiga Plains and Taiga Shield, northwestern Canada. *Earth-Science Reviews*, 232, 104104. <https://doi.org/10.1016/j.earscirev.2022.104104>
- Xu, Y. (2020). *hyfo: Hydrology and climate forecasting R package for data analysis and visualization*. Retrieved from <http://yuanchao-xu.github.io/hyfo/>
- Zhang, Y., Feng, X., Wang, X., & Fu, B. (2018). Characterizing drought in terms of changes in the precipitation–runoff relationship: a case study of the Loess Plateau, China. *Hydrology and Earth System Sciences*, 22(3), 1749–1766. <https://doi.org/10.5194/hess-22-1749-2018>
- Zheng, L., Overeem, I., Wang, K., & Clow, G. D. (2019). Changing Arctic River Dynamics Cause Localized Permafrost Thaw. *Journal of Geophysical Research: Earth Surface*, 124(9), 2324–2344. <https://doi.org/10.1029/2019JF005060>

Chapter 3 Hydrological Modeling of Climate Change, Permafrost Thaw, and Wildfire Impacts on River Discharge in a Discontinuous Permafrost Watershed

Abstract

Accelerated climate warming in northern Canada is driving significant changes in temperature, precipitation patterns, permafrost dynamics, and wildfire frequency and severity. These changes have individually been linked to observed increases in both annual and winter streamflow, though the underlying drivers and cumulative effects remain complex and poorly understood. This study investigated the relative and cumulative contributions of climate change, permafrost thaw, and wildfire activity to streamflow variability in La Martre River watershed in the central Northwest Territories. Using hydrological modeling, the study examined the impact of these drivers in the recent past (1976–2000), present (2001–2025), and future (2026–2050) under a high emissions scenario (RCP 8.5). The results revealed that increased precipitation was the dominant driver, causing a pronounced upward shift in the hydrograph. Permafrost thaw also played a role in enhancing discharge, though its effect was less significant than precipitation. Wildfire, while having a relatively small individual impact, accelerated permafrost thaw, further amplifying streamflow. The cumulative effect of these factors resulted in increased annual and winter discharge greater than any individual factor, with projections indicating that these trends will continue under future climate conditions. These findings highlight the vulnerability of northern watersheds to the interplay of climate, landscape, and permafrost changes, with wide-ranging implications for water availability, ecosystem health, and infrastructure in (sub-)Arctic regions.

3.1 Introduction

Anthropogenic climate warming is altering the hydrologic cycle across Arctic and sub-Arctic river systems, although the rate and pattern of these changes vary by region. Pan-Arctic observations have documented shifts in both the amount and timing of river discharge, with large Eurasian rivers exhibiting consistent increases in total annual flow (Peterson et al., 2002; Berezovskaya et al., 2005; Wang et al., 2021). In contrast, river discharge trends in northern Canada remain less well characterized, with studies reporting inconsistent directions and magnitudes of change (Déry & Wang, 2005; Déry et al., 2009; Overeem & Syvitski, 2010). Nonetheless, several investigations have identified increases in annual discharge (Box et al., 2019; Déry et al., 2016), enhanced winter baseflow (Brabets & Walvoord, 2009; Spence, 2002; St. Jacques & Sauchyn, 2009), and shifts in the timing and intensity of peak flows (Bennett et al., 2023; Yang et al., 2015). These changes are often most pronounced in discontinuous permafrost watersheds (Bennett et al., 2023; Cannon et al., 2014), where hydrological regimes are particularly sensitive to climate change and environmental disturbances, such as wildfire (Gibson et al., 2018).

Changes to hydrological regimes in northern watersheds can trigger cascading physical and ecological consequences, influencing stream chemistry and temperature (Docherty et al., 2019; Tank et al., 2023), promoting river icings (Pavelsky & Zarnetske, 2017), and accelerating erosion and sediment transport (Syvitski, 2002; Moragoda & Cohen, 2020). These shifts have important implications for water availability, quality, and infrastructure in Arctic and sub-Arctic communities (Aygün et al., 2020), yet their underlying mechanisms remain poorly understood. In permafrost-dominated

watersheds, changes in temperature and precipitation (McClelland et al., 2004; Liu et al., 2022), permafrost thaw that alters surface and subsurface connectivity (Connon et al., 2014; Karlsson et al., 2012), and disturbances such as wildfire (Ackley et al., 2021; Gibson et al., 2018) each influence runoff generation and timing. These drivers often interact in complex, nonlinear ways (Rawlins et al., 2021), complicating attribution of observed hydrological changes. Isolating their relative and combined impacts is therefore critical for advancing process-based understanding of watershed responses, informing water resource management, and anticipating future hydrological and climate feedbacks in northern environments.

Warming and wetting patterns driven by climate change are contributing to increasing streamflow across northern watersheds. Observational studies show that surface air temperatures in the (sub-)Arctic have risen in recent decades, accompanied by significant increases in precipitation, with a growing proportion falling as rain rather than snow (Box et al., 2019; Vincent et al., 2015). Northern Canada has experienced some of the most pronounced relative increases in precipitation nationally, particularly during winter months (Wang et al., 2023). For instance, Yellowknife, one of the few stations in the Northwest Territories (NWT) with more than a decade of continuous precipitation data, recorded a 120 mm increase between 1943 and 2011 (Laing & Binyamin, 2013). Meteorological drivers, including changes in temperature and especially precipitation, have been linked to streamflow increases across northern Canada and the pan-Arctic (Liu et al., 2022; Mack et al., 2021; Rawlins et al., 2009). While precipitation increases are more directly associated with discharge increase, ongoing warming in the pan-Arctic likely also contributes to observed streamflow increases through faster and earlier snowmelt and increased evapotranspiration

(Berezovskaya et al., 2005; Wang et al., 2021). These trends are expected to persist under continued climate change (Bintanja, 2018; Cai et al., 2018). However, the scarcity of reliable long-term precipitation records in remote northern regions such as the NWT limits our ability to fully assess the magnitude, significance, and hydrological implications of these temperature and precipitation trends.

Changes in temperature and precipitation regimes are altering hydrological patterns in permafrost regions, reflected in shifts in flow timing and hydrograph shape. In Eurasian rivers, strong evidence indicates widespread increases in peak flow magnitude and earlier timing across large basins (Bennett et al., 2023; Durocher et al., 2019; Overeem & Syvitski, 2010). In contrast, northern Canada shows more consistent increases in winter baseflow than peak discharge. In the Mackenzie and Yukon Rivers, for instance, winter discharge has increased up to five times more than annual streamflow (Liu et al., 2022), with similar patterns observed in smaller catchments. St. Jacques & Sauchyn (2009) reported statistically significant winter baseflow increases in 20 of 23 NWT rivers, compared to annual discharge increases in only nine, particularly within the Taiga Plains ecoregion. Collectively, these findings suggest that while Eurasian systems exhibit pronounced peak flow changes, enhanced winter discharge may be a more sensitive indicator of climatic and permafrost thaw-related hydrological change in northern Canada, reflecting altered runoff pathways and evolving subsurface connectivity.

Permafrost thaw is increasingly recognized as a key mechanism altering streamflow in northern watersheds, particularly in the discontinuous permafrost zone. In the southern Taiga Plains ecoregion, permafrost typically persists beneath raised forested peat plateaus surrounded by low-lying, peat-dominated wetlands (Quinton &

Baltzer, 2013). This permafrost is highly vulnerable to degradation through both vertical and lateral heat transfer, especially where fragmented plateaus border thawed collapse scar bogs (Devoie et al., 2021; Haynes et al., 2021; Kurylyk & Watanabe, 2013). As thaw progresses, thermokarst erosion transforms plateaus into collapse scar bogs lacking near-surface permafrost (Jorgenson & Osterkamp, 2005; Pelletier et al., 2017). These bogs may remain hydrologically isolated or become connected to channel fens, enhancing downstream discharge (Connon et al., 2014). Thaw-driven shifts in the extent of peat plateaus, collapse scar bogs, and channel fens are reshaping surface and subsurface connectivity across the landscape (Connon et al., 2014; Quinton et al., 2003). Concurrently, active-layer deepening promotes the formation of supra-permafrost taliks that enable lateral water flow even in winter (Chesnokova et al., 2020; O'Connor et al., 2019), while enhanced vertical connectivity facilitates deeper subsurface flowpaths that sustain elevated winter baseflow (Evans et al., 2020). Collectively, these processes indicate that permafrost thaw–driven land cover change and hydro(geo)logical reorganization are central to the observed discharge increases in northern Canada.

Increasing wildfire frequency and severity are further transforming hydrological regimes in northern watersheds by altering the surface energy balance and accelerating permafrost thaw. Although wildfire is a natural disturbance in the boreal forest, its occurrence has intensified, with statistically significant increases in both the number of large fires and the total area burned since the mid-20th century (Haynes et al., 2019). These trends are attributed to longer fire seasons and more frequent summer lightning strikes (Chen et al., 2021; Coogan et al., 2020; Smith et al., 2020). Historically, recently burned forests were protected from re-burning for 30–100 years due to limited fuel availability; however, post-fire drought and vegetation shifts have shortened these

intervals to less than 30 years in some regions (Whitman et al., 2019). Recent fires have also burned more deeply into organic soil layers, particularly in well-drained uplands (Kasischke et al., 2010), exposing mineral soils and reducing surface insulation. Canopy loss increases solar radiation at the ground surface (Ackley et al., 2021), while soil scorching and ash deposition modify albedo and heat absorption (Gibson et al., 2018). These changes elevate summer soil temperatures, deepen active layers, and reduce winter refreeze, promoting talik development and the expansion of thermokarst bogs (Connon et al., 2018; Gibson et al., 2018). Consequently, climate-driven increases in wildfire activity amplify permafrost degradation and enhance streamflow by reinforcing thaw-driven changes in landscape connectivity and subsurface hydrology and changes to the water and energy balance of the landscape.

Previous studies have demonstrated that multiple factors contribute to increasing streamflow in Arctic and sub-Arctic catchments, including altered precipitation and temperature regimes, enhanced hydrological connectivity from permafrost thaw, and wildfire-driven acceleration of thaw-related processes. However, the relative importance and cumulative impacts of these drivers remain poorly understood. McClelland et al. (2004) attributed streamflow increases across five large Eurasian basins to several mechanisms, including poleward moisture transport, wildfire-induced changes to the water balance, and the release of permafrost meltwater, which is now considered a less significant contributor (Wright et al., 2022). While precipitation emerged as the dominant driver, their analysis relied on simplified models that did not fully capture feedbacks or cumulative interactions among drivers. More broadly, existing research tends to focus either on large-scale continental basins, emphasizing precipitation-driven change (e.g., Liu et al., 2022), or on small headwater catchments that investigate runoff

generation processes in permafrost terrain (e.g., Connon et al., 2015). This division has left a gap in understanding how these processes interact within intermediate or regional-scale watersheds. In reality, climate change, permafrost thaw, and wildfire interact to drive complex and often non-linear changes in streamflow. Increased precipitation can accelerate permafrost degradation and alter subsurface hydrology (Douglas et al., 2020), while wildfire enhances both vertical and lateral thaw processes (Gibson et al., 2018). The resulting increases in subsurface connectivity may elevate winter streamflow, but only when sufficient precipitation sustains higher groundwater levels (Ge et al., 2011). Because these responses emerge from the interplay of multiple concurrent drivers, disentangling their relative contributions using observations alone remains challenging. Consequently, advancing hydrological models capable of integrating these overlapping influences is critical for developing a process-based understanding of watershed responses and predicting future hydrological change in northern environments.

Hydrological modeling is essential for understanding the impacts of climate change on permafrost-dominated catchments, where direct observation of processes is limited by data scarcity and the complex, non-linear nature of storage–discharge relationships (Hinzman et al., 2020). Semi-distributed models are particularly valuable in these environments, as they capture spatial heterogeneity and land cover dynamics while maintaining manageable data and computational requirements (Brown & Craig, 2020; Flügel, 1995; Guthke, 2017). Several hydrological models have been successfully applied to small headwater catchments in permafrost regions, including the Soil and Water Assessment Tool (SWAT; Ahmed et al., 2022; Fabre et al., 2017; Lee et al., 2018), the Cold Regions Hydrological Model (CRHM; Krogh et al., 2017) and the Variable

Infiltration Capacity model (VIC; Bowling & Lettenmaier, 2010). Raven, a flexible hydrological modeling framework, allows the model to incorporate components of various other hydrological models (Craig et al., 2020), making it well-suited for simulating complex wetland systems and northern permafrost watersheds (Ahmed et al., 2023; Taheri et al., 2023). It has previously been applied to develop a model of the Liard River watershed in the NWT (Brown & Craig, 2020), and is increasingly adopted by environmental agencies across Canada, including the Government of the Northwest Territories.

The objective of this study is to quantify the relative importance and cumulative impact of altered climate, permafrost thaw, and wildfire activity on streamflow variability in a medium-sized discontinuous permafrost watershed. La Martre River watershed (~14,500 km²), located in the southern Taiga Plains ecoregion of the central NWT, was selected as the study site due to its unusually large increases in annual and winter discharge (St. Jacques & Sauchyn, 2009). A hydrological model will be employed to assess how these drivers influence the volume and timing of discharge. The findings will provide insights into the key processes controlling streamflow in permafrost-dominated landscapes and support improved projections of water resources in the region under future climate and disturbance scenarios.

3.2 Study Site

La Martre River flows southeast from Lac La Martre to the Marian River, eventually draining into the north arm of Great Slave Lake (Figure 3.1). The Water Survey of Canada (WSC) gauging station (07TA001), located downstream of Lac La Martre, has recorded discharge data continuously since 1977. The river captures runoff from an area

of approximately 14,500 km². Lac La Martre is a large, shallow lake (1,776 km²) with an average depth of 10-12 meters and a maximum depth of 18 meters (Herdendorf, 1982; Bond, 1972). For several hundred meters near Whatì, the lake is particularly shallow, with depths generally less than 3 meters.

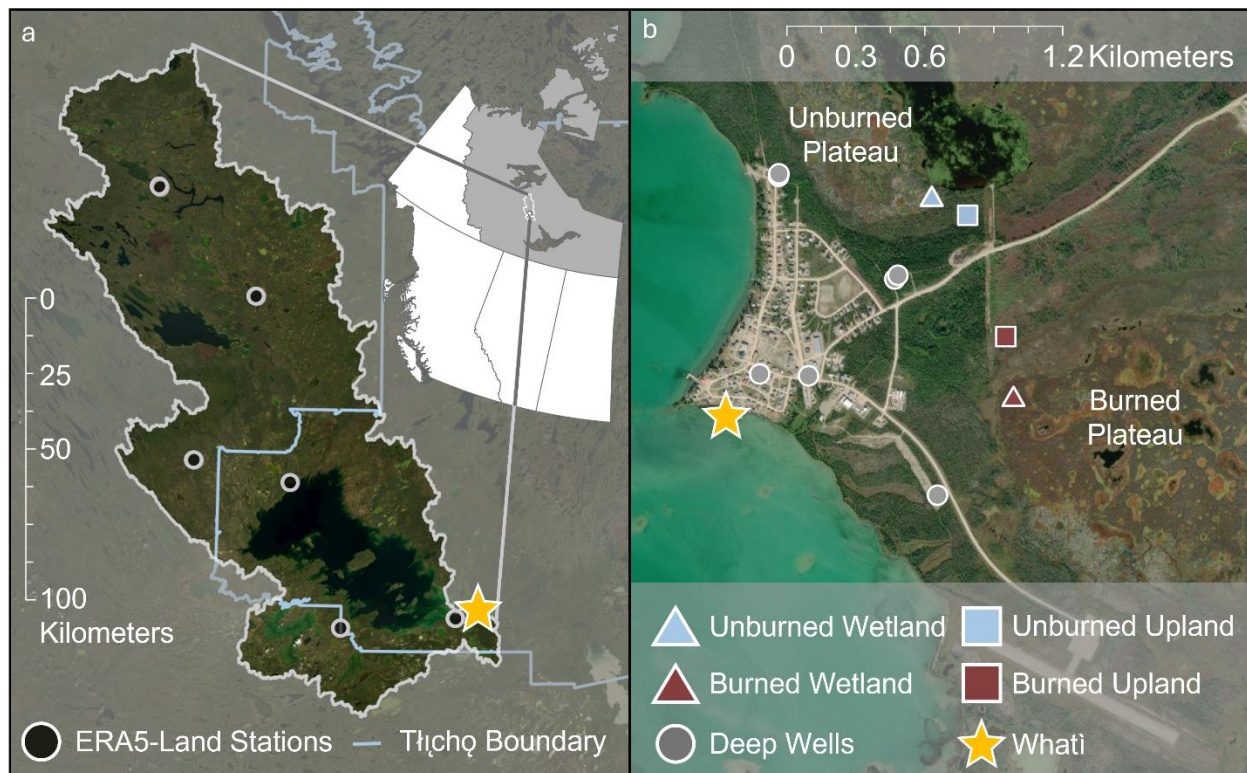


Figure 3.1. Map of field sites and virtual meteorological stations. Map (a) of La Martre River watershed boundary, the Tłı̨chǫ lands boundary, and the location within the Northwest Territories (inset), and the locations used for downloading ERA5-Land meteorological data (virtual meteorological stations). Map (b) of field sites within burned and unburned wetland and upland land-cover types, as well as the locations of drilled deep wells.

Discharge at La Martre River gauging station is typically characterized by a prominent snowmelt-driven peak in late June or early July. After this peak, flow gradually declines to winter baseflow conditions by November, with occasional secondary peaks in late September or October. Minimum flows are generally observed in late February and early March. Over the period of record, discharge has ranged from a low of 6.6 m³ s⁻¹ on April 10, 1980, to a high of 92.9 m³ s⁻¹ on July 1, 2007 (Wiebe et al.,

2023). During the period of record, the average rate of specific discharge increase in the watershed is 10.1 mm decade⁻¹ (1977-2023; Chapter 2).

The Th̓ch̓ community of Whatì is located near the outlet of Lac La Martre and has a population of approximately 550 people (Statistics Canada, 2023). The average annual air temperature at the Environment and Climate Change Canada (ECCC) weather station in Whatì is -4.7°C (1994–2022) (ECCC, 2025a). Although long-term precipitation records are not available for Whatì, data from the nearest long-term station in Yellowknife, 164 km southeast, indicate an average annual precipitation of 294 mm over 1991–2020, with just over half falling as rain (ECCC, 2025b). Since 1950, mean annual air temperature in the region has increased by 0.32°C decade⁻¹ (Chapter 2). While trends in precipitation remain uncertain (Mack et al., 2021), the rate of precipitation increase in Whatì may be as high as 10.91 mm decade⁻¹ (Chapter 2).

La Martre River watershed lies within the extensive discontinuous permafrost zone (50-90% permafrost extent) in the Taiga Plains ecoregion (Obu et al., 2019). This ecoregion is characterized by peatland dominated peat plateau-wetland complexes (Wright et al., 2022), and flat topography. In Whatì, the permafrost table is typically between 2 and 5 meters below the surface, as indicated by geotechnical investigations conducted in the 1980s and 1990s, with low ground ice content (less than 10% visible ice by volume in the upper 10-20 meters; Heginbottom et al., 1995). Permafrost in the area is expected to be warm (> -2°C) and is predominantly found in forested regions underlain by organic or fine-grained soils, as well as in low-lying peatlands and wetlands (Stantec, 2017; Daly et al., 2022). The watershed is underlain by fractured dolostone and minor shale and sandstone units with a 2 to 25-meter glacial till overburden (SNC-Lavalin, 2012; Earth Tech, 2007). Groundwater flow is expected to occur primarily in

the overburden and in the upper portion of the fractured dolostone in areas without permafrost (Wiebe et al., 2023). The subsurface is spatially heterogeneous, consistent with the characteristics of a proglacial environment. In 2014, a wildfire burned nearly 1,000 km² of La Martre River watershed, including 84% of the 60 km² municipal area of Whatì (Daly et al., 2022). The land cover of the watershed is approximately 28% lakes, including Lac La Martre, 27% peat plateau wetland complexes, 37% forest, and 8% exposed bedrock (Ducks Unlimited Canada, 2010).

3.3 Methods

In this study, a semi-distributed model of La Martre River watershed (14,500 km²) was constructed using the Raven hydrological modelling framework (Craig et al., 2020). The flexible framework enabled control over key modeling aspects, such as spatial discretization, wetland and permafrost representation, and hydrological process selection. Field studies were conducted in the community of Whatì, located at the southern end of the watershed near the outlet of Lac La Martre, during the summers of 2022-2024 (Figure 3.1). The structure, hydrological processes, and parameterization of the model were informed by these field studies.

3.3.1 Climate Forcing Data

A single ECCC weather station is located within the watershed at the Whatì Airport providing daily air temperature records since 1995 and daily precipitation records since September 2018 (ECCC, 2025). Due to the short duration and lack of spatial coverage of meteorological data in the watershed, hourly air temperature and precipitation data were obtained from the ERA5-Land reanalysis product developed by the European Centre for Medium-Range Weather Forecasts (ECMWF; Muñoz-Sabater

et al., 2021). ERA5-Land is produced using monthly observations from meteorological stations where available, assimilated into a land-surface model and downscaled to a spatial resolution of $0.1^\circ \times 0.1^\circ$. To capture spatial variability across the watershed while maintaining a manageable structure for modeling purposes, six ERA5-Land grid cells were selected to represent virtual meteorological stations for the period 1976–2023, aligning with the available discharge record (Figure 3.1). Two of these virtual stations correspond to the locations of the Whatì Airport ECCC station and a meteorological station installed on the north side of Lac La Martre as part of a related study. Additional ERA5-Land data were extracted for the grid cell encompassing the Yellowknife Airport ECCC station, with corresponding observational data from this station for the period 1950–2012 for the purpose of bias-correction described below. All temperature and precipitation data were aggregated to daily values for use in subsequent analyses and hydrological modeling.

Hydrological models are highly sensitive to variations in precipitation input due to the nonlinear nature of hydrological processes. To minimize discrepancies between modeled and observed meteorological data, bias correction was applied to the ERA5-Land precipitation time series. While a variety of bias correction techniques exist (Pierce et al., 2015), a simple monthly scaling approach was chosen. Scaling factors were calculated for each calendar month by comparing observed precipitation from the Yellowknife ECCC station with corresponding ERA5-Land values. These monthly factors were then applied to adjust the ERA5-Land precipitation data across all virtual meteorological stations. Bias correction was performed using the *getBiasFactor* function from the *hyfo* R package, with a precipitation threshold of 0.02 mm to exclude

trace values (Xu, 2023). A detailed evaluation of ERA5-Land and the selected bias correction method are provided in Chapter 2 and Appendix A.

3.3.2 Model Discretization

Watershed and sub-basin delineations were generated using the BasinMaker tool, with watershed boundaries derived from the North American Lake-River Routing Product v2.1 (NALRRP; Han et al., 2023). Sub-basins were delineated using major confluences of the river network or significant lake outlets, and limited to areas greater than 150 km (Figure 3.2). The NALRRP watershed delineation did not include the area of Bartlett Lake (sub-basin 12, in figure). However, comparison with watershed delineation from the 1m x 1m ArcticDEM product suggests that the Bartlett Lake watershed likely discharges into Lac La Martre (Porter et al., 2023). Therefore, sub-basin 12 is included in the watershed (Appendix B). Field studies revealed extensive exposed bedrock throughout the upland land covers on the eastern shore of Lac La Martre, justifying the definition of a separate sub-basin with a unique forest bedrock soil profile (sub-basin 11 in figure). This yielded a total of 17 sub-basins, including three representing the three largest lakes in the watershed, Lac La Martre (1700 km²), Grandin Lake (200 km²), and Bartlett Lake (150 km²). These lakes are modeled as lake-type reservoirs; the inflow, outflow, and lake ice processes were parameterized through calibration, described below. All other small lakes, which make up 16.7% of the watershed area, are represented as lake-type hydrological response units (HRUs) within each sub-basin.

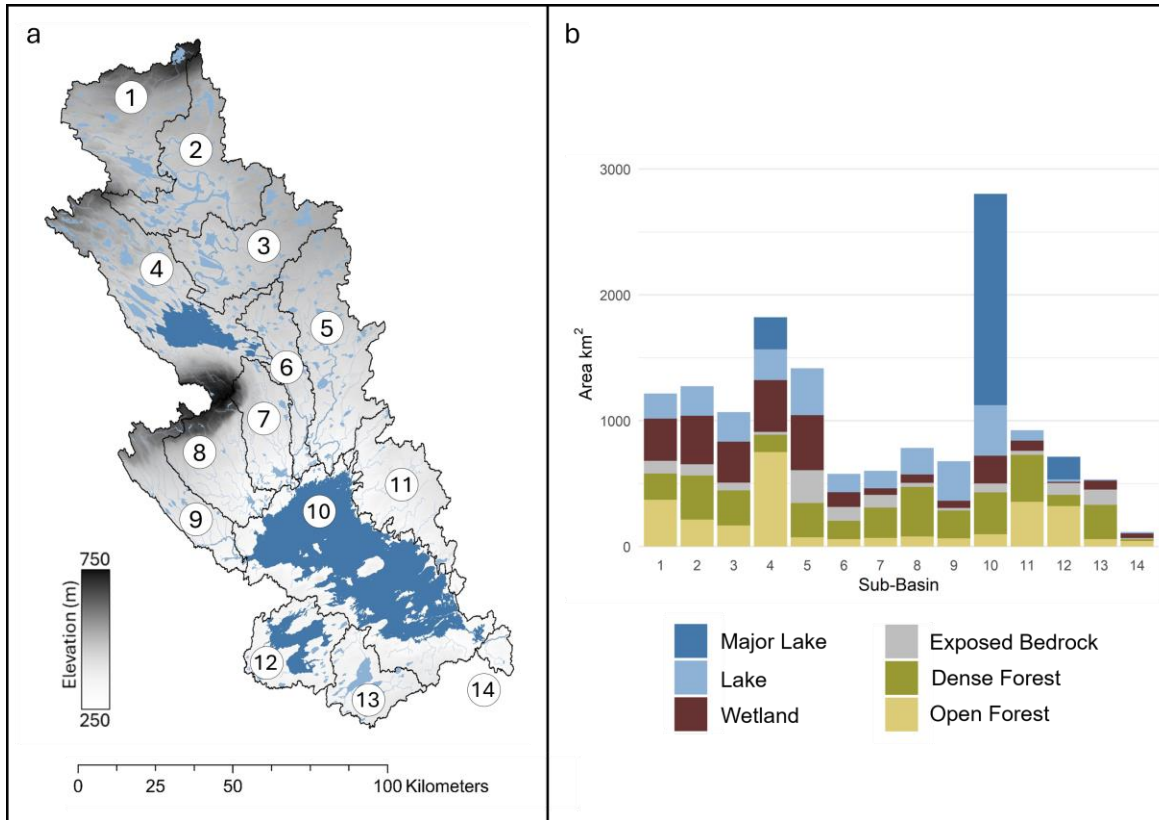


Figure 3.2. Representation of sub-basins and land-cover types in the model. Map (a) shows sub-basins 1–14 within the watershed. Major lakes that were modeled as lake-type reservoirs (Lac La Martre in sub-basin 10, Grandin Lake in sub-basin 4, and Bartlett Lake in sub-basin 12) are shown in dark blue, while all other lakes and rivers are shown in light blue. Elevation is displayed in the background. (b) The total area and land-cover composition are displayed by sub-basin.

