ALBERTA-NWT TRANSBOUNDARY REGION

Permafrost Characterization and Impacts of Thaw on Water Quantity and Quality

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Table of Contents

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Figure i. Mosaic of peat plateaus and permafrost-free wetlands in the Hay River basin. Photo: David Olefeldt.

Executive Summary

The objectives of this report are to 1) understand the spatial extent and distribution of permafrost in the Alberta-Northwest Territories transboundary region, 2) identify areas most vulnerable to gradual permafrost thaw, and 3) review literature of the current state-of-knowledge on potential impacts of permafrost thaw on water quality and quantity in transboundary regions. To support the Bilateral Water Management Agreement (BWMA) signed between the Governments of Alberta (AB) and the Northwest Territories (NT) in 2015, knowledge and data gaps are identified for the transboundary region. Key findings of the report are summarized in Table i.

Study Region

The study area applies to all transboundary waters shared between AB and NT, focusing on the Liard/Petitot, Kakisa, Hay, Buffalo, Slave, and Taltson River basins. The AB-NT BWMA assigns a Risk-Informed Management approach that classifies transboundary water bodies based on the risks from current and planned development and downstream uses and other factors. The Hay and Slave rivers are the only AB-NT transboundary water bodies designated as class 3 for surface water due to development level, high traditional use, existing trends in winter flows, existing trends in naturalized annual flows, existing annual trends in water quality and community drinking water supply, and class 2 for groundwater, allowing for further studies. All other transboundary water bodies are designated as class 1 due to little or no development.

The transboundary region spans the Taiga Plains and Taiga Shield ecoregions. The Taiga Plains are characterized by low relief and poor drainage and have accumulated thick organic deposits within extensive peatlands that cover nearly half the total area. Vegetation includes closed-canopy mixed-wood forests of aspen and white spruce. The Taiga Shield ecoregion is dominated by lakes and exposed bedrock with vegetation of mixed-wood forests and wetlands on lacustrine deposits.

Based on the Canadian Water Resource Vulnerability Index to Permafrost Thaw ($CWRVI_{PT}$) developed by Spence et al. (2020), water resources within the transboundary region have previously been identified as highly vulnerable to permafrost thaw related to the organic terrain within peatlands that are susceptible to permafrost thaw and climatic change. The influence on permafrost thaw and subsequent water balance from these stressors and further impacts on water quantity and quality are discussed throughout this report.

Permafrost Characterization

Permafrost in the transboundary region is predominantly discontinuous, with sporadic and isolated patches along the southern boundaries. Continuous permafrost may be possible in the northeast portion of the Taltson River basin. However, up-to-date and accurate maps of permafrost extent are lacking for most of the sub-Arctic. Relative abundance of excess ice (segregated and wedge ice) is minimal for most of the study area, with virtually no excess ice in the low-moisture content bedrock of the Taiga Shield. Regional maps of permafrost peatland distribution are available for the Taiga Plains' NT-portion, but not in the Taiga Shield. In general, limited investigations have been conducted in the Shield portion of the transboundary region. It is recommended that the same methods used for permafrost characterization and mapping in the North Slave region be applied to the Taltson River basin in the Taiga Shield. Additionally, regional-scale mapping efforts should delineate areas based on basin boundaries instead of provincial boundaries.

Due to the insulative properties of peat and organic matter, much of the permafrost found in the transboundary region is associated with the extensive peatlands in the Taiga Plains and fine-grained soils covered by thick organic matter. Permafrost underlain peatlands are comprised of peat plateaus with ice-rich permafrost cores and black spruce forest cover. Plateaus rise 1–2 m above surrounding collapse (thermokarst) bogs and fens that are permafrost-free. Peat plateaus are the most common permafrost landform in the study region, but palsas and polygonal peat plateaus have been observed in the Taiga Plains, and lithalsas are possibly present in the Taiga Shield.

Permafrost in the Taiga Plains can reach up to 17 m thick in the Petitot River basin but is more commonly less than 10 m. Mean annual ground temperatures are near 0℃, indicating permafrost is undergoing internal thaw and/or is sensitive to disturbances in land cover. Few permafrost investigations have been conducted in the Taiga Shield transboundary region. However, observations in the North Slave region near Yellowknife indicate that permafrost is absent beneath bedrock outcrops and is most common in bedrock valleys filled with black spruce peatlands and forests underlain by fine-grained soils. Permafrost can be up to 55 m thick with mean annual ground temperatures between -2–0℃. Short-term and multi-decadal measurements of ground temperature are largely unavailable outside the Mackenzie River Valley. It is recommended that ground temperature monitoring networks be established. Private/governmental databases of ground temperatures should be made publicly available to aid in transboundary region monitoring and permafrost investigations throughout the subarctic.

Permafrost Degradation

In the Taiga Plains transboundary region, permafrost extent has decreased between ~10–50% since the 1950s. Based on the spatial extent of thermokarst, permafrost plateau-wetland complexes have degraded by ~25–77% in the Taiga Plains with lower permafrost degradation at higher elevations. In the Taiga Shield external to the transboundary region, permafrost has degraded by about 30% in forested areas and up to 84% in peatlands since the 1950s. Across the transboundary region, mean annual air temperatures have been increasing at rates between 0.25–0.41℃ per decade.

Air temperatures under all emission scenarios are projected to continue increasing at rates similar to present-day until about 2050. Summer rainfall is projected to increase in the coming decades, which is linked to increased permafrost thaw and hydrologic connectivity rates. Projected decreases in snow cover may temporarily help preserve permafrost by facilitating ground cooling in winter. However, shorter winters will likely lead to net-warming of soils and permafrost thaw. Under projected climate regimes, it has been predicted that little permafrost will remain in the transboundary region by 2100 and may only be associated with highly favorable hydrologic and landcover conditions in peatlands.

Wildfire and human-induced land disturbances that remove insulative vegetation have been observed to increase active layer thicknesses, increase talik extent, and accelerate permafrost thaw throughout the transboundary area. However, regions with less forest cover and more exposed bedrock and lakes are more hydrologically resilient to forest fires. In the Taiga Plains, it has been observed that permafrost degradation can recover from old wildfires (>30 years old), but active layer deepening and permafrost thaw from recent wildfire may be irreversible under current climate warming trends. Thaw beneath recent human-induced land disturbances may be similarly irreversible.

Impacts of Thaw on Landcover and Hydrology

Several significant trends in landcover change and hydrology have been observed in the transboundary region due to permafrost thaw (Table i). However, some trends (e.g., lake area and streamflow) are confounded by decadal atmospheric circulation patterns and built environments. Much of the hydrological investigations in the transboundary region have been concentrated in the lower Liard River valley, leaving considerable knowledge gaps for the remaining transboundary basins, particularly the Taltson basin in the Taiga Shield.

As permafrost thaws under climate warming, forested peat plateaus are converted to collapsed bogs and channel fens. Collapsed bogs and plateaus store water in the basin, whereas channel fens convey water to the basin outlet and increase runoff. Thus, the development of collapsed bogs (thermokarst) results in temporary increases in groundwater storage. However, as permafrost thaw continues and drainage networks become increasingly interconnected, the basin is converted to a greater runoff-producing landcover. Land disturbances (e.g., wildfire or land clearing) further accelerate this transformation. This landcover change is attributed mainly to the increases in annual streamflow that have been observed throughout the lower Liard River Valley. However, this increase may be temporary as the continued loss of permafrost enables bogs to drain, promoting wetland drying. Under drier conditions, permafrost-free afforestation can occur. The time-scale and resulting hydrologic changes of afforestation are uncertain but may be on the timescale of decades with implications for groundwater recharge and basin runoff.

The Taiga Shield is unlikely to have substantial landcover changes associated with thermokarst due to high spatial coverage of bedrock and low occurrence of peatlands. Thaw-induced landcover change may instead be related to changes in the spatial extent of lakes in this region. The low volume ice content of Shield environments means water from melting ice in permafrost will not considerably impact lake levels. Lake levels in the Taiga Shield are more likely to be impacted by permafrost thaw through the reactivation of subsurface flow paths and increasing basin storage capacity that reduces basin runoff and lake inflow. Lake extent in the Taiga Plains may be influenced by river inflow, infilling of fen vegetation, and thaw-induced lake shore collapse (thermokarst).

When the active layer deepens to the point it can no longer re-freeze in winter, a talik develops above the permafrost. This talik can allow for groundwater flow year-round, increasing hydrologic connectivity between landcover types and accelerating permafrost thaw. The spatial distribution of such taliks has been increasing in the Taiga Plains, particularly beneath areas burned by wildfire. Talik extent in the Taiga Shield, especially beneath lakes, is not well known. It is possible that permafrost thaw beneath soil-filled valleys and lakes may increase groundwater recharge and reactivate deep groundwater flow systems in fractured and faulted bedrock. Groundwater monitoring throughout the transboundary area is greatly lacking, leaving considerable knowledge gaps for the impacts of permafrost thaw on groundwater systems.

Increases in shallow talik development have been attributed to increasing winter baseflow in both transboundary ecozones. Higher winter baseflow can increase the development of riverine icings, which are more common in the Taiga Shield. Icings are not well documented in the Taiga Plains, and their trajectories in the Taiga Shield are highly uncertain.

Impacts of Thaw on Water Quality and Biogeochemistry

The transboundary rivers have fair water quality, where the exceedance of water quality guidelines is primarily associated with the natural characteristics of basins. High levels of dissolved organic matter (including carbon, nutrients, and bound metals) are delivered from widespread peatlands. High levels of metals are associated with suspended solids that increase during periods of high flows. Limited long-term data, high inter- and intra-annual variability, and a relatively limited fraction of each basin with permafrost peatlands, obscure the detection of water quality trends associated with permafrost thaw.

Continued permafrost thaw in peatlands is expected to significantly influence headwater stream, river, and lake water quality within today's sporadic and discontinuous permafrost regions. As permafrost thaws in peatlands, the expansion of thermokarst wetlands will likely cause increased hydrological connectivity of vast organic peat soils to stream networks. This thaw may result in increased downstream delivery of dissolved organic matter, including carbon, nutrients, and bound metals such as methylmercury.

Anoxic conditions in thermokarst wetlands that develop post-thaw may be hotspots for the production of methylmercury. However, it is unknown how much these hotspots will contribute to the overall basin delivery of methylmercury and to what degree it can be expected to affect the biomagnification of mercury in downstream food webs. Downstream delivery of other metals bound to organic compounds are also likely to increase from thawing peatlands (e.g., iron, selenium, and lead). Hay River is the transboundary river most likely to be affected by these processes, given the greater extent of current permafrost peatlands. Overall, the influence of permafrost thaw in peatlands on downstream water quality is still poorly understood, both with regards to the magnitude of change and to what degree these impacts might be attenuated within larger rivers and basins with longer water residence times.

Climate change is likely to influence water quality in the transboundary rivers through mechanisms other than peatland permafrost thaw. Altered timing and magnitude of runoff generation due to an altered water balance will change the relative contribution to streamflow of different flow paths with distinct water chemistry. Wildfire is likely to cause short-term pulses of nutrients, particularly phosphorous. Increased hydrological connectivity of deeper groundwater flow-paths can elevate pH, total dissolved solids, and salinity; however, this is more likely to occur further north at the transition from continuous to discontinuous permafrost zones.

While there is a continued need for long-term monitoring of large rivers, smaller sub-basins with large peatland extents should be considered for long-term monitoring (e.g., Scotty Creek in NT or Lutose Creek in AB), as well as site-level research into processes that may help predict future changes. While many processes can be inferred from research in other regions, specific regional characteristics may modify the response, and thus, predictions should be based on research carried out within the region.

A summary of the current state of knowledge for different permafrost characteristics and related hydrological and water quality response is provided in Table i.

Table i. Summary of the state of knowledge for permafrost landforms, hydrology, and biogeochemistry in the NT-AB transboundary regions. The bracketed number indicates the report section where the topic is elaborated.

Green = High confidence, data and studies available to support findings

Yellow = Medium confidence, data is available at select locations, but more studies or data is required to better support findings

Red = Low confidence, data is unavailable or not publicly recorded across the transboundary region

Permafrost Characterization (Section 0)	
Topic	**Summary**
Permafrost extent (4.1)	• The study area is in the zone of isolated-sporadic-discontinuous permafrost. • Excess ice (segregated and wedge ice) is minimal for most of the Taiga Plains and generally absent throughout the Taiga Shield.
Permafrost distribution (4.2)	• Permafrost is associated with ground covered by thick organic matter and peatlands that exhibit collapsed wetland expansion. • In the Taiga Plains, permafrost is thin (<20 m) and mean annual ground temperatures are near 0°C, indicating permafrost is undergoing internal thaw and/or is sensitive to disturbances in land cover. • In the Taiga Shield, permafrost is associated with bedrock valleys filled with peatlands and black spruce forests underlain by fine-grained mineral soils. • Permafrost in the forested areas of the Shield may be colder and thicker (up to 55 m) than in the Plains. Studies are greatly lacking for the transboundary Shield region. Detailed permafrost mapping of the Taiga Shield should be conducted. • Publicly available, long-term monitoring of ground temperatures is absent for most regions outside of the Mackenzie River Valley and should be established.
Permafrost landforms (4.3)	• Ice-rich peat plateaus are the most common permafrost landform found interspersed with collapsed bogs and fens. • Palsas and polygonal peat plateaus are less common. • Lithalsas may be present in fine grained mineral soils in the Taltson River basin. Mapping should be undertaken.

Permafrost Degradation (Section 5)	
Topic	**Summary**
Degradation in the study area (5)	• Permafrost extent in the Taiga Plains transboundary region has decreased between ~10–50% since the 1950s. • Permafrost plateau-wetland complexes have degraded by ~25–77% based on the thermokarst area, with lower degradation at higher elevations. • In the Taiga Shield, permafrost has degraded by ~28% in forested areas and up to 84% in peatlands. Estimates are based on similar environments outside the study area. Region-specific assessments of permafrost thaw should be attempted.
Climate Change (5.1)	• Air temperatures have been increasing at a rate between 0.25–0.41℃/decade, leading to widespread decreases in permafrost extent. • Projected increases in mean annual air temperature will result in little permafrost remaining in the study area by 2100. • Projected increases in summer precipitation may enhance permafrost thaw and increase hydrologic connectivity. • Projected declines in snowpack may buffer this by promoting ground cooling in winter, but longer growing seasons will lead to ground heating.
Wildfire (5.2)	• Wildfire results in increased active layer thickness and talik extent that can accelerate permafrost degradation. • Portions of the Taiga Shield with less forest cover and more exposed bedrock and lakes are more hydrologically resilient to forest fire. • Permafrost degradation can recover from old wildfires (>30 years old), but increases in active layer thickness and permafrost thaw from recent wildfire may be irreversible under current climate warming trends.
Human land disturbances (5.3)	• Land disturbance that removes vegetative cover (e.g., for roads, pipelines, seismic line surveys and community infrastructure) can initiate and enhance permafrost thaw. • Permafrost thaw resulting from land disturbance may not recover under climate warming regimes, but snow depth and soil moisture determine rates of permafrost aggradation.
Thaw-induced Landcover Change (Section 6.1)	
Topic	**Summary**
Peat Plateau Wetlands (6.1.1)	• Permafrost degradation results in a transition from a landscape dominated by forested plateaus to one dominated by permafrost-free bogs and fens. • Wetland area has been increasing in the Lower Liard River valley. • Landcover transition is accelerated by climate change, wildfire, and land disturbances. • Draining of permafrost-free wetlands is leading to the re-establishment of forests and a landcover change to permafrost-free treed wetlands. • Timing of this trajectory is uncertain but possibly on the scale of decades. • Forest cover has been declining in the Liard River basin, but forest gains in the Petitot River basin limit net loss in this area.
Lake Environments (6.1.2)	• Lake extent in the Taiga Plains may be influenced by river inflow, infilling of fen vegetation, and thaw-induced lake shore collapse. • Decadal atmospheric circulation patterns and increasing air temperatures influence lake extent which may confound impacts of permafrost thaw. • Taiga Shield is unlikely to have substantial landcover changes associated with thermokarst due to high spatial coverage of bedrock and low occurrence of peatlands. • Long-term trend assessment of Lake extent in the Taiga Shield is recommended.