Each sub-basin is further discretized into HRUs which represent non-contiguous regions of similar land cover, vegetation, and soil profile representing an area that responds similarly to an input of water (Flügel, 1995). HRU discretization was based on land cover data from the Ducks Unlimited (DU) Hybrid Wetland Layer, supplemented by the DU Tłıchǵ Wetland Classification, which covers the southern portion of the watershed within the Tłıchǵ boundary (Figure 3.2; DU Canada, 2010; DU Canada, 2023). Details of the land cover classification are provided in Appendix B.

HRUs are delineated based on a combination of land cover, wildfire impact, and soil profile. The landscape is categorized into five primary land cover types: lake, wetland, dense forest, open forest, and exposed bedrock. The proportion of each land cover type

by sub-basin is shown in Figure 3.2. Wetlands are further divided into peat plateaus, bogs, and fens. For each land cover type, multiple soil profiles are defined to represent different permafrost conditions, including permafrost-free, talik-bearing, and non-talik permafrost. Exceptions include lakes, which do not have a soil profile, and both exposed bedrock and fens, which are considered to have limited permafrost due to their thermal properties and higher groundwater flow rates, respectively.

3.3.3 Permafrost and Wetland Representation

Raven does not have the capability to connect explicitly model soil thermal states. Therefore, permafrost was represented as a low conductivity layer and thaw progression was modeled by manually adjusting the soil profiles. The subsurface was represented as a 37 meter, five-layer soil model. The depth and soil type are unique to each soil profile. Frost table transects were conducted at five sites in the watershed representing upland and peat plateau-wetland complex terrain at 3m intervals across 120-156m transects at the beginning and end of the summer thaw season in 2023 and 2024 using a 2m long square frost probe. The active layer thicknesses (ALT) were informed by the results of the frost table transects (Lackey et al, *in prep.*) and modified to represent base case conditions (1977-1984), and organic layer thicknesses were informed by measurements taken during piezometer installation in summer 2022 (Table 3.1).

Table 3.1 Table of base period model soil profile properties informed by field investigations. Detailed soil profiles in Appendix C. Note, Org: Organic, Min: Mineral, PF: Permafrost, FB: Fractured bedrock.

	Measured ALT (m)	Base Period ALT (m)	Organic Layer Thickness (m)	Permafrost Depth (m)	Soil Types
Peat Plateau	0.54 (n=51)	0.40	2.0	0.4-17	Org, PF, FB
Bog	0.49 (n=9)	0.35	1.4	1.9-17	Org, PF, Min, FB
Fen	–	0.60	1.9		Org, Min, FB
Forest	0.25 (n=60, June)	0.30	0.2	0.3-17	Org, Sandy Min, PF, FB
Forest Bedrock	–	0.70	0.1	7-17	Org, PF, FB
Exposed Bedrock	–	1.4	0.0		FB

Across the seven land covers, eight soil types were defined. For simplicity, all organic soil including peat in wetlands and forest topsoil were characterized as *organic* and *frozen organic* when cryotic. Mineral soil samples were collected from all four field sites through auguring and analyzed for particle size distributions using sieve analysis and the Horiba Particle Size Analyzer (LA-950V2) for silt and clay fractions. Soil samples were used to develop a conceptual model of the soil types present in the near subsurface. Wetland mineral soils were classified as silt loam, while the upland site soils were classified as sandy loam according to the USGS soil classification (Appendix C); these layers were represented as *mineral*, *sandy mineral*, and *frozen mineral* in the model. The soil classification was used to determine a range of porosity values for the mineral soils, an estimated porosity range for organic, permafrost soils, and equivalent porosity of fractured bedrock were used (Table 3.2). All parameter range estimates used for calibration are given in Appendix E.

Table 3.2. Hydraulic conductivity ranges from slug tests. Calibrated porosity, M_{base} and M_{perc} values based on hydraulic conductivity and assumed gradient and anisotropy ranges.

	Measured Hydraulic Conductivity (m s ⁻¹)	Calibrated Porosity	Max Baseflow Rate (mm d ⁻¹)	Max Percolation Rate (mm d ⁻¹)
Organic	9.1x10 ⁻⁷ – 1.4x10 ⁻⁴	0.80	1400	170
Frozen Organic	–	–	78	6.5
Sandy Mineral	1.0x10 ⁻⁶ – 2.7x10 ⁻⁵	0.44	230	68
Frozen Sandy Mineral	–	–	8.5	4.10
Mineral	6.7x10 ⁻⁸ – 5.7x10 ⁻⁷	0.39	14	44
Permafrost	–	0.19	0.13	0.46
Fractured Bedrock	5.4x10 ⁻⁵ – 3.2x10 ⁻⁴	0.0031	2200	2800
Frozen Fractured Bedrock	–	–	9.3	39

In June 2024, seven wells were drilled within the community of Whatì, to depths between 6 and 28m into the mineral and glacial till overburden and the fractured dolostone aquifer. Drilling revealed frozen ground up to 30 m below land covers that are lacking shallow permafrost within the community of Whatì. Therefore, a deep

permafrost layer was included between 7 and 17 meters in all soil profiles except fens and bedrock to allow sub-permafrost groundwater to recharge. Although the model does not compute lateral flow of groundwater between soil stores, deep groundwater storage was equilibrated across all non-lake HRUs each model day, as a proxy for regional groundwater flow. The fractured bedrock aquifer was modeled as a high hydraulic conductivity layer in the lower 30 meters of the modeled subsurface profile. Deep permafrost storage was also equilibrated within each sub-basin on a 90-model day timescale, to simulate slow moving groundwater within warm permafrost.

Wetland processes are known to be difficult to represent accurately in hydrological models (Taheri et al., 2023). In this study, peat plateau wetland complexes were represented as three land covers with unique vegetation, land cover parameters, and soil profiles. Bogs and fens are fed by upland runoff (Connon et al., 2014), which in the model was represented by splitting peat plateau surface runoff between fen and bog depression storage. Each wetland land cover was divided into 20ths, with each portion represented by a single HRU. Each peat plateau HRU was linked to a randomized bog and fen HRU, ensuring that regardless of permafrost or burn state divisions, each bog and fen HRU received runoff from an equal area of peat plateau (further details in Appendix D), bog and fen depression storage then either infiltrated, evaporated, or overflowed into the stream network.

3.3.4 Model Processes

Raven is highly adaptable, enabling hydrological processes to be selected from existing models for each component of the hydrological model. The model processes were selected based on their ability to represent physically-based processes, measured

parameters, and the temporal variation of these parameters to represent seasonal freeze/thaw. Special attention was given to the soil processes. Baseflow from soil layers, here represented as discharge from each layer directly into the stream channel, and percolation from one soil layer to the layer below, were defined using the Raven VIC baseflow method (Equation 3.1) and power law percolation method (Equation 3.2), respectively (Craig et al., 2020):

$$Baseflow = M_{base} \left(\frac{\phi_{soil}}{\phi_{max}} \right)^n \quad (3.1)$$

$$Percolation = M_{perc} \left(\frac{\phi_{soil}}{\phi_{max}} \right)^n \quad (3.2)$$

where *maximum baseflow rate* (M_{base}) and *maximum percolation rate* (M_{perc}) are assumed to be proxy variables for hydraulic conductivity. The n value is a unitless shape parameter, and ϕ_{soil} and ϕ_{max} refer to the current and maximum soil storage in that layer.

Slug tests were performed at each of the deep wells and the piezometers installed in each of the field stations in Whatì (Figure 3.1). The slug tests were analyzed with Bouwer Rice and Hvorslev methods for confined and unconfined aquifers, given the uncertainty surrounding the seasonal frost as a confining layer (detailed in Appendix C). Early and late time response curves were fitted to provide a range of hydraulic conductivity for each piezometer/well. The M_{base} and M_{perc} parameters were determined from the hydraulic conductivities in each of the soil types, organic, sandy mineral, mineral, and fractured bedrock, by assuming that the selected baseflow and percolation methods are comparable to the unsaturated Darcy's law, where the M_{base} and M_{perc} are equivalent to the hydraulic conductivity multiplied by an appropriate hydraulic gradient, and the

exponential term represents the shape of the soil water characteristic curve. Therefore, the hydraulic conductivity range (Table 3.2) multiplied by the horizontal gradient range of 0.0001 – 0.1 for baseflow, and by an anisotropy range of 0.001 – 0.1 to represent the lower vertical hydraulic conductivity and a vertical gradient range of 0.5 – 1 for percolation. Then, the M_{base} and M_{perc} were calibrated as described below. The calibrated value is shown in Table 3.2. The Raven process input file which represents the selection of hydrological processes in the model is included in Appendix D.

The transient parameter subroutine was used to represent seasonal freeze–thaw processes in soil layers. For each soil type, distinct parameter values are assigned for frozen and unfrozen conditions, including those governing infiltration, percolation, baseflow, and seepage from depression storage. The onset of freeze (thaw) was determined by the average date of last positive (negative) temperature at 5 cm (30 cm) depth below the ground surface recorded by ground temperature sensors at field sites throughout Whatì between September 2019 and October 2020 from a previous study (Daly et al., 2022) and the thermistor strings installed in the Whatì field upland and peat plateau sites between October 2023 to August 2024 (Appendix C). In the base model, the date of winter freeze is October 15th, and the date of summer thaw is May 20th.

3.3.5 Model Calibration and Validation

Measured parameter values were not subject to calibration but were instead directly assigned based on observed data. Prior to automatic calibration, a manual calibration step was carried out to ensure that key hydrologic processes and system representation were appropriately captured.

Automatic model calibration was performed using the Dynamically Dimensioned Search (DDS) algorithm implemented within the Ostrich optimization framework (Tolson & Shoemaker, 2007; Matott, 2017). The calibration ranges for all variables are provided in Appendix E. Calibration was based on a comparison between simulated and observed discharge for the model base period from October 1, 1976, to September 30, 1984. A 10-year model spin-up preceded the calibration period to allow hydrological stores, such as deep soil moisture and major lakes, to equilibrate against mean temperature and precipitation conditions for the base period. The calibration assessed the model performance using the Nash–Sutcliffe Efficiency (NSE) and was run for 10,000 DDS iterations.

The calibrated model was compared with the observed record of discharge in the base period. Seasonal water stores, such as depression storage in bogs and fens, major lake storage, and soil storage in shallow and deep groundwater, were assessed against a conceptual model of watershed hydrology in the base period. The parameter set from the base period-calibrated model was used for all simulations except as otherwise stated and is provided as the Raven parameter input file in Appendix D.

3.3.6 Model Simulations

Model simulations were conducted to evaluate the relative importance and cumulative impacts of changing meteorological forcings, permafrost thaw, and wildfire on streamflow in La Martre River watershed. Simulations were structured around three 25-year periods: the recent past (1976–2000), the present (2001–2025), and the near future under RCP 8.5 (2026–2050). Each of the three driving forces was further subdivided into component drivers contributing to observed and projected hydrological

changes. For each model experiment, all parameters other than the variable under investigation were held constant at base period values to isolate the individual effect.

For each test case, a single representative year of meteorological forcing was repeated, with altered values for meteorological and cumulative scenarios. The use of a single year removed interannual variability while preserving the natural intra-annual distribution of temperature and precipitation and enabling direct comparison across simulations. The year 1982 was selected as the representative meteorological year, as it exhibited near average annual and monthly precipitation of the base period, and slightly cooler-than-average temperatures, making it characteristic of an earlier portion of the record, and the model demonstrated strong performance in reproducing the observed hydrograph. Initial conditions were standardized across simulations, with soil stores set to 60% capacity and reservoirs to full capacity. Each simulation was run for 25 model years, with only the final year retained for analysis to allow sufficient time for model equilibration.

3.3.7 Test Cases

For each period, three test cases were developed to assess the individual and combined impacts of meteorological change, permafrost thaw, and wildfire on watershed hydrology. Each test case is composed of multiple component drivers, which are summarized in Table 3.3 for the past, present, and future periods. A detailed description of the representation of each component driver is included in Appendix F.

Meteorological forcing data were derived from bias-corrected ERA5-Land reanalysis for past and present cases, and from CMIP5 (50th percentile, RCP 8.5) for the future case. CMIP5 data were bias-corrected against ERA5-Land virtual station data

using the same monthly scaling factor method. A single representative year was then adjusted so that mean temperature and precipitation matched the average 8-year running mean of the relevant 25-year period (2001–2023 for the present). Annual adjustments were based on the hydrological year, while seasonalized adjustments were calculated and applied by month. Daily temperature values (minimum, maximum, and average) were shifted by the difference between the target and representative means, and daily precipitation was rescaled using each day's fraction of the total. This preserved both the number and timing of precipitation events. Further details are provided in Appendix F.

Permafrost thaw was represented in the model by modifying soil profiles, the fraction of HRUs with thaw-affected soils, and the baseflow characteristics of bog subsurface flow (Table 3.3, and detailed in Appendix F). Wetland connectivity was increased by expanding the proportion of thermokarst features (bogs and fens) and by allowing the upper layers of bogs to discharge directly to streams (Connon et al., 2014). Active layer thickness (ALT) and supra-permafrost layer thickness (SLT) were increased by reducing the depth of seasonally frozen soil classes, as well as by increasing talik thickness and the fraction of talik-bearing HRUs within forest, bog, and peat plateau land covers (Devoie et al., 2019). In bogs, the extent of open taliks was expanded, while in forests and peat plateaus the thickness of the deep permafrost layer was reduced (Evans et al., 2020). Freeze–thaw timing was adjusted by shifting the transition date between cryotic and non-cryotic soil parameters to reflect earlier thaw and later freeze-up under warmer conditions (Quinton & Baltzer, 2013). These changes were evaluated both collectively as a net permafrost thaw case and individually as component drivers: wetland connectivity, ALT/SLT, permafrost state, and freeze/thaw timing.

Table 3.3. Description of changes made in each simulation case. Changes are relative to the base case, where == means that there is no change from the base case. Note, PF: permafrost, PP: peat plateau.

	Past		Present		Future	
Meteorological						
Precip	↑		↑↑		↑↑↑	
Seasonalized Precip	Winter	↑	Winter	↓	Winter	↑↑
	Spring	↑	Spring	↑	Spring	↑↑↑
	Summer	==	Summer	↑↑↑	Summer	↑↑↑
Temp	↑		↑↑		↑↑↑	
Seasonalized Temp	Winter	↓	Winter	↑↑	Winter	↑↑↑
	Spring	↑	Spring	↑↑	Spring	↑↑↑
	Summer	↑	Summer	↑↑	Summer	↑↑↑
Permafrost Thaw						
ALT/SLT	No Talik	ALT ↑	No Talik	ALT ↑↑	No Talik	ALT ↑↑↑
	Talik	ALT ==	Talik	ALT ↓	Talik	ALT ↓↓
		SLT ↑		SLT ↑↑		SLT ↑↑↑
	No PF	ALT ↓	No PF	ALT ↓↓	No PF	ALT ↓↓
	Talik %	↑	Talik %	↑	Talik %	↑
	Freeze/Thaw Timing	Freeze Earlier	Freeze	==	Freeze	Later
	Thaw	Later	Thaw	==	Thaw	Earlier
	Wetland Connectivity	PP ↓	PP	↓↓	PP	↓↓↓
		Bog/Fen ↑	Bog/Fen	↑↑↑	Bog/Fen	↑↑↑
Permafrost State	Open Talik	↑	Open Talik	↑↑	Open Talik	↑↑↑
	PF Loss	↑	PF Loss	↑↑	PF Loss	↑↑↑
Wildfire						
Wildfire Burn Area	↑		↑↑		↑↑↑	
Wildfire Burn Location	North		East		West	
Wildfire Thaw Severity	LAI	↓	LAI	↓	LAI	↓
	PP	↓	PP	↓↓	PP	↓↓↓
	Bog/Fen	↑	Bog/Fen	↑↑	Bog/Fen	↑↑↑
	ALT/SLT	== / ↑	ALT/SLT	== / ↑↑	ALT/SLT	== / ↑↑↑
	Talik %	↑	Talik %	↑↑	Talik %	↑↑↑

Wildfires were represented in the model by modifying wetland and forest HRUs to reflect fire impacts. Fire effects included increasing thermokarst coverage (bogs and fens; Gibson et al., 2018), increasing the depth to permafrost to create temporary taliks in previously non-talik soil profiles, increasing the proportion of talik-bearing HRUs, and altering the surface energy balance (Ackley et al., 2021) by reducing vegetation height, rain/snow interception, and leaf area index (LAI). The location, area, and severity of these impacts varied by period. The total watershed area burned was set to 5%, 8%, and 11% for the past, present, and future cases, respectively. The proportion of burned wetlands to forests (32% wetland, 68% forest) was determined from pre-fire

land cover ratios using the Ducks Unlimited hybrid wetland layer and NWT fire history shapefiles. Three fire locations were selected: North (sub-basins 1 and 2), East (5, 6, and 11), and West (7, 8, 9, and 10). Within each sub-basin, the burned area was scaled according to the relative fraction of wetland and forest land cover. Fire locations were assigned to each period based on spatial similarity to historical burn patterns, with North representing the past, East the present, and West the future (Appendix F).

For each period, the model was run first with individual component drivers applied separately, then as a net case combining all components of a single driver. A final cumulative case included all drivers, including meteorological changes, permafrost thaw, and wildfire, simultaneously.

3.3.8 Simulation Evaluation

Simulations outputs were compared to the base case to assess impacts on discharge volume, timing, and hydrograph shape. All statistics were calculated using only the final year of the 25-year simulation. Percent change for each statistic was calculated relative to the base case using the following equation:

$$\text{Percent Change} = \left(\frac{\text{Simulation Value} - \text{Base Case Value}}{\text{Base Case Value}} \right) \times 100\% \quad (3.3)$$

Winter discharge was defined as the total discharge for January, February, and March, when the surface is frozen. Peak discharge was calculated as the maximum 30-day rolling mean. The runoff ratio was calculated as the annual specific discharge (total discharge per watershed area, in mm) divided by total precipitation (mm).

These comparisons allow for an assessment of the relative importance of altered meteorological forcing, permafrost thaw, and wildfire on watershed hydrology. They also enable quantification of the combined, cumulative impacts of all drivers acting

simultaneously, providing insight into how interacting environmental changes may influence discharge, runoff timing, and hydrograph dynamics.

3.4 Results and Discussion

3.4.1 Evaluation of the Base Period Model

The model calibrated against the base period (1977–1984) compared well with observed discharge at La Martre River gauging station (Appendix E). During the eight-year calibration, the NSE was 0.70 and the KGE was 0.74. The selected simulation year, 1982, showed a stronger fit with NSE of 0.81 and KGE of 0.78. The model captured the timing and magnitude of peak discharge and summer recession, though it overestimated the fall peak. The overall fit of the model was appropriate for use as a base for the sensitivity analysis performed in this study.

The base period model was also used to simulate the full discharge record (1976–2023) for comparison to the observational record using bias-corrected ERA5-Land meteorological forcing data (Figure 3.3). Modeled annual discharge aligned well with observations during the calibration period and in low-flow years throughout the record, and the interannual variability of the observed timeseries was preserved, indicating that the model responded to changing inputs similarly to the natural system. However, the model underestimated the long-term increase in discharge. Hydrological models are not well suited to transient conditions; the base period-calibrated model reflected a state with contiguous upland permafrost and minimal thaw or wildfire effects. Although precipitation and temperature increased significantly between 1977 and 2023 (Chapter 2), these changes alone did not produce a comparable increase in modeled discharge.

This suggests that other factors, such as permafrost thaw and wildfire are essential drivers of increasing discharge in La Martre River.

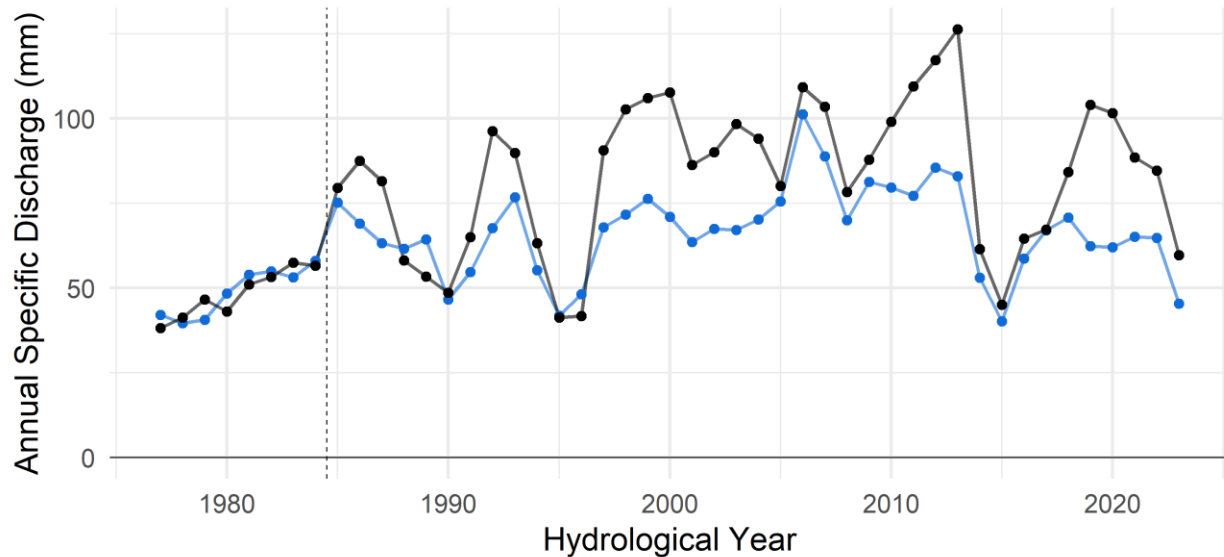


Figure 3.3. Simulated (blue) and observed (black) mean annual specific discharge (mm) in La Martre River in hydrological years 1977-2023. The dashed line represents the end of the base period (1977-1984).

3.4.2 Individual Driver Response

The model was used to simulate a range of scenarios involving changes in climate, permafrost conditions, and wildfire disturbance. The resulting impacts on hydrology were evaluated for each of these driving factors by analyzing their individual components and comparing the outcomes to the base period model. Hydrological impacts for each scenario are presented as hydrographs (Figure 3.4), and as percent changes in annual, winter, and peak discharge relative to the base case (Figure 3.5).

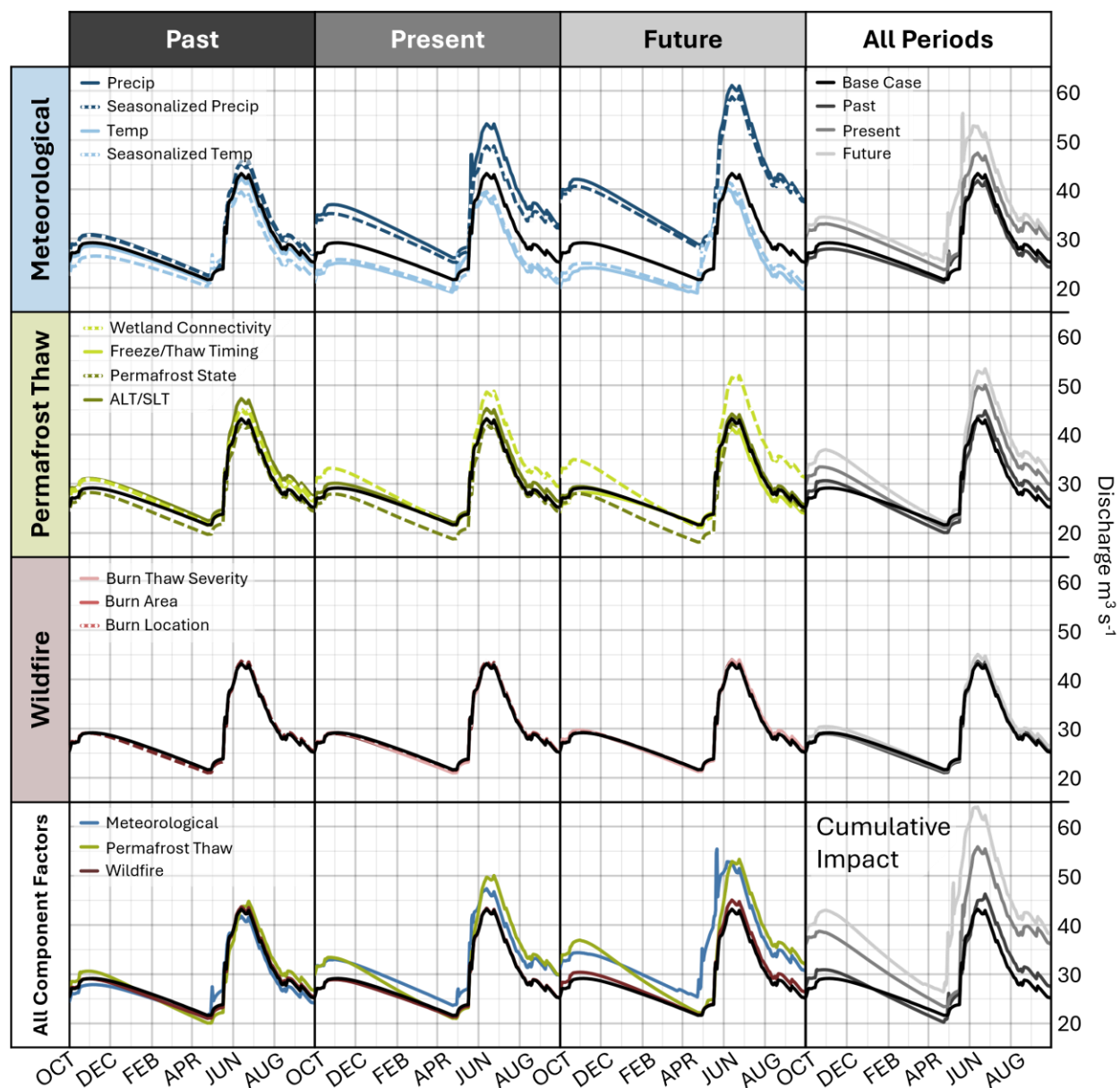


Figure 3.4. Daily hydrographs for all simulations. Rows 1–3 present hydrographs for the isolated component-driver simulations: Meteorological, Permafrost Thaw, and Wildfire, respectively. Row 4 presents the comparison of the driving factors for each period. Columns 1–3 present hydrographs for each period: past, present, and future. Column 4 presents the comparison of the period for each driving factor. The lower-right panel summarizes the cumulative influence of all three driving factors across the three time periods.