Thaw-induced Hydrologic Change (Section 6.2)	
Topic	**Summary**
Active Layer Thickness (6.2.1)	• Increasing in the Liard River valley • Fairly stable in northern Hay River basin and Petitot Basin.
	• Unknown for Taltson River Basin.
Groundwater (6.2.2)	• Long-term monitoring of groundwater levels is unavailable for most of the study area. Integrated monitoring of existing transboundary wells should be conducted, and a dedicated groundwater monitoring network should be established. • Impacts of permafrost thaw on large-scale and deep groundwater flow systems is unknown for the region. Further investigations are recommended.
	• Permafrost thaw increases surface-subsurface hydrologic connectivity through the development and expansion of taliks.
	• Permafrost thaw in soil-filled bedrock valleys will result in increased groundwater recharge and storage.
	• Deep permafrost thaw into bedrock beneath lakes and soil-filled valleys could increase groundwater recharge and reactivate groundwater flow systems. Further investigation is recommended.
Icings (6.2.3)	• Common in the Taiga Shield and controlled by autumn precipitation and mid-winter warming periods. Uncertain trajectory.
	• Limited knowledge of icings in the southern Taiga Plains or the trajectory. Further investigation is recommended.
Peat plateau wetlands (6.2.4)	• Permafrost thaw results in peatlands transitioning to higher runoff-producing landcover. • Groundwater storage temporarily increases for peat plateau-wetland complexes under thaw but declines as plateaus collapse and wetlands drain.
	• Groundwater recharge and storage following afforestation is highly uncertain. • Linear disturbances (e.g., seismic lines and winter roads) hydrologically function like isolated bogs but may begin to function more like channel fens with progressive thaw.
Lakes (6.2.5)	• In the Taiga Shield, permafrost thaw may increase the storage threshold required for basin runoff, thereby decreasing basin runoff and lake inflow. • Thaw in peat plateaus has increased runoff into lakes in the Caribou Mountains of Buffalo River basin
	• Permafrost thaw beneath lakes in the Taiga Shield may result in lake levels declining but the configuration of these taliks is relatively unknown. Further investigation is recommended.
Streamflow (6.2.6)	• Annual streamflow is increasing in the Liard River, remaining stable for Hay and Taltson River, and declining for the Slave River. • Increasing annual streamflow in the lower Liard River basin is primarily due to a thaw-induced transition from landcovers that store water to ones that produce runoff (i.e., forested plateau to wetland). Minor contributions include water from the melting of ice.
	• Groundwater contributions to streamflow will likely increase as permafrost thaws, but additional investigations across a range in geologic landscapes is needed to improve prediction. The influence of sub-permafrost groundwater is uncertain.
Winter baseflow (6.2.6)	• Increases for the Liard River valley due to supra-permafrost talik development. • Increases for the Hay River. • Increases in the North Slave region due to increasing autumn rain but non-significant trends for the Taltson River.

Impacts of Thaw on Water Quality and Biogeochemistry (Section 7)	
Topic	**Summary**
pH (7.2.1)	• Increased groundwater contributions may increase pH levels. • pH increases were observed in the Slave and Hay rivers.
Conductivity and total dissolved solids (7.2.1)	• Increased groundwater contributions may increase specific conductance and total dissolved solids (TDS). • Specific conductance, TDS were typically stable for the basins. • Slave River had an annual decreasing TDS trend with no identified driver.
Total suspended solids (7.2.1)	• Total suspended solids may increase with permafrost thaw in regions with hillslope permafrost, but peatland thaw is unlikely to influence sediment loads. • Total suspended solids trends for the basins were stable.
Organic matter (7.2.2)	• Increased dissolved organic carbon (DOC) concentrations are expected with permafrost thaw of peatlands. • Liard River has increasing DOC export due to increased streamflow with no change in concentrations. • No change in concentration or export for Slave and Hay River.
Nutrients (7.2.3)	• Long-term transboundary basin trends show increases in nutrients in the Slave River basin that may be related to agricultural activities. • As the release of nutrients has been identified in thawing peatlands and wildfire, continued monitoring is necessary.
Mercury (7.2.4)	• Long-term temporal trends have not been assessed in the transboundary region due to insufficient data. Reanalysis of temporal data is recommended. • Current monitoring programs are collecting mercury and should include methylmercury. • Permafrost thaw and release of carbon/mercury may be contributing to elevated bioaccumulation as thawing peatlands are environments suitable for the production of methylmercury.
Metals (7.2.5)	• Metals have frequently exceeded water quality guidelines due to high particulate loads. • As release of metals such as iron, lead, and selenium have been identified in thawing peatlands outside of the transboundary region, continued monitoring is necessary. • Re-analysis of long-term datasets is of interest to observe more recent patterns in the basins.
Persistent organic pollutants (7.2.6)	• Persistent organic pollutants (PoPs) have been detected in the transboundary regions but have not consistently exceeded water quality guidelines. • Temporal analyses of PoPs have been sparse due to inconsistent data and continued monitoring is recommended.
Tritium (7.2.7)	• The release of tritium (radioactive isotope of hydrogen) with permafrost thaw has been established in the transboundary regions, particularly in the discontinuous permafrost region. • Elevated concentrations of tritium are an indicator of increased hydrological connectivity of rapidly thawing peatlands in the sporadic and discontinuous permafrost zone.
Groundwater biogeochemistry (7.2.8)	• Increased connection to groundwater is expected with the advance of permafrost thaw. • Multiple reports found insufficient groundwater data and long-term data of groundwater quality has not been analyzed and/or are not available in the transboundary region.

1 Introduction

A Bilateral Water Management Agreement (BWMA) was signed between Alberta (AB) and Northwest Territories (NT) in 2015, a provision of the Mackenzie River Basin Transboundary Waters Master Agreement signed in 1997, to cooperatively manage the river basins they share and ensure the health of the aquatic ecosystem is maintained. The AB-NT transboundary region is warming at least twice the global rate (Vincent et al., 2015), leading to the rapid thaw of the discontinuous-sporadic permafrost, which is typically constrained to organic soils with high volumetric ice content. Water resources in the transboundary region are highly vulnerable to permafrost thaw (or degradation) due to the predominance of peatland terrain (Spence et al., 2020). This report aims to understand permafrost thaw and water dynamics (both surface and subsurface) in the shared AB-NT basins in the context of a warming climate.

The scope of this report is to review the literature on the spatial extent of permafrost in the transboundary region and describe the causes of permafrost degradation and controls on basin hydrology. In addition, impacts of permafrost thaw on water chemistry and nutrient cycling and gaps in understanding of permafrost thaw-induced changes to hydrology and biogeochemical properties will be discussed.

2 Background

The following section details general permafrost terminology and concepts that are important to understanding permafrost occurrence and thaw. Most of this information stems from the text *Permafrost Hydrology* by Woo (2012) unless otherwise cited. These concepts and terms are commonly referred to throughout this report. The reader is directed here and to the Glossary of Terms when clarification is needed.

2.1 Permafrost Definitions

Permafrost is defined as soil, sediment, or rock that remains at or below 0ºC for at least two consecutive years (Woo, 2012). The active layer is subject to seasonal freeze-thaw cycles and extends down from the surface (Figure 1). Across the permafrost domain, active layers range in thickness from tens of centimeters to several meters. The base of permafrost typically extends several meters up to 1000 m below the surface at high latitudes (Walvoord and Kurylyk, 2016). The depth of zero annual amplitude (DZAA) is where seasonal air temperature variations are no longer detected in ground temperatures. The upper boundary surface of the permafrost layer is defined as the permafrost table. Liquid water can exist below 0ºC in the pore spaces of soil or rock due to drivers of freezing point depression such as adsorption or capillary forces, high pressures, or solutes (Woo, 2012). Sub-zero liquid water typically occurs at the base of the permafrost layer, termed a basal cryopeg, but isolated cryopegs can also occur within the permafrost. Geothermal gradients drive the perennially unfrozen ground beneath the base of the permafrost termed subpermafrost groundwater. Patches of perennially unfrozen ground in areas of permafrost are generally termed taliks, or thaw bulbs.

Segregated ice forms when water migrates toward the freezing front and forms ice lenses (Woo, 2012). Wedge ice forms when cracks in the ground expand due to the freezing of infiltrating water. The result is a wedge-shaped cross-section and a polygonal pattern on the surface. Both segregated and wedge ice result in ice volumes exceeding available soil or rock pore space, called excess ice. When excess ice melts, it releases large volumes of water, leading to slope failure/mass wasting and thermokarst features (e.g., linear troughs, irregular depressions with bogs and lakes).

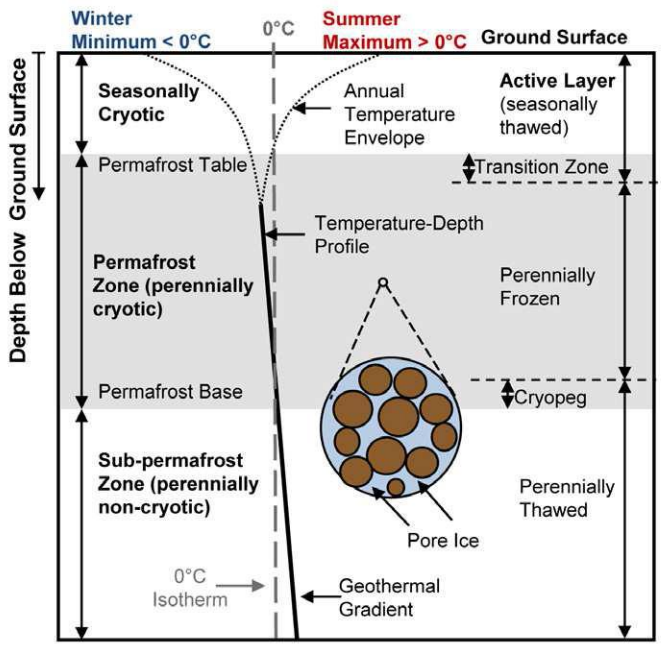

Figure 1. Vertical profile of ground temperature and permafrost zone classification (Walvoord and Kurylyk, 2016).

2.2 Influences on Permafrost Occurrence

Various factors at local and regional scales can influence the development of permafrost and active layer thickness (ALT). These factors can determine whether permafrost is present in subarctic regions and how long it can persist under warming climates.

2.2.1 Latitude and Topography

Permafrost is associated with increases in latitude, elevation, and continentality (Woo, 2012). These factors generally control mean annual air temperature (MAAT), which plays an important role in permafrost formation and degradation. Depending on the persistence and connectivity of permafrost, areas can be classified as continuous (>90% areal coverage), discontinuous (50–90% areal coverage), sporadic (10–50% areal coverage), or isolated (<10% areal coverage) (Brown et al., 1997; Obu et al., 2019). The direction a slope faces can also influence permafrost occurrence, particularly in the subarctic, where permafrost is discontinuous. Permafrost might be present beneath shadowed north-facing slopes but not south-facing slopes that receive more direct sunlight. Low-lying areas are generally wetter than upland areas, which can influence the thermal ground conditions.

2.2.2 Snow Cover and Vegetation

Snow cover is an excellent insulator, particularly dry and low-density snow (Woo, 2012). This insulation can delay ground warming in spring, but a greater effect of snow cover on permafrost is in the winter months. Thick (>0.3 m) snow cover prevents cold winter air from penetrating the subsurface and limits heat loss from the ground. This snow cover can result in higher ground temperatures and subsequent permafrost thaw. Vegetation can influence snow cover dynamics, where forested areas can maintain thicker snow covers than open areas exposed to wind and solar radiation. Deciduous forests can accumulate thicker snow cover than coniferous trees due to lower snow interception on branches. Thicker snow cover may accumulate along margins of forests and peat plateaus, promoting permafrost thaw in these areas. Bare ground albedo is also altered by vegetation which influences heat transfer to the ground. For example, layers of dry moss and lichen can effectively insulate the ground against summer heating. Forest canopies can further limit ground warming in summer by filtering and reducing radiative fluxes that reach the ground surface.

2.2.3 Soil and Rock

Differing surface albedos between soil and rock influence subsurface absorption of solar energy. Thermal conductivity and heat capacity of subsurface material dictate the rate of heat propagation to the permafrost table and resulting ALT. The intrinsic differences of these properties for soil and rock are not substantial, but when pore spaces are filled with air, water, or ice, the thermal properties of soils can vary by orders of magnitude. These properties vary more for higher porosity (80–95%) materials such as peat, compared to low porosity (<5%) fractured bedrock. For example, typical thermal conductivities of dry, water-saturated, and ice-saturated peat are 0.06 $Wm^{-1}K^{-1}$, 0.5 $Wm^{-1}K^{-1}$, and 1.9 $Wm^{-1}K^{-1}$, respectively (Woo, 2012). The low thermal conductivity of dry peat insulates against ground heating in the summer months, and the high thermal conductivity of saturated/icy peat facilitates ground cooling in the winter. As climate change has been shown to increase evapotranspiration in the summer and increase precipitation in the fall and winter, an understanding of these thermal properties is imperative to predict future conditions. The insulative properties provided by peat are critical in subarctic discontinuous permafrost, where organic material can support the presence of permafrost where it otherwise would not exist. In contrast to peat, the relatively low moisture content (<5%) and high thermal conductivity (2–3 $Wm^{-1}K^{-1}$) of bedrock allow for active layers to develop up to several meters thick (Bonnaventure and Lamoureux, 2013). This high conductivity generally inhibits permafrost presence beneath bedrock outcrops in the subarctic (Brown, 1973).

2.2.4 Water Bodies and Water Flow

Water bodies such as lakes and rivers influence the presence of permafrost by warming or inhibiting permafrost beneath the water body and along its shores, leading to the formation of talik (Woo, 2012). Taliks are likely to develop under lakes when the mean annual air temperature is > –6°C and in lakes deeper than 2 m as they do not typically freeze to the lake bottom in winter (Jorgenson & Shur, 2007;

Kokelj & Jorgenson, 2013). The solar heating of water and latent heat effects can lead to high contrast in surface and lake bottom temperatures and contribute to thawing adjacent to lakes and ponds (Jorgenson et al., 2010; Kokelj & Jorgenson, 2013; Lin et al., 2010). Taliks can also develop above the permafrost table and below the active layer (supra-permafrost talik) when the active layer becomes too deep to refreeze in winter. Supra-permafrost taliks enable groundwater flow year-round and carry heat that can thaw underlying permafrost. Groundwater can also flow beneath permafrost (sub-permafrost groundwater), where the upward geothermal gradient prevents groundwater from freezing. If a talik connects groundwater systems above and below permafrost, it is termed an open talik.

The presence of permafrost strongly influences the movement, storage, and connectivity of surface and subsurface waters because it is relatively impermeable (Walvoord and Kurylyk, 2016). Saturated frozen ground, particularly high porosity peat, restricts infiltration and promotes surface and near-surface runoff. However, infiltration may still occur in partially frozen ground until pore water completely freezes. The degree to which the active layer is frozen controls subsurface storage capacity and can therefore dictate the magnitude and direction of near-surface flow.