3.4.2.1 Comparison of Meteorological Forcing Component Drivers

The increased precipitation simulations resulted in higher annual, peak, and especially winter discharge relative to the base case, whereas increased temperature consistently reduced discharge (Figure 3.5). When temperature and precipitation

changes were combined, temperature-driven reductions dominated in the past period, resulting in a slight decrease in annual, winter, and peak flows. In contrast, in the present and future periods, precipitation increases outweighed temperature effects, producing higher discharge and an overall upward shift in the hydrograph (Figure 3.4), consistent with observed trends in La Martre River (Chapter 2).

Increases in temperature and precipitation both affect the water balance and the seasonal timing of discharge. Higher temperatures drive enhanced evapotranspiration (ET), which contributes to a reduction in discharge. In the seasonalized temperature scenario, where warming was concentrated in the seasons that historically experienced the greatest temperature change, the discharge response was less pronounced compared to the uniformly distributed warming scenario, except in the past period (Figure 3.5). This reflects the dominance of winter warming in the Arctic (Box et al., 2019) and the comparatively smaller effect of summer ET. Warming also reduced peak discharge by decreasing snow accumulation and advancing the timing of the spring freshet, consistent with pan-Arctic observations (Figure 3.4; Park et al., 2024; Overeem & Syvitski, 2010; Yang et al., 2015).

Seasonalized precipitation increases also produced weaker discharge responses than uniformly distributed precipitation increases, with the difference becoming more pronounced in later periods. Summer precipitation has increased faster than in other seasons, contributing to higher winter discharge (Liu et al., 2022; Spence et al., 2014). However, the model shows that discharge volume is more closely tied to the total volume of precipitation. Thus, comparing the annual rates of warming and wetting to total discharge may overstate the role of temperature and precipitation on the observed discharge increase.

			Annual Discharge			Winter Discharge			Peak Discharge			
Precip	5.2%	24.7%	41.1%	5.4%	25.4%	42%	5%	23.8%	41.9%	Meteorological		
Seasonalized Precip	5.3%	18%	37%	4.9%	19.2%	37.3%	6%	13.3%	36.7%			
Temp	-2.2%	-12.1%	-13.2%	-2.2%	-14%	-17.4%	-2.5%	-10.5%	-7.6%			
Seasonalized Temp	-7.9%	-10.6%	-9.7%	-8.9%	-11.5%	-13.9%	-8.7%	-8.7%	-4.1%			
	-2.7%	11.9%	21.3%	-4.1%	12.2%	17.4%	-3.2%	9.6%	22.6%			
ALT/SLT	7%	3.5%	1.2%	6.1%	3%	0.6%	9.5%	4.8%	2.3%	Permafrost Thaw		
Freeze/Thaw Timing	3.4%	0%	-2.8%	5.1%	0%	-2.7%	4.1%	0%	-4.6%			
Permafrost State	-4.5%	-6.2%	-6.7%	-3.9%	-5.6%	-5.8%	-2.6%	-2.7%	-1.8%			
Wetland Connectivity	4.4%	9.7%	13.6%	5.4%	11.3%	15.3%	4.7%	12.8%	19.9%			
	1%	10.2%	18.3%	3.4%	11.8%	22.6%	2.4%	15.5%	23%			
Wildfire Burn Area	-0.6%	-0.7%	0.6%	-0.9%	-1.2%	0.3%	1.1%	0.9%	1.8%	Wildfire		
Wildfire Burn Location	-0.6%	0.2%	0.2%	-0.9%	-0.4%	0.2%	1.1%	1%	0.4%			
Wildfire Thaw Severity	-0.6%	-0.5%	0.8%	-0.9%	-0.5%	1%	1.1%	0.8%	1.9%			
	-0.6%	-0.6%	3.3%	-0.9%	-1.2%	3.8%	1.1%	0.4%	4.2%			
			Past	Present	Future	Past	Present	Future	Past	Present	Future	

Figure 3.5. Percent change in annual discharge (columns 1–3), winter discharge (columns 4–6), and peak discharge (columns 7–9) for all simulations relative to the base case. Each row reports the percent change for a single component driver within one of the three driving factors: meteorological forcing (rows 1–5), permafrost thaw (rows 6–10), and wildfire (rows 11–14). The net effect of all component drivers within each driving factor is shown below the dashed line. Columns corresponding to the past (1, 4, 7), present (2, 5, 8), and future (3, 6, 9) periods follow the same order across each discharge metric.

3.4.2.2 Comparison of Permafrost Thaw Component Drivers

Permafrost thaw had a consistently positive influence on simulated annual discharge, with increases of 1.0%, 10.2%, and 18.3% relative to the base case in the past, present, and future periods, respectively (Figure 3.5). The effect was even more pronounced in winter (JFM), aligning with documented increases in cold-season flows in the Taiga Plains and other pan-Arctic watersheds (St. Jacques & Sauchyn, 2009; Liu et al., 2022; Song et al., 2020; Walvoord et al., 2012). As surface pathways are frozen in

winter, elevated cold-season discharge indicates enhanced subsurface connectivity. As thaw progresses, lateral and vertical permeability increase, promoting more efficient subsurface flow (Walvoord & Striegl, 2007; Chasmer & Hopkinson, 2017). Modeled hydrographs show a steeper winter baseflow recession (Figure 3.4), supporting an interpretation of increased subsurface transmissivity. This effect may be amplified in La Martre watershed due to the prevalence of high-conductivity peat and fractured bedrock aquifers.

Among the thaw-related component drivers, wetland connectivity produced the greatest increase in annual, peak, and especially winter discharge (Figure 3.5). As connectivity increases, wetlands that previously attenuated flow instead enhance runoff efficiency as permafrost barriers thaw (Haynes et al., 2018). These findings reinforce conclusions from Cannon et al. (2014), who identified wetland connectivity as a major hydrological driver of permafrost degradation.

Changes in ALT/SLT and talik extent also increased discharge, particularly in the past period, consistent with studies showing an initial increase in runoff efficiency followed by a decline (Figure 3.5; Lamontagne-Hallé et al., 2018). As ALT deepens, the water table can drop below high-conductivity zones, reducing subsurface flow efficiency (Koch et al., 2014; Quinton & Baltzer, 2013). Simultaneously, deeper active layers and taliks enhance subsurface storage, sustaining baseflow (Evans et al., 2020). The percent increase from the ALT/SLT component driver is greater on annual than winter discharge, indicating that active layer depth is more influential than the fraction talik-bearing permafrost (Figure 3.5). The permafrost-state component driver, which increased the proportion of permafrost-free soil profiles, slightly reduced total discharge but increased the baseflow recession rate, consistent with higher bulk transmissivity

(Figure 3.5). Overall, all thaw-related drivers contributed to a more connected subsurface system, together driving substantial increases in annual, winter, and peak discharge, as well as a faster baseflow recession.

3.4.2.3 Hydrological Impact of Wildfire Component Drivers

Wildfire generated relatively modest changes in simulated discharge but consistently increased peak discharge (Figure 3.5) and the baseflow recession rate (Figure 3.4). These patterns are consistent with wildfire-induced increases in subsurface transmissivity observed in boreal regions of northern Canada and Alberta (Putz et al., 2003; Mahat et al., 2016). Observed increases in annual discharge have also been linked to wildfire in Canada (Bayley et al., 1992; Lamontagne et al., 2000; Schindler et al., 1980). Although the simulated increases are smaller than those documented, the modeled rise in peak flows and faster recession align with known wildfire impacts.

The hydrological response to wildfire is influenced by several competing processes. ET typically declines immediately after fire due to canopy loss (Spence et al., 2020a; Liu et al., 2005), although recovery is relatively fast in boreal systems where understory vegetation plays a significant role in ET (Wilson et al., 2000). Snow accumulation can increase in areas with reduced canopy cover (Ackley et al., 2021; Gibson et al., 2018; Hedstrom & Pomeroy, 1998), but this does not always lead to higher melt infiltration or runoff (Spence et al., 2020a). Post-fire ground thermal changes are substantial: the SLT often increases by more than 50%, and talik formation is common, which in turn enhances permafrost-thaw related hydrological connectivity (Gibson et al., 2018; Yoshikawa et al., 2002). These opposing processes explain why some wildfire scenarios resulted in slight declines in annual discharge, despite increases in peak flow

and faster recession. A matrix of simulations, incorporating all combinations of past, present, and future burn area, location, and thaw severity, showed that discharge responses were most strongly influenced by the degree of permafrost thaw induced by wildfire (Appendix F). This suggests that the primary hydrological impact of wildfire is its ability to accelerate permafrost thaw, thereby amplifying the thaw processes that drive increased discharge.

3.4.3 Relative Importance of Driving Factors

At the scale of La Martre River, results indicate that only a minor proportion of the observed increase in discharge can be directly attributed to wildfire. The influence of wildfire, however, may be stronger in smaller catchments where burns cover a larger fraction of the landscape. McClelland (2004) similarly found that only extreme burn extents or long recovery times could generate the magnitude of discharge changes observed alone, highlighting that while wildfire contributes to increasing discharge, its primary role is indirect, as it amplifies permafrost thaw and alters ground temperature, soil moisture, and subsurface flow pathways (Gibson et al., 2018; Zhang et al., 2015; Smith et al., 2015). Beyond hydrology, wildfire disrupts livelihoods, health, and cultural connections to the land (Dodd et al., 2018), and may affect water quality, though studies in the Taiga Plains report minimal changes in outlet chemistry (Spence et al., 2020a; Tank et al., 2019; Hutchins et al., 2023).

Across all periods, the magnitude of the increase in discharge compared to the base case was similar between net meteorological forcing and net permafrost thaw (Figure 3.5). However, the increase in annual, winter, and peak discharge due to precipitation alone was much larger. While temperature increases tend to reduce

discharge, a more appropriate comparison of the roles of precipitation and permafrost thaw is made by contrasting the seasonalized precipitation simulations with the combined effects of permafrost thaw and wildfire, which primarily accelerates permafrost thaw. The impact on annual and winter discharge from precipitation alone is roughly twice as large as that from permafrost thaw and wildfire in the present period (Figure 3.5). This suggests that increases in discharge in La Martre River are mainly driven by increased precipitation, with permafrost thaw and wildfire also contributing to the overall rise.

While increased precipitation has the most significant effect on the percent change in discharge, combined permafrost thaw and wildfire similarly influence the runoff ratio, the proportion of total precipitation converted into discharge (Figure 3.6). This indicates that precipitation and permafrost thaw contribute comparably to increased discharge efficiency within the watershed. In the case of precipitation alone, the additional water is either stored or lost via ET, with runoff increasing approximately in proportion to excess precipitation inputs. Similar increases in the runoff ratio have been observed in the Taiga Plains, where permafrost thaw has been identified as a key factor (Chasmer & Hopkinson, 2017). This supports the conclusion that climate- and wildfire- derived permafrost thaw, rather than precipitation alone, play a pivotal role in enhancing discharge efficiency and accelerating runoff generation.

Seasonalized Precip	5.3%	4.9%	6%	3.8%	Past Present Future
Permafrost Thaw and Wildfire	1.4%	3.6%	2.9%	1.4%	
Seasonalized Precip	18%	19.2%	13.3%	8.4%	
Permafrost Thaw and Wildfire	8.9%	10.5%	13.6%	8.9%	
Seasonalized Precip	37%	37.3%	36.7%	21.3%	
Permafrost Thaw and Wildfire	19%	23.3%	23.9%	19%	
	Annual Discharge	Winter Discharge	Peak Discharge	Runoff Ratio	

Figure 3.6. Relative importance of past, present, and future period seasonalized precipitation (rows 1, 3, and 5) and combined permafrost thaw and wildfire (rows 2, 4, and 6) on annual, winter, and peak discharge and the runoff ratio (columns 1, 2, 3, and 4, respectively) compared to the base case.

Climate change is expected to drive continued increases in precipitation in northern Canada (McCrystall et al., 2021). The future precipitation simulation used an annual total of 357 mm yr⁻¹, a 12% increase from the base period (Appendix F, Table F.1) leading to a 37% increase in annual, winter, and peak discharge (Figure 3.6). However, precipitation variability is also projected to increase (Bintaja et al., 2020; Cai et al., 2018). The historical record of precipitation in the Taiga Plains is uncertain due to the limited number of monitoring stations, adding uncertainty to the volume and timing of future precipitation. In contrast, the rate of warming from climate change is much more certain (Ono et al., 2022; Hu et al., 2021). Warming is driving permafrost loss across the pan-Arctic, especially in the discontinuous permafrost zone (Smith et al., 2022). The simulated increase in discharge for the combined permafrost thaw and wildfire scenario shows a 19% increase in annual discharge and a 23% increase in winter and peak discharge (Figure 3.6). Both precipitation and permafrost thaw are likely to drive further increases in discharge in the future. However, the rate of precipitation increase, and the impact of permafrost thaw and wildfire are unknown.

To predict with greater confidence the impacts of these drivers on the hydrological system in northern watersheds, it is essential to improve both precipitation forecasting and our understanding of permafrost thaw dynamics. Better measurement of precipitation, particularly in data-sparse regions like the Taiga Plains, will help refine and validate predictions of future precipitation. Meanwhile, improving our understanding of the mechanisms that control permafrost and its interactions with surface water is crucial for anticipating how permafrost thaw will affect future hydrology. This includes improving models of permafrost-thaw dynamics and incorporating these changes into hydrological forecasts to better predict both seasonal and annual discharge patterns. This study suggests that precipitation forecasts can be used to predict hydrological outcomes.

3.4.4 Cumulative Impact of Driving Factors

The combined effects of increased temperature and precipitation, permafrost thaw, and wildfire together amplify discharge beyond the independent impact of any of the drivers, though less than the sum of individual drivers. In the past, present, and future periods, annual discharge increases are 3.6%, 25.7%, and 42.7%, respectively, with slightly greater impacts on winter and peak discharge (Figure 3.7). This includes a steeper baseflow recession and an earlier, sharper spring freshet (Figure 3.4), suggesting more efficient downstream transfer of water. Across all periods, the cumulative runoff ratio exceeds that of any single forcing (2%, 15.5%, 26.3%; Figure 3.7), with values slightly higher than those in the permafrost thaw scenario. This indicates that enhanced discharge efficiency is primarily driven by thaw-induced lateral and vertical connectivity, while additional precipitation mainly increases discharge in proportion to the excess input.

Past	3.6%	4.3%	5.6%	2%
Present	25.7%	27.7%	29.1%	15.5%
Future	42.7%	42.7%	48.1%	26.3%
	Annual Discharge	Winter Discharge	Peak Discharge	Runoff Ratio

Figure 3.7. Percent change in annual, winter, and peak discharge (columns 1, 2, and 3) and runoff ratio (column 4) for the cumulative-impact simulations that combine all three component drivers. Rows represent the past (1), present (2), and future (3) periods.

Compared to meteorological forcing alone, the hydrograph shape shows steeper freshet peaks, with early breakthroughs evident in the present and future periods, though less pronounced over time. Discharge also remains elevated through the summer, and the late-fall peak is greater in the present and future periods. While the hydrograph shapes in the present and future are broadly similar, they are shifted upward by approximately $5 \text{ m}^3 \text{ s}^{-1}$ (Figure 3.4). This suggests that the largest structural changes in the watershed occurred between the past and present, with future shifts representing an intensification of these processes.

The cumulative impact scenarios suggest that the watershed may now be more vulnerable to large fluctuations in precipitation and temperature than in the past. The amplified discharge responses likely reflect a stronger hydrological sensitivity to precipitation conditions, caused by enhanced wetland connectivity (Connon et al., 2014) and subsurface flow pathways associated with permafrost degradation (Evans et al., 2020). In reality, precipitation trends are highly variable and do not follow the monotonic increases imposed in our simulations, where precipitation rises stepwise from the base case through the past, present, and future scenarios (Bitanja et al., 2020). Observational records further illustrate this variability: in Yellowknife, mean annual

precipitation during 2020–2025 was markedly lower at 190 mm than the 1980–2010 climate normal precipitation of 289 mm (ECCC, 2025b), contributing to the lowest recorded discharge in La Martre River in summer 2025 (as low as 15.5 m³/s in May and September 2025; WSC, 2025). These examples highlight that the hydrological consequences of warming and thaw are not simply a function of increasing precipitation, but also of its timing, magnitude, and interannual variability. The timing of precipitation inputs further shapes these outcomes, as evidenced by contrasts between seasonalized and non-seasonalized precipitation cases (Figure 3.4, Figure 3.5), which demonstrate how shifts in the seasonal distribution of rainfall and snowmelt can amplify or dampen discharge responses. Coupled with ongoing changes in meteorological regimes, land cover, and subsurface pathways, this variability suggests that the system may be increasingly sensitive to extreme precipitation periods and events, highlighting the need for further research on how permafrost loss influences watershed vulnerability to climate extremes.

Previous work has highlighted the Taiga Plains as unique within the pan-Arctic for exhibiting discharge increases without corresponding changes in precipitation (Mack et al., 2021). However, our results suggest that changes in annual precipitation, along with shifts in its seasonal distribution, have likely contributed substantially to the observed increasing trend in La Martre River discharge. Permafrost thaw alone can significantly elevate annual, winter, and peak flows, while additional precipitation amplifies these effects beyond what would be expected from either factor alone. In La Martre River watershed, the highest annual discharge occurred in 2012, producing 1.83 km³ of total discharge, 103% greater than modeled base case of 0.903 km³. Precipitation that year (385 mm) exceeded both the present- and future-period

simulation values (344 mm and 357 mm, respectively). The large increase in discharge and runoff ratio observed in 2012 surpasses the cumulative responses predicted by the present and future period simulations.

Although the model indicates that the three primary drivers, temperature and precipitation, permafrost thaw, and wildfire, have all contributed to the observed discharge increase, the rate of change remains greater than the model's predictions. This suggests that a key factor is still missing from the model to fully explain the observed discharge increase. For example, the current model's representation of groundwater flow may not adequately capture changes occurring in La Martre River watershed. Previous studies have shown that basins with greater permafrost coverage tend to experience more substantial discharge increases under warming conditions (McClelland et al., 2004; Niu et al., 2011; Wang et al., 2021; Song et al., 2020). Drilling in Whatì has revealed more permafrost than previously expected (Daly et al., 2022), suggesting that La Martre watershed may contain more permafrost than currently estimated. With permafrost thaw already advanced, this combination of factors, particularly in a highly conductive aquifer, has likely contributed to the pronounced discharge increases observed in the watershed. Additionally, the difference between the WSC and NALRRP watershed delineations (see Appendix B) suggests that the Bartlett Lake sub-basin (sub-basin 12) may flow intermittently into Lac La Martre, could have seasonal variations in its flow direction, or may have changed its discharge path over time due to the loss of permafrost barriers or subsidence.

3.4.5 Implications

La Martre River has experienced uniquely large increases in discharge compared to other watersheds in the Taiga Plains ecoregion and the pan-Arctic. Modeling results from this study suggest that coincident precipitation increase, permafrost thaw, and wildfire resulted in greater increases in annual, winter, and peak discharge than any individual driving factor alone. Across the pan-Arctic increasing temperature and precipitation have been observed (Box et al., 2019) and are predicted to continue (Bintanja et al., 2020; Cai et al., 2018). Where other risk factors exist, such as high permeability materials with rapidly thawing permafrost, peat plateau-wetland complexes, and the development and expansion of supra-permafrost taliks, severe hydrological implications should be expected, especially during extreme precipitation periods. At the watershed scale, likely consequences may include drying of lakes and wetlands as they become connected to deeper flow paths and are able to drain toward the basin outlet (Haynes et al., 2018; Carpino et al., 2021), altered biogeochemistry from increased groundwater contributions (Frey & McClelland, 2009), impacts on fish habitat through shifts in lake regimes and temperature (Docherty et al., 2019), and risks to water quantity and quality for communities such as Whatì, where water resources are vulnerable to permafrost thaw (Spence et al., 2020b; Wiebe et al., 2023). Understanding the cumulative effects of climate change on streamflow at intermediate-scales, like this study is needed to anticipate larger, continental-scale effects, such as in the Mackenzie River where La Martre River discharges. Ultimately, such changes will not only influence navigability of these major waterways, but in turn influence the chemistry and temperature of the Arctic Ocean (Zhang et al., 2021).

3.4.6 Limitations

This study used the Raven hydrological modeling framework to assess the hydrological impacts of increasing temperature, precipitation, permafrost thaw, and wildfire in a wetland-dominated discontinuous permafrost watershed. Due to the lack of local meteorological data, ERA5-Land temperature and precipitation data were used, though these have biases and may overrepresent temporal trends (Chapter 2). While Raven is a flexible tool, it has inherent limitations in explicitly simulating permafrost, groundwater flow, and wetland dynamics. Although some integrated surface-subsurface models can handle freeze-thaw processes and permafrost thaw at the watershed scale (Sridhar et al., 2017), these models are computationally complex and require high-quality subsurface data that were unavailable for this study. As a result, the Raven model was modified to simulate thaw dynamics, but the representation of groundwater remains inherently limited. Improved integration of freeze-thaw dynamics and temperature would allow for better incorporation of permafrost thaw into the model (Lamontagne-Hallé et al., 2020). Wetlands in discontinuous permafrost regions present additional challenges: although new algorithms have been developed to model wetland processes (Mekonnen et al., 2014; Taheri et al., 2023), they remain poorly suited to the unique peat plateau–wetland complexes present in the Taiga Plains. This limitation is reflected in the exaggerated fall peak in simulated streamflow, which likely results from errors in representing wetland processes and is much less pronounced in the observational discharge data. Continued refinement of wetland algorithms within Raven and other models are crucial for improving the representation of these complex landscapes.

3.5 Conclusions

This study aimed to evaluate the relative importance and cumulative impacts of increasing temperature and precipitation, permafrost thaw, and wildfire on discharge volume, timing, and hydrograph shape in La Martre River watershed. Using the Raven hydrological modeling framework, three distinct periods were simulated to assess the relative importance and cumulative impact of the drivers. The results highlight that all three factors affect streamflow in different ways:

- Increased precipitation had the most significant impact on discharge, causing an upward shift in the hydrograph. While higher temperatures alone led to a slight reduction in discharge, the combined effects of warming and increased precipitation resulted in higher discharge. Yet, meteorological change alone could not account for the observed increases in discharge in La Martre River, indicating other drivers were influential.
- Permafrost thaw contributed to increased discharge, though its effect was smaller in magnitude compared to precipitation. Wildfires primarily accelerate permafrost thaw, and together, these factors increased the runoff ratio to a level comparable to precipitation alone.
- Annual, winter, and peak discharge were highest under the combined influence of all three drivers. The cumulative impact resulted in annual discharge being 6.5% and 4.1% greater than precipitation alone in the present and future periods, respectively.

These findings underscore the high sensitivity of discharge in northern watersheds to interacting changes in climate, land cover, and subsurface flow processes. As climate change accelerates shifts in temperature, precipitation, and permafrost

conditions, understanding their combined effects will be essential for predicting hydrological responses across northern Canada and the pan-Arctic. The implications of these changes extend beyond streamflow to affect water quality, ecosystem function, and biogeochemical cycles.

Future scenarios suggest that continued increases in precipitation and permafrost thaw will drive ongoing hydrological impacts. While permafrost thaw is likely to persist in the north, the rate and magnitude of precipitation changes, along with growing interannual variability, will complicate predictions of future water resources in these regions. A deeper understanding of how these factors interact is crucial for improving predictions of hydrological responses in northern regions.