2.2.5 Latent Heat Effects

Permafrost can persist under warming climate conditions due to the amount of latent heat needed for phase change (solid to liquid water). All of the energy added to the system from the surface is absorbed as latent heat, resulting in an isothermal system where temperatures remain near 0℃ (van Huissteden, 2020). Temperatures are rarely exactly 0℃ during thaw due to the common presence of solutes that lower the freezing point of water (Woo, 2012). When permafrost temperatures remain stable near 0℃, it is an indication that permafrost is unstable, internally thawing, and sensitive to disturbance (Smith et al., 2010).

Latent heat exchange for the seasonal freezing and thawing of the active layer can dampen the propagation of surface temperatures to the permafrost table (Smith et al., 2010; Woo, 2012). Soil moisture is an important driver of this, where wetter soils require more energy for phase change than drier soils (Morse et al., 2015; Shur et al., 2005). Saturated soils with higher porosities, such as peat and clays, are likely to have greater latent heat effects due to higher proportions of water. Permafrost with higher proportions of liquid water can also attenuate responses to rising air temperatures (Osterkamp, 2003; Romanovsky & Osterkamp, 2000). Generally, latent heat effects become more important as permafrost approaches 0℃ (Smith et al., 2010).

3 Study Region

The study area applies to all transboundary waters shared between AB and NT, which include Liard/Petitot, Kakisa, Hay, Buffalo, Slave, and Taltson River basins (Figure 2). Sub-basins were selected instead of larger basins (e.g., Athabasca, Great Slave, Peace) to better associate observed changes in water quantity and quality to permafrost thaw. Impacts at a larger scale can be confounded by various land disturbances and uses and can consist of various landcover. Additionally, many studies within this literature review occur at a site or small tributary scale, making it challenging to extrapolate to a larger area. A portion of the Liard River basin is not part of the AB-NT BWMA. However, it has been included in the report due to relevant permafrost and hydrology studies conducted in the Liard River basin; similar land cover characteristics between a part of the Liard (Lower Liard/Mouth) and the Hay rivers basins suggest the transferability of physical processes. The study area communities include Fort Liard, Hay River, Kakisa, Enterprise, Fort Smith and Fort Resolution in NT, and Meander River, and Zama City in AB. Key attributes of the transboundary region of interest have been summarized in Table 1.

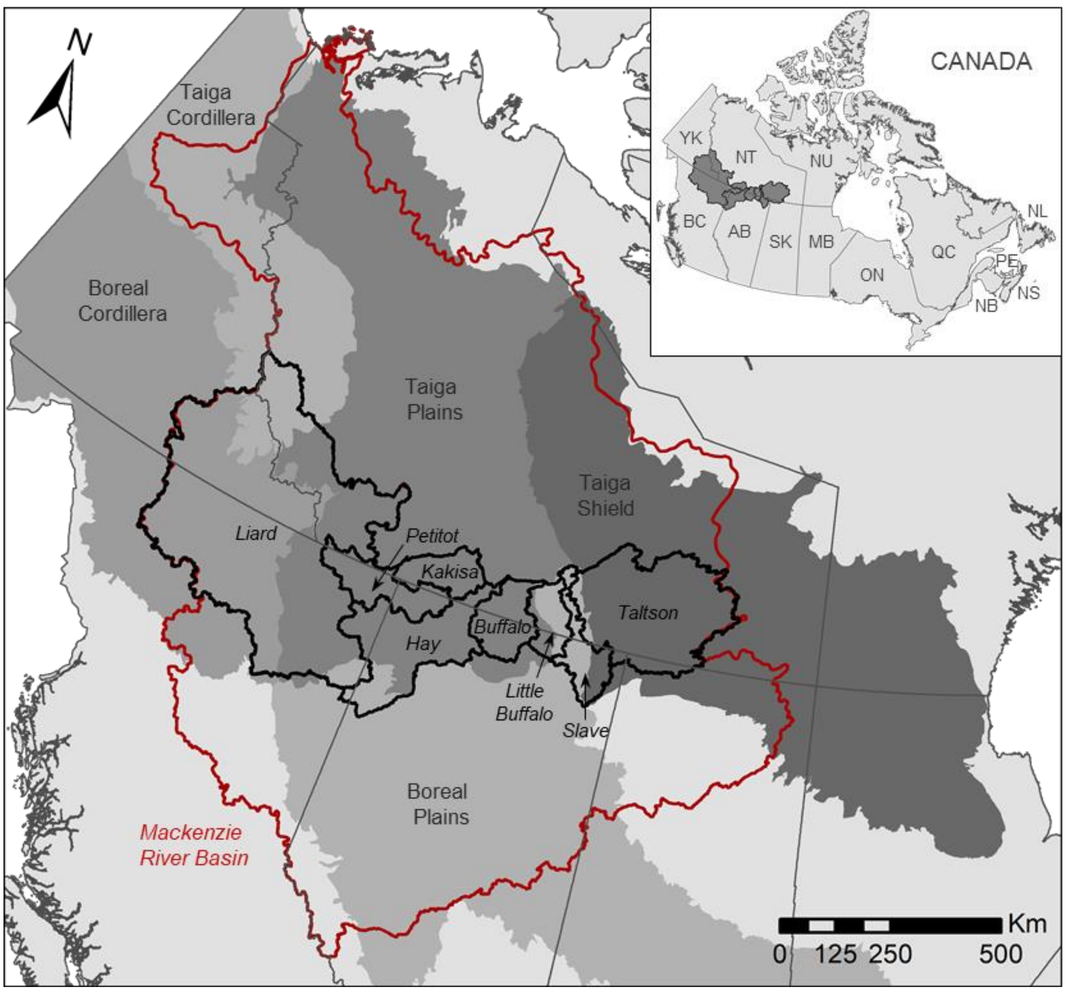

Figure 2. Transboundary sub-basins of interest (black outline) and ecozones (shaded grey) in the context of Canada and within the Mackenzie River Basin (red outline). Ecozones are based on the national ecological framework for Canada

A Risk-Informed Management approach classifies transboundary waters based on the risks associated with the use or impacts to a water body and the aquatic ecosystem's sensitivity to determine the water body class (Class 1–4). Water bodies can move up or down classes depending on different factors, including the level of development, water use, natural or other anthropogenic stressors or vulnerabilities, sensitive water or ecosystem uses, use conflicts or controversy, water quality and quantity conditions or trends and aquatic ecosystem conditions or trends t. Class 1 indicates little or no development, and current water management practices in use are meeting transboundary commitments. Class 2 water bodies have moderate existing or projected development/use, and learning plans are required to prepare for the setting of transboundary objectives. High levels of development, or a combination of moderate development with natural vulnerabilities, sensitive uses, use conflicts or controversy and/or undesirable conditions or trends, are class 3 water bodies. Class 3 water bodies require specific objectives and monitoring programs. If objectives are not being met, the water body will be moved to class 4, at which point the responsible party or parties will identify and implement action to meet objectives and return to class 3 (Government of Alberta and Government of the Northwest Territories, 2018). The Hay and Slave rivers are the only AB-NT transboundary water bodies designated as class 3 for surface water due to development level, high traditional use, existing trends in winter flows, existing trends in naturalized annual flows, existing annual trends in water quality and community drinking water supply, and as class 2 for groundwater, in acknowledgment of the lack of information in the area and need for further studies. All other AB-NT transboundary waters are designated as class 1 (Table 1).

Water resources within the transboundary region have been identified as highly vulnerable to permafrost thaw based on the Canadian Water Resource Vulnerability Index to Permafrost Thaw ($CWRVI_{PT}$) developed by Spence et al. (2020) (Figure 3). The $CWRVI_{PT}$ is a linear additive index that incorporates known factors and stressors impacting water budgets and aquatic chemistry, including permafrost change, land disturbance (human and wildfire), terrain, and climatic conditions. While a portion of the Hay River is highly vulnerable due to oil and gas production activities (Figure 3b), the remainder of the vulnerability is related to the organic terrain within peatlands susceptible to permafrost thaw and climatic change. The influence on permafrost thaw and subsequent water balance from these stressors and further impacts on water quantity and quality will be discussed throughout this report.

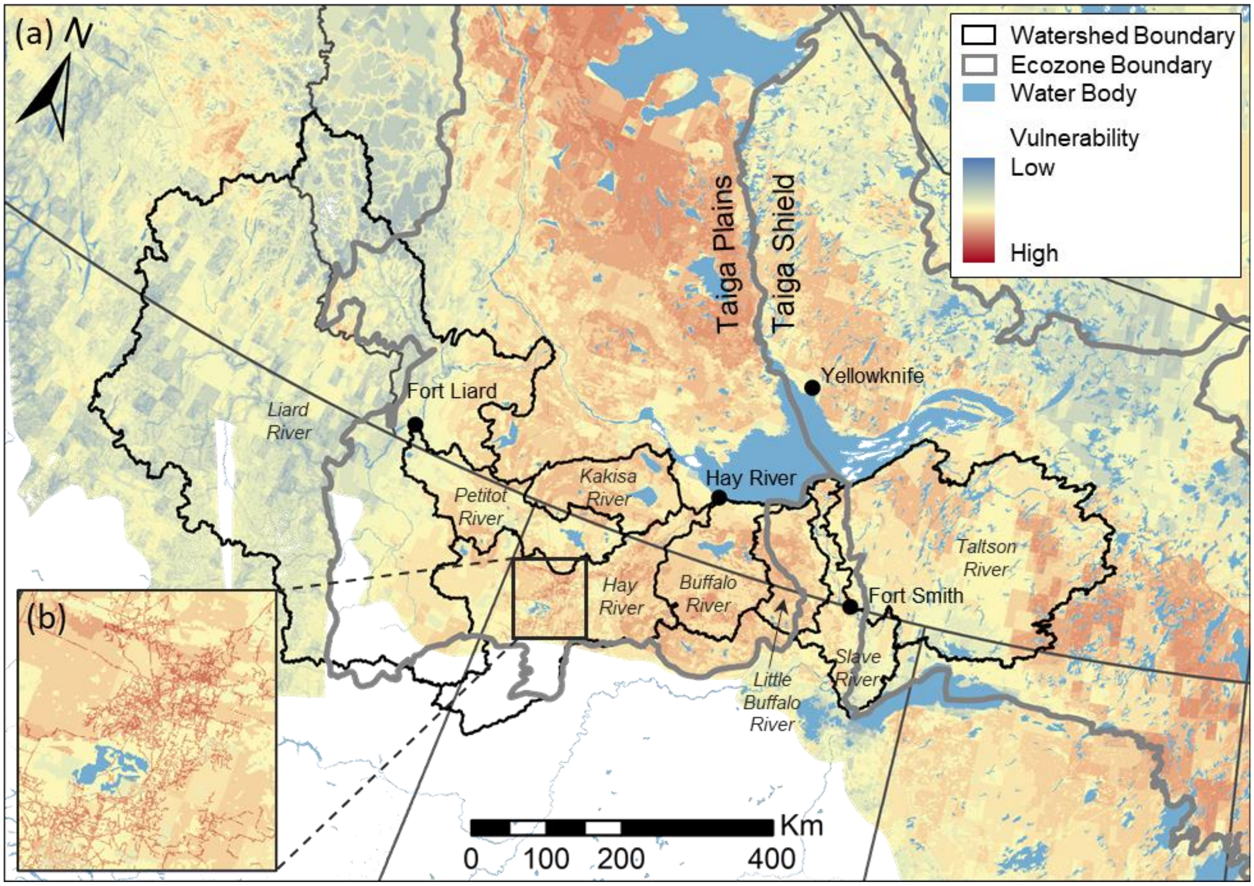

Figure 3. (a) Sub-basins of interest within the transboundary area and the Water Resource Vulnerability Index to Permafrost Thaw ($CWRVI_{PT}$) for the transboundary region and (b) magnified region in the Hay River basin with high water resource vulnerability due to human-induced land disturbance. The $CWRVI_{PT}$ basemap is from Spence et al. (2020) and basin boundaries are from Natural Resources Canada (2016).

Table 1. Attributes of the transboundary region of interest. Class refers to the Risk Informed Management class.

Basin	Area (km^2)[1,2]	Ecozone(s)[3]	Flow Direction[4]	Human Use	Special Features	Class[9]	Class Rationale[9]
Liard/ Petitot	299,600	Taiga Plains, Taiga Cordillera, Boreal Plains, Boreal Cordillera	AB-NT, NT-AB	Fishing, hunting, trapping, gathering, tourism, oil and gas[1]	Nahanni National Park Reserve[1]	1	Little/no development in the AB-NT transboundary portion of the basins
Hay	47,900	Taiga Plains, Boreal Plains	AB-NT, NT-AB	Fishing, hunting, trapping, gathering, tourism, oil and gas[1]	Hay-Zama Lakes wetlands[1]	3 (surface water)	Development, high traditional use[†], existing trend of increasing winter flows, existing annual trends in water quality, community drinking water supply
						2 (ground water)	Lack of information in the area requiring further studies
Kakisa	15,900	Taiga Plains	AB-NT, NT-AB	Fishing, hunting, trapping, gathering, oil and gas[6]	Lady Evelyn Falls	1	Little/no development, or management practices are meeting commitments
Buffalo	17,600	Taiga Plains	AB-NT, NT-AB	Fishing, hunting, trapping, gathering, mining[7]	Caribou Mountains, Wood Buffalo National Park	1	Little/no development, or management practices are meeting commitments
Little Buffalo	13,400	Taiga Plains, Boreal Plains	AB-NT	Fishing, hunting, trapping, gathering, mining[7]	Caribou Mountains, Wood Buffalo National Park	1	Little/no development, or management practices are meeting commitments
Slave	15,100/ 615,000*	Taiga Shield, Boreal Plains	AB-NT	Fishing, hunting, trapping, gathering, oil and gas, hydro-electricity[1]	Wood Buffalo National Park, Slave River and Peace-Athabasca deltas[1]	3 (surface water)	Development is present, high traditional use[†], existing trend of decreasing annual flows, existing trends in water quality, community drinking water supply
						2 (ground water)	Lack of information in the area requiring further studies
Taltson	65,000	Taiga Shield, Boreal Plains	AB-NT, NT-AB	Fishing, hunting, trapping, gathering, mining[7], hydro-electricity[8]		1	Little/no development, or management practices are meeting commitments

*Catchment area of the Slave River includes the area of the Slave River at the confluence of the Peace and Riviere des Rochers rivers and the Slave River Delta basin area.

†Traditional use in BWMA Appendices refers to human use through traditional activities (Government of Alberta and Government of the Northwest Territories, 2015),[1]Culp et al., 2005, [2]Natural Resources Canada, 2016, [3]Agriculture and Agri-Food Canada, 2013, [4]Government of Alberta & Government of the Northwest Territories, 2015, [5]Golder Associates, 2017, [6]Zantoko & Simba, 2019, [7]Government of the Northwest Territories, n.d., [8]Northwest Territories Power Corporation, 2014, [9]Government of Alberta & Government of the Northwest Territories, 2018

3.1 Ecozones

The primary ecozones within the study area include the Taiga Plains and Taiga Shield (Figure 2). Based on the National Ecological Framework for Canada, a portion of the Little Buffalo and Slave basins falls within the Boreal Plains Ecoregion (Ecological Stratification Working Group, 1995). However, in an updated Government of NT framework, these basins fall within the Taiga Plains ecozone and share similar characteristics as the neighboring Hay River and Kakisa basins (Table 2; Ecosystem Classification Group, 2009). Many permafrost-based studies that cover all of the Taiga Plains (e.g., Carpino et al., 2021; Gibson et al., 2021) also typically include the Little Buffalo and Slave basins. Since permafrost is not typical for the Boreal Plains and due to similarities with the Taiga Plains for the transboundary region, the Boreal Plains will not be the focus of this study. Additionally, the Boreal Cordillera ecozone extends into the western half of the Liard River basin, which is not part of the AB-NT BWMA and, therefore, will not be a focus of the study. Each ecozone can be further categorized into ecoregions that have distinct characteristics and permafrost landforms, as described in Table 2 and Section 4.3.

3.1.1 Taiga Plains

The Taiga Plains spans the northeast corner of British Columbia, the central and western portions of northern AB, and dominate the southwest and central portions of NT. The Taiga Plains ecoregion is characterized by low relief and poor drainage and has accumulated thick organic deposits within extensive peatlands that cover nearly half the total area. Development after the Laurentide Ice Sheets' recession is reflected by the till plains in uplands and widespread lacustrine deposits remnant of the vast postglacial Lake McConnell. In the southern Taiga Plains, summers are warm and moist, and winters are cold and snowy. Mean annual air temperatures range from -4.4℃ to -1.0℃, and mean annual precipitation is between 300 mm and 410 mm. Vegetation includes closed-canopy mixed-wood forests of aspen and white spruce (Ecosystem Classification Group, 2007a).

Permafrost in the Taiga Plains is associated with peatlands due to the insulative properties of peat (Woo, 2012). Peatlands in the southern Taiga Plains commonly consist of forested peat plateaus with permafrost cores that are interspersed with permafrost-free fens and flat bogs (Figure 4; Quinton et al., 2003; Zoltai and Tarnocai, 1974). Plateau vegetation includes black spruce (*Picea mariana*) trees, Labrador tea, lichen, and bog areas containing various sphagnum moss species (Ecosystem Classification Group, 2007a). Black spruce trees are associated with permafrost plateaus because raised ground surface provides sufficiently dry conditions to support its shallow (20 cm) root system in the upper organic horizon (Viereck and Johnston, 1990). Black spruce trees are tolerant to the acidic and high moisture conditions of subarctic peatlands, but their root system cannot tolerate being completely waterlogged (Baltzer et al., 2014).

Common permafrost features in the Taiga Plains are collapse scar (or thermokarst) lakes and bogs that develop when permafrost thaws, causing peat plateaus to collapse internally or along its margins (Zoltai, 1993). Thermokarst refers to thaw-induced surface subsidence or land-cover change, commonly associated with ice-rich or ice-saturated ground. Peat plateaus and collapsed wetlands are referred to in this report as "plateau-wetland complexes" (Figure 4). Collapsed bogs can either be relatively small (e.g., tens of meters in diameter) and isolated within the complex (isolated bog) or interconnected (connected bog) and eventually drain to channel fens (Connon et al., 2014; Quinton et al., 2009). Plateau-wetland complexes are separated by channel fens that primarily convey water to the basin outlet (Hayashi et al., 2004a).

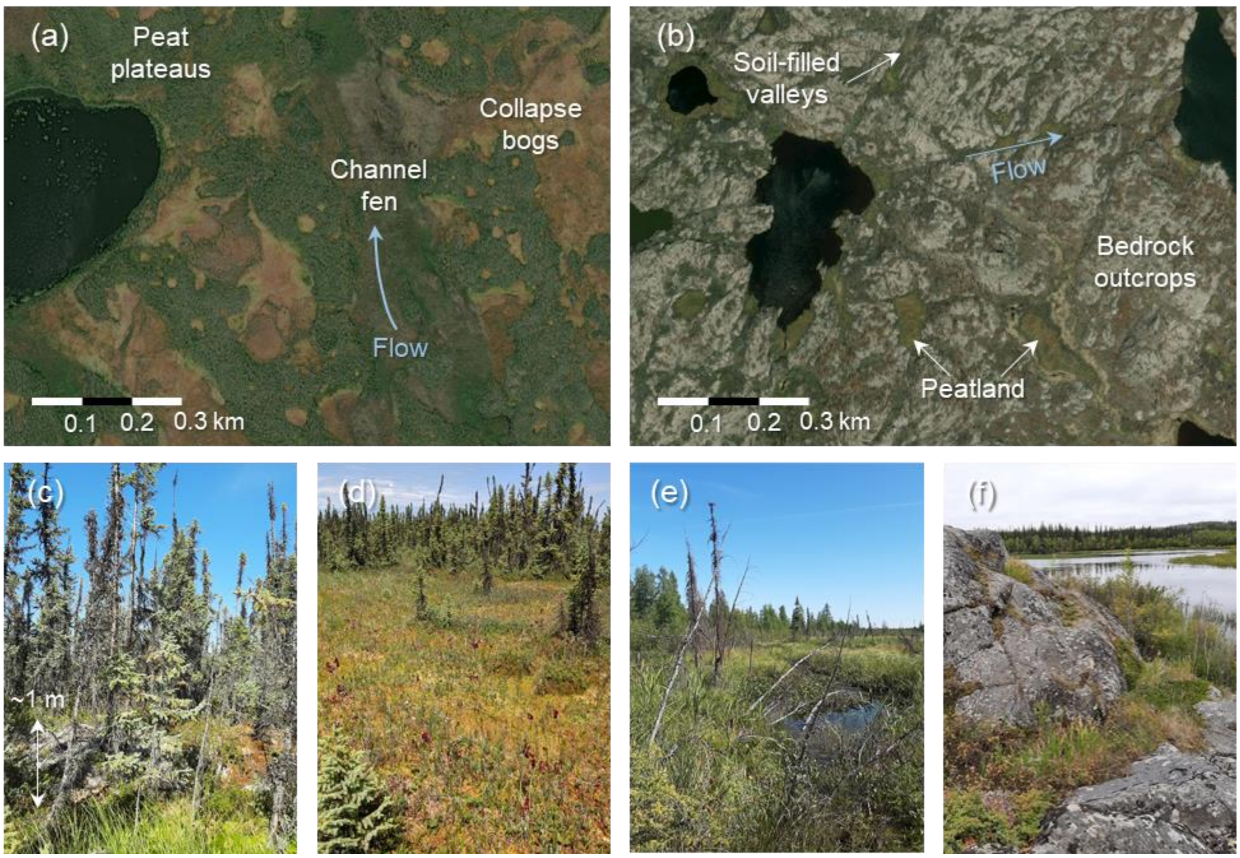

Figure 4. (a) Plateau-wetland complexes in the Taiga Plains (61.297°, -121.224°). Green areas are intact permafrost-underlain peat plateaus, dark grey areas are permafrost-free runoff-conveying channel fens, and orange/brown areas are permafrost-free collapse bogs and fens. From Zoom Earth. (b) Bedrock uplands in the Taiga Shield (61.005°, -111.646°). Grey areas are permafrost-free bedrock outcrops, and green/brown areas are permafrost-underlain soil-filled valleys and peatlands. (c) Forested peat plateau underlain by permafrost that rises approximately 1 m above surrounding permafrost-free (d) bogs and (e) channel fens. (f) Permafrost-free bedrock outcrop.

3.1.2 Taiga Shield

The Taiga Shield ecoregion extends from AB's northeast corner through northern Saskatchewan, Manitoba, southern Nunavut, and southeast NT. The Taiga Shield geology includes lacustrine deposits and glacial till from postglacial lakes and bedrock plains and hills from eroded Precambrian mountains and volcanos. The southern Taiga Shield is generally characterized by short, cool summers and very cold winters. Mean annual air temperatures range from -6.9℃ to -3.3℃, and mean annual precipitation is between 251 mm and 400 mm. Lakes and exposed bedrock dominate the landscape with vegetation of mixed-wood forests and wetlands on lacustrine deposits (Ecosystem Classification Group, 2008a).

The Taiga Shield landscape consists of bedrock uplands and soil-filled valleys that contain wetlands and the largest proportion of lakes in the study area (Figure 4; Spence, 2000; Spence & Woo, 2002a, 2002b, 2003). Soil-filled valleys and depressions form where there are structural weaknesses in the underlying bedrock (Spence and Woo, 2003). The hydrology of the bedrock uplands and soil-filled valleys generally follows a “fill-and-spill” process (Spence and Woo, 2003; Woo and Marsh, 2005). Due to bedrock's low water storage capacity, rock outcrops are runoff generators (Woo et al., 2008). Water that runs off bedrock outcrops collects in valley bottoms until the valley storage capacity is met, at which point basin runoff flows into the next valley or lake. Permafrost in the Taiga Shield generally does not occur beneath exposed bedrock and has only been observed in the bedrock where it is covered by overburden and organic matter (Brown, 1973; Zhang et al., 2014). Permafrost presence is closely tied to black spruce forests underlain by fine-grained silts and clays and black spruce peatlands to a lesser extent (Morse et al., 2016, 2015).

Table 2. Level III ecoregions, permafrost features, and landforms for the transboundary region (Bradley et al., 1982; Ecosystem Classification Group, 2008a, 2009; Strong and Leggat, 1992). Refer to Glossary of Terms for definitions.

NT Level III Ecoregion	Transboundary Basins	Characteristic permafrost features and landforms
Taiga Plains Mid-Boreal	Slave River, Little Buffalo River, Buffalo River, Northern portion of Hay River, Kakisa, Liard River lowlands	• Thermokarst lakes and bogs common. • Localized peat plateaus with permafrost >60 cm depth and large collapse scars. • No polygonal peat plateaus, patterned ground, or runnels. • Peat plateaus, palsas, northern ribbed fens, and horizontal fens.
Taiga Plains High Boreal	Liard River uplands	• Organic landforms uncommon due to hummocky/rolling terrain. • Peat plateaus are the most common permafrost form. • Weakly developed polygonal peat plateaus. • Peat palsas, northern ribbed fens, and horizontal fens, some earth hummocks.
Taiga Shield Mid-Boreal	Western edge of Taltson River	• Peat plateaus within and between bedrock exposures with permafrost >60 cm depth and large collapse scars. • No polygonal peat plateaus or patterned ground. • Peat plateaus, palsas, floating fens and shore fens.

Taiga Shield High Boreal	Central Taltson River	• Organic landforms uncommon due to hummocky/rolling bedrock or bouldery till terrain. • Segregated ice crystals, vein ice, and ice lenses. • Medium to high ice content. • No polygonal peat plateaus or patterned ground. • Peat plateaus, peat palsas, floating fens and shore fens.
Taiga Shield Low Subarctic	Eastern edge of Taltson River	• Organic landforms uncommon due to hummocky/rolling bedrock or bouldery till terrain. • Peat plateaus are most common, palsas are rare. • Segregated ice crystals, vein ice, and ice lenses. • Medium to high ice content. • Shore fens and floating fens less extensive.

4 Permafrost Characterization

4.1 Permafrost Extent

Permafrost extent in the transboundary region is generally discontinuous to isolated (Brown et al., 1997). Along the AB-NT boundary, permafrost extent follows a typical continental Arctic trend of increasing coverage moving northward (Figure 5). Shallow ground temperatures are generally related to mean annual air temperature (MAAT), where near-surface ground temperatures (within the top meter) are usually 2–4 ºC warmer than air temperature depending on landcover type (Burgess & Smith, 2000). Permafrost is present throughout the entire transboundary region (Liard, Petitot, Buffalo, Little Buffalo, Slave, and Taltson River Basins), except for the Hay River basin's southern-most region (Figure 5a; Brown et al., 1997; Gruber, 2012). Continuous permafrost is only present in the Liard River basin's northern-most extent, with sporadic and discontinuous permafrost being predominant throughout the AB-NT boundary basins. Taltson River basin in the Taiga Shield is expected to have greater permafrost coverage than many of the basins directly along the AB-NT border (Brown et al., 1997; Obu et al., 2019).

Obu et al. (2019) have recently attempted to improve near-surface permafrost distribution estimates across the northern hemisphere at 1 km^2 resolution using an equilibrium state model, climate data, landcover classifications, and remotely-sensed land surface temperature records from 2000–2016 (Figure 5b). These recent estimates of permafrost extent for the transboundary area remain similar to those by Gruber (2012) that were based on MAAT and topography (not shown here). Permafrost extent by Obu et al. (2019) was generally overestimated relative to previous estimates (Brown et al., 1997), particularly in the peatlands of Petitot River, Kakisa River, and eastern Liard River basins. Obu et al. (2019) compared their predictions of mean annual ground temperatures (MAGT) to borehole temperatures along the Mackenzie Valley extending from the northwest corner of AB to just north of Norman Wells, NT (Figure A.1). Predictions of permafrost probabilities were over-estimated for nearly all boreholes along this transect. The sporadic permafrost zone of the Canadian subarctic also had the lowest model accuracies for Canada. The most widely used map of permafrost extent continues to be Brown et al. (1997), which was generated over two decades ago with relatively limited data.

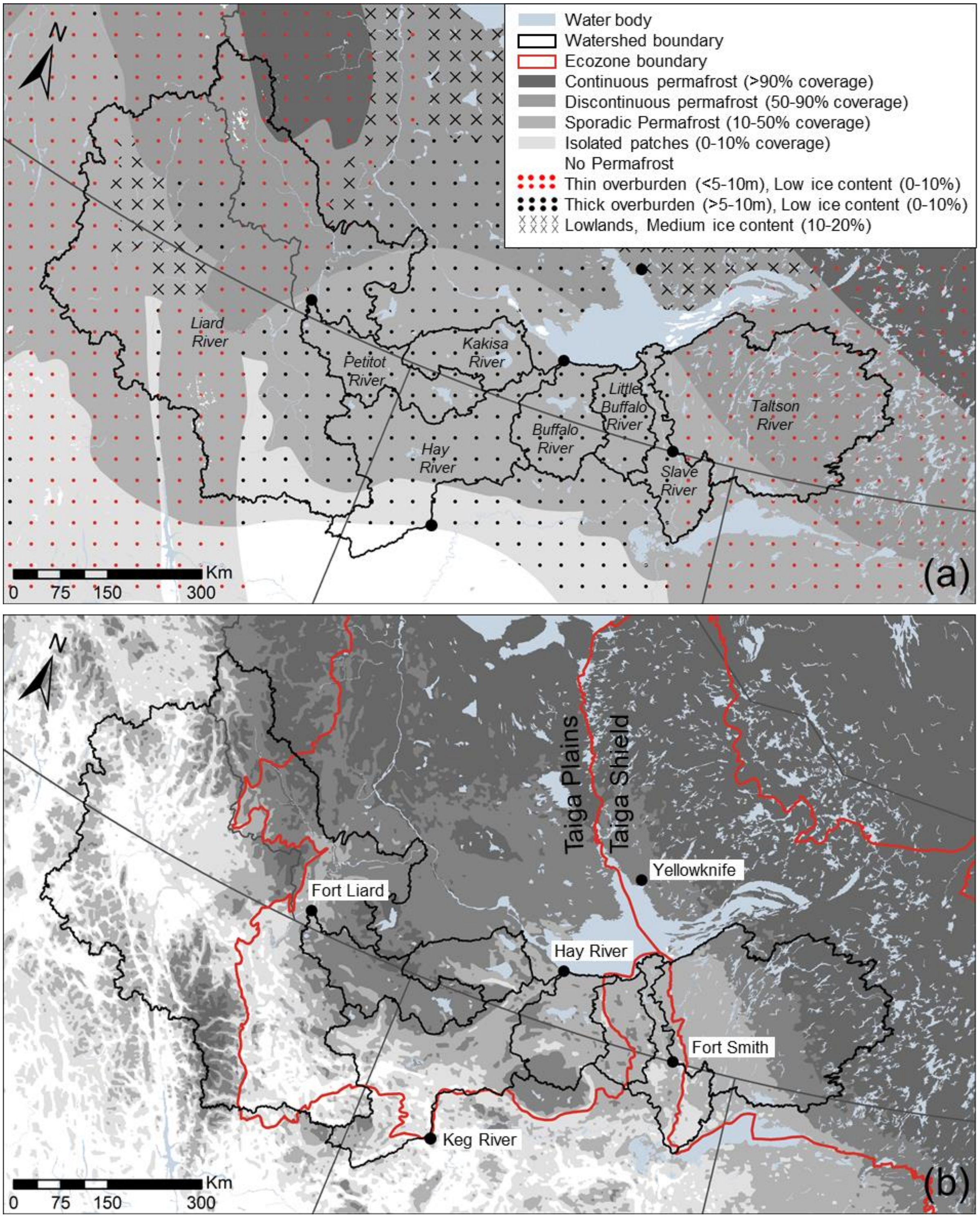

Figure 5. (a) Permafrost extent and relative abundance of ground ice by percent volume in the upper 20 m for the area of interest from Brown et al. (1997). Regions of thin overburden consist of exposed bedrock, mountains, highlands, ridges, and plateaus. Areas of thick overburden include lowlands, highlands, and intra- and intermontane depressions. Basemap data from Brown et al. (2002) (b) Permafrost extent data from Obu et al. (2019) and ecozone boundaries in the area of interest. Basemap data from Obu et al. (2018).