3.6 Literature Cited

- Ackley, C., Tank, S. E., Haynes, K. M., Rezanezhad, F., McCarter, C., & Quinton, W. L. (2021). Coupled hydrological and geochemical impacts of wildfire in peatland-dominated regions of discontinuous permafrost. *Science of The Total Environment*, 782, 146841. <https://doi.org/10.1016/j.scitotenv.2021.146841>
- Ahmed, M. I., Stadnyk, T., Pietroniro, A., Awoye, H., Bajracharya, A., Mai, J., Tolson, B. A., Shen, H., Craig, J. R., Gervais, M., Sagan, K., Wruth, S., Koenig, K., Lilhare, R., Déry, S. J., Pokorny, S., Venema, H., Muhammad, A., & Taheri, M. (2023). Learning from hydrological models' challenges: A case study from the Nelson basin model intercomparison project. *Journal of Hydrology*, 623, 129820. <https://doi.org/10.1016/j.jhydrol.2023.129820>
- Ahmed, N., Wang, G., Booij, M. J., Marhaento, H., Pordhan, F. A., Ali, S., Munir, S., & Hashmi, M. Z.-R. (2022). Variations in hydrological variables using distributed hydrological model in permafrost environment. *Ecological Indicators*, 145, 109609. <https://doi.org/10.1016/j.ecolind.2022.109609>
- Aygün, O., Kinnard, C., & Campeau, S. (2020). Impacts of climate change on the hydrology of northern midlatitude cold regions. *Progress in Physical Geography: Earth and Environment*, 44(3), 338–375. <https://doi.org/10.1177/0309133319878123>
- Bayley, S. E., Schindler, D. W., Beaty, K. G., Parker, B. R., & Stainton, M. P. (1992). Effects of Multiple Fires on Nutrient Yields from Streams Draining Boreal Forest and Fen Watersheds: Nitrogen and Phosphorus. *Canadian Journal of Fisheries and Aquatic Sciences*, 49(3), 584–596. <https://doi.org/10.1139/f92-068>
- Bennett, K. E., Schwenk, J., Bachand, C., Gasarch, E., Stachelek, J., Bolton, W. R., & Rowland, J. C. (2023). Recent streamflow trends across permafrost basins of North America. *Frontiers in Water*, 5. <https://www.frontiersin.org/articles/10.3389/frwa.2023.1099660>
- Berezovskaya, S., Yang, D., & Hinzman, L. (2005). Long-term annual water balance analysis of the Lena River. *Global and Planetary Change*, 48(1), 84–95. <https://doi.org/10.1016/j.gloplacha.2004.12.006>
- Bintanja, R. (2018). The impact of Arctic warming on increased rainfall. *Scientific Reports*, 8(1), 16001. <https://doi.org/10.1038/s41598-018-34450-3>
- Bintanja, R., van der Wiel, K., van der Linden, E. C., Reusen, J., Bogerd, L., Krikken, F., & Selten, F. M. (2020). Strong future increases in Arctic precipitation variability linked to poleward moisture transport. *Science Advances*, 6(7), eaax6869. <https://doi.org/10.1126/sciadv.aax6869>
- Bond, W. A. (1972). An Investigation of the Commercial Fishery at Lac La Martre, N.W.T., 1972. <https://waves-vagues.dfo-mpo.gc.ca/Library/38900.pdf>

- Bowling, L. C., & Lettenmaier, D. P. (2010). Modeling the Effects of Lakes and Wetlands on the Water Balance of Arctic Environments. <https://doi.org/10.1175/2009JHM1084.1>
- Box, J. E., Colgan, W. T., Christensen, T. R., Schmidt, N. M., Lund, M., Parmentier, F.-J. W., Brown, R., Bhatt, U. S., Euskirchen, E. S., Romanovsky, V. E., Walsh, J. E., Overland, J. E., Wang, M., Corell, R. W., Meier, W. N., Wouters, B., Mernild, S., Mård, J., Pawlak, J., & Olsen, M. S. (2019). Key indicators of Arctic climate change: 1971–2017. *Environmental Research Letters*, 14(4), 45010. <https://doi.org/10.1088/1748-9326/aafc1b>
- Brabets, T. P., & Walvoord, M. A. (2009). Trends in streamflow in the Yukon River Basin from 1944 to 2005 and the influence of the Pacific Decadal Oscillation. *Journal of Hydrology*, 371(1), 108–119. <https://doi.org/10.1016/j.jhydrol.2009.03.018>
- Brown, G., & Craig, J. R. (2020). Structural calibration of an semi-distributed hydrological model of the Liard River basin. *Canadian Water Resources Journal / Revue Canadienne Des Ressources Hydriques*, 45(4), 287–303. <https://doi.org/10.1080/07011784.2020.1803143>
- Cai, L., Alexeev, V. A., Walsh, J. E., & Bhatt, U. S. (2018). Patterns, Impacts, and Future Projections of Summer Variability in the Arctic from CMIP5 Models. *Journal of Climate*, 31(24), 9815–9833. <https://doi.org/10.1175/JCLI-D-18-0119.1>
- Carpino, O., Haynes, K., Connon, R., Craig, J., Devoie, É., & Quinton, W. (2021). Long-term climate-influenced land cover change in discontinuous permafrost peatland complexes. *Hydrology and Earth System Sciences*, 25(6), 3301–3317. <https://doi.org/10.5194/hess-25-3301-2021>
- Chasmer, L., & Hopkinson, C. (2017). Threshold loss of discontinuous permafrost and landscape evolution. *Global Change Biology*, 23(7), 2672–2686. <https://doi.org/10.1111/gcb.13537>
- Chesnokova, A., Baraër, M., & Bouchard, É. (2020). Proglacial icings as records of winter hydrological processes. *The Cryosphere*, 14(11), 4145–4164. <https://doi.org/10.5194/tc-14-4145-2020>
- Connon, R., Devoie, É., Hayashi, M., Veness, T., & Quinton, W. (2018). The Influence of Shallow Taliks on Permafrost Thaw and Active Layer Dynamics in Subarctic Canada. *Journal of Geophysical Research: Earth Surface*, 123(2), 281–297. <https://doi.org/10.1002/2017JF004469>
- Connon, R., Quinton, W. L., Craig, J. R., & Hayashi, M. (2014). Changing hydrologic connectivity due to permafrost thaw in the lower Liard River valley, NWT, Canada. *Hydrological Processes*, 28(14), 4163–4178. <https://doi.org/10.1002/hyp.10206>
- Connon, R., Quinton, W. L., Craig, J. R., Hanisch, J., & Sonnentag, O. (2015). The hydrology of interconnected bog complexes in discontinuous permafrost terrains. *Hydrological Processes*, 29(18), 3831–3847. <https://doi.org/10.1002/hyp.10604>

- Coogan, S. C. P., Daniels, L. D., Boychuk, D., Burton, P. J., Flannigan, M. D., Gauthier, S., Kafka, V., Park, J. S., & Wotton, B. M. (2021). Fifty years of wildland fire science in Canada. *Canadian Journal of Forest Research*, 51(2), 283–302. <https://doi.org/10.1139/cjfr-2020-0314>
- Craig, J. R., Brown, G., Chlumsky, R., Jenkinson, R. W., Jost, G., Lee, K., Mai, J., Serrer, M., Sgro, N., Shafii, M., Snowdon, A. P., & Tolson, B. A. (2020). Flexible watershed simulation with the Raven hydrological modelling framework. *Environmental Modelling & Software*, 129, 104728. <https://doi.org/10.1016/j.envsoft.2020.104728>
- Daly, S. v, Bonnaventure, P. P., & Kochtitzky, W. (2022). Influence of ecosystem and disturbance on near-surface permafrost distribution, Whatì, Northwest Territories, Canada. *Permafrost and Periglacial Processes*, 33(4), 339–352. <https://doi.org/10.1002/ppp.2160>
- Déry, S. J., & Wood, E. F. (2005). Decreasing river discharge in northern Canada. *Geophysical Research Letters*, 32(10). <https://doi.org/10.1029/2005GL022845>
- Déry, S. J., Hernández-Henríquez, M. A., Burford, J. E., & Wood, E. F. (2009). Observational evidence of an intensifying hydrological cycle in northern Canada. *Geophysical Research Letters*, 36(13). <https://doi.org/10.1029/2009GL038852>
- Déry, S. J., Stadnyk, T. A., MacDonald, M. K., & Gaudi-Sharma, B. (2016). Recent trends and variability in river discharge across northern Canada. *Hydrology and Earth System Sciences*, 20(12), 4801–4818. <https://doi.org/10.5194/hess-20-4801-2016>
- Devoie, É. G., Craig, J. R., Connon, R. F., & Quinton, W. L. (2019). Taliks: A Tipping Point in Discontinuous Permafrost Degradation in Peatlands. *Water Resources Research*, 55(11), 9838–9857. <https://doi.org/10.1029/2018WR024488>
- Devoie, É. G., Craig, J. R., Dominico, M., Carpino, O., Connon, R. F., Rudy, A. C. A., & Quinton, W. L. (2021). Mechanisms of Discontinuous Permafrost Thaw in Peatlands. *Journal of Geophysical Research: Earth Surface*, 126(11), e2021JF006204. <https://doi.org/10.1029/2021JF006204>
- Docherty, C. L., Dugdale, S. J., Milner, A. M., Abermann, J., Lund, M., & Hannah, D. M. (2019). Arctic river temperature dynamics in a changing climate. *River Research and Applications*, 35(8), 1212–1227. <https://doi.org/10.1002/rra.3537>
- Dodd, W., Scott, P., Howard, C., Scott, C., Rose, C., Cunsolo, A., & Orbinski, J. (2018). Lived experience of a record wildfire season in the Northwest Territories, Canada. *Canadian Journal of Public Health*, 109(3), 327–337. <https://doi.org/10.17269/s41997-018-0070-5>
- Douglas, T. A., Turetsky, M. R., & Koven, C. D. (2020). Increased rainfall stimulates permafrost thaw across a variety of Interior Alaskan boreal ecosystems. *Npj Climate and Atmospheric Science*, 3(1), 1–7. <https://doi.org/10.1038/s41612-020-0130-4>
- Ducks Unlimited Canada. (2010). Hybrid Wetland Layer.

- Ducks Unlimited Canada. (2023). Tłı̨chǫ Wetland Classification.
- Durocher, M., Requena, A. I., Burn, D. H., & Pellerin, J. (2019). Analysis of trends in annual streamflow to the Arctic Ocean. *Hydrological Processes*, 33(7), 1143–1151. <https://doi.org/10.1002/hyp.13392>
- Earth Tech Canada Inc. (Earth Tech). (2007, July 11). *Water licence renewal: Tlı̨cho Community Government of Whatı̨, NT* (Prepared for the Tlı̨cho Community Government of Whatı̨, NT). Earth Tech Canada Ltd.
- Environment and Climate Change Canada. (2025a). *Meteorological data for Whatı̨, Northwest Territories* (Station: 2202678). Retrieved September 22, 2025, from https://climate.weather.gc.ca/climate_data/daily_data_e.html
- Environment and Climate Change Canada. (2025b). *Climate normals for Yellowknife, Northwest Territories* (30-year normals). Retrieved September 22, 2025, from https://climate.weather.gc.ca/climate_normals/index_e.html
- Evans, S. G., Yokeley, B., Stephens, C., & Brewer, B. (2020). Potential mechanistic causes of increased baseflow across northern Eurasia catchments underlain by permafrost. *Hydrological Processes*, 34(11), 2676–2690. <https://doi.org/10.1002/hyp.13759>
- Fabre, C., Sauvage, S., Tananaev, N., Srinivasan, R., Teisserenc, R., & Sánchez Pérez, J. M. (2017). Using Modeling Tools to Better Understand Permafrost Hydrology. *Water*, 9(6), 418. <https://doi.org/10.3390/w9060418>
- Flügel, W.-A. (1995). Delineating hydrological response units by geographical information system analyses for regional hydrological modelling using PRMS/MMS in the drainage basin of the River Bröl, Germany. *Hydrological Processes*, 9(3–4), 423–436. <https://doi.org/10.1002/hyp.3360090313>
- Ge, S., McKenzie, J., Voss, C., & Wu, Q. (2011). Exchange of groundwater and surface-water mediated by permafrost response to seasonal and long term air temperature variation. *Geophysical Research Letters*, 38(14). <https://doi.org/10.1029/2011GL047911>
- Gibson, C. M., Chasmer, L. E., Thompson, D. K., Quinton, W. L., Flannigan, M. D., & Olefeldt, D. (2018). Wildfire as a major driver of recent permafrost thaw in boreal peatlands. *Nature Communications*, 9(1), 3041. <https://doi.org/10.1038/s41467-018-05457-1>
- Guthke, A. (2017). Defensible Model Complexity: A Call for Data-Based and Goal-Oriented Model Choice. *Groundwater*, 55(5), 646–650. <https://doi.org/10.1111/gwat.12554>
- Han, M., Shen, H., Tolson, B. A., Craig, J. R., Mai, J., Lin, S. G. M., Basu, N. B., & Awol, F. S. (2023). BasinMaker 3.0: A GIS toolbox for distributed watershed delineation of complex lake-river routing networks. *Environmental Modelling & Software*, 164, 105688. <https://doi.org/10.1016/j.envsoft.2023.105688>

- Haynes, K. M., Carpino, O. A., Connon, R. F., Devoie, É., & Quinton, W. L. (2019). Thaw-induced land-cover change in the southern margin of discontinuous permafrost, northeastern British Columbia and southwestern Northwest Territories. *Geoscience BC Summary of Activities 2018: Energy and Water, Geoscience BC Report 2019-2*, 123–132.
- Haynes, K. M., Connon, R. F., & Quinton, W. L. (2018). Permafrost thaw induced drying of wetlands at Scotty Creek, NWT, Canada. *Environmental Research Letters*, 13(11), 114001. <https://doi.org/10.1088/1748-9326/aae46c>
- Haynes, K. M., Smart, J., Disher, B., Carpino, O., & Quinton, W. L. (2021). The role of hummocks in re-establishing black spruce forest following permafrost thaw. *Ecohydrology*, 14(3), e2273. <https://doi.org/10.1002/eco.2273>
- Hedstrom, N. R., & Pomeroy, J. W. (1998). Measurements and modelling of snow interception in the boreal forest. *Hydrological Processes*, 12(10–11), 1611–1625. [https://doi.org/10.1002/\(SICI\)1099-1085\(199808/09\)12:10/11<1611::AID-HYP684>3.0.CO;2-4](https://doi.org/10.1002/(SICI)1099-1085(199808/09)12:10/11<1611::AID-HYP684>3.0.CO;2-4)
- Heginbottom, J. A., Dubreuil, M. A., & Harker, P. T. (1995). Canada, permafrost. In *The National Atlas of Canada* (5th ed.; MCR Series no. 4177, 1 sheet). Natural Resources Canada, Geomatics Canada. <https://doi.org/10.4095/294672>
- Herdendorf, C. E. (1982). Large lakes of the world. *Journal of Great Lakes Research*, 8(3), 379–412. [https://doi.org/10.1016/S0380-1330\(82\)71982-3](https://doi.org/10.1016/S0380-1330(82)71982-3)
- Hinzman, L. D., Bettez, N. D., Bolton, W. R., Chapin, F. S., Dyurgerov, M. B., Fastie, C. L., Griffith, B., Hollister, R. D., Hope, A., Huntington, H. P., Jensen, A. M., Jia, G. J., Jorgenson, T., Kane, D. L., Klein, D. R., Kofinas, G., Lynch, A. H., Lloyd, A. H., McGuire, A. D., ... Yoshikawa, K. (2005). Evidence and Implications of Recent Climate Change in Northern Alaska and Other Arctic Regions. *Climatic Change*, 72(3), 251–298. <https://doi.org/10.1007/s10584-005-5352-2>
- Hutchins, R. H. S., Tank, S. E., Olefeldt, D., Quinton, W. L., Spence, C., Dion, N., & Mengistu, S. G. (2023). Influence of Wildfire on Downstream Transport of Dissolved Carbon, Nutrients, and Mercury in the Permafrost Zone of Boreal Western Canada. *Journal of Geophysical Research: Biogeosciences*, 128(10). <https://doi.org/10.1029/2023JG007602>
- Jorgenson, M. T., & Osterkamp, T. E. (2005). Response of boreal ecosystems to varying modes of permafrost degradation. *Canadian Journal of Forest Research*, 35(9), 2100–2111. <https://doi.org/10.1139/x05-153>
- Karlsson, J. M., Lyon, S. W., & Destouni, G. (2012). Thermokarst lake, hydrological flow and water balance indicators of permafrost change in Western Siberia. *Journal of Hydrology*, 464–465, 459–466. <https://doi.org/10.1016/j.jhydrol.2012.07.037>
- Kasischke, E. S., Verbyla, D. L., Rupp, T. S., McGuire, A. D., Murphy, K. A., Jandt, R., Barnes, J. L., Hoy, E. E., Duffy, P. A., Calef, M., & Turetsky, M. R. (2010). Alaska's changing fire regime — implications for the vulnerability of its boreal

- forests. *Canadian Journal of Forest Research*, 40(7), 1313–1324.
<https://doi.org/10.1139/X10-098>
- Koch, J. C., Gurney, K., & Wipfli, M. S. (2014). Morphology-Dependent Water Budgets and Nutrient Fluxes in Arctic Thaw Ponds. *Permafrost and Periglacial Processes*, 25(2), 79–93. <https://doi.org/10.1002/ppp.1804>
- Krogh, S. A., Pomeroy, J. W., & Marsh, P. (2017). Diagnosis of the hydrology of a small Arctic basin at the tundra-taiga transition using a physically based hydrological model. *Journal of Hydrology*, 550, 685–703.
<https://doi.org/10.1016/j.jhydrol.2017.05.042>
- Kurylyk, B. L., & Watanabe, K. (2013). The mathematical representation of freezing and thawing processes in variably-saturated, non-deformable soils. *Advances in Water Resources*, 60, 160–177. <https://doi.org/10.1016/j.advwatres.2013.07.016>
- Lackey, R., Wright, S. N., & MacKenzie, J. M. (in prep.) Groundwater recharge, storage, and flow in supra-permafrost taliks.
- Laing, J., & Binyamin, J. (2013). Climate Change Effect on Winter Temperature and Precipitation of Yellowknife, Northwest Territories, Canada from 1943 to 2011. *American Journal of Climate Change*, 2(4), 275–283.
<https://doi.org/10.4236/ajcc.2013.24027>
- Lamontagne, S., Carignan, R., D'Arcy, P., Prairie, Y. T., & Paré, D. (2000). Element export in runoff from eastern Canadian Boreal Shield drainage basins following forest harvesting and wildfires. *Canadian Journal of Fisheries and Aquatic Sciences*, 57(S2), 118–128. <https://doi.org/10.1139/f00-108>
- Lamontagne-Hallé, P., McKenzie, J. M., Kurylyk, B. L., & Zipper, S. C. (2018). Changing groundwater discharge dynamics in permafrost regions. *Environmental Research Letters*, 13(8), 84017. <https://doi.org/10.1088/1748-9326/aad404>
- Lamontagne-Hallé, P., McKenzie, J. M., Kurylyk, B. L., Molson, J., & Lyon, L. N. (2020). Guidelines for cold-regions groundwater numerical modeling. *WIREs Water*, 7(6), e1467. <https://doi.org/10.1002/wat2.1467>
- Lee, S., Yeo, I.-Y., Lang, M. W., Sadeghi, A. M., McCarty, G. W., Moglen, G. E., & Evenson, G. R. (2018). Assessing the cumulative impacts of geographically isolated wetlands on watershed hydrology using the SWAT model coupled with improved wetland modules. *Journal of Environmental Management*, 223, 37–48.
<https://doi.org/10.1016/j.jenvman.2018.06.006>
- Liu, H., Randerson, J. T., Lindfors, J., & Chapin, F. S. (2005). Changes in the surface energy budget after fire in boreal ecosystems of interior Alaska: An annual perspective. *Journal of Geophysical Research: Atmospheres*, 110(D13).
<https://doi.org/10.1029/2004JD005158>
- Liu, S., Wang, P., Yu, J., Wang, T., Cai, H., Huang, Q., Pozdniakov, S. P., Zhang, Y., & Kazak, E. S. (2022). Mechanisms behind the uneven increases in early, mid- and late winter streamflow across four Arctic river basins. *Journal of Hydrology*, 606, 127425. <https://doi.org/10.1016/j.jhydrol.2021.127425>

- Mack, M., Connon, R., Makarieva, O., McLaughlin, J., Nesterova, N., & Quinton, W. (2021). Heterogenous runoff trends in peatland-dominated basins throughout the circumpolar North. *Environmental Research Communications*, 3(7), 75006. <https://doi.org/10.1088/2515-7620/ac11ed>
- Mahat, V., Silins, U., & Anderson, A. (2016). Effects of wildfire on the catchment hydrology in southwest Alberta. *CATENA*, 147, 51–60. <https://doi.org/10.1016/j.catena.2016.06.040>
- Matott, L. S. (2017). OSTRICH – An Optimization Software Toolkit for Research Involving Computational Heuristics Documentation and User’s Guide Version 17.12.19.
- McClelland, J. W., Holmes, R. M., Peterson, B. J., & Stieglitz, M. (2004). Increasing river discharge in the Eurasian Arctic: Consideration of dams, permafrost thaw, and fires as potential agents of change. *Journal of Geophysical Research: Atmospheres*, 109(D18). <https://doi.org/10.1029/2004JD004583>
- McCrystall, M. R., Stroeve, J., Serreze, M., Forbes, B. C., & Screen, J. A. (2021). New climate models reveal faster and larger increases in Arctic precipitation than previously projected. *Nature Communications*, 12(1), 6765. <https://doi.org/10.1038/s41467-021-27031-y>
- Mekonnen, M. A., Wheeler, H. S., Ireson, A. M., Spence, C., Davison, B., & Pietroniro, A. (2014). Towards an improved land surface scheme for prairie landscapes. *Journal of Hydrology*, 511, 105–116. <https://doi.org/10.1016/j.jhydrol.2014.01.020>
- Moragoda, N., & Cohen, S. (2020). Climate-induced trends in global riverine water discharge and suspended sediment dynamics in the 21st century. *Global and Planetary Change*, 191, 103199. <https://doi.org/10.1016/j.gloplacha.2020.103199>
- Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D. G., Piles, M., Rodríguez-Fernández, N. J., Zsoter, E., Buontempo, C., & Thépaut, J.-N. (2021). ERA5-Land: a state-of-the-art global reanalysis dataset for land applications. *Earth System Science Data*, 13(9), 4349–4383. <https://doi.org/10.5194/essd-13-4349-2021>
- Niu, L., Ye, B., Li, J., & Sheng, Y. (2011). Effect of permafrost degradation on hydrological processes in typical basins with various permafrost coverage in Western China. *Science China Earth Sciences*, 54(4), 615–624. <https://doi.org/10.1007/s11430-010-4073-1>
- O’Connor, M. T., Cardenas, M. B., Neilson, B. T., Nicholaides, K. D., & Kling, G. W. (2019). Active Layer Groundwater Flow: The Interrelated Effects of Stratigraphy, Thaw, and Topography. *Water Resources Research*, 55(8), 6555–6576. <https://doi.org/10.1029/2018WR024636>
- Obu, J., Westermann, S., Bartsch, A., Berdnikov, N., Christiansen, H. H., Dashtseren, A., Delaloye, R., Elberling, B., Etzelmüller, B., Kholodov, A., Khomutov, A., Kääb, A., Leibman, M. O., Lewkowicz, A. G., Panda, S. K., Romanovsky, V., Way, R. G.,

- Westergaard-Nielsen, A., Wu, T., ... Zou, D. (2019). Northern Hemisphere permafrost map based on TTOP modelling for 2000–2016 at 1 km² scale. *Earth-Science Reviews*, 193, 299–316. <https://doi.org/10.1016/j.earscirev.2019.04.023>
- Overeem, I., & Syvitski, J. P. M. (2010). Shifting Discharge Peaks in Arctic Rivers, 1977–2007. *Geografiska Annaler: Series A, Physical Geography*, 92(2), 285–296. <https://doi.org/10.1111/j.1468-0459.2010.00395.x>
- Park, H., Kim, Y., Suzuki, K., & Hiyama, T. (2024). Influence of snowmelt on increasing Arctic river discharge: numerical evaluation. *Progress in Earth and Planetary Science*, 11(1), 13. <https://doi.org/10.1186/s40645-024-00617-y>
- Pavelsky, T. M., & Zarnetske, J. P. (2017). Rapid decline in river icings detected in Arctic Alaska: Implications for a changing hydrologic cycle and river ecosystems. *Geophysical Research Letters*, 44(7), 3228–3235. <https://doi.org/10.1002/2016GL072397>
- Pelletier, N., Talbot, J., Olefeldt, D., Turetsky, M., Blodau, C., Sonnentag, O., & Quinton, W. L. (2017). Influence of Holocene permafrost aggradation and thaw on the paleoecology and carbon storage of a peatland complex in northwestern Canada. *The Holocene*, 27(9), 1391–1405. <https://doi.org/10.1177/0959683617693899>
- Peterson, B. J., Holmes, R. M., McClelland, J. W., Vörösmarty, C. J., Lammers, R. B., Shiklomanov, A. I., Shiklomanov, I. A., & Rahmstorf, S. (2002). Increasing River Discharge to the Arctic Ocean. *Science*, 298(5601), 2171–2173. <https://doi.org/10.1126/science.1077445>
- Pierce, D. W., Cayan, D. R., Maurer, E. P., Abatzoglou, J. T., & Hegewisch, K. C. (2015). Improved Bias Correction Techniques for Hydrological Simulations of Climate Change. <https://doi.org/10.1175/JHM-D-14-0236.1>
- Porter, C., Howat, I., Noh, M.-J., Husby, E., Khuvis, S., Danish, E., Tomko, K., Gardiner, J., Negrete, A., Yadav, B., Klassen, J., Kelleher, C., Cloutier, M., Bakker, J., Enos, J., Arnold, G., Bauer, G., Morin, P., & Polar Geospatial Center. (2023). ArcticDEM - Mosaics, Version 4.1. Harvard Dataverse. <https://doi.org/10.7910/DVN/3VDC4W>
- Putz, G., Burke, J. M., Smith, D. W., Chanasyk, D. S., Prepas, E. E., & Mapfumo, E. (2003). Modelling the effects of boreal forest landscape management upon streamflow and water quality: Basic concepts and considerations. *Journal of Environmental Engineering and Science*, 2(Supplement 1), S87–S101. <https://doi.org/10.1139/s03-032>
- Quinton, W. L., & Baltzer, J. L. (2013). The active-layer hydrology of a peat plateau with thawing permafrost (Scotty Creek, Canada). *Hydrogeology Journal*, 21(1), 201–220. <https://doi.org/10.1007/s10040-012-0935-2>
- Quinton, W. L., Hayashi, M., & Pietroniro, A. (2003). Connectivity and storage functions of channel fens and flat bogs in northern basins. *Hydrological Processes*, 17(18), 3665–3684. <https://doi.org/10.1002/hyp.1369>

- Rawlins, M. A., Serreze, M. C., Schroeder, R., Zhang, X., & McDonald, K. C. (2009). Diagnosis of the record discharge of Arctic-draining Eurasian rivers in 2007. *Environmental Research Letters*, 4(4), 045011. <https://doi.org/10.1088/1748-9326/4/4/045011>
- Rawlins, M., Yang, D., & Ge, S. (2021). Regional and Basin Streamflow Regimes and Changes: Climate Impact and Human Effect. In D. Yang & D. L. Kane (Eds.), *Arctic Hydrology, Permafrost and Ecosystems* (pp. 159–186). Springer International Publishing. https://doi.org/10.1007/978-3-030-50930-9_6
- Schindler, D. W., Newbury, R. W., Beaty, K. G., Prokopowich, J., Ruszczynski, T., & Dalton, J. A. (1980). Effects of a Windstorm and Forest Fire on Chemical Losses from Forested Watersheds and on the Quality of Receiving Streams. *Canadian Journal of Fisheries and Aquatic Sciences*, 37(3), 328–334. <https://doi.org/10.1139/f80-046>
- Smith, A. J. P., Jones, M. W., Abatzoglou, J. T., Canadell, J. G., & Betts, R. A. (2020). Climate Change Increases the Risk of Wildfires. *ScienceBrief*. https://sciencebrief.org/uploads/reviews/ScienceBrief_Review_WILDFIRES_Sep2020.pdf
- Smith, S. L., Riseborough, D. W., & Bonnaventure, P. P. (2015). Eighteen Year Record of Forest Fire Effects on Ground Thermal Regimes and Permafrost in the Central Mackenzie Valley, NWT, Canada. *Permafrost and Periglacial Processes*, 26(4), 289–303. <https://doi.org/10.1002/ppp.1849>
- SNC-Lavalin Inc. (SNC-Lavalin). (2012, April 30). *La Martre Falls - Hydroelectric development: Final feasibility report* (Prepared for Tlicho Investment Corporation). SNC-Lavalin Inc.
- Song, C., Wang, G., Mao, T., Dai, J., & Yang, D. (2020). Linkage between permafrost distribution and river runoff changes across the Arctic and the Tibetan Plateau. *Science China Earth Sciences*, 63(2), 292–302. <https://doi.org/10.1007/s11430-018-9383-6>
- Spence, C., Hedstrom, N., Tank, S. E., Quinton, W. L., Olefeldt, D., Goodman, S., & Dion, N. (2020a). Hydrological resilience to forest fire in the subarctic Canadian shield. *Hydrological Processes*, 34(25), 4940–4958. <https://doi.org/10.1002/hyp.13915>
- Spence, C., Kokelj, S. A., Kokelj, S. v., & Hedstrom, N. (2014). The process of winter streamflow generation in a subarctic Precambrian Shield catchment. *Hydrological Processes*, 28(14), 4179–4190. <https://doi.org/10.1002/hyp.10119>
- Spence, C., Norris, M., Bickerton, G., Bonsal, B. R., Brua, R., Culp, J. M., Dibike, Y., Gruber, S., Morse, P. D., Peters, D. L., Shrestha, R., & Wolfe, S. A. (2020b). The Canadian Water Resource Vulnerability Index to Permafrost Thaw (CWRVIPT). *Arctic Science*, 6(4), 437–462. <https://doi.org/10.1139/as-2019-0028>