Up-to-date and accurate maps of permafrost probability are unavailable for the entire transboundary region. However, a permafrost probability model for northern Alberta at a 15 m resolution (Figure 6) was generated using machine learning methods, field observations, and a suite of predictors, including topography, satellite imagery, and climate data (Pawley and Utting, 2018). A preliminary permafrost probability map for the Taiga Plains portion of the transboundary region is currently in preparation by a mapping team at Wilfrid Laurier University (Carpino et al., in preparation). However, the map has not yet been field validated. No such probability map exists for the Taiga Shield transboundary region.

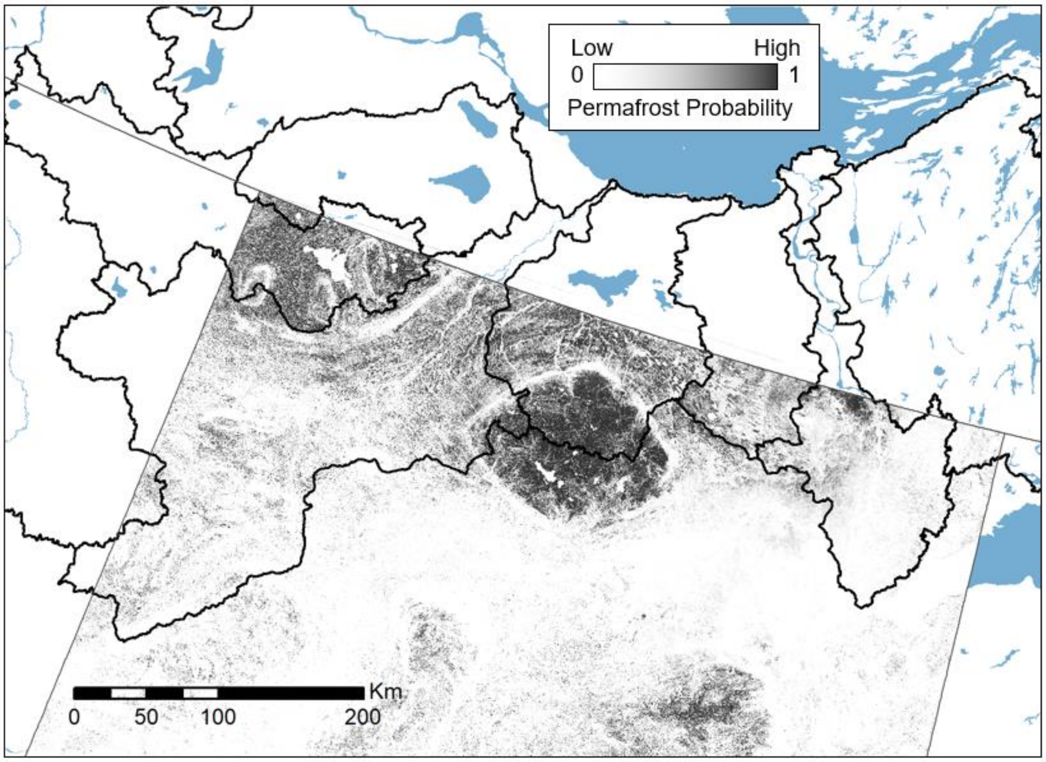

Figure 6. Probability of near-surface permafrost at a 15 m resolution (Pawley and Utting, 2018).

O'Neill et al. (2019) have made efforts to predict ground ice distribution (relict, segregated, and wedge ice) in northern Canada. In the transboundary region, excess ice in the top 5 m of the ground is generally limited to the northeastern portion of the Liard River basin, with low to negligible abundances found elsewhere (Figure 7). Both maps produced by Brown et al. (1997) and O'Neill et al. (2019) indicate relative abundance of ice is low (<10% by volume) throughout the transboundary region. The lowest ice contents are associated with Taiga Shield environments due to the prevalence of low moisture content fractured bedrock (Spence et al., 2014). Wolfe et al. (2021) compared modelled ground ice by O'Neill et al. (2019) to field observations across Canada, including at Scotty Creek, NT, and the North Slave lowlands near Yellowknife, NT. The authors suggest the modelled ground ice for Scotty Creek is reasonable, owing to segregated ice being limited to peat plateaus that cover 10–50% of the area. However, the model poorly represented segregated ice in the North Slave as the glaciolacustrine sediments associated with segregated ice were not mapped in this region. These sediments are less prevalent in the Taltson River basin (Ferbey et al., 2015), suggesting no or negligible ground ice is appropriate for this region.

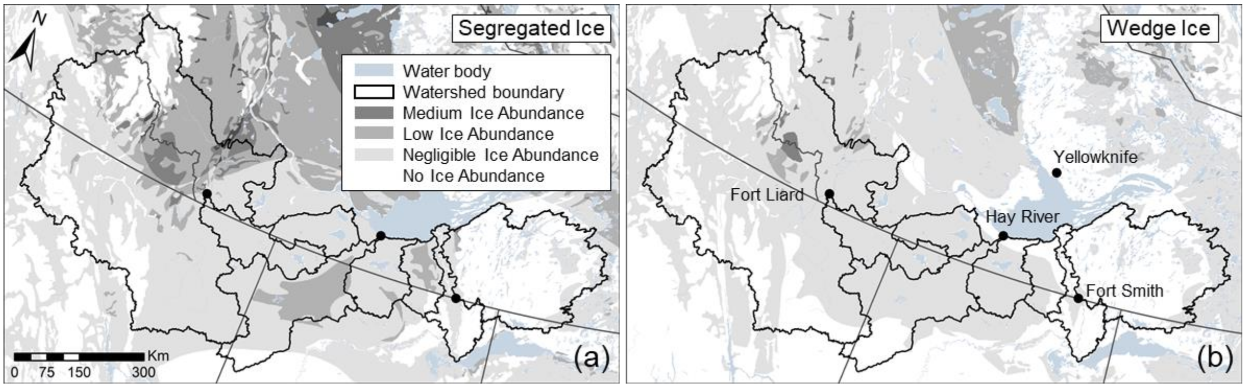

Figure 7. Spatial distribution of segregated ice abundance (a) and wedge ice abundance (b) as a percent of excess ice volume in the top 5 m of permafrost (O'Neill et al., 2019, 2020). Negligible = >0–2%, low ice = >2–5%, and medium = >5–10%.

4.2 Permafrost Distribution

Due to the insulative properties of peat, peatland distribution and MAAT have been used to estimate permafrost distribution across the Arctic. Frozen peatland extent was estimated by Tarnocai et al. (2011) and, most recently, Hugelius et al. (2020) (Figure 8). Estimates of areal coverage of permafrost peatlands by Tarnocai et al. (2011) are higher than Hugelius et al. (2020) for most of the transboundary region, except for the Taltson River basin. However, it should be noted that there is some overlap between the datasets used to generate both maps. Both estimates indicate that higher proportions of permafrost peatlands are expected in the Petitot, Kakisa, Little Buffalo, and Buffalo River basins relative to the other transboundary basins. Limited areal coverage of permafrost peatlands is anticipated in the southern extents of the Slave and Hay River basins (Figure 8).

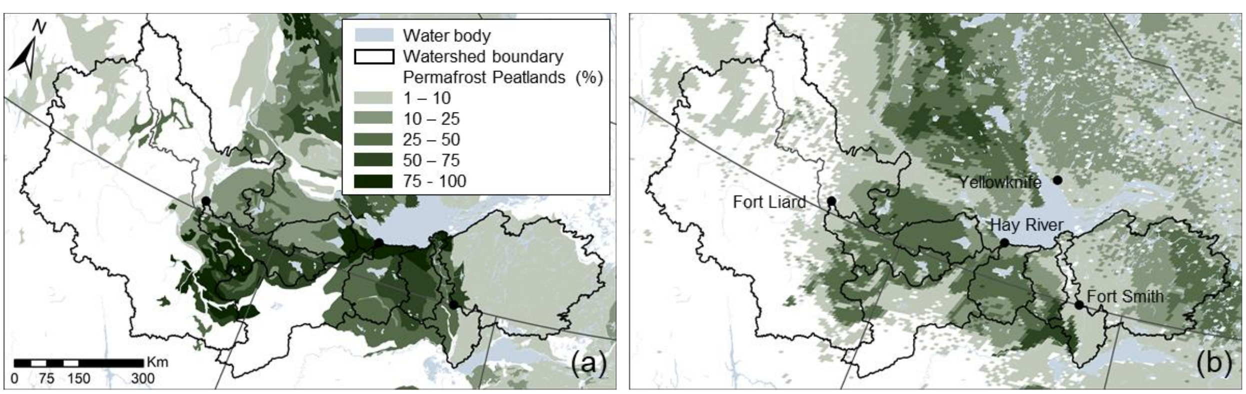

Figure 8. (a) Percent coverage of permafrost peatlands from Tarnocai et al. (2011) (b) Percent coverage of permafrost peatlands from Hugelius et al. (2020).

4.2.1 Taiga Plains

Maps of permafrost extent produced by Tarnocai et al. (2011) and Hugelius et al. (2020) were created at national and circumpolar spatial scales, respectively. Recent mapping by Gibson et al. (2020) generated estimates of permafrost peatlands at a regional scale for the Taiga Plains' NT-portion (Figure 9), which resulted in considerably lower estimates of permafrost peatland extent compared to the circumpolar-scale maps. Gibson et al. (2020) suggest differences between regional and circumpolar maps may be due to coarser-scale input data and the classification approach of low-lying organic-dominated terrain used to generate circumpolar maps. In contrast, Gibson et al. (2020) manually digitized the peatland area using satellite imagery and expert analysis. This study highlights that where spatially explicit information is needed for community use and planning, similar mapping methods as Gibson et al. (2020) should be employed. From maps produced by Gibson et al. (2020), the highest concentration of permafrost plateau-wetland complexes (76–100% areal coverage) in the transboundary area can be found along the AB-NT border in the Petitot, northern Hay, and Buffalo River basins. It should be noted that this mapping does not include permafrost occurrence outside of plateau-wetland complexes.

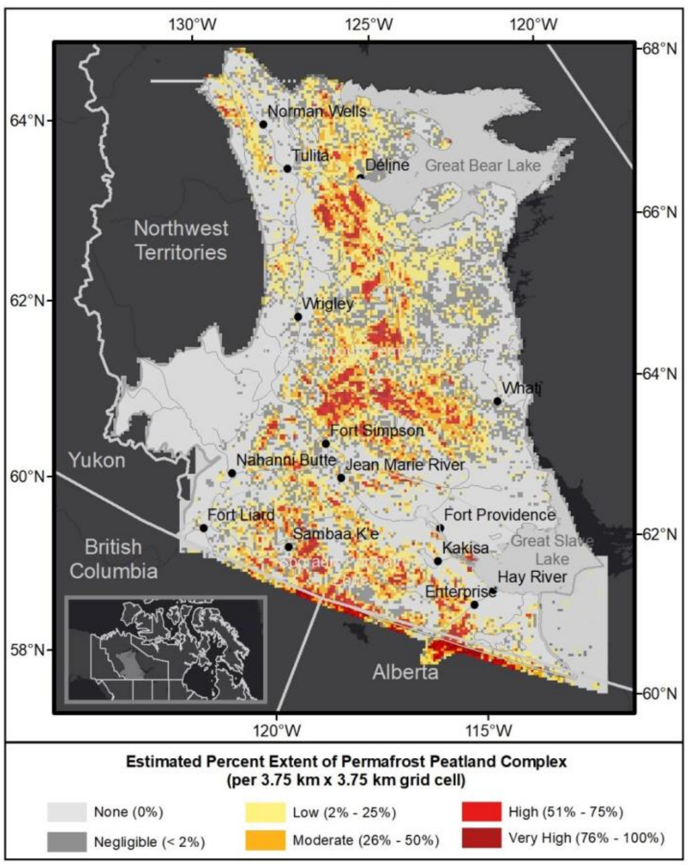

Figure 9. Estimated spatial extent of plateau-wetland complexes in the NT-portion of the Taiga Plains (Gibson et al., 2020).

Although permafrost is usually associated with peatlands, it is not constrained to this landcover type in discontinuous and sporadic permafrost terrains. For example, in the northern Hay River basin, Holloway and Lewkowicz (2020) found permafrost beneath low-lying forested areas of black spruce, jack pine, and tamarack stands with understoreys of mosses, lichen, and Labrador tea that form a thick organic layer. Generally, permafrost in the Taiga Plains is associated with fine-grained sediment (silts and clays) overlain by thick organic layers (>0.3 m), black spruce forest (*Picea mariana*), and relatively dry surface conditions absent of surface ponding (Aylsworth & Kettles, 2000; Burgess & Smith, 2000; Gibson et al., 2018; Holloway & Lewkowicz, 2020). Ground temperature envelopes near Fort Smith demonstrate how organic layers are the primary control on permafrost occurrence, followed by fine-grained substrate (Figure 10).

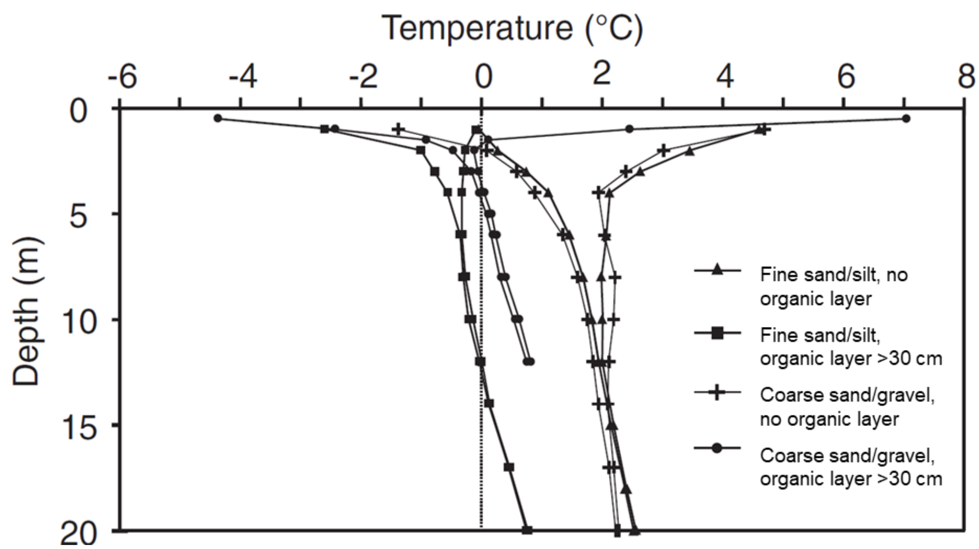

Figure 10. Ground temperature envelope in 1986 for several mineral soils near Fort Simpson (modified from Burgess & Smith (2000)).

Long-term monitoring (since the 1980s) of ground temperature in the transboundary region is concentrated along infrastructure corridors, resulting in large spatial and temporal data gaps. However, the available measurements show that permafrost present in the Taiga Plains portion of the study area is relatively thin (several meters) and warm (>-2 ºC) (Burgess and Smith, 2000; Smith et al., 2010). Smith et al. (2005) found that ground temperatures remained stable near 0℃ between 1987–2002 at 10 m depth near Fort Simpson (Manner's Creek) and at a peat plateau in the Petitot River basin. When this dataset was extended to 2008 by Smith et al. (2010), temperatures remained stable despite increases in air temperature over this period. These results, as well as more recent measurements of ground temperatures in the Taiga Plains at the freezing point, indicate that permafrost is undergoing internal thaw and is sensitive to land disturbances (e.g., Devoie et al., 2019; Holloway and Lewkowicz, 2020; Smith et al., 2010).

Along the Liard/Petitot River basin extending from northwest Alberta to Fort Simpson, permafrost ranges from 3–17 m thick with mean annual ground temperatures (MAGT) between -0.4 ºC to -0.1 ºC at depths of 4–6 m (GTN-P, 2016; Smith et al., 2013). Along the Hay River basin, permafrost thickness varies between 1.5–8.0 m, MAGT is >–0.2 ºC, and average permafrost table depths range from 0.4 m to >1.5 m (Brown, 1964; Holloway and Lewkowicz, 2020). It should be noted that these studies assumed the frost table depth was equal to the permafrost table depth in late summer (August and September). Permafrost and site characteristics for the Liard/Petitot and Hay Rivers basins have been summarized in Table B.1 and Table B.2 in the appendices.

In the Slave River basin, permafrost near Fort Smith, NT, has been observed at depths of 0.3–0.6 m below thick organic layers (McConnell, 1966). Pihlainen (1962) identified the presence of permafrost in Fort Resolution and Fort Smith but noted conflicting opinions for Fort Smith. Borehole drilling by Brown (1966) found no permafrost near the Fort Smith airport but stated that permafrost could be found in peat bogs in the Fort Smith area. Based on records from Uranium City, Saskatchewan, permafrost thickness in the northeast corner of AB is likely variable but may be up to 9 m thick with MAGT between –0.5 ºC and 0 ºC (Brown, 1960). More recent observations of permafrost occurrence in the Slave River basin are unavailable. Therefore, it is recommended that permafrost surveys be conducted in the Slave River basin to assess water resource vulnerability to permafrost thaw.

4.2.2 Taiga Shield

Regional-scale permafrost distribution maps, like those created by Gibson et al. (2020) (Figure 9), are not available for the Taiga Shield portion of the transboundary area. However, using field measurements, satellite imagery, and a process-based model, Zhang et al. (2014) estimated permafrost distribution in the Taiga Shield for the North Slave region near Yellowknife with 52% of the area covered by permafrost. It is recommended that similar mapping approaches as Gibson et al. (2020) and Zhang et al. (2014) be conducted for the Taiga Shield transboundary region to better assess the impacts of permafrost thaw on water resources.

Permafrost research and related studies in the Taiga Shield are generally limited to the North Slave region. As a result, there are significant data and knowledge gaps in the Taiga Shield portion of the transboundary region regarding permafrost research. However, the Taltson River basin is predominantly classified as the same ecoregion as North Slave, allowing for comparisons between the two regions. Permafrost is discontinuous throughout the North Slave region and is closely tied to forests (mainly black spruce) underlain by fine-grained silts and clays (Morse et al., 2016, 2015). Permafrost is also present beneath black spruce peatlands, but this land cover only comprises ~2% of the landcover in the North Slave lowlands (Morse et al., 2016). Transitions between frozen and unfrozen terrain can be abrupt and occur over short distances (on the order of meters) (Wolfe et al., 2011). Permafrost thickness ranges from a few meters up to 57 m with active layers between 0.3–3.0 m (Table 3; Brown, 1973; Karunaratne et al., 2008; Morse et al., 2016).

Since exposed bedrock is strongly coupled to surface temperatures (described in 2.2.3), bedrock outcrops generally do not contain permafrost in the North Slave region (Brown, 1973; Morse et al., 2016; Wolfe, 1998). Table 3 shows the wider range of ground temperatures in exposed bedrock and till compared to more insulative peat terrain. Bedrock permafrost in the Taiga Shield has only been observed where it is covered by overburden and/or organic matter (Brown, 1973; Zhang et al., 2014). As such, areas with more exposed bedrock, like the North Slave uplands, likely have lower permafrost extents (10–50% areal coverage) than the North Slave lowlands (Morse et al., 2016). Similar concepts of permafrost occurrence can likely be extended to the Taltson river basin.

Table 3. Summary of mean annual ground temperatures, active layer thicknesses, and permafrost thickness for different terrain in Yellowknife. Table reproduced from Wolfe (1998).

	Sedge Peat Temperature (ºC)			**Spruce Peat Temperature (ºC)**			**Beach Ridge Temperature (ºC)**			**Till Temperature (ºC)**			**Black Bedrock Temperature (ºC)**		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Surface	-4.2	2.9	-0.6	-9.2	3.7	-2.1	-4.2	5.8	0	-7.5	14	2.2	-10.8	14.6	1.0
5 m depth	-0.8	0	-0.4	-1.6	-0.7	-0.9	0.8	1.7	0.6	0	2.5	1.3	-4.2	6.7	0.9
10 m depth	-0.2	-0.2	-0.2	-0.8	-0.4	-0.6	0	1.2	0.8	0.8	1.7	1.2	0	2.1	1.1
Active Layer Thickness	0.68 m			0.30 m			-			-			-		
Permafrost thickness	30 m			50 m			No Permafrost			No Permafrost			No Permafrost		

More recent ground temperature measurements have been made by Morse et al. (2016) in the North Slave region (Table 4). The authors compared permafrost conditions beneath three "ecotopes": black spruce, white birch (*Betula papyrifera*), and black spruce peatlands. In this study, snow cover was regionally consistent, resulting in variation of permafrost temperatures being mainly controlled by the effects of latent heat during freezing. Other properties influencing permafrost temperature can include organic layer thickness, ALT, and soil moisture. Freeze-back periods (time for active layer freezing in winter) were shortest for black spruce forests with thinner and drier active layers than white birch forests and peatlands. Temperatures in peatlands were warmer than forested areas; however, the authors suggest that the ecosystem protection for permafrost in peatlands outweigh the latent heat effects and ecosystem protection of forested areas, leaving forested permafrost more vulnerable to degradation.

Table 4. Ranges of permafrost table depth, mean annual temperature at the top of permafrost (TTOP), depth of zero annual amplitude (DZAA), mean annual ground temperature at the DZAA, and depth to the permafrost base beneath different land covers in the North Slave region between 2010–2013. Summarized from Morse et al. (2016).

Forest Type	**Permafrost Table (m)**	**TTOP (ºC)**	**DZAA (m)**	**MAGT at DZAA (ºC)**	**Permafrost Base (m)**
Black Spruce	0.9 – 2.0	-2.91 – -0.44	2.9-7	-1.43 – -0.24	9.3 – 56.8
White Birch	0.8 – <3.3	-0.43 – -0.11	2.0-5.6	-0.97 – -0.12	8.8 – 23.9
Open Black Spruce Peatland	1.5 – <2.4	-0.09 – -0.02	1.5-6.0	-0.71 – -0.02	7.7 – 14.9

An investigation of peatland vegetation by Jasieniuk and Johnson (1982) is perhaps one of the only permafrost-related studies in the Taltson River basin. These authors found “permafrost” at depths of 0.3–0.4 m throughout July and August using coring methods. However, if seasonal thaw had not yet reached a maximum during this time, it is possible these authors instead measured the frost table, not the permafrost table. In this study, frozen ground in the summer months was only found beneath black spruce peatlands and, more commonly, in treeless peatlands. The stronger association between frozen ground and treeless peatlands was attributed to these areas being less susceptible to wildfire from a lack of fuel and bedrock/lake geometry, limiting the spread of fire.

4.3 Permafrost Landforms

The expansion caused by pore ice or segregated ice in layered peat can form a peat plateau that rises 0.5–2 m above neighboring unfrozen channel fens and flat bogs, as illustrated in Figure 11 (McClymont et al., 2013; Quinton et al., 2009; Woo, 2012; Zoltai and Tarnocai, 1974). Peat plateaus are the dominant permafrost landform in the transboundary region (Table 2; Gibson et al., 2021). These landforms are generally flat, ranging in size from tens to hundreds of meters, and are commonly covered in stands of black spruce (Figure 4a). Stratigraphy of the plateaus consists of a thick layer (1.5–8 m) of peat underlain by fine-grained, low permeability deposits (Aylsworth & Kettles, 2000; Quinton et al., 2019). Permafrost in the Scotty Creek (NWT) basin was found to be 5–13 m thick with near-vertical transitions adjacent to unfrozen wetlands (McClymont et al., 2013). Polygonal peat plateaus (crisscrossed trenches forming polygonal patterns approximately 15 m in diameter) rarely occur throughout the area of interest but have similar characteristics as peat plateaus (Zoltai and Tarnocai, 1974). Additional permafrost landform characteristics are summarized in Table 5.

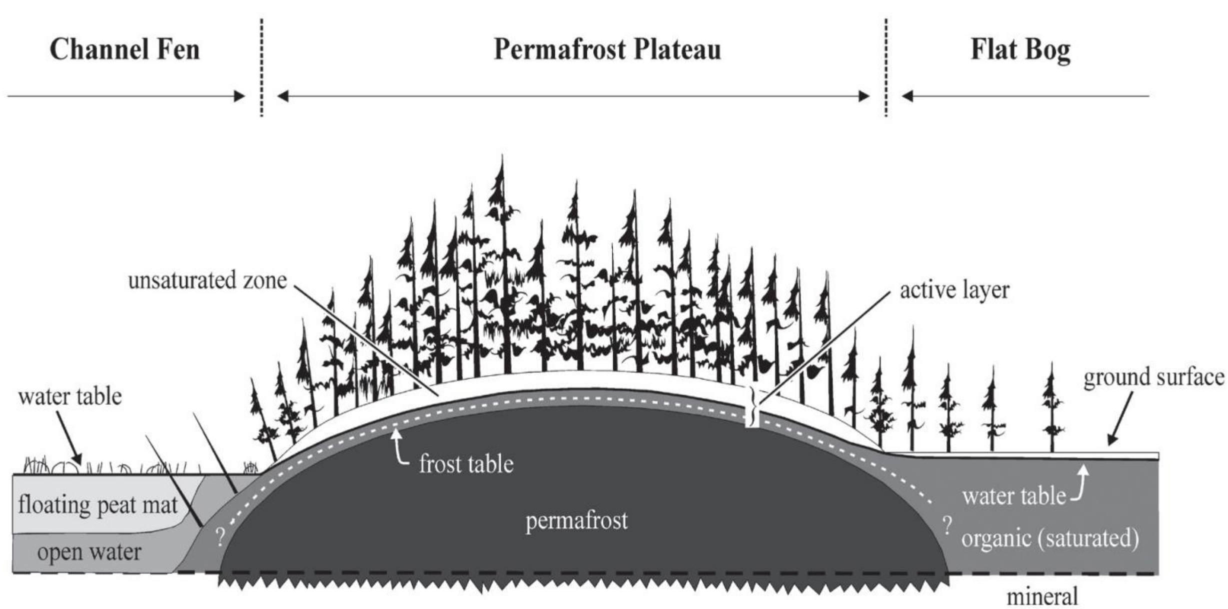

Figure 11. Cross-section of a peat plateau with neighboring channel fen and flat bog (Quinton et al., 2009).

Table 5. Characteristics of permafrost landforms found in the transboundary region in order from most common to least common.

Permafrost Landform	Stratigraphy	Active layer thickness	Permafrost thickness & temperature	Ice content (% by volume)	Segregated ice	Occurrence in area of interest
Peat Plateau (PP)	1.5–8.0 m of peat overlying fine-grained sediment[(1-4)]	0.3–1.3 m [(1,2,11)]	1.5–17 m [(4,10-12)] > −0.4 ºC [(10)]	Up to 80% in peat[(2)] Avg. 20% in mineral soil & peat[(2)]	Uncommon, up to 0.2 m lenses.[(1)] More common at peat-soil contact, up to 3 m thick.[(1,2)]	Most common[6-8]
Palsa	3.5–6.5 m of peat overlying fine-grained sediment[(1)]	Similar to PP[(1)]	Similar to PP[(1)]	Similar to PP[(1)]	< 0.35 m lenses, up to 1 m at peat-soil contact. Pure ice layers common in underlying mineral soil.[(1)]	Less common[7,8]
Polygonal Peat Plateau	0.9–3.6 m of peat overlying fine-grained sediment[(1)]	Similar to PP[(1)]	Similar to PP[(1)]	Similar to PP[(1)]	Wedge of pure ice extending 2-4 m in depth[(1)]	Rare[7-9]
Lithalsa[(5)]	10–15 m of silt and clay	0.9–1.3 m	5–10 m, ~ −0.8°C	50%	Horizontal lenses up to 10 cm thick	Uncertain

Sources: [1]Zoltai and Tarnocai (1974), [2]Aylsworth and Kettles (2000),[3]Quinton et al. (2019) [4]McClymont et al., 2013, [5]Wolfe et al. (2014), [6]Gibson et al. (2020), [7]Ecosystem Classification Group (2009), [8]Ecosystem Classification Group (2008a), [9]Wolfe et al. (2021), [(10)](Smith et al., 2013), [(11)]Holloway and Lewkowicz (2020), [(12)]Brown (1964)

Palsas are peat mounds with a permafrost core of alternating layers of segregated ice, peat, and/or mineral soil and have similar characteristics as peat plateaus (French, 2007; Table 5). The primary difference between a palsa and peat plateau is the growth process. For a peat plateau, segregated ice lenses may, or may not, extend downwards into underlying mineral soils, whereas ice segregation in the mineral soil is always the case for palsas (French, 2007). They can be found in the transboundary region but are less common than peat plateaus. Palsas in the southern Northwest Territories range in diameter from 10–30 m with heights up to 5 m (Zoltai and Tarnocai, 1974). They typically occur as islands in wet peatlands and have black spruce tree cover.

Lithalsas are permafrost mounds or ridges that form in warm discontinuous permafrost in mineral-rich soils and often adjacent to water bodies. In the Taiga Shield, lithalsas are 0.5–8.0 m tall and 10–120 m wide. In the North Slave region, these landforms are widespread within the fine-grained sediment of the Great Slave Lowlands but quickly decrease in occurrence throughout the Great Slave Uplands (Wolfe et al., 2014). The occurrence of lithalsas in the transboundary region is uncertain, but it is anticipated to be low. Suitable conditions for lithalsa formation may exist in the Taltson River basin's discontinuous permafrost, where fine-grained glaciolacustrine deposits are present but uncommon (Ferbey et al., 2015). However, this will depend on the thickness of organic soil horizons and groundwater supply for growth.

5 Permafrost Degradation

Permafrost temperatures nearing 0℃ in many locations in the transboundary area suggest that permafrost is currently undergoing thaw and/or is highly sensitive to changes in the ecosystem that allow permafrost to persist (Morse and Spence, 2017; Quinton et al., 2019). As such, disturbances such as wildfire, water table rise, windthrow, and road construction, that perturb the insulative peat layer or vegetative cover can initiate or accelerate permafrost thaw (e.g., Gibson et al., 2018; Vitt et al., 1994; Williams et al., 2013). Fens and bogs with internal lawns, dead trees, and collapse scars, as well as thermokarst lakes, have been used to indicate areas undergoing permafrost degradation (Gibson et al., 2021; Olefeldt et al., 2016; Quinton et al., 2019; Vitt et al., 1994; Zoltai and Tarnocai, 1974).