- Sridhar, V., Billah, M. M., & Hildreth, J. W. (2018). Coupled Surface and Groundwater Hydrological Modeling in a Changing Climate. *Groundwater*, 56(4), 618–635. <https://doi.org/10.1111/gwat.12610>
- St. Jacques, J.-M., & Sauchyn, D. J. (2009). Increasing winter baseflow and mean annual streamflow from possible permafrost thawing in the Northwest Territories, Canada. *Geophysical Research Letters*, 36(1). <https://doi.org/10.1029/2008GL035822>
- Stantec Consulting Ltd. (Stantec). (2017, November 10). *Geotechnical report, road alignment, proposed Tlicho all-season road, Northwest Territories* (Prepared for Tlicho Engineering and Environmental Services Ltd.). Stantec Consulting Ltd.
- Statistics Canada. (2023). *Census profile, 2021 Census of Population* (Catalogue no. 98-316-X2021001). Statistics Canada. Released November 15, 2023. Retrieved November 22, 2025, from <https://www12.statcan.gc.ca/census-recensement/2021/dp-pd/prof/index.cfm?Lang=E>
- Syvitski, J. P. M. (2002). Sediment discharge variability in Arctic rivers: implications for a warmer future. *Polar Research*, 21(2), 323–330. <https://doi.org/10.3402/polar.v21i2.6494>
- Taheri, M., Ranjram, M., & Craig, J. R. (2023). An Upscaled Model of Fill-And-Spill Hydrological Response. *Water Resources Research*, 59(5), e2022WR033494. <https://doi.org/10.1029/2022WR033494>
- Tank, S. E., McClelland, J. W., Spencer, R. G. M., Shiklomanov, A. I., Suslova, A., Moatar, F., Amon, R. M. W., Cooper, L. W., Elias, G., Gordeev, V. v, Guay, C., Gurtovaya, T. Y., Kosmenko, L. S., Mutter, E. A., Peterson, B. J., Peucker-Ehrenbrink, B., Raymond, P. A., Schuster, P. F., Scott, L., ... Holmes, R. M. (2023). Recent trends in the chemistry of major northern rivers signal widespread Arctic change. *Nature Geoscience*, 16(9), 789–796. <https://doi.org/10.1038/s41561-023-01247-7>
- Tank, S., Olefeldt, D., Quinton, W., Spence, C., Dion, N., Ackley, C., Burd, K., Hutchins, R., & Mengistu, S. (2019). Fire in the Arctic: The effect of wildfire across diverse aquatic ecosystems of the Northwest Territories. *Polar Knowledge: Aqhaliat Report*, 1(1), 31–38. <https://doi.org/10.35298/pkc.2018.04>
- Tolson, B. A., & Shoemaker, C. A. (2007). Dynamically dimensioned search algorithm for computationally efficient watershed model calibration. *Water Resources Research*, 43(1). <https://doi.org/10.1029/2005WR004723>
- Vincent, L. A., Zhang, X., Brown, R. D., Feng, Y., Mekis, E., Milewska, E. J., Wan, H., & Wang, X. L. (2015). Observed Trends in Canada's Climate and Influence of Low-Frequency Variability Modes. *Journal of Climate*, 28(11), 4545–4560. <https://doi.org/10.1175/JCLI-D-14-00697.1>
- Walvoord, M. A., & Kurylyk, B. L. (2016). Hydrologic Impacts of Thawing Permafrost—A Review. *Vadose Zone Journal*, 15(6), vzj2016.01.0010. <https://doi.org/10.2136/vzj2016.01.0010>

- Walvoord, M. A., Voss, C. I., & Wellman, T. P. (2012). Influence of permafrost distribution on groundwater flow in the context of climate-driven permafrost thaw: Example from Yukon Flats Basin, Alaska, United States. *Water Resources Research*, 48(7). <https://doi.org/10.1029/2011WR011595>
- Water Survey of Canada (WSC). (2025). *Daily discharge data for La Martre River below outlet of Lac La Martre (07TA001) [NT]*. Environment and Climate Change Canada. Retrieved September 22, 2025, from https://wateroffice.ec.gc.ca/report/historical_e.html?stn=07TA001
- Whitman, E., Parisien, M.-A., Thompson, D. K., & Flannigan, M. D. (2019). Short-interval wildfire and drought overwhelm boreal forest resilience. *Scientific Reports*, 9(1), 18796. <https://doi.org/10.1038/s41598-019-55036-7>
- Wiebe, A., Langston, G., McKenzie, J. M., Grandpré, I. de, & Connon, R. (2023). Groundwater Supply Vulnerability Assessment for Whatì, Northwest Territories.
- Wilson, K. B., Hanson, P. J., & Baldocchi, D. D. (2000). Factors controlling evaporation and energy partitioning beneath a deciduous forest over an annual cycle. *Agricultural and Forest Meteorology*, 102(2–3), 83–103.
- Wright, S. N., Thompson, L. M., Olefeldt, D., Connon, R. F., Carpino, O. A., Beel, C. R., & Quinton, W. L. (2022). Thaw-induced impacts on land and water in discontinuous permafrost: A review of the Taiga Plains and Taiga Shield, northwestern Canada. *Earth-Science Reviews*, 232, 104104. <https://doi.org/10.1016/j.earscirev.2022.104104>
- Xu, Y. (2023). *hyfo: Hydrology and climate forecasting R package for data analysis and visualization*. Retrieved from <http://yuanchao-xu.github.io/hyfo/>
- Yang, D., Shi, X., & Marsh, P. (2015). Variability and extreme of Mackenzie River daily discharge during 1973–2011. *Quaternary International*, 380–381, 159–168. <https://doi.org/10.1016/j.quaint.2014.09.023>
- Yoshikawa, K., Bolton, W. R., Romanovsky, V. E., Fukuda, M., & Hinzman, L. D. (2002). Impacts of wildfire on the permafrost in the boreal forests of Interior Alaska. *Journal of Geophysical Research: Atmospheres*, 107(D1), FFR 4-1-FFR 4-14. <https://doi.org/10.1029/2001JD000438>
- Zhang, S.-M., Mu, C.-C., Li, Z.-L., Dong, W.-W., Wang, X.-Y., Streletskaia, I., Grebenets, V., Sokratov, S., Kizyakov, A., & Wu, X.-D. (2021). Export of nutrients and suspended solids from major Arctic rivers and their response to permafrost degradation. *Advances in Climate Change Research*, 12(4), 466–474.
- Zhang, Y., Wolfe, S. A., Morse, P. D., Olthof, I., & Fraser, R. H. (2015). Spatiotemporal impacts of wildfire and climate warming on permafrost across a subarctic region, Canada. *Journal of Geophysical Research: Earth Surface*, 120(11), 2338–2356. <https://doi.org/10.1002/2015JF003679>

Chapter 4 Conclusions

4.1 Summary of Results

This thesis investigated hydrological changes in northern Canadian watersheds, focusing on La Martre River in the Taiga Plains ecoregion of the Northwest Territories. The overarching goal was to assess how climate variability, permafrost thaw, and wildfire disturbances interact to influence river discharge and baseflow within a landscape underlain by discontinuous permafrost.

Chapter 2 examined temporal changes in temperature and precipitation, highlighting the relationships between climate variability and observed discharge patterns. Chapter 3 presented the development and application of a hydrological model for La Martre River watershed, which simulated the influence of climate variability, permafrost thaw, and wildfire, and evaluated their relative contributions to observed streamflow changes and cumulative hydrological responses. From this research, several key conclusions can be drawn:

1. ERA5-Land reanalysis datasets are valuable supplements to sparse observational data in northern regions and are appropriate for assessing long-term annual and seasonal trends (Chapter 2).
2. Temperature and precipitation in the watershed show statistically significant increases, though the strength of these trends varies by period and dataset (Chapter 2). Discharge has also increased significantly each year and in all seasons, with the largest relative increase in the winter. The annual increase in discharge exceeds what can be explained by precipitation alone (Chapter 2).

3. Precipitation, particularly its increase and variability, is the primary driver of hydrological change in the watershed, although it does not fully account for the observed increase in discharge. Permafrost thaw, which is accelerated by wildfire, is strongly associated with increases in winter discharge and the runoff ratio (Chapter 2 and Chapter 3).
4. La Martre River watershed has experienced some of the largest increases in discharge in the region. The model indicates that cumulative effects from climate change, permafrost thaw, and wildfire are driving these changes (Chapter 3). Permafrost thaw and wildfire disturbance increase the watershed's sensitivity to variability in precipitation and temperature, amplifying the effects of climate change. These findings suggest that other northern watersheds with similar vulnerabilities may experience comparable discharge variability as these cumulative factors intensify.

Overall, these results highlight the interplay between the drivers of hydrological change in discontinuous permafrost. As climate warming continues, this work shows that ongoing permafrost loss and increases in landscape hydrological connectivity will amplify watershed responses to future changes in precipitation, temperature, and climate variability. These findings provide important insights into the vulnerability of northern water resources and ecosystems.

4.2 Contributions

This research advances understanding of the mechanisms driving hydrological change in thawing, discontinuous permafrost watersheds. The main contributions to the northern hydrology and hydrogeology research community are summarized below:

1. While increased precipitation has been linked to increased discharge in the pan-Arctic, in the Taiga Plains ecoregion increases in annual and winter discharge have generally not been attributed to precipitation. However, statistically significant trends in precipitation were identified here and directly linked to increases in discharge in La Martre River watershed (Chapter 2). The modeled impact of increased precipitation suggests a similar pattern of increase to the observed change in the discharge hydrograph (Chapter 3).
2. This study highlights the importance of considering temporal scale when analyzing trends in temperature and precipitation (Chapter 2). Time windows shorter than 30 years are typically inadequate for detecting robust trends due to high interannual variability. Short-term analyses may overestimate trends if the period begins or ends with anomalously wet, dry, warm, or cool years. While this limitation is difficult to overcome in northern Canada, it is essential for accurately assessing climate warming rates and their implications for permafrost stability and hydrology.
3. The assessment of ERA5-Land reanalysis data demonstrated its effectiveness in representing temperature and precipitation records and trends in non-assimilated northern regions (Chapter 2). This evaluation supports its use in future hydrological and climatological studies in meteorologically data-sparse areas of northern Canada, while clarifying the limitations of this dataset in such contexts.
4. The research offers an updated assessment of the relative contributions and cumulative effects of increased precipitation, permafrost thaw, and wildfire disturbances on observed discharge increases (Chapter 3). These findings

enhance our understanding of cumulative hydrological impacts, supporting better monitoring and decision-making for resource management across northern watersheds. Notably, the study identifies precipitation as the primary driving factor, underscoring the need for expansion of meteorological monitoring, forecasting, and improved long-term projections.

5. The hydrological model developed for this research demonstrates a practical approach for representing subsurface layering in discontinuous permafrost terrain (Chapter 3). The fractional representation of taliks and permafrost within land-cover classes, combined with wetland routing mechanisms, provides a customizable modeling framework that bridges the gap between complex numerical subsurface models and large-scale surface-water models. This approach can be applied to other hydrological modeling efforts in hydrogeologically complex northern landscapes.

4.3 Recommendations

The development of a physically based hydrological model of La Martre River watershed was an important outcome of this research. While the model adequately represented permafrost, taliks, and freeze/thaw processes, several improvements could enhance its application in this and similar environments:

1. This study revealed a four-degree mean annual temperature gradient and over 100 mm mean annual precipitation gradient across the watershed. The representation in the spatial variability of inputs could be improved by increasing the density of “virtual” meteorological stations from ERA5-Land or using gridded

inputs. In addition, the quality of these data could be improved with bias-correction methods sensitive to the spatial variation in bias.

2. The spatial variability of soil and land-cover parameters could be improved using new field data from the northern and eastern sides of Lac La Martre for model parameterization and validation. Soil profiles, talik and permafrost prevalence, and peat plateau–wetland complex composition could be represented with a spatial component to better reflect environmental gradients influencing hydrological processes.
3. Establishing an explicit connection between air temperature, the thaw state of soil layers, and hydraulic conductivity would improve physical realism and allow more accurate simulation of the impact of changing thermal and moisture conditions on subsurface flow.
4. Running the model in a continuous-time configuration would enable more realistic simulation of hydrological dynamics and feedbacks. While this was not feasible in this study due to computational complexity, future work could explore strategies for continuous simulation without substantially increasing model complexity.

On a broader scale, several methodological and data-related improvements could strengthen hydrological analysis in northern environments:

1. Advances in modeling are constrained by limited availability of subsurface data. In discontinuous permafrost regions, more field observations are needed to characterize subsurface properties and cold-region hydrological processes. Sustained investment in long-term observational networks for both

hydrogeological and permafrost subsurface data is therefore crucial to advancing predictive capabilities.

2. Sparse meteorological networks across northern Canada also restrict model calibration and validation, despite ongoing efforts to expand and maintain long-term monitoring stations. While reanalysis products show promise for filling gaps, direct observations remain essential for high-quality modeling. In regions where in situ observations are sparse or discontinuous, such as La Martre River watershed, the development of simple yet robust methods for estimating and correcting biases in reanalysis datasets is particularly important. These methods should include spatially explicit bias-correction techniques to provide reliable input for hydrological analyses and modeling in ungauged or data-limited basins.
3. Further research should explore the sensitivity of thawing permafrost systems to variability in climate forcing across larger spatial scales or multiple basins. Such studies would improve understanding of watershed responses under a range of environmental conditions and help determine the generality of relationships identified in this research.
4. Improving the representation of permafrost and subsurface processes in hydrological models is necessary. Future modeling efforts should aim to simulate transient thaw processes explicitly, capturing the dynamic evolution of active layer and permafrost conditions and their influence on watershed hydrology.

A.1 Observational Data Gap-Filling

Figure 1 displays hydrologic year (1963-2022) of precipitation and temperature anomalies for the YK, WT, and SR watersheds. The figure is divided into two main sections: TEMP (Temperature) and PRECIP (Precipitation). The x-axis represents the Hydrologic Year, ranging from 1963 to 2022. The y-axis lists the watersheds: YK, WT, and SR. The bars are color-coded: black for negative anomalies, blue for positive anomalies, and grey for zero anomalies. Numerical values are provided for each bar.

Watershed	Year	TEMP Anomaly	PRECIP Anomaly
YK	1963	-	-
YK	1964	-	-
YK	1965	-	-
YK	1966	-	-
YK	1967	-	-
YK	1968	-	-
YK	1969	-	-
YK	1970	-	-
YK	1971	-	-
YK	1972	-	-
YK	1973	-	-
YK	1974	-	-
YK	1975	1	2
YK	1976	-	-
YK	1977	-	-
YK	1978	-	-
YK	1979	-	-
YK	1980	-	-
YK	1981	-	-
YK	1982	-	-
YK	1983	-	-
YK	1984	-	-
YK	1985	-	-
YK	1986	4	6
YK	1987	11	10
YK	1988	11	8
YK	1989	-	-
YK	1990	-	-
YK	1991	-	-
YK	1992	-	-
YK	1993	-	-
YK	1994	-	-
YK	1995	-	-
YK	1996	-	-
YK	1997	-	-
YK	1998	-	-
YK	1999	-	-
YK	2000	-	-
YK	2001	-	-
YK	2002	-	-
YK	2003	-	-
YK	2004	-	-
YK	2005	-	4
YK	2006	-	11
YK	2007	-	10
YK	2008	-	11
YK	2009	-	10
YK	2010	-	11
YK	2011	-	10
YK	2012	-	11
YK	2013	-	10
YK	2014	-	11
YK	2015	-	10
YK	2016	-	11
YK	2017	-	10
YK	2018	-	11
YK	2019	-	10
YK	2020	-	11
YK	2021	-	2
YK	2022	-	7
WT	1963	-	-
WT	1964	-	-
WT	1965	-	-
WT	1966	-	-
WT	1967	-	-
WT	1968	-	-
WT	1969	-	-
WT	1970	-	-
WT	1971	-	-
WT	1972	-	-
WT	1973	-	-
WT	1974	-	-
WT	1975	1	2
WT	1976	-	-
WT	1977	-	-
WT	1978	-	-
WT	1979	-	-
WT	1980	-	-
WT	1981	-	-
WT	1982	-	-
WT	1983	-	-
WT	1984	-	-
WT	1985	-	-
WT	1986	-	-
WT	1987	-	-
WT	1988	-	-
WT	1989	-	-
WT	1990	-	-
WT	1991	-	-
WT	1992	-	-
WT	1993	-	-
WT	1994	-	-
WT	1995	-	-
WT	1996	-	-
WT	1997	-	-
WT	1998	-	-
WT	1999	-	-
WT	2000	-	-
WT	2001	-	-
WT	2002	-	-
WT	2003	-	-
WT	2004	-	

115

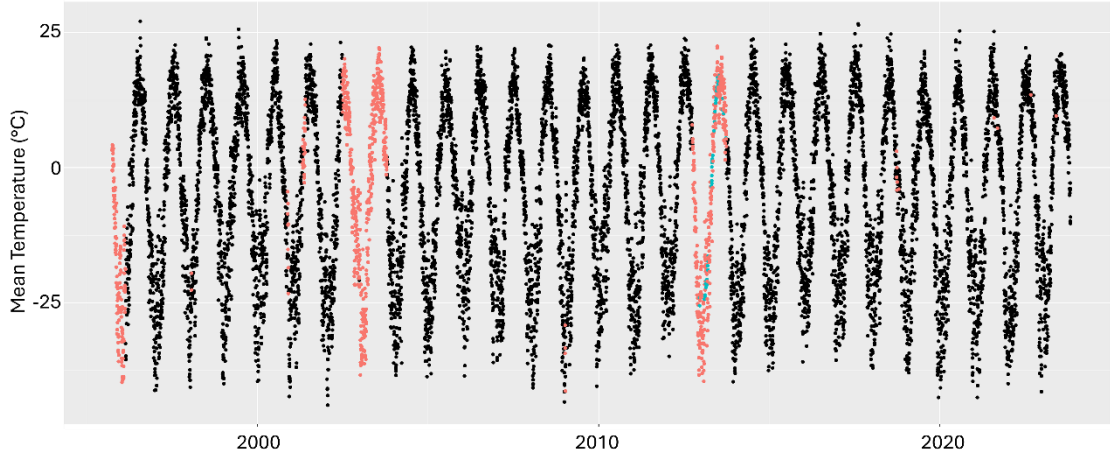


Figure A.2 Plot of Whatì daily temperature (black) with gap filling from linear comparison with Yellowknife (red) and long-term daily mean temperature at Whatì (blue).

A.2 Complete Results of ERA5-Land Anomaly Comparison

Observational data for Whatì, Yellowknife, and Snare Rapids meteorological stations were compared against ERA5-Land and bias-corrected ERA5-Land anomalies calculated against the 1999-2019 base period of observational data. An abridged table of results are presented in Table 2.2. Comparison on a seasonal and monthly basis were also calculated to evaluate the skill of ERA5-Land to represent temperature and precipitation throughout the year (Figure A.3).

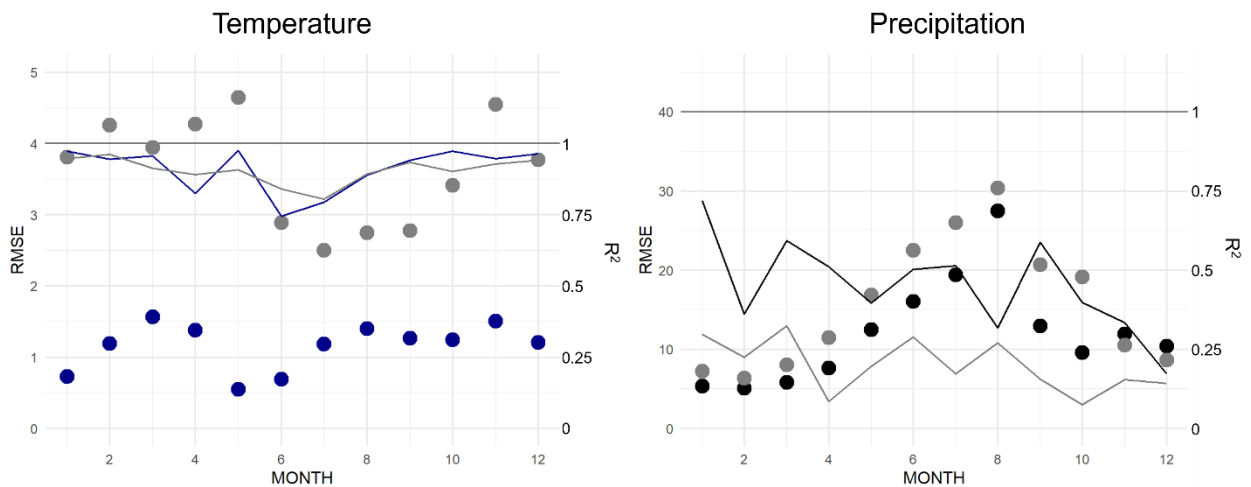


Figure A.3 Plot of RMSE (points) and R^2 (line) for each month for Yellowknife (grey), Whatì (blue), Snare Rapids (black). Note, R^2 axis is on the right.

A.3 ERA5-Land Bias Correction

The code to execute the scaling method bias correction is included below. The script is written in R and can be adapted for various data types as long as the column names are adjusted to match the code.

```
library(hyfo); library(tidyverse)

# function for bias correction
biasCorrectbyMonth <- function(st_df, obs_df, sim_df){

  st_bias <- data.frame(row.names = c("DATE", "PRECIP", "TEMP_AVE"));

  for (m in 1:12){

    #Precipitation Correction
    sim_pr <- sim_df %>% filter(!is.na(OBS_PRECIP)) %>%
      subset(select = c(DATE,PRECIP)) %>%
      filter(month(DATE) == m)
    obs_pr <- obs_df %>% filter(!is.na(OBS_PRECIP)) %>%
      subset(select = c(DATE,OBS_PRECIP)) %>%
      filter(month(DATE) == m)

    frc_pr <- st_df %>% subset(select = c(DATE,PRECIP)) %>%
      filter(month(DATE) == m)

    biasFactor_pr <- getBiasFactor(hindcast = sim_pr,
                                  obs = obs_pr, preci = T, method = 'scaling',
                                  scaleType = 'multi', prThreshold = 0.02)

    st_pr_new <- applyBiasFactor(frc_pr, biasFactor_pr)

    #Temperature Correction
    sim_t <- sim_df %>% filter(!is.na(OBS_TEMP_AVE)) %>%
      subset(select = c(DATE,TEMP_AVE)) %>%
      filter(month(DATE) == m)
    obs_t <- obs_df %>% filter(!is.na(OBS_TEMP_AVE)) %>%
      subset(select = c(DATE,OBS_TEMP_AVE)) %>% filter(month(DATE) == m)

    frc_t <- st_df %>% subset(select = c(DATE,TEMP_AVE)) %>%
      filter(month(DATE) == m)

    biasFactor_t <- getBiasFactor(hindcast = sim_t,
                                  obs = obs_t, preci = F, method = 'scaling',
                                  scaleType = 'multi')

    st_t_new <- applyBiasFactor(frc_t, biasFactor_t)

    # combine
    st_new <- merge(st_t_new, st_pr_new, key = 'DATE')
    st_bias <- rbind(st_bias, st_new)

  }

  return(st_bias)
}
```

Appendix B Model Discretization

B.1 Watershed and Sub-Basin Delineation

The watershed delineation is based on the North American Lake and River Routing Product (NALRRP). However, the delineation was adjusted to include Bartlett Lake to better compare with the Water Survey of Canada (WSC) delineation of the watershed (Figure B.1). This was further confirmed by delineating the watershed using ArcticDEM, a 1m x 1m resolution elevation model (Figure B.2). The WSC delineation has an area of 14,248 km², and the combined area of the two NALRRP basins is 14,527 km², an error of 1.96%.



Figure B.1 Comparison of WSC watershed delineation (black outline), NALRRP delineation (yellow) and additional Bartlett sub-watershed (pink), and major lakes (blue) and rivers.