Recent mapping of thermokarst features in the Taiga Plains by Gibson et al. (2020) indicates that permafrost plateau-wetland complexes have degraded by ~25–77% (total degradation based on the thermokarst area), for latitudes of 60–62°. Lower degradation was associated with higher elevation sites, which should be considered when assessing future thaw rates in the transboundary region. Most plateau-wetland complexes exhibited a high (67–100%) degree of degradation in the transboundary area based on the area covered by thermokarst bogs (Figure 12; Gibson et al., 2020). The authors suggest that most permafrost in the discontinuous zone of the NT will completely disappear by 2100. Although northern AB peatlands were not included in the study by Gibson et al. (2020), a strong latitudinal trend suggests these peatlands have undergone similarly high degrees of degradation.

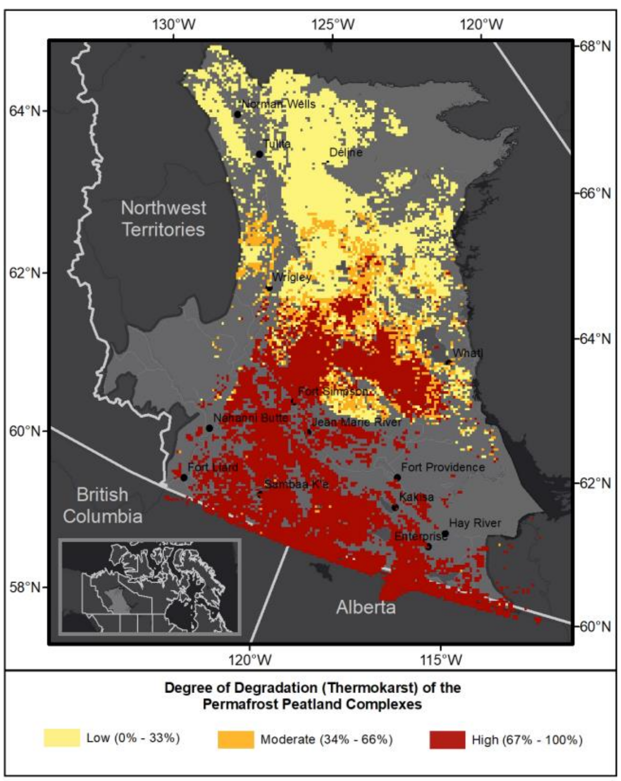

Figure 12. Estimated degree of degradation of permafrost peatland complexes in the Taiga Plains based on visual estimates associated with thermokarst (Gibson et al., 2020).

Permafrost investigations along the Mackenzie Highway, with sections running parallel to the Hay River, found isolated permafrost as far south as Keg River (Brown, 1964). Additional permafrost surveys by Kwong and Gan (1994) along this corridor (1988–1989) indicated the southern limit of isolated permafrost had migrated approximately 120 km northward within 26 years, and permafrost extent had decreased by 75%. However, Holloway & Lewkowicz (2020) conducted repeat surveys of permafrost and ALT from Brown (1964) and found only a 32% loss of permafrost. The authors argued their study was a more robust estimate of change than Kwong & Gan (1994) because they limited their observations to the same sites as Brown (1964). The sites south of Meander River that Brown (1964) identified as having permafrost did not have permafrost present in the 2017-18 surveys by Holloway & Lewkowicz (2020). This finding supports the concept of the southern extent of permafrost migrating northward.

In the Taiga Plains, Beilman & Robinson (2003) investigated permafrost thaw using aerial photographs in Mackenzie Valley and found the areal extent of peat plateaus along the Liard River had decreased by as much as 50% over 50 years (1% per year; 1950-2000; Table 6). Despite similar MAAT as the Liard River study sites, frost mounds in the Buffalo Head Hills, AB had only degraded 32% over a longer period of 100-150 years (~0.2-0.3% per year), indicating that permafrost landform differences may play a role in future permafrost degradation. This variability points to the spatial complexity in permafrost processes and predicting their change in the future. Similarly, permafrost peat plateaus at Scotty Creek (NT) have degraded by 38.5% between 1947 and 2008 (0.6% per year).

Table 6. Estimated permafrost degradation based on percent areal reduction in permafrost-dominated landcover within transboundary region or ecozones.

Approximate Location	Coordinates	MAAT (°C)	Landform or Landcover type	Permafrost Degradation	Time period
Taiga Plains					
Liard River, NT[1]	61.4°N, 121.8°W	-2.7	Peat plateau	34–51%	1947–2000
Buffalo Head Hills, AB[1]	57.9°N, 116.1°W	-2.7	Frost mound	32%	1900–2000
Trout Lake, NT[1]	60.5°N, 120.7°W	-2.0	Peat plateau	10–12%	1950–2000
Scotty Creek, NT[2]	61.3°N, 121.3°W	-2.8	Peat plateau	38.5%	1947–2008
Taiga Shield					
North Slave, NT[3]	62.8°N, 114.3°W	-4.1	Forests in bedrock terrain	~28%	1950–2009
Umiujaq, QC[4]	56.6°N, 76.5°W	-3	Lithalsas and thermokarst ponds	40%	1957–2005
Eastern coast of Hudson Bay, QC[5]	56.2°N, 75.9°W	-3	Peatlands (palsas, collapse scars, thermokarst ponds)	84%	1957–2003

Sources: [1]Beilman & Robinson (2003), [2]Quinton et al. (2011), [3]Zhang et al. (2014), [4]Fortier and Aubé-Maurice (2008), [5]Payette et al. (2004)

Estimations of permafrost degradation for the transboundary region in the Taiga Shield are unavailable. For other regions in the Taiga Shield ecozone, such as the North Slave, Zhang et al. (2014) estimated permafrost degradation of ~28% (~0.5% per year; 1950–2009; Table 6). The Taiga Shield also extends into northern Quebec along the eastern coast of Hudsons Bay. Fortier and Aubé-Maurice (2008) estimated permafrost degradation of 40% (0.8% per year; 1957–2005) based on aerial and satellite photographs. In the same region, Payette et al. (2004) used aerial photographs to assess permafrost degradation in peatlands between 1957–2003. These authors estimated permafrost degradation of 84% over the study period with accelerating rates of degradation from 1957–1983 (2.5% per year), 1983–1993 (2.8% per year), and 1993–2003 (5.3% per year).

5.1 Climate Change

Warming under climate change and associated changes in precipitation have implications on the rates of permafrost thaw that can be expected by the end of the century. Historical and projected annual temperature, snow depth, and daily summer precipitation for Hay River and Fort Liard have been extracted from global climate model scenarios (Environment and Climate Change Canada, 2018) and presented in Figure 13. Projections are based on the average (50th percentile) of an ensemble of twenty-nine Coupled Model Intercomparison Project Phase 5 (CMIP5) global climate models. Three emission scenarios were considered: (i) high emission scenario (RCP8.5) with average global warming of 3.2 to 5.4°C by 2090; (ii) medium emission scenario (RCP4.5) with average global warming of 1.7 to 3.2°C by 2090; and (iii) low emission scenario (RCP2.6) with average warming of 0.9 to 2.3°C by 2090. Implications of these climate projections on permafrost conditions in the transboundary region are discussed below.

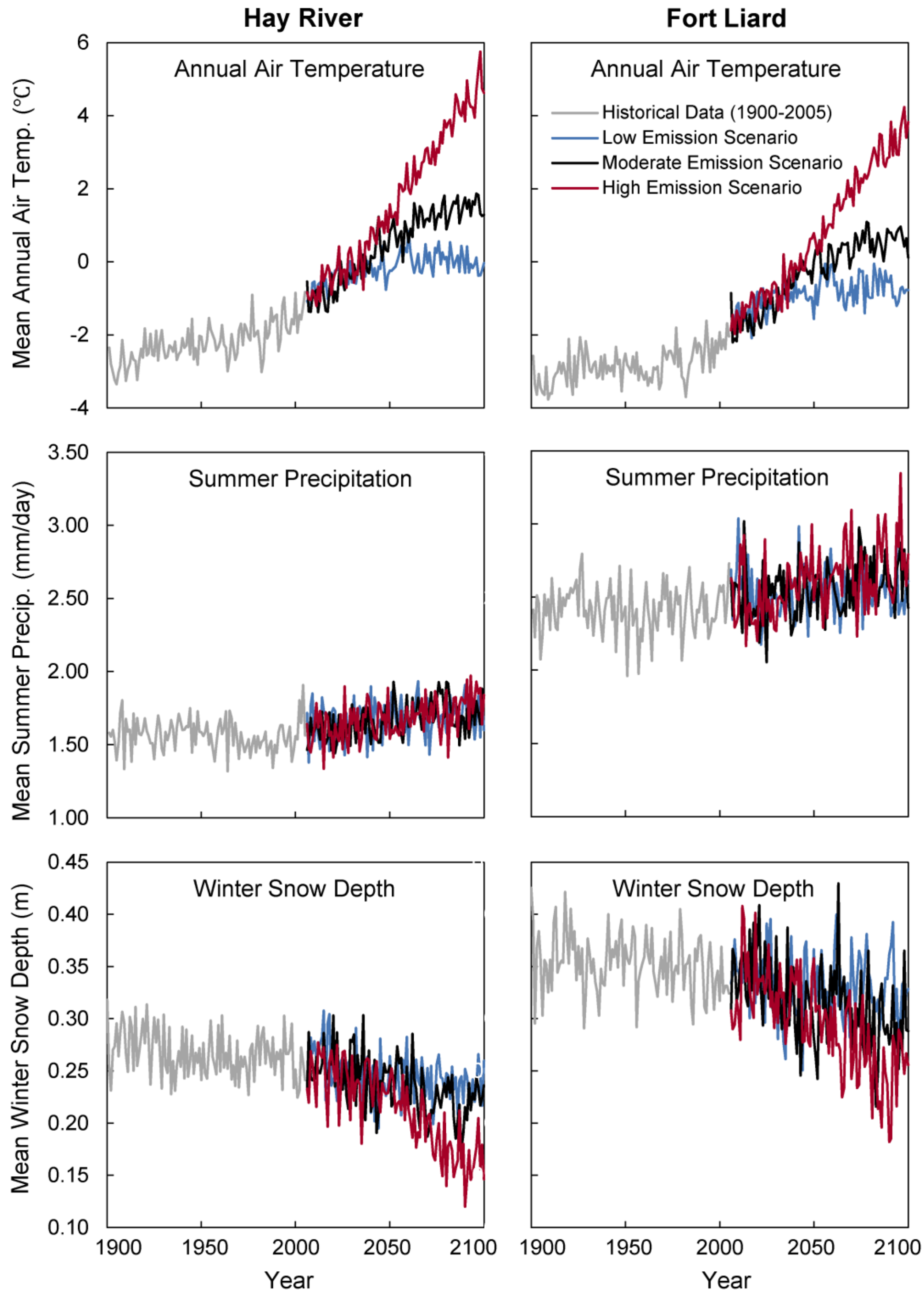

Figure 13. Historical and projected percent change in annual temperature, summer precipitation, and annual snow depth for Hay River and Fort Liard with respect to the reference period 1986-2005. Summer refers to the months of June to August. Data were retrieved from Environment and Climate Change Canada (2018).

5.1.1 Temperature

The study area is undergoing warming at twice the global rate (Vincent et al., 2015). Historical records in the transboundary area indicate that air temperatures have been increasing at a rate between 0.25–0.41°C /decade (Figure 14). Climate projections for the study area indicate this rate of warming is likely to continue until about 2050 (Figure 13). Under the low emission scenario (RCP 2.6), temperature increases may plateau after the year 2050. However, under the high emission scenario (RCP 8.5), places like Hay River could have MAATs up to 5.7°C by 2100 (Figure 13). As the climate warms, more heat is driven into the ground through conduction, leading to increases in permafrost temperature (Biskaborn et al., 2019) and widespread losses of near-surface permafrost (Koven et al., 2013; Pastick et al., 2015; Slater and Lawrence, 2013). Climate warming since the 1950s has resulted in accelerated permafrost degradation in peatlands in central Canada, leading to predictions of complete permafrost loss in sporadic permafrost zone by 2100 (Camill, 2005; Gibson et al., 2021). The permafrost degradation observed for the transboundary region in the Taiga Plains has largely been attributed to rises in MAAT (Holloway and Lewkowicz, 2020; Kwong and Gan, 1994).

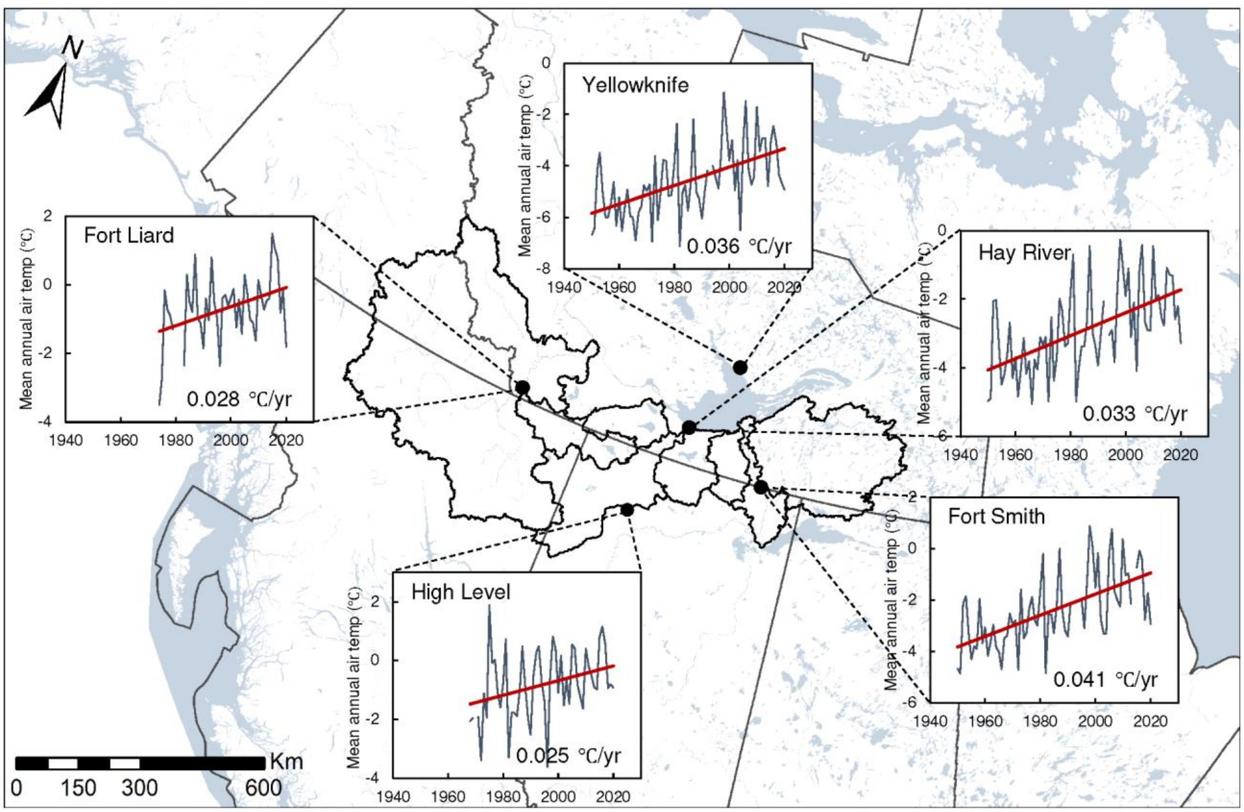

Figure 14. MAAT and linear trends within the transboundary region. Historical data from Environment and Climate Change Canada (2020).