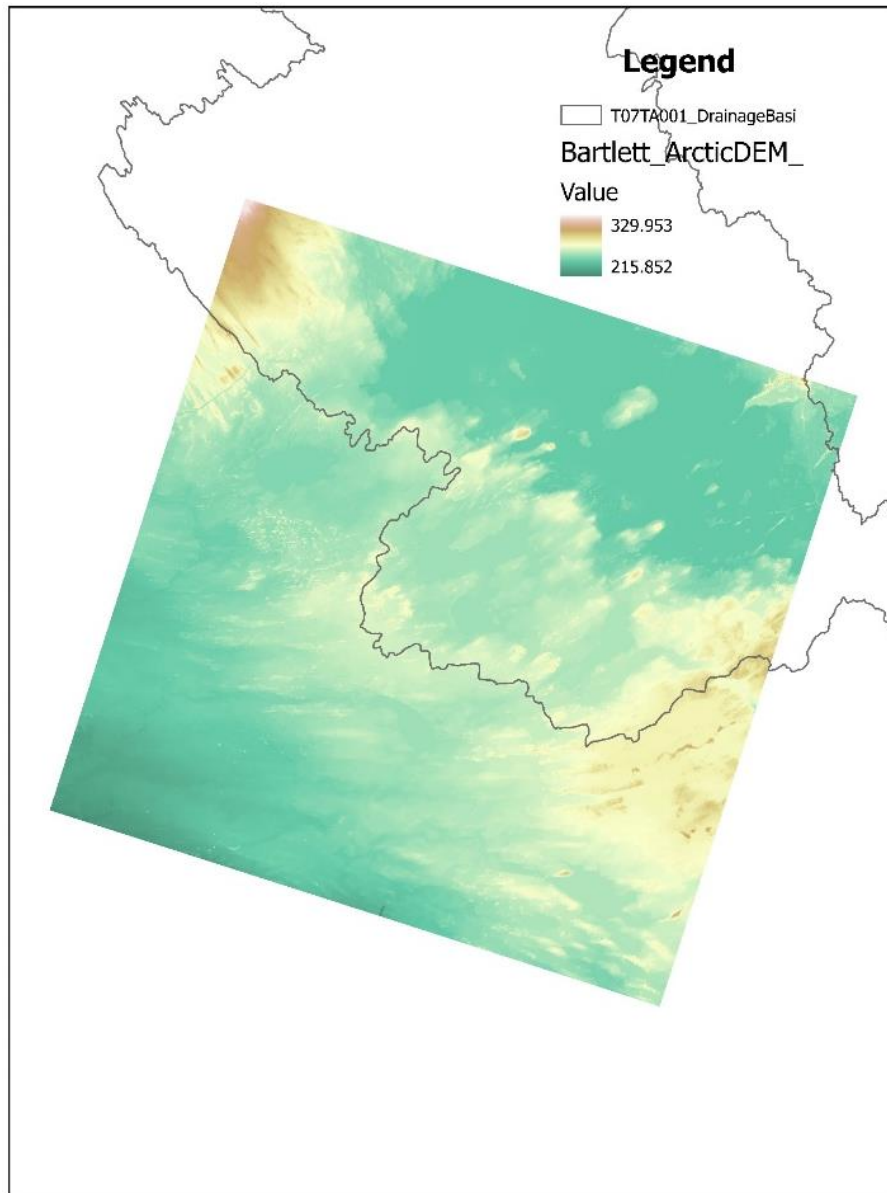


Figure B.2 ArcticDEM watershed delineation and elevation of region surrounding Bartlett Lake.

The final watershed sub-basin delineation also included an extra basin on the east shore of Lac La Martre to represent the unique subsurface properties of the “boulder field” identified during helicopter reconnaissance (Figure B.3, Figure B.4). This sub-basin was extracted from the sub-basin including Lac La Martre using a finer resolution sub-basin map generated using BasinMaker (Han et al., 2023). The final sub-basin map is displayed in Chapter 3, Figure 3.2.



Figure B.3 Aerial photo of boulder field landscape on eastern shore of Lac La Martre.



Figure B.4 Photo of ground cover in burned exposed bedrock forest land cover type of the eastern shore of Lac La Martre. The boulders are interpreted to be highly weathered exposed bedrock.

The sub-basin discretization level was based on an initial comparison of four levels of discretization using an early version of the model (Figure B.5). It was found that the medium discretization version (Case 3) with 14 sub-basins produced the most accurate hydrograph and reduced the model complexity (Figure B.6).

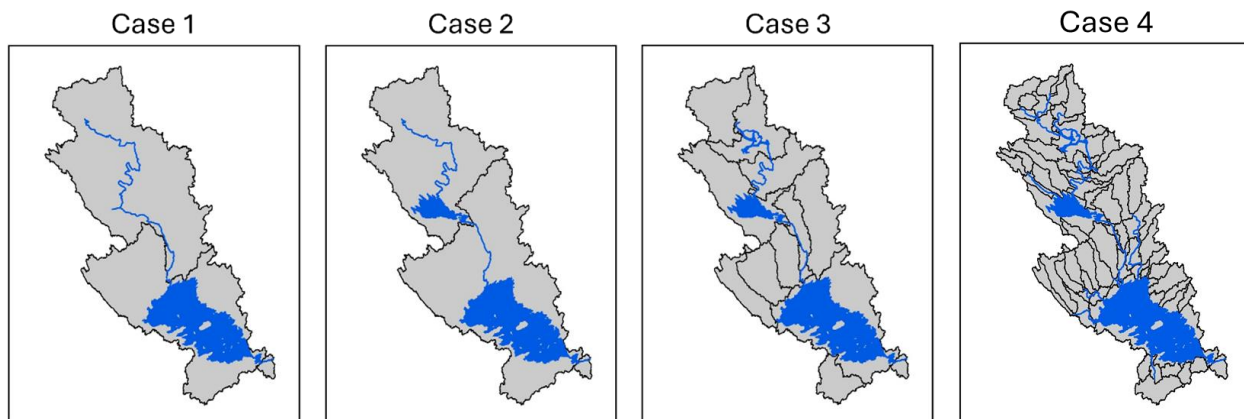


Figure B.5 Tested discretization schemes.

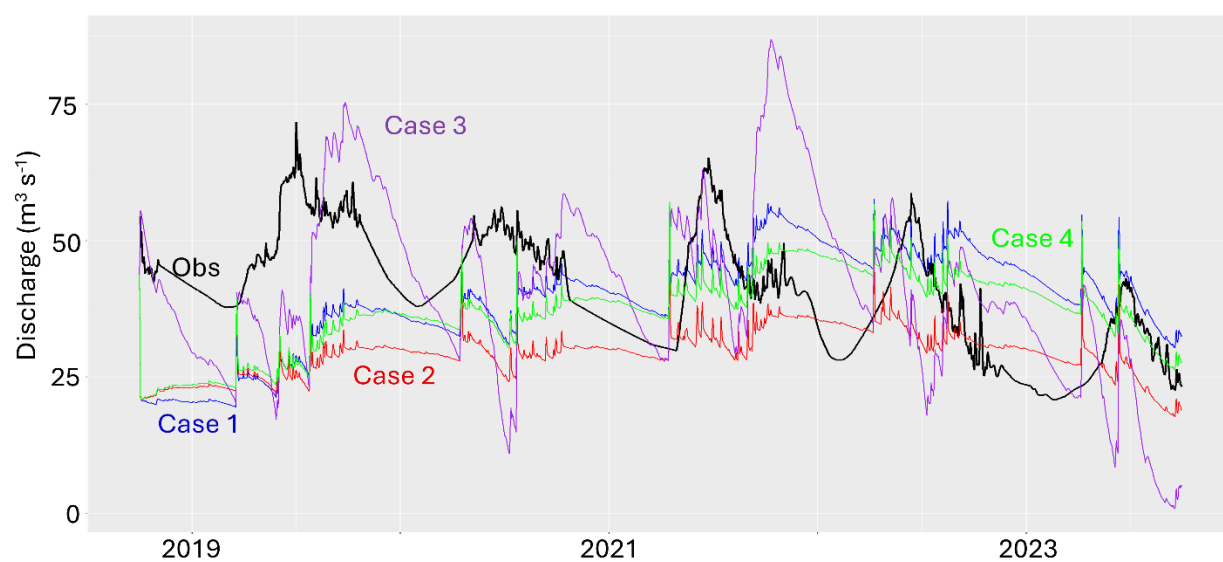


Figure B.6 Hydrograph output of early model simulation using discretization schemes described in Figure B.4. Case 3 (purple) was found to best represent the observed hydrograph (black).

B.2 Land Cover Classification Details

The land cover classification used in the hydrological model (Chapter 3), is based on the Ducks Unlimited Hybrid Wetland Layer (HWL; Ducks Unlimited Canada, 2010).

However, this layer included more land cover types than the field data were able to parameterize (Table B.1). describes the HWL land cover classification description of the land covers that are present in La Martre River watershed area. The number of unique land covers represented in the model were based on a simplification of the HWL made through comparison with the greater specificity Ducks Unlimited Thichq Wetland Classification (DUC;Figure B.7). Land cover types that were non-specific, including *No Data*, *Cloud*, *Shadow*, and *Snow/Ice*, were reclassified according to the nearest neighbor using the nibble tool in ArcGIS. The percentage distribution of each model land cover by sub-basin is included in Chapter 3, Figure 3.2.

HWL/DUC	Open Water	WETLAND	Upland Shr	Upland Cor	UPLAND M	BARREN / A
Water	93.04	5.6	0.06	1.3	0	0
Wetland	4.25	84.81	0.67	10.21	0	0.05
Snow / Ice	39.87	55.38	0.56	4.17	0.03	0
Shadow	39.58	32.05	0	25.08	3.29	0
Rock / Rubble	1.03	18.55	2.06	18.11	1.03	59.22
Exposed / Barren Land	4.05	28.51	2.37	22.91	0.65	41.51
Shrub - Low	1.15	42.64	32.68	17.84	2.29	3.4
Shrub - Tall	25.27	34.78	34.1	2.65	1.47	1.73
Herb	1.95	79.49	1.18	11.94	4.79	0.66
Coniferous - Dense	1.1	11.95	0.72	76.86	1.08	8.28
Coniferous - Sparse	1.96	47.34	0.49	47.77	1.34	1.1
Coniferous - Open	1.17	24.11	0.48	65.18	1.93	7.13
Broadleaf - Dense	2.12	30.87	0.47	20.96	43.9	1.68
Mixedwood - Dense	0.77	13.63	0.12	10.41	74.27	0.8
Mixedwood - Sparse	0.26	25.24	0.88	17.82	53.49	2.31
Mixedwood - Open	1.64	29.55	0.88	20.69	46.18	1.06

Figure B.7 Comparison of HWL and DUC land cover classifications. The values represent the percentage of the HWL land cover classification that is present within each DUC classification for the overlapping area. Green indicates greater agreement between the two land cover classification schemes, and red represents no agreement. Note that the sparse coniferous forest land cover is highly correlated to the DUC WETLAND land cover.

Table B.1 Description of HWL land cover classes and classification within model land cover scheme. Modified from EOSD Land Cover Classification Legend Report (Wulder & Nelson, 2003).

Model Class	HWL Class	HWL Description
N/A	No Data	
N/A	Cloud	
N/A	Shadow	
N/A	Snow/Ice	Glacier/snow.
Bedrock	Rock/Rubble	Bedrock, rubble, talus, blockfield, rubblely mine spoils, or lava beds.
Bedrock	Exposed Land	River sediments, exposed soils, pond or lake sediments, reservoir margins, beaches, landings, burned areas, road surfaces, mudflat sediments, cutbanks, moraines, gravel pits, tailings, railway surfaces, buildings and parking, or other non-vegetated surfaces.
Lake	Water	Lakes, reservoirs, rivers, streams, or salt water.
Wetland	Wetland	Land with a water table near/at/above soil surface for enough time to promote wetland or aquatic processes.
Wetland	Shrub – Tall	At least 20% ground cover which is at least one-third shrub; average shrub height greater than or equal to 2 m.
Wetland	Shrub - Low	At least 20% ground cover which is at least one-third shrub; average shrub height less than 2 m.
Wetland	Herb	Vascular plant without woody stem (grasses, crops, forbs, graminoids); minimum of 20% ground cover or one-third of total vegetation must be herb.
Wetland	Coniferous - Sparse	10-25% crown closure; coniferous trees are 75% or more of total basal area.
Dense Forest	Coniferous - Dense	Greater than 60% crown closure; coniferous trees are 75% or more of total basal area.
Dense Forest	Broadleaf - Dense	Greater than 60% crown closure; broadleaf trees are 75% or more of total basal area.
Dense Forest	Mixed Wood - Dense	Greater than 60% crown closure; neither coniferous nor broadleaf tree account for 75% or more of total basal area.
Open Forest	Coniferous – Open	Greater than 60% crown closure; broadleaf trees are 75% or more of total basal area.
Open Forest	Broadleaf – Open	26-60% crown closure; broadleaf trees are 75% or more of total basal area.
Open Forest	Mixed Wood – Open	26-60% crown closure; neither coniferous nor broadleaf tree account for 75% or more of total basal area.
Open Forest	Mixed Wood - Sparse	10-25% crown closure; neither coniferous nor broadleaf tree account for 75% or more of total basal area.

Appendix C Field Data Analysis for Model Parameterization

C.1 Soil Properties

Soil samples were collected during installation of piezometers in burned and unburned peat plateau wetland (UP, BP) and coniferous forest upland (UC, BC) field sites in August 2022. The location of the field sites are presented in Chapter 3, Figure 3.1. In the peat plateau sites, samples were collected from the lower mineral soil layer. The samples were analyzed for particle size distribution using sieve analysis and for silt and clay particles using the Horiba Particle Size Analyzer. The sand, silt, and clay fractions were defined using the USGS definitions and are presented as the mean composition for each site (Figure C.1). The soil types were grouped into a *sandy mineral* and *mineral* soil types for modeling and the porosity ranges used for calibration were based on the USGS classification.

	SAND	SILT	CLAY
BC	72.45	20.11	7.43
BP	19.25	58.67	22.08
UC	62.48	29.22	8.30
UP	34.83	49.07	16.10

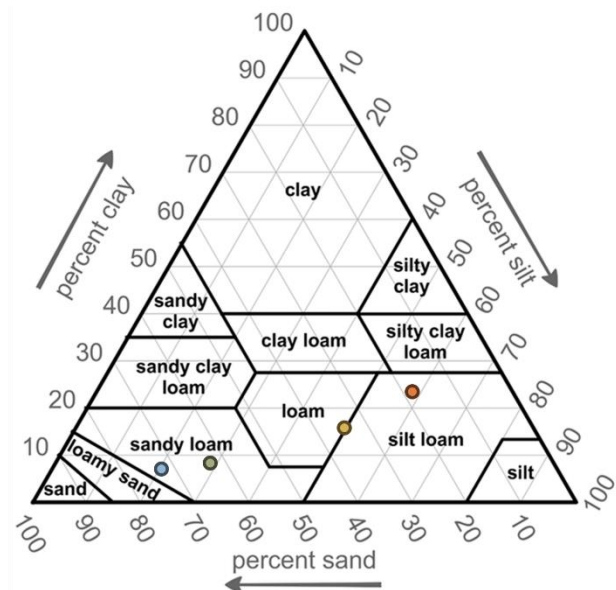


Figure C.1 Mean composition of soil samples for each field site (left), and USGS soil classification (right).

C.2 Slug Test Analysis

Pour-in slug tests were conducted in each piezometer in the four field sites in Whatì and four deep wells (Figure 3.1), to determine the maximum range of hydraulic conductivity for each soil type: *organic*, *mineral*, *sandy mineral*, and *fractured bedrock*. The wells/piezometers were grouped based on which soil type they are most likely to represent (Figure C.2). Each slug test was analyzed four times, early and late time response using a confined and unconfined analysis method due to the uncertainty of the seasonal frost table acting as a confining layer (Figure C.3). This allowed a large range of hydraulic conductivity values to be established for each soil type, which were then calibrated. In general, the difference between the confined and unconfined analyzes were closer than the early- and late-time response fit results.

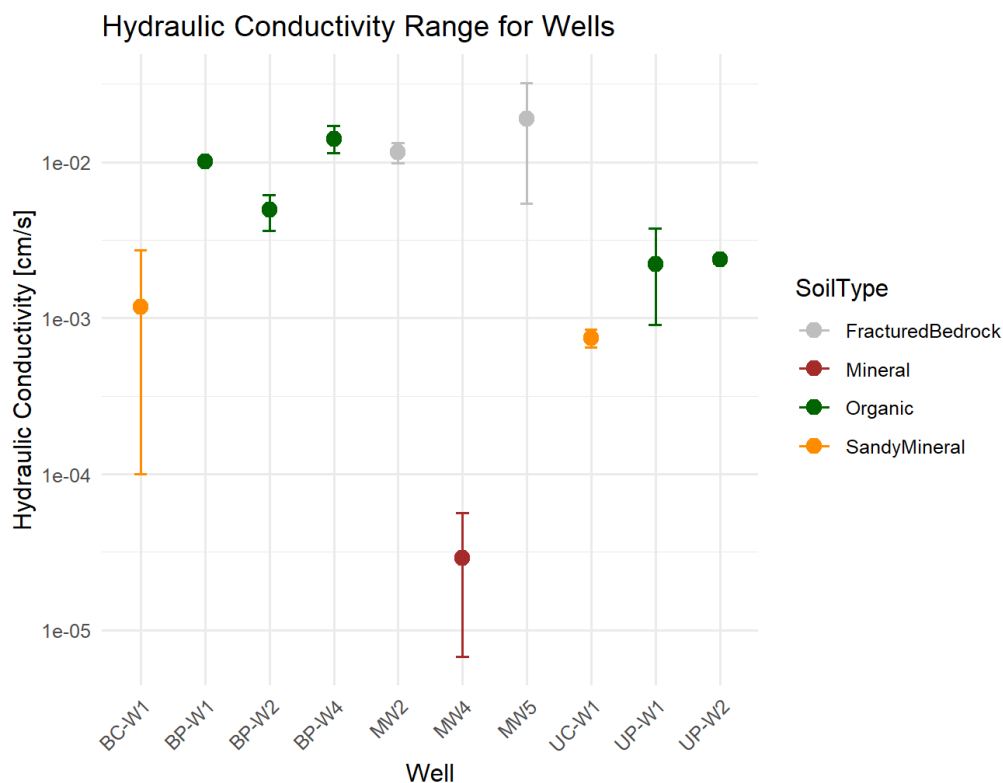


Figure C.2 Range of hydraulic conductivity for each piezometer/well, color identified the soil type that each is taken to represent.

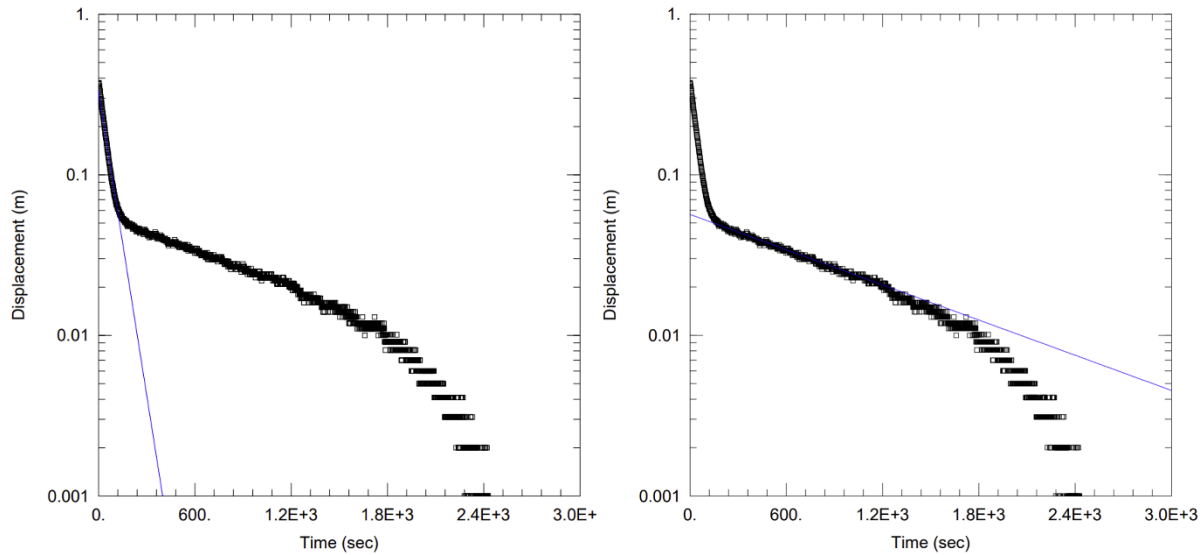


Figure C.3 Fitted slug test to early (left) and late (right) time response using Bouwer Rice Unconfined method for well BC-W1.

C.3 Freeze/Thaw Timing

Ground temperature data from Whatì were used to establish timing for the onset of winter soil freeze-up and summer thaw in the model. Winter freeze-up was based on field data collected by Seamus Daly in 2019-2020 for a previous project (Daly et al., 2022). A ground temperature network with 50 Hobo Tidbit sensors were installed in various land cover types throughout the community at approximately 5cm depth. The mean temperature profile was calculated from the sensors and the last date that temperatures above 0°C were recorded was used as the final day of the summer season (Figure C.4). Thaw timing was based on the 30 cm soil depth from thermistor string installed in the burned and unburned coniferous field sites (Figure 3.1). A deeper measurement depth for thaw was chosen to represent the capacity to infiltrate water into lower layers. The active layer depths for nearly all soil profiles is greater than 30 cm. The mean date of ground temperature exceeding 0°C was used as the thaw date (Figure C.4). The thaw date of May 20th, and freeze date of October 15th were used in the

base model and present period freeze/thaw timing, net permafrost, and cumulative impact simulations. The dates selected for the past and future periods were based on literature and linearly estimated from the difference, respectively.

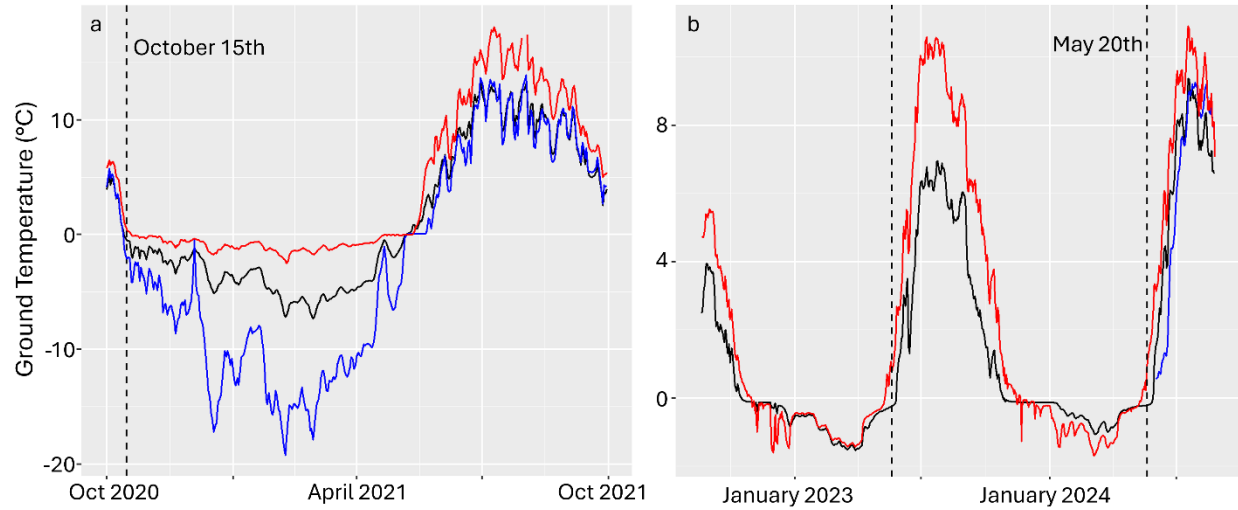


Figure C.4 Ground temperature at 5 cm depth (a) and 30 cm depth (b) for temperature sensors in Whatì. Minimum (blue), mean (black), and maximum (red) daily temperature in a. Burned coniferous (red) and unburned coniferous (black) in b. Dashed line represents the onset of freeze-up (a), and summer thaw (b).

Appendix D Model Processes

D.1 Raven Hydrological Processes Input File (.rvi)

```
#####
:FileType rvi ASCII Raven 3.8
:WrittenBy      Abbi Baran
:CreationDate   Aug 2024
# La Martre Watershed -- Calibration Period
#-----
#

:StartDate 2000-10-01 00:00:00
:Duration 9131
:TimeStep 1

:Method      ORDERED_SERIES
:Interpolation INTERP_NEAREST_NEIGHBOR

:Routing      ROUTE_DIFFUSIVE_WAVE
:CatchmentRoute ROUTE_TRI_CONVOLUTION

:SoilModel    SOIL_MULTILAYER 5

:RainSnowFraction RAINSNOW_DINGMAN
:PotentialMeltMethod POTMELT_HBV
:LakeStorage    LAKE_STORAGE
:PrecipIceptFract PRECIP_ICEPT_USER
:Evaporation    PET_HARGREAVES_1985
:OW_Evaporation PET_HARGREAVES_1985
:SWRadiationMethod SW_RAD_DEFAULT
:LWRadiationMethod LW_RAD_DEFAULT

#-----
# HRU Groups
:DefineHRUGroups LandHRUs Soil3_PF PP_ALL
:DefineHRUGroups PP1 PP2 PP3 PP4 PP5 PP6 PP7 PP8 PP9 PP10
:DefineHRUGroups PP11 PP12 PP13 PP14 PP15 PP16 PP17 PP18 PP19 PP20
:DefineHRUGroups B1 B2 B3 B4 B5 B6 B7 B8 B9 B10
:DefineHRUGroups B11 B12 B13 B14 B15 B16 B17 B18 B19 B20
:DefineHRUGroups F1 F2 F3 F4 F5 F6 F7 F8 F9 F10
:DefineHRUGroups F11 F12 F13 F14 F15 F16 F17 F18 F19 F20

#-----
# Hydrologic process order
#-----
:Alias SOIL0      SOIL[0]
:Alias SOIL1      SOIL[1]
:Alias SOIL2      SOIL[2]
:Alias SOIL3      SOIL[3]
:Alias SOIL4      SOIL[4]

:HydrologicProcesses
# Precipitation Processes
:Precipitation    PRECIP_RAVEN          ATMOS_PRECIP    MULTIPLE
```

:SnowBalance	SNOBAL_CRHM_EBSM	MULTIPLE	MULTIPLE
:SnowAlbedoEvolve	SNOALB_BAKER		
:CanopyEvaporation	CANEVP_MAXIMUM	CANOPY	ATMOSPHERE
:CanopySublimation	CANEVP_MAXIMUM	CANOPY_SNOW	ATMOSPHERE
:CanopyDrip	CANDRIP_RUTTER	CANOPY	PONDED_WATER

Wetland Processes

:Flush	RAVEN_DEFAULT	PONDED_WATER	DEPRESSION
:-->Conditional LAND_CLASS IS BOG			
:Flush	RAVEN_DEFAULT	PONDED_WATER	DEPRESSION
:-->Conditional LAND_CLASS IS BOG_CONNECT			
:Flush	RAVEN_DEFAULT	PONDED_WATER	DEPRESSION
:-->Conditional LAND_CLASS IS FEN			
:Seepage	SEEP_LINEAR	DEPRESSION	SOIL0
:-->Conditional LAND_CLASS IS BOG			
:Seepage	SEEP_LINEAR	DEPRESSION	SOIL0
:-->Conditional LAND_CLASS IS BOG_CONNECT			
:Seepage	SEEP_LINEAR	DEPRESSION	SOIL0
:-->Conditional LAND_CLASS IS FEN			
:OpenWaterEvaporation	OPEN_WATER_EVAP	DEPRESSION	ATMOSPHERE
:OpenWaterEvaporation	OPEN_WATER_EVAP	SURFACE_WATER	ATMOSPHERE
:DepressionOverflow	DFLOW_THRESHPOW	DEPRESSION	SURFACE_WATER
:-->Conditional LAND_CLASS IS BOG			
:DepressionOverflow	DFLOW_THRESHPOW	DEPRESSION	SURFACE_WATER
:-->Conditional LAND_CLASS IS BOG_CONNECT			
:DepressionOverflow	DFLOW_THRESHPOW	DEPRESSION	SURFACE_WATER
:-->Conditional LAND_CLASS IS FEN			

Soil Processes

:Infiltration	INF_GREEN_AMPT	PONDED_WATER	MULTIPLE
:-->Conditional HRU_GROUP IS NOT PP_ALL			
:Infiltration	INF_PARTITION	PONDED_WATER	MULTIPLE
:-->Conditional HRU_GROUP IS PP_ALL			

Deeper Soil Processes

:Percolation	PERC_POWER_LAW	SOIL0	SOIL1
:Percolation	PERC_POWER_LAW	SOIL1	SOIL2
:Percolation	PERC_POWER_LAW	SOIL2	SOIL3
:Percolation	PERC_CONSTANT	SOIL3	SOIL4
:Baseflow	BASE_VIC	SOIL0	SURFACE_WATER
:-->Conditional LAND_CLASS IS PP			
:Baseflow	BASE_VIC	SOIL1	SURFACE_WATER
:-->Conditional LAND_CLASS IS NOT BEDROCK			
:-->Conditional LAND_CLASS IS NOT BOG			
:Baseflow	BASE_VIC	SOIL2	SURFACE_WATER
:-->Conditional LAND_CLASS IS NOT BEDROCK			
:-->Conditional LAND_CLASS IS NOT BOG			
:Baseflow	BASE_VIC	SOIL3	SURFACE_WATER
:-->Conditional LAND_CLASS IS NOT BEDROCK			
:-->Conditional LAND_CLASS IS NOT BOG			
:Baseflow	BASE_VIC	SOIL4	SURFACE_WATER
:Percolation	PERC_POWER_LAW	SOIL0	SOIL1
:Percolation	PERC_POWER_LAW	SOIL1	SOIL2
:Percolation	PERC_CONSTANT	SOIL2	SOIL3
:Percolation	PERC_CONSTANT	SOIL3	SOIL4

```

:SoilEvaporation SOILEVAP_LINEAR          SOIL0          ATMOSPHERE
:-->Conditional LAND_CLASS IS_NOT BOG
:-->Conditional LAND_CLASS IS_NOT BOG_CONNECT
:-->Conditional LAND_CLASS IS_NOT FEN
:LateralEquilibrate RAVEN_DEFAULT          LandHRUs        SOIL4 1 INTERBASIN
:LateralEquilibrate RAVEN_DEFAULT          Soil3_PF        SOIL3 0.0111

# Wetland Hydrological Connectivity Processes
:LateralFlush RAVEN_DEFAULT PP1 SURFACE_WATER To B1 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP2 SURFACE_WATER To B2 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP3 SURFACE_WATER To B3 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP4 SURFACE_WATER To B4 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP5 SURFACE_WATER To B5 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP6 SURFACE_WATER To B6 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP7 SURFACE_WATER To B7 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP8 SURFACE_WATER To B8 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP9 SURFACE_WATER To B9 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP10 SURFACE_WATER To B10 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP11 SURFACE_WATER To B11 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP12 SURFACE_WATER To B12 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP13 SURFACE_WATER To B13 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP14 SURFACE_WATER To B14 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP15 SURFACE_WATER To B15 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP16 SURFACE_WATER To B16 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP17 SURFACE_WATER To B17 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP18 SURFACE_WATER To B18 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP19 SURFACE_WATER To B19 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP20 SURFACE_WATER To B20 DEPRESSION

:LateralFlush RAVEN_DEFAULT PP1 SOIL0 To F1 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP2 SOIL0 To F2 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP3 SOIL0 To F3 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP4 SOIL0 To F4 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP5 SOIL0 To F5 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP6 SOIL0 To F6 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP7 SOIL0 To F7 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP8 SOIL0 To F8 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP9 SOIL0 To F9 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP10 SOIL0 To F10 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP11 SOIL0 To F11 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP12 SOIL0 To F12 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP13 SOIL0 To F13 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP14 SOIL0 To F14 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP15 SOIL0 To F15 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP16 SOIL0 To F16 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP17 SOIL0 To F17 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP18 SOIL0 To F18 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP19 SOIL0 To F19 DEPRESSION
:LateralFlush RAVEN_DEFAULT PP20 SOIL0 To F20 DEPRESSION

# Lake Processes
:LakeRelease LAKEREL_LINEAR LAKE_STORAGE SURFACE_WATER
:LakeFreeze LFREEZE_BASIC
:LakeEvaporation LAKE_EVAP_BASIC LAKE_STORAGE ATMOSPHERE

:EndHydrologicProcesses

```

D.2 Raven Parameters Input File (.rvp)

```
#-----
# Global Parameters
#-----
:GlobalParameter      SNOW_SWI      0.05089236
:GlobalParameter      BARE_GROUND_ALBEDO  0.25
:GlobalParameter      SNOWFALL_ALBTHRESH  10
:GlobalParameter      TOC_MULTIPLIER      4.967804
:GlobalParameter      TIME_TO_PEAK_MULTIPLIER  2.974856
:GlobalParameter      GAMMA_SHAPE_MULTIPLIER  5
:GlobalParameter      GAMMA_SCALE_MULTIPLIER  5

#-----
# Soil Classes
#-----
:SoilClasses
  :Attributes,
  :Units,
    ORGANIC,
    ORGANIC_AL,
    FROZEN_ORGANIC,
    MINERAL,
    SANDY_MINERAL,
    SANDY_MINERAL_AL,
    FROZEN_MINERAL,
    PERMAFROST,
    FRACTURED_BEDROCK,
    FRACTURED_BEDROCK_AL,
    FROZEN_BEDROCK,
:EndSoilClasses

#-----
# Soil Profiles
#-----
:SoilProfiles
  LAKE,0,,,,,,,,,
  PP_PF_T,5,ORGANIC_AL,0.4,ORGANIC,1.5,PERMAFROST,5,PERMAFROST,10,FRACTURED_BEDROCK,20
  PP_PF,5,ORGANIC_AL,0.4,PERMAFROST,1.5,PERMAFROST,5,PERMAFROST,10,FRACTURED_BEDROCK,20
  BOG_PF,5,ORGANIC_AL,0.35,ORGANIC,1.05,MINERAL,0.5,PERMAFROST,15,FRACTURED_BEDROCK,20
  BOG,5,ORGANIC_AL,0.35,ORGANIC,1.05,MINERAL,5.5,PERMAFROST,10,FRACTURED_BEDROCK,20
  FEN,5,ORGANIC_AL,0.6,ORGANIC,1.3,MINERAL,5,FRACTURED_BEDROCK,10,FRACTURED_BEDROCK,20
  BEDROCK,5,FRACTURED_BEDROCK_AL,0.4,FRACTURED_BEDROCK_AL,1,FRACTURED_BEDROCK,5.5,
  FRACTURED_BEDROCK,10,FRACTURED_BEDROCK,20
  FOREST_BEDROCK,5,ORGANIC_AL,0.1,FRACTURED_BEDROCK_AL,0.6,FRACTURED_BEDROCK,6.2,
  PERMAFROST,10,FRACTURED_BEDROCK,20
  FOREST,5,ORGANIC_AL,0.2,SANDY_MINERAL_AL,0.1,SANDY_MINERAL,6.6,PERMAFROST,10,FRACTURED_BEDROCK,20
  FOREST_PF_T,5,ORGANIC_AL,0.2,SANDY_MINERAL_AL,0.1,SANDY_MINERAL,0.25,PERMAFROST,16.35,
  FRACTURED_BEDROCK,20
  FOREST_PF,5,ORGANIC_AL,0.2,SANDY_MINERAL_AL,0.1,PERMAFROST,0.25,PERMAFROST,16.35,
  FRACTURED_BEDROCK,20
  FOREST_B,5,ORGANIC_AL,0.1,SANDY_MINERAL_AL,0.2,SANDY_MINERAL,6.6,PERMAFROST,10,
  FRACTURED_BEDROCK,20
  FOREST_B_PF_T,5,ORGANIC_AL,0.1,SANDY_MINERAL_AL,0.2,SANDY_MINERAL,0.45,PERMAFROST,16.15,
  FRACTURED_BEDROCK,20
```

```

:EndSoilProfiles

#-----
# Soil Parameters
#-----
:SoilParameterList

:Parameters,POROSITY,HYDRAUL_COND,WETTING_FRONT_PSI,MAX_PERC_RATE,MAX_BASEFLOW_RATE,PERC_N,BASEFLOW_N,
:Units,
    ORGANIC,0.798787,0,0,172.3248,1416.193,9.362128,1.074902
    ORGANIC_AL,0.798787,724.0584,494.2979,172.3248,1416.193,9.362128,1.074902
    FROZEN_ORGANIC,0.798787,58.47625,470.6837,6.495031,77.96425,19.89516,1.030822
    MINERAL,0.3916637,0,0,44.38954,14.44272,1.289133,6.60917
    SANDY_MINERAL,0.442438,0,0,68.09164,234.8457,19.97074,6.809942
    SANDY_MINERAL_AL,0.442438,0,0,68.09164,234.8457,19.97074,6.809942
    FROZEN_MINERAL,0.442438,0,0,4.107326,8.519176,12.20478,9.705522
    PERMAFROST,0.1970267,0,0,0.4580343,0.1278839,19.89996,1.177564
    FRACTURED_BEDROCK,0.003127227,0,0,2773.571,2249.657,4.626471,1.672161
    FRACTURED_BEDROCK_AL,0.003127227,2142.684,203.5515,2773.571,2249.657,4.626471,1.672161
    FROZEN_BEDROCK,0.003127227,33.30306,282.2524,39.24424,9.258673,5.36497,8.229764
:EndSoilParameterList

#-----
# Land Use Classes
#-----
:LandUseClasses
:Attributes,IMPERMEABLE_FRAC,FOREST_COVERAGE,
:Units,
    LAKE,0,0
    PP,0,1
    BOG,0,0
    BOG_CONNECT,0,0
    FEN,0,0
    BEDROCK,0.3478673,0
    DENSE_FOREST,0,1
    OPEN_FOREST,0,1
:EndLandUseClasses

#-----
# Land Use Parameters
#-----
:LandUseParameterList

:Parameters,FOREST_SPARSENESS,OW_PET_CORR,AET_COEFF,LAKE_REL_COEFF,PARTITION_COEFF,SNOW_PATCH_LIMIT,LAKESNOW_BUFFER_HT,MELT_FACTOR,DEP_MAX_FLOW,DEP_N,DEP_THRESHOLD,DEP_MAX,DEP_SEEP_K,
:Units,
    LAKE,0,-1.2345,-1.2345,0.09237564,-1.2345,10,18.64429,5.71373,-1.2345,-1.2345,-1.2345,0,1e-04
    PP,0.02793782,1.199343,0.09148851,-1.2345,0.5076199,5,-1.2345,9.502582,-1.2345,-1.2345,-1.2345,10,0.01
    BOG,0,1.197029,0.05,-1.2345,-1.2345,5,-1.2345,6.55524,99.59146,1.001012,600,800,0.1
    BOG_CONNECT,0,1.197029,0.05,-1.2345,-1.2345,5,-1.2345,6.55524,99.59146,1.001012,600,800,0.1
    FEN,0,1.189131,0.05,-1.2345,-1.2345,5,-1.2345,6.472903,97.65668,2.992502,20,100,0.005
    BEDROCK,0,1.145504,0.02883341,-1.2345,-1.2345,5,-1.2345,2.332919,-1.2345,-1.2345,2,0.01
    DENSE_FOREST,0.01084657,0.273038,0.07079194,-1.2345,-1.2345,10,-1.2345,5.508251,-1.2345,-1.2345,-1.2345,2,0.01

```

```

OPEN_FOREST,0.3905459,0.2818487,0.08698197,-1.2345,-1.2345,10,-1.2345,5.59604,-
1.2345,-1.2345,-1.2345,2,0.01
:EndLandUseParametersList

#-----
# Vegetation Classes
#-----
:VegetationClasses
:Attributes,MAX_HT,MAX_LAI,MAX_LEAF_COND,
:Units,
OPEN,0,0,0
PP,3,2,5.3
PP_B,1,1,9
BOG,3,1.7,5.3
BOG_B,1,0.7,9
FEN,3,1.7,5.3
FEN_B,1,0.7,9
FOREST,15,3.25,5.3
FOREST_B,3,2,5.3
:EndVegetationClasses

#-----
# Vegetation Parameters
#-----
:VegetationParameterList
:Parameters,RAIN_ICEPT_PCT,SNOW_ICEPT_PCT,MAX_CAPACITY,MAX_SNOW_CAPACITY,
:Units,
OPEN,0.02,0.02,0,0
PP,0.02,0.02,1.6,1.2
PP_B,0.02,0.02,1,0.6
BOG,0.02,0.02,0.2,1.02
BOG_B,0.02,0.02,0.2,0.42
FEN,0.02,0.02,0.5,1.02
FEN_B,0.02,0.02,0.5,0.42
FOREST,0.02,0.02,1.6,1.95
FOREST_B,0.02,0.02,1,1.2
:EndVegetationParametersList
:SeasonalRelativeLAI
OPEN,1,1,1,1,1,1,1,1,1,1,1
PP,0.3,0.4,0.4,0.5,0.9,1,1,1,0.9,0.5,0.4,0.3
PP_B,0.3,0.4,0.4,0.5,0.9,1,1,1,0.9,0.5,0.4,0.3
BOG,0.3,0.4,0.4,0.5,0.9,1,1,1,0.9,0.5,0.4,0.3
BOG_B,0.3,0.4,0.4,0.5,0.9,1,1,1,0.9,0.5,0.4,0.3
FEN,0.3,0.4,0.4,0.5,0.9,1,1,1,0.9,0.5,0.4,0.3
FEN_B,0.3,0.4,0.4,0.5,0.9,1,1,1,0.9,0.5,0.4,0.3
FOREST,0.6,0.6,0.6,0.7,0.9,1,1,1,0.9,0.7,0.6,0.5
FOREST_B,0.6,0.6,0.6,0.7,0.9,1,1,1,0.9,0.7,0.6,0.5
:EndSeasonalRelativeLAI
:SeasonalRelativeHeight
OPEN,1,1,1,1,1,1,1,1,1,1,1
PP,0.1,0.1,0.1,0.1,0.3,0.8,1,1,0.8,0.5,0.2,0.1
PP_B,0.1,0.1,0.1,0.1,0.3,0.8,1,1,0.8,0.5,0.2,0.1
BOG,0.1,0.1,0.1,0.1,0.3,0.8,1,1,0.8,0.5,0.2,0.1
BOG_B,0.1,0.1,0.1,0.1,0.3,0.8,1,1,0.8,0.5,0.2,0.1
FEN,0.1,0.1,0.1,0.1,0.3,0.8,1,1,0.8,0.5,0.2,0.1
FEN_B,0.1,0.1,0.1,0.1,0.3,0.8,1,1,0.8,0.5,0.2,0.1
FOREST,1,1,1,1,1,1,1,1,1,1,1
FOREST_B,1,1,1,1,1,1,1,1,1,1,1
:EndSeasonalRelativeHeight

:RedirectToFile C:/HydroModel/Raven/Simulations/channels/channel_sections100.rvp
:AvgAnnualRunoff 45
:RedirectToFile TransientParameter_p2.rvt

```

The .rvp file presented above represents the base model parameters. Note, -1.2345 represents a parameter that is not used in the model. A description of each parameter is found in the Raven modeling manual (Craig et al., 2020).

D.3 Description of Wetland Processes in Raven Manual

The wetland land cover types represented in the model include peat plateaus, bogs, and fens. The fraction of the wetland land cover represented by each land cover is determined based on the time period and simulation. In the base period model peat plateaus make up 75% of the wetland area, 15% bogs, and 10% fens. Figure D.1 represents the land covers and wetland land use breakdown for sub-basin 5 in the net permafrost present period simulation case. In the permafrost thaw, wildfire, and cumulative impact simulation cases, each of the three land use classes is further broken down into burned and unburned, permafrost free, permafrost with talik, and permafrost with talik, and the bog class is also divided into connected and isolated bogs.

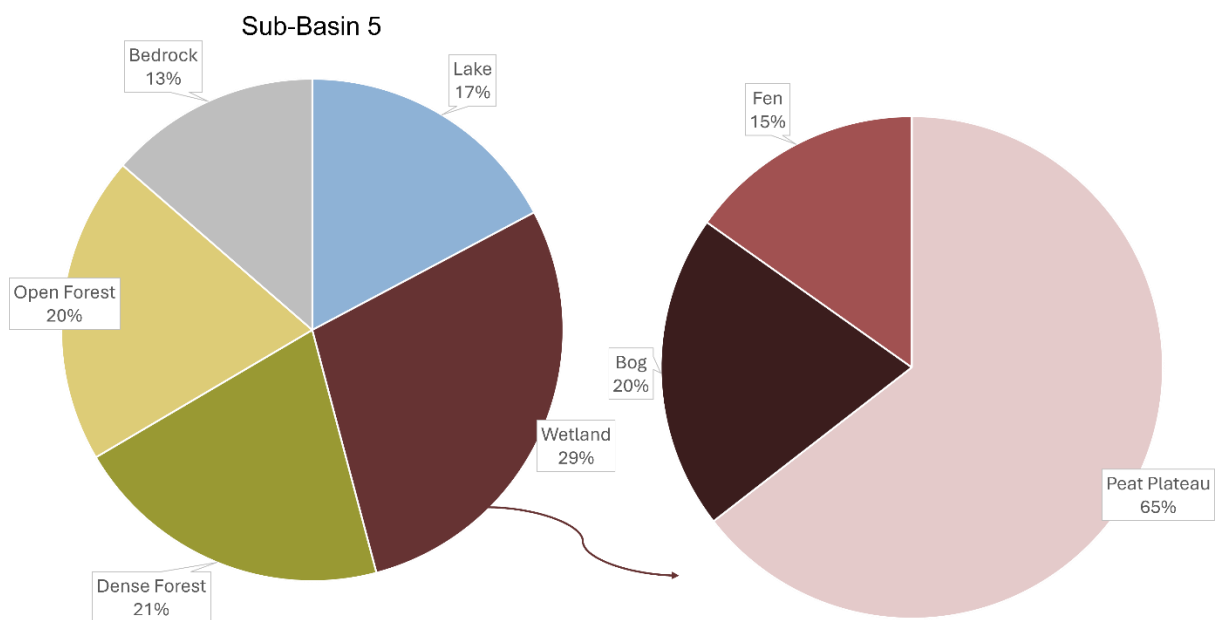


Figure D.1 Land use representation of sub-basin 5 in the present period net permafrost thaw simulation case (left). The wetland fraction break-down for this case (right).

To represent the runoff from peat plateaus to bogs and fens, water that falls onto peat plateaus is partially redirected into the depression storage of bogs and fens. This is done using the lateral flush hydrological process in Raven. The amount of water that is moved into depression storage during this process is directly proportional to the area of the peat plateau. Therefore, the relative area of each form of the three land use classes (e.g., permafrost vs. no permafrost), must be equal. To accomplish this, each wetland land use class were divided into equal twentieths (Figure D.2). This fraction was chosen as it allowed a sufficiently fine resolution of the breakdown to allow each soil profile, burn state, and bog connectivity state to be expressed for each simulation without excessively increasing the complexity of the model. Finally, the order of the forms of each wetland land use class were randomized to ensure that there was no undue influence from the order.

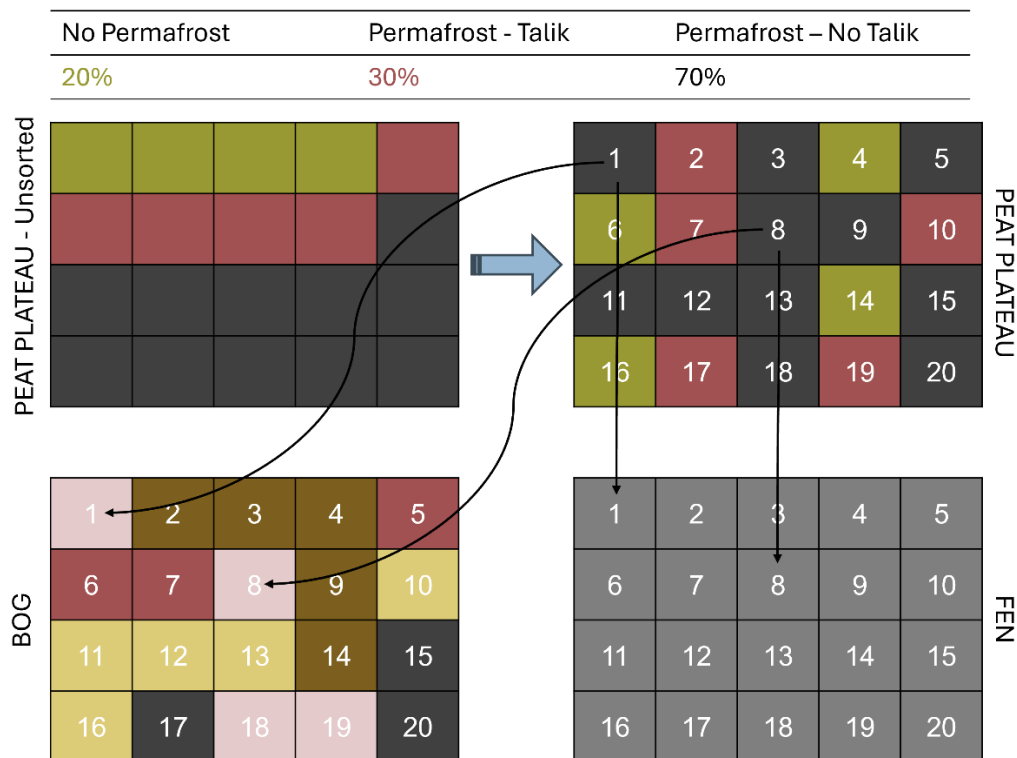


Figure D.2 Representation of 20ths of peat plateau by soil profile type (top left), randomization (top right), and connection to bog (bottom left) and fen (bottom right) land use classes.

Appendix E Model Calibration

E.1 Calibration Ranges

The base period model (1976-1984) was calibrated against observational discharge data from La Martre River (WSC 07TA001). The automatic calibration was completed using the Ostrich software and the Dynamically Dimensioned Search algorithm with 10,000 iterations. The calibration ranges for each calibrated parameter and the calibrated values are provided in Table E.1.

Table E.1 Table of automatic calibration variables, range, and calibrated values. The calibrated values can be found in place in the .rvp file in Appendix D.

Parameter Type	Class Name	Parameter Name	Unit	Lower Range	Upper Range	Calibrated Value
GLOBAL		TIME_TO_PEAK_				
		MULTIPLIER	none	0	3	2.97
		TOC_MULTIPLIER	none	0	5	4.97
		SNOW_SWI	[0,1]	0.04	0.07	0.0509
LandClasses	BEDROCK	IMPERMEABLE_FRAC	[0,1]	0	0.35	0.348
LandUse	PP	AET_COEFF	1/d	0.001	0.1	0.0915
	BEDROCK	AET_COEFF	1/d	0.001	0.1	0.0288
	DENSE_FOREST	AET_COEFF	1/d	0.001	0.1	0.0708
	OPEN_FOREST	AET_COEFF	1/d	0.001	0.1	0.087
	BOG	DEP_MAX_FLOW	mm/d	0.001	100	99.6
	FEN	DEP_MAX_FLOW	mm/d	0.001	100	97.7
	BOG	DEP_N	none	0.5	3	1
	FEN	DEP_N	none	0.5	3	2.99
	PP	FOREST_SPARSENESS	[0,1]	0	1	0.0279
	DENSE_FOREST	FOREST_SPARSENESS	[0,1]	0.01	0.2	0.0108
	OPEN_FOREST	FOREST_SPARSENESS	[0,1]	0.2	0.4	0.391
	LAKE	LAKE_REL_COEFF	1/d	0.001	0.5	0.0924
		LAKESNOW_				
	LAKE	BUFFER_HT	mm	0	500	18.6
	LAKE	MELT_FACTOR	mm/d/C	2	10	5.71
	PP	MELT_FACTOR	mm/d/C	2	10	9.5
	BOG	MELT_FACTOR	mm/d/C	2	10	6.56
	FEN	MELT_FACTOR	mm/d/C	2	10	6.47
	BEDROCK	MELT_FACTOR	mm/d/C	2	10	2.33
	DENSE_FOREST	MELT_FACTOR	mm/d/C	2	10	5.51
	OPEN_FOREST	MELT_FACTOR	mm/d/C	2	10	5.6
	PP	OW_PET_CORR	none	0.2	1.2	1.2
	BOG	OW_PET_CORR	none	0.2	1.2	1.2

	FEN	OW_PET_CORR	none	0.2	1.2	1.19
	BEDROCK	OW_PET_CORR	none	0.2	1.2	1.15
	DENSE_FOREST	OW_PET_CORR	none	0.2	1.2	0.273
	OPEN_FOREST	OW_PET_CORR	none	0.2	1.2	0.282
	PP	PARTITION_COEFF	[0,1]	0.15	0.55	0.508
Reservoir						
Parameters	Grandin	CrestWidth		50	115	102
	LacLaMartre	CrestWidth		100	350	308
	Bartlett	CrestWidth		35	80	79.5
	Grandin	MaxDepth		3	10	6.91
	LacLaMartre	MaxDepth		10	20	10.6
	Bartlett	MaxDepth		3	10	3.5
	Grandin	WeirCoefficient		0.001	0.99	0.985
	LacLaMartre	WeirCoefficient		0.001	0.99	0.0622
	Bartlett	WeirCoefficient		0.001	0.99	0.987
Soil						
Parameters	ORGANIC	BASEFLOW_N	none	1	10	1.07
	FROZEN_ORGANIC	BASEFLOW_N	none	1	10	1.03
	MINERAL	BASEFLOW_N	none	1	10	6.61
	SANDY_MINERAL	BASEFLOW_N	none	1	10	6.81
	FROZEN_MINERAL	BASEFLOW_N	none	1	10	9.71
	PERMAFROST	BASEFLOW_N	none	1	10	1.18
	FRACTURED_BEDROCK	BASEFLOW_N	none	1	10	1.67
	FROZEN_BEDROCK	BASEFLOW_N	none	1	10	8.23
	ORGANIC_AL	HYDRAUL_COND	mm/d	0.785	1475	724
	FRACTURED_BEDROCK_AL	HYDRAUL_COND	mm/d	4.703	2774	2140
	FROZEN_ORGANIC	HYDRAUL_COND	mm/d	0.01	78.5	58.5
	FROZEN_BEDROCK	HYDRAUL_COND	mm/d	0.01	40	33.3
	ORGANIC	MAX_BASEFLOW_RATE	mm/d	0.0785	1475	1420
	FROZEN_ORGANIC	MAX_BASEFLOW_RATE	mm/d	0	78.5	78
	MINERAL	MAX_BASEFLOW_RATE	mm/d	0.006	49	14.4
	SANDY_MINERAL	MAX_BASEFLOW_RATE	mm/d	0.086	236.4	235
	FROZEN_MINERAL	MAX_BASEFLOW_RATE	mm/d	0.001	8.6	8.52
	PERMAFROST	MAX_BASEFLOW_RATE	mm/d	0.001	0.6	0.128
	FRACTURED_BEDROCK	MAX_BASEFLOW_RATE	mm/d	4.703	2774	2250
	FROZEN_BEDROCK	MAX_BASEFLOW_RATE	mm/d	0.001	40	9.26
	ORGANIC	MAX_PERC_RATE	mm/d	0.03925	1475	172
	FROZEN_ORGANIC	MAX_PERC_RATE	mm/d	0.001	78.5	6.5

ORGANIC					
MINERAL	MAX_PERC_RATE	mm/d	0.0003	49	44.4
SANDY_MINERAL	MAX_PERC_RATE	mm/d	0.0043	236.4	68.1
FROZEN_MINERAL	MAX_PERC_RATE	mm/d	1	8.6	4.11
PERMAFROST	MAX_PERC_RATE	mm/d	0.0001	0.6	0.458
FRACTURED_					
BEDROCK	MAX_PERC_RATE	mm/d	0.23515	2774	2770
FROZEN_					
BEDROCK	MAX_PERC_RATE	mm/d	1	40	39.2
ORGANIC	PERC_N	none	1	20	9.36
FROZEN_					
ORGANIC	PERC_N	none	1	20	19.9
FRACTURED_					
BEDROCK	PERC_N	none	1	20	4.63
FROZEN_					
BEDROCK	PERC_N	none	1	20	5.36
SANDY_MINERAL	PERC_N	none	1	20	20
MINERAL	PERC_N	none	1	20	1.29
FROZEN_MINERAL	PERC_N	none	1	20	12.2
PERMAFROST	PERC_N	none	1	20	19.9
ORGANIC	POROSITY	[0,1]	0.65	0.96	0.799
MINERAL	POROSITY	[0,1]	0.3	0.4	0.392
SANDY_MINERAL	POROSITY	[0,1]	0.25	0.45	0.442
PERMAFROST	POROSITY	[0,1]	0.001	0.2	0.197
FRACTURED_					
BEDROCK	POROSITY	[0,1]	0.0001	0.01	0.00313
ORGANIC_AL	WETTING_FRONT_PSI	`-mm`	10	500	494
FRACTURED_					
BEDROCK_AL	WETTING_FRONT_PSI	`-mm`	10	500	204
FROZEN_					
ORGANIC	WETTING_FRONT_PSI	`-mm`	1	500	471
FROZEN_					
BEDROCK	WETTING_FRONT_PSI	`-mm`	1	500	282

E.2 Calibrated Base Period Model

The calibrated base period model was found to adequately represent the watershed processes and reproduce the discharge hydrograph (Figure E.1).

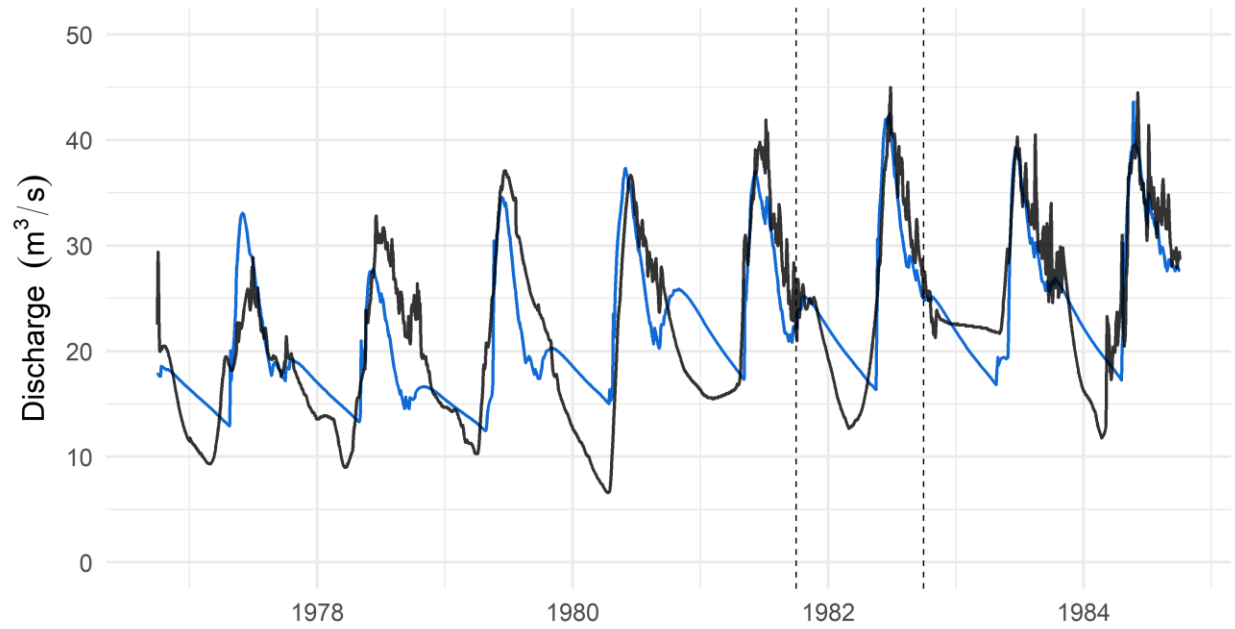


Figure E.1 Calibrated base period model (blue) compared to observed discharge (black) during the base period. The selected year, hydrological year 1982, is between the dashed lines.

Appendix F Model Test Cases

F.1 Simulations Case Details

Table F.1 Detailed description of changes made to model for each simulation case.

	Base	Past	Present	Future
Meteorological	Precipitation			
	316 mm*	320 mm*	344 mm*	357 mm*
	Seasonalized Precipitation			
	J: 4, F: 14, M: 7, A: 13, M: 33, J: 28, J: 38, A: 51, S: 19, O: 57, N: 39, D: 14 mm*	J: 4, F: 16, M: 9, A: 11, M: 31, J: 32, J: 36, A: 50, S: 22, O: 53, N: 39, D: 18 mm*	J: 5, F: 13, M: 9, A: 10, M: 32, J: 32, J: 50, A: 60, S: 29, O: 42, N: 45, D: 18 mm*	J: 5, F: 15, M: 10, A: 11, M: 35, J: 34, J: 45, A: 58, S: 28, O: 51, N: 46, D: 20 mm**
	Temperature			
	-5.15 °C*	-4.98 °C*	-4.08 °C*	-2.55 °C**
	Seasonalized Temperature			
	J: -36.07, F: -24.28, M: -18.21, A: -5.83, M: 2.93, J: 12.26, J: 18.18, A: 13.16, S: 9.08, O: -2.11, N: -11.8, D: -20.23 °C*	J: -36.62, F: -24.13, M: -17.24, A: -5.01, M: 2.83, J: 12.83, J: 18.51, A: 13.88, S: 9.13, O: -2.40, N: -14.03, D: -18.52 °C*	J: -35.11, F: -22.70, M: -17.45, A: -5.44, M: 3.93, J: 13.57, J: 18.99, A: 13.94, S: 9.88, O: -0.78, N: -11.70, D: -17.18 °C*	J: -33.31, F: -21.01, M: -15.29, A: -3.68, M: 4.23, J: 14.31, J: 20.12, A: 15.63, S: 11.51, O: -0.43, N: -9.12, D: -14.61 °C**
	* ERA5-Land, ** CMIP5			
	Wetland Connectivity			
Permafrost Thaw	75% Peat Plateau, 15% Bog, 10% Fen*; 0% connected Bog	71% Peat Plateau, 17% Bog, 12% Fen*; 20% connected Bog†	64.5% Peat Plateau, 20.3% Bog, 15.2 % Fen**; 50% connected Bog†	56% Peat Plateau, 24.5% Bog, 19.5% Fen***; 80% connected Bog†
	ALT/SLT			
	Peat Plateau: 40 cm, Bog: 35 cm, Fen: 60 cm, Forest: 30 cm, Forest Bedrock: 70 cm, Bedrock: 140 cm*; 0% Talik**	No Talik: ALT +10 cm, Talik: SLT +15 cm, ALT ==, No Permafrost: ALT -5 cm††; Peat Plateau: 8% Talik†, Bog: 20% Talik, Forest: 10% Talik**	No Talik: ALT + 15 cm, Talik: SLT +30 cm, ALT -10 cm, No Permafrost: ALT -10 cm††; Peat Plateau: 30% Talik, Bog: 60% Talik, Forest: 25% Talik°	No Talik: ALT +25 cm, Talik: SLT +50cm, ALT -10cm, No Permafrost: ALT -15 cm††; Peat Plateau: 60% Talik, Bog: 100% Talik, Forest: 45% Talik**
	Permafrost State			
	Permafrost: Peat Plateau, Bog, Forest, No Permafrost: Fen, Bedrock°	Bog: 50% Open Talik**	Bog: 75% Open Talik Peat Plateau: 20% Basal Permafrost Loss, Forest: 20% Upper Permafrost Loss°	Bog: 100% Open Talik Peat Plateau: 50% Basal Permafrost Loss, Forest: 50% Upper Permafrost Loss**
	Freeze/Thaw Timing			
	Freeze: October 15th, Thaw: May 19th°	Freeze: October 1st, Thaw: June 1st†††	Freeze: October 15th, Thaw: May 19th°	Freeze: October 30th, Thaw: May 5th**
	° Informed by Field Data, °° Hypothetical, * Gibson et al., 2018, ** Baltzer et al., 2014, *** Chasmer & Hopkinson, 2017, † Informed by Connon et al., 2014, †† Connon et al., 2018, ††† Quinton & Baltzer, 2013			
	Wildfire Area			
Wildfire	No Wildfire	5% of Watershed: 726 km ² °	8% of Watershed: 1162 km ² °	11% of Watershed: 1598 km ² °°
	Wildfire Location			
	No Wildfire	North: Sub-Basins 1 & 2*	East: Sub-Basins 5, 6, & 11*	West: Sub-Basins 7, 8, 9, 10**
	Thaw Impact Severity			
	No Wildfire	Vegetation height and LAI are reduced*; Peat Plateau: 65.3%, Bog: 19.9%, Fen: 14.8%*; SLT +40%, ALT ==**; Talik: 200% of ALT/SLT case***	Vegetation height and LAI are reduced*; Peat Plateau: 59%, Bog: 23%, Fen: 18%*; SLT +60%, ALT ==**; Talik: 200% of ALT/SLT case***	Vegetation height and LAI are reduced*; Peat Plateau: 50.3%, Bog: 27.3%, Fen: 22.2%*; SLT +80%, ALT ==**; Talik: 200% of ALT/SLT case***
	° Informed by Field Data, °° Hypothetical, * Informed by NWT Historical Fires, * Gibson et al., 2018, ** Viereck et al., 2008, *** Yoshikawa et al., 2002			

F.2 HRU Generation Table

In order to generate the HRUs used in the model, a set of scripts were used to translate the base model land cover classifications into the Raven input file format. To streamline this procedure, the following table was used to summarize the changes made for each simulation in burned and unburned land and is provided here for repeatability (Figure F.1).

FileSuffix	Period	WF_pp	WF_bog	WF_fen	LC_bog_connect	SP_bog_np	SP_bog	SP_bog_pf	SP_pp	SP_pp_pf	SP_pp_pf_t	SP_forest	SP_forest_pf	SP_forest_pf_t	noFire	Fire
baseCase	0	0.75	0.15	0.1	0	0	0	1	0	1	0	0	1	0	1	0
wetlandConnectivity	1	0.71	0.17	0.12	0.2	0	0	1	0	1	0	0	1	0	1	0
wetlandConnectivity	2	0.645	0.203	0.152	0.5	0	0	1	0	1	0	0	1	0	1	0
wetlandConnectivity	3	0.56	0.245	0.195	0.8	0	0	1	0	1	0	0	1	0	1	0
activeLayer	1	0.75	0.15	0.1	0	0	0.2	0.8	0	0.9	0.1	0	0.9	0.1	1	0
activeLayer	2	0.75	0.15	0.1	0	0	0.6	0.4	0	0.7	0.3	0	0.75	0.25	1	0
activeLayer	3	0.75	0.15	0.1	0	0	1	0	0	0.4	0.6	0	0.55	0.45	1	0
permafrostState	1	0.75	0.15	0.1	0	0.5	0	1	0	1	0	0	1	0	1	0
permafrostState	2	0.75	0.15	0.1	0	0.75	0	1	0.2	1	0	0.2	1	0	1	0
permafrostState	3	0.75	0.15	0.1	0	1	0	1	0.5	1	0	0.5	1	0	1	0
Net_PF	1	0.71	0.17	0.12	0.2	0.5	0.2	0.8	0	0.9	0.1	0	0.9	0.1	1	0
Net_PF	2	0.645	0.203	0.152	0.5	0.75	0.6	0.4	0.2	0.7	0.3	0.2	0.75	0.25	1	0
Net_PF	3	0.56	0.245	0.195	0.8	1	1	0	0.5	0.4	0.6	0.5	0.55	0.45	1	0
wildfireImpact	1	0.75	0.15	0.1	0	0	0	1	0	1	0	0	1	0	1	0
wildfireImpact	1	0.653	0.199	0.148	0.3	0.5	0.6	0.4	0	0.76	0.24	0	0.7	0.3	0	1
wildfireImpact	2	0.75	0.15	0.1	0	0	0	1	0	1	0	0	1	0	1	0
wildfireImpact	2	0.59	0.23	0.18	0.6	0.75	1	0	0.2	0.1	0.9	0.2	0.25	0.75	0	1
wildfireImpact	3	0.75	0.15	0.1	0	0	0	1	0	1	0	0	1	0	1	0
wildfireImpact	3	0.503	0.274	0.223	0.9	1	1	0	0.5	0	1	0.5	0	1	0	1
CI	1	0.71	0.17	0.12	0.2	0.5	0.2	0.8	0	0.92	0.08	0	0.9	0.1	1	0
CI	1	0.653	0.199	0.148	0.3	0.5	0.6	0.4	0	0.76	0.24	0	0.7	0.3	0	1
CI	2	0.645	0.203	0.152	0.5	0.75	0.6	0.4	0.2	0.7	0.3	0.2	0.75	0.25	1	0
CI	2	0.59	0.23	0.18	0.6	0.75	1	0	0.2	0.1	0.9	0.2	0.25	0.75	0	1
CI	3	0.56	0.245	0.195	0.8	1	1	0	0.5	0.4	0.6	0.5	0.55	0.45	1	0
CI	3	0.503	0.274	0.223	0.9	1	1	0	0.5	0	1	0.5	0	1	0	1

Figure F.1 Representation of input parameter for generating the HRUs used in simulation cases.

F.3 Meteorological Forcing Simulation Details

The precipitation and temperature data were adjusted to match the mean annual temperature and total precipitation, or monthly mean temperature and precipitation for the seasonalized cases, from the mean eight-year period during each of the periods: past (1976-2000), present (2000-2025), future (2026-2050). Bias-corrected ERA5-Land and CIMP data were used to determine the mean values. The selected temperatures and precipitation are shown in context in Figure F.2 and Figure F. 3.



Figure F.2 Mean annual temperature in each hydrological year (points), 8-year running average temperature (thin line), selected mean annual 8-year running average temperature (thick horizontal lines) for each model period, separated by dashed vertical lines.

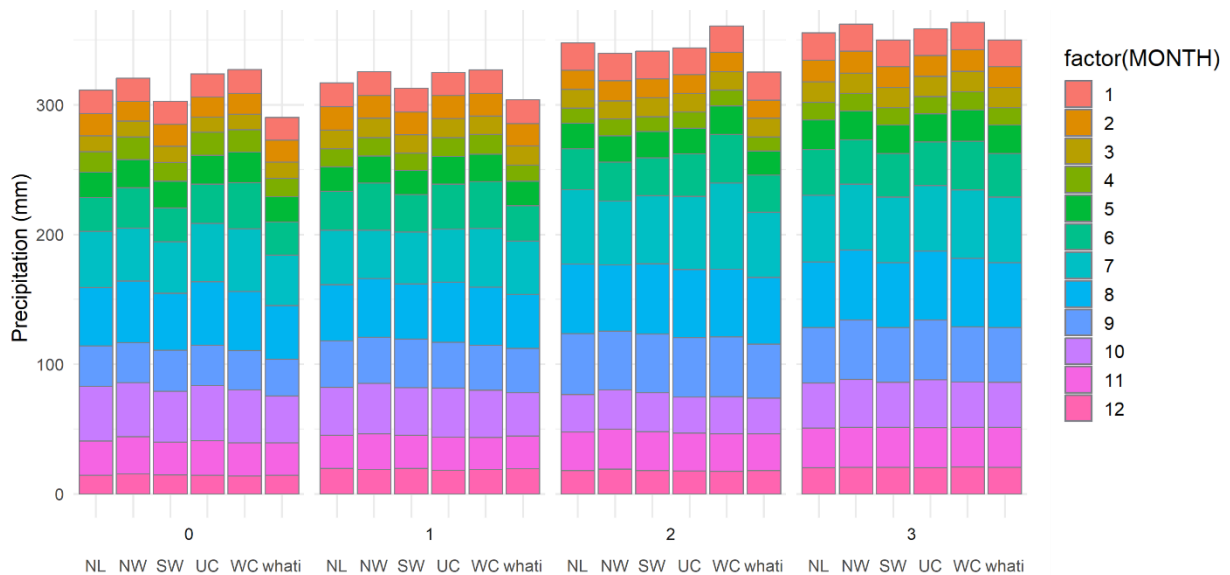


Figure F.3 Selected modeled temperature for each period: base case (0), past (1), present (2), and future (3) for each of the virtual meteorological stations.

F.4 Wildfire Simulation Details

The wildfire simulations represent a simplification of the true occurrence of wildfires within the watershed in the previous 50 years. The base period model does not represent any wildfires. In the past, present, and future periods, wildfire covers 5, 8, and 11% of the watershed total area distributed between several sub-basins (Figure F.5). The percentages are derived from the historical burn scar record. For example, in 2014, a very large wildfire burned approximately 8% of the watershed area. The locations of the wildfires were selected such that the total burn percent could be distributed between the upland and wetland land covers to match the historical distribution according to the Ducks Unlimited Canada Hybrid Wetland Layer land cover classification and the NWT historical burn scar boundaries (Figure F.4).

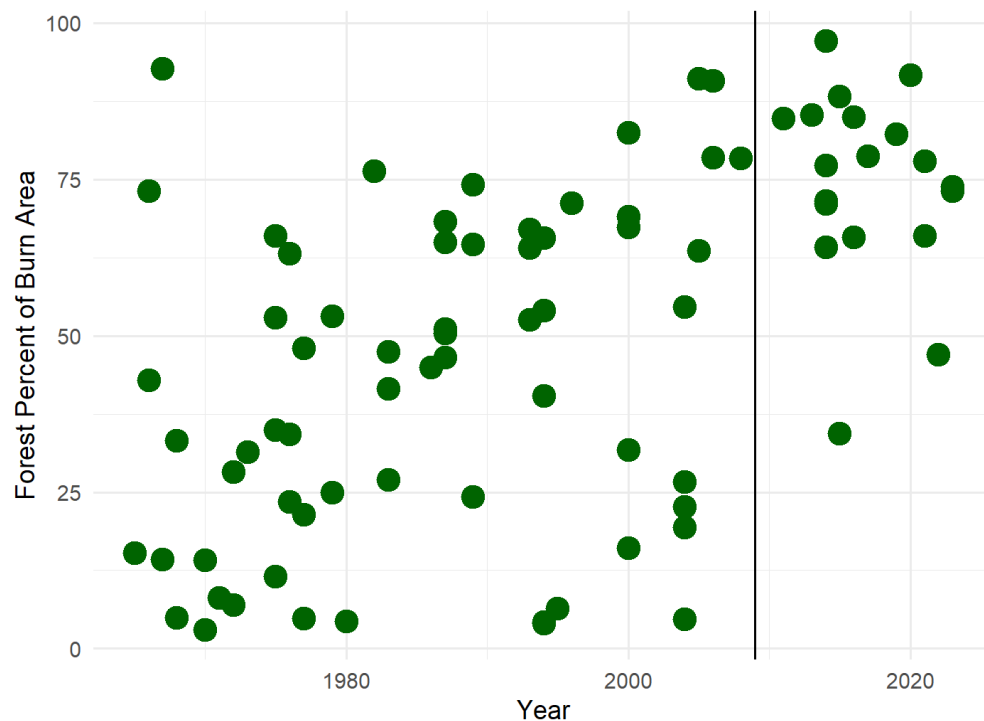


Figure F.4 Historical percentage of forest land cover type burned by wildfire. The remaining percentage is wetland and all other land cover types are excluded. The HWL layer is based on 2009 imagery, represented as the vertical black line. The percentage of forest changes after this year.

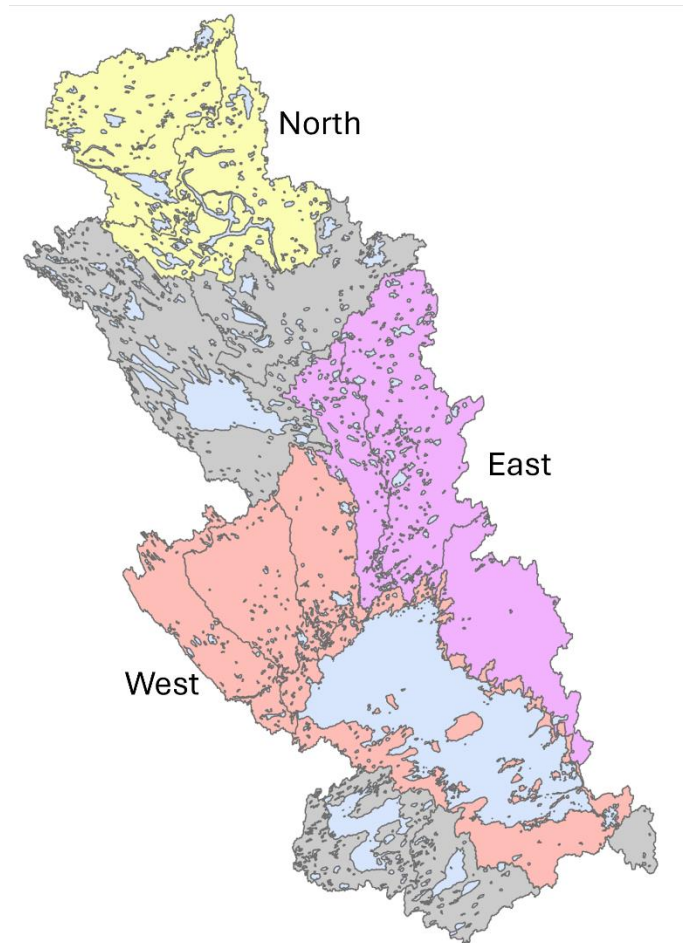


Figure F.5 Wildfire simulation sub-basins North, East, and West.

F.5 Wildfire Sensitivity Analysis

A matrix of simulations was run to compare the impact of the wildfire burn area, location, and thaw severity impacts (Figure F.6). Fires in the western sub-basins produced modest increases in discharge more often than those in the north or east. This difference likely reflects land cover and geology: the western sub-basins forest-dominated, the northern are wetland-dominated, and the eastern region is underlain by shallow bedrock with a thicker pre-fire active layer. Wildfire in the eastern region resulted in reduced annual discharge most often. Although the concurrent drought

complicates attribution, the largest eastern sub-basin (11), which burned in 2014, experienced a substantial discharge decline that year (Spence et al., 2020).

		Annual Discharge					
Wildfire Burn Area	5%	-0.6%	-0.5%	0.8%	North	Wildfire Burn Location	
		8%	-0.7%	0.1%			2.4%
			11%	0.6%			1.8%
	5%	-0.7%		-1.1%	0.4%		East
		8%	0.2%	-0.6%	0.5%		
			11%	0.5%	-0.5%		
	5%	-0.7%		0.1%	1.5%		West
		8%	0%	1.2%	2.7%		
			11%	0.2%	2.1%		
		Past		Present	Future		
		Thaw Severity					

Figure F.6 Results of the wildfire sensitivity analysis. Percent change in annual discharge relative to the base case for all combinations of wildfire burn characteristics. Rows are grouped by burn location (North in rows 1–3, East in rows 4–6, and West in rows 7–9) and, within each location, by burn area (5% in rows 1, 4, and 7; 8% in rows 2, 5, and 8; and 11% in rows 3, 6, and 9). Columns represent burn-thaw severity for the past (1), present (2), and future (3) periods.

Burned area had a stronger influence on discharge than location, though fires affected only a small fraction of the watershed (5–11%). While these disturbances can strongly alter local hydrology, their effect on discharge was muted. Larger burned areas amplified the effect of thaw severity, which consistently increased annual discharge, with the magnitude depending on both burn area and location. Thaw severity thus represents the dominant factor controlling post-fire hydrological response, effectively reproducing the impacts of permafrost thaw but limited to burned portions of the watershed. Broadly, these results suggest that wildfire’s long-term hydrological

consequences will be driven primarily by accelerated permafrost degradation (Zhang et al., 2015). In contrast, surface effects from forest loss are likely transient, as vegetation and evapotranspiration typically recover within 10–30 years (Gibson et al., 2018). Together, this indicates that while surface impacts may fade within decades, deeper effects on permafrost and subsurface storage are likely to persist, exerting a lasting influence on watershed hydrology.