Long-term climate predictions of increasing air temperatures into the end of the 21st century will almost certainly lead to widespread permafrost degradation (IPCC, 2019). However, short-term climate variations (years to decades) can be buffered by a vegetative cover and soil properties, as they govern the rate of heat propagation into the subsurface. The spatial variability and degree of degradation can also vary depending on the subsurface thermal regime and latent heat effects. These factors make it challenging to predict patterns and rates of permafrost thaw across scales and timeframes.

Morse et al., 2016 suggest permafrost in the fine-grained sediment beneath forests in the North Slave region (Taiga Shield) is presently ecosystem-protected by considerable latent heat effects (Section 2.2.5) and organic ground cover. The authors propose that although this protection may slow permafrost degradation beneath forests, it is still less effective at buffering climate warming than strongly ecosystem-protected peatlands. Since it is estimated that less than 2% of the North Slave area is covered by peatland, a considerable reduction in permafrost extent can be expected under climate warming (Morse et al., 2016). This concept was supported by permafrost and climate modelling in the North Slave conducted by Zhang et al. (2014). Authors projected that permafrost extent would decline to 12.4% by the 2050s and 2.5% by the 2090s, with permafrost extent likely only persisting within peatlands. However, the authors did not incorporate latent heat effects into the simulations, suggesting that permafrost may persist in fine-grained sediments for longer than Zhang et al. (2014) predicted. Simulations of permafrost thaw in bedrock by Kukkonen and Šafanda (2001) indicate that bedrock with higher porosities (even 5% porosity) can better attenuate the effects of climate warming on permafrost thaw due to increases in bulk heat capacity of the rock. These authors found that the permafrost in lower porosity bedrock, like the bedrock in the Taiga Shield, is expected to thaw by the end of this century. However, weathering of bedrock and secondary porosity from fractures/faulting can increase total porosity, which could slow permafrost thaw.

5.1.2 Rainfall

In the study region, summer precipitation is projected to increase by 10–20% in every emission scenario, with high interannual variability (Figure 13). Changes in summer rainfall can impact rates of permafrost thaw (Beel et al., 2021; Douglas et al., 2020; van Huissteden, 2020) because moisture content affects the thermal conductivity of soils, particularly peat (Section 2.2.3). For example, drier summer conditions were associated with anomalous decreases in ALT in the upper Mackenzie Valley (Park et al., 2013). Douglas et al. (2020) also demonstrated that regardless of landcover, increases in summer rainfall drive the deepening of active layers and enhances permafrost thaw. The authors suggested this was due to advective heat from warm summer rain and upslope subsurface runoff. Additionally, end-of-summer frost depths for peat plateaus and palsas are deepest in years with greater precipitation (Seppälä, 2011; Wright et al., 2009), as saturated peat in summer can transfer more heat to the frost table (van Huissteden, 2020; Walvoord and Kurylyk, 2016). If active layers in summer deepen to the point that supra-permafrost taliks begin to develop, freeze-back in winter will be inhibited, and permafrost thaw may be accelerated (Devoie et al., 2019). Summer rainfall may be a critical driver of this.

Douglas et al. (2020) proposed that the associated subsurface warming from anomalously wet summers likely lasts for multiple years. This effect is sustained as the highly saturated conditions can slow freeze-back in winter, limiting ground cooling and supporting warmer subsurface conditions for the following summer. Higher rainfall in late summer and autumn would likely exacerbate this, as freeze-back would be even further delayed. However, when frozen, saturated peat is the most effective at cooling the ground in winter (Woo, 2012). These opposing effects suggest a threshold for the timing and degree of saturation, resulting in effective heat loss in winter that protects permafrost or heat storage that subsequently thaws permafrost. This threshold is not well understood and requires further investigation.

5.1.3 Snowfall

The average annual snow depth in the study region is expected to decline by over 50% in the high emission scenario and 20–30% in the low emissions scenario by 2100 (Figure 13). The widespread warming of permafrost in the circumpolar discontinuous zone has been attributed to increases in snow depth due to insulation against winter heat loss (Biskaborn et al., 2019; Section 2.2.2). However, decreases in ALT in the Mackenzie Valley were observed between 1995–2006 (Park et al., 2013). The authors suggest that this was partly due to thinner snow cover promoting ground cooling. More importantly, reduced snowmelt from thinner snowpacks in early spring results in drier soil conditions, thereby insulating against warming temperatures. However, rising summer precipitation may combat this, resulting in a net-normal or possibly net increase in soil moisture.

Declines in snowpack may lead to increased ground cooling in winter, but the number of days with snow cover is also declining (Environment and Climate Change Canada, 2018). With longer snow-free seasons, the net effect of declining snow depths will likely increase ground warming. Carpino et al. (2018) also suggest that decreases in snowpack, increased rain-on-snow, and earlier spring melts observed from climate change will enhance permafrost thaw. This enhanced thaw may be driven by thinner snow depths that limit insulation from warming winter air temperatures.

5.2 Wildfire

Vegetative cover is critical for insulating the ground against high summer temperatures. Wildfires are increasing in frequency, severity, and magnitude in the northern hemisphere (Hanes et al., 2019; Jafarov et al., 2013; Wotton et al., 2017; Zhang et al., 2015). Wildfires result in the disturbance or removal of tree cover and organic layer horizons that act to filter radiative fluxes to the ground surface and insulate permafrost. Across most landscapes, increases in surface and soil temperatures have been observed immediately following wildfires and can persist for decades (Holloway et al., 2020). The degree of subsurface warming post-fire generally increases with burn intensity and can be similar in winter and summer (Smith et al., 2015). The poor drainage and high soil moisture content of lowlands result in lower burn severity than upland regions (Dillon et al., 2011).

When tree cover is removed by fire, snow accumulation and redistribution dynamics are altered. Reduced canopies lead to greater snow depths, wind-driven redistribution, compaction, and higher ablation rates in spring (Jafarov et al., 2013; Smith et al., 2015). Snow albedo is decreased by particulate carbon, and less protection from tree canopies increases solar radiation reaching the snow surface. In summer, increased soil albedo from charred debris and removal of insulative vegetative cover promotes surface and subsurface warming (Gibson et al., 2018; Smith et al., 2015). Higher albedo leads to rapid increases in ALT that continue for 5–10 years, after which recovery can occur (Holloway et al., 2020).

Conversely, persistent active layer increases can lead to the development of supra-permafrost taliks, which can accelerate and likely irreversibly thaw underlying permafrost (Devoie et al., 2019).

A comparison between burned and unburned basins in the Taiga Shield found greater ALTs, warmer soils in summer, and delayed winter freeze back in the burned basin (Spence et al., 2020). The authors also found that areas of the Shield with less forest cover and more exposed bedrock and lakes were more hydrologically resilient to forest fire, likely due to less combustible landcover and lower permafrost extent. In the Taiga Plains peatlands, Gibson et al. (2018) found ALT increases of more than 60% in recently burned sites compared to unburned peat plateaus. Over the last 30 years, talik extent also increased from 20% in unburned sites to 70–100% in burned sites. The greatest effects of wildfire on ALT and thaw rates were at recently burned sites, followed by 10–20-year-old burn sites, with no detectable effects at old burn sites. These results indicated that permafrost degradation within peat plateaus (i.e., the ALT increase) was reversible under the climate of the past 30 years but irreversible along plateau margins as they underwent complete landcover changes. However, under the current climate warming regime, permafrost recovery beneath burned sites may be limited or non-existent. Zhang et al. (2015) also found that for many burned sites in the peatlands and forests of the North Slave region, ALT does not recover from burns after 1990 due to climate change.

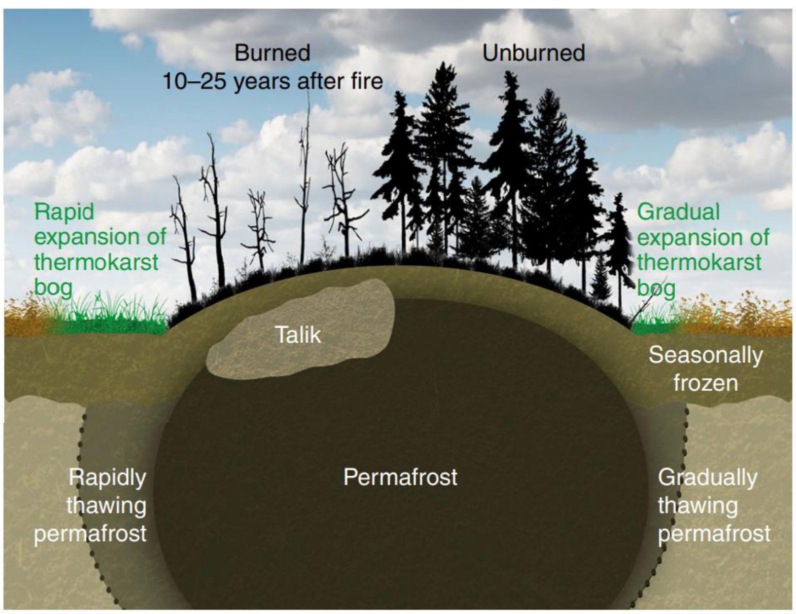

Figure 15. Illustration of the role of forest fire on the subsurface thermal regime in peat plateau complexes (Gibson et al., 2018).

In contrast to most studies, Holloway & Lewkowicz (2020) found that along the Mackenzie Highway (Hay River basin), permafrost persisted beneath most areas subjected to wildfire since 1962. Only two burned sites where organic layers were less than 25 cm had complete loss of permafrost. Areas with greater than 50 cm of organic matter had permafrost that persisted after being burned, mainly where *Sphagnum* moss was the organic cover since its thermal conductivity remains similar pre-and post-fire (Zhang et al., 2015). Holloway & Lewkowicz (2020) suggest that permafrost in forested areas of the transboundary region may be less sensitive to wildfires than the peatlands in the Liard River valley since the same rapid permafrost degradation described by Gibson et al., 2021, was not observed here. Differences may be driven by hydrological and ground ice conditions. However, when Zhang et al. (2015) modelled future permafrost extent for a region in the Taiga shield, just north of Yellowknife, the greatest reductions in permafrost extent occurred in forested areas (16%) followed by tundra and spruce-lichen bogs (10%), and fens (4%). Contradictory findings between modelling and field investigations in the transboundary study region may indicate key processes are missing from modelling tools, or there is a gap in knowledge between the wildfire responses of permafrost in the Taiga Shield and the Taiga Plains.

5.3 Human-induced Land Disturbance

It has been well documented that human-induced land disturbances such as roads, pipelines, communities, mines/gravel pits, oil and gas infrastructure, and seismic lines lead to enhanced permafrost thaw (Cao et al., 2016; de Grandpré et al., 2012; Huntington et al., 2007; Smith et al., 2008; Williams et al., 2013; Wolfe, 2015). Construction typically requires the removal of insulative vegetative cover and ground compaction, which leads to an increased moisture content that promotes permafrost degradation (de Grandpré et al., 2012; Wolfe, 2015). The placement of common fill material like sand and gravel for road construction or foundations is also more thermally conductive than the original vegetative substrate, increasing heat transfer and thaw rates (Goering, 2003). Where linear disturbances are compacted or paved, runoff can transport heat to the margins (Chen et al., 2020). This advective heat transport and the accumulation of snow (from road geometry and plowing) accelerates thaw at road shoulders. These changes can result in supra-permafrost groundwater flow that generates positive feedback and accelerates permafrost thaw (Braverman and Quinton, 2016; de Grandpré et al., 2012; Devoie et al., 2019).

Road density and maintained linear infrastructure in the Taiga Plains of the NT (i.e., main, winter roads, recreational roads, pipelines, and transmission lines) is 0.75 km/100 km^2 (Environment and Natural Resources, 2016). In the Taiga Shield, road density is 0.34 km/100 km^2, with most infrastructure associated with the Yellowknife region. Land clearing for seismic line surveys and winter roads used for mineral and oil/gas exploration has resulted in a network of 6–10 m wide lines across the study area (Environment and Natural Resources, 2016; Williams et al., 2013). Seismic lines cover at least 1900 km^2 of Alberta, with some of the highest densities (>2.0 km/km^2) concentrated in the peatland-rich Hay River (Figure A.4; Strack et al., 2019). The Liard River and Kakisa River basins additionally have high seismic line densities of 2.0-3.0 km/km^2 (Figure A.3 in appendices). Examples of this can be seen near the oil fields in northwestern AB (Figure 16) and near the Pine Point mine in the NT (Figure 17), which are both underlain by sporadic permafrost.

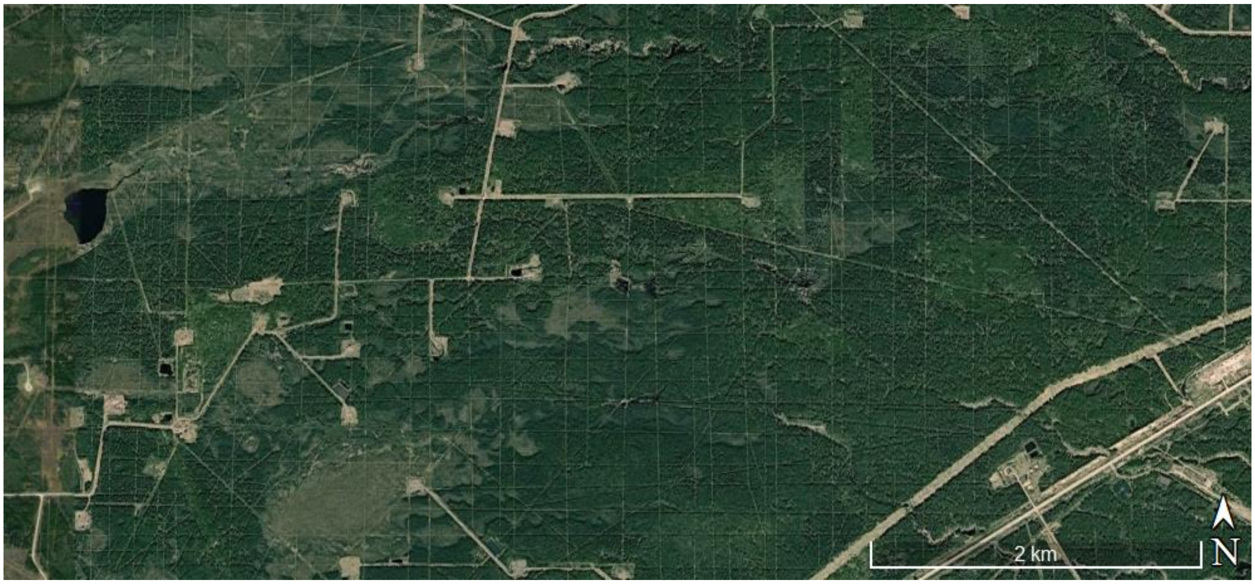

Figure 16. Land disturbance and clearing associated with oil and gas exploration and production in the Hay River basin near Rainbow Lake, AB which is underlain by sporadic permafrost (center coordinates: 58.566°, -119.103 °). Landsat imagery taken from Google Earth.

In the Liard River valley, seismic lines have led to permafrost degradation beneath the linear disturbance (Williams et al., 2013). Upon land clearing, solar filtration from the canopy is removed, which promotes ground heating. Initial ground displacement from construction promotes higher soil moisture contents and higher heat transfer rates from the surface. Surface and subsurface drainage are driven toward the depression, further increasing soil moisture and permafrost degradation (Williams et al., 2013). Hydrological connections between wetlands form with seismic line construction, developing taliks as perennial water conduits to promote further thaw (Braverman and Quinton, 2016). Where water tables are high, linear disturbances are converted to wetland landcover (Figure 17).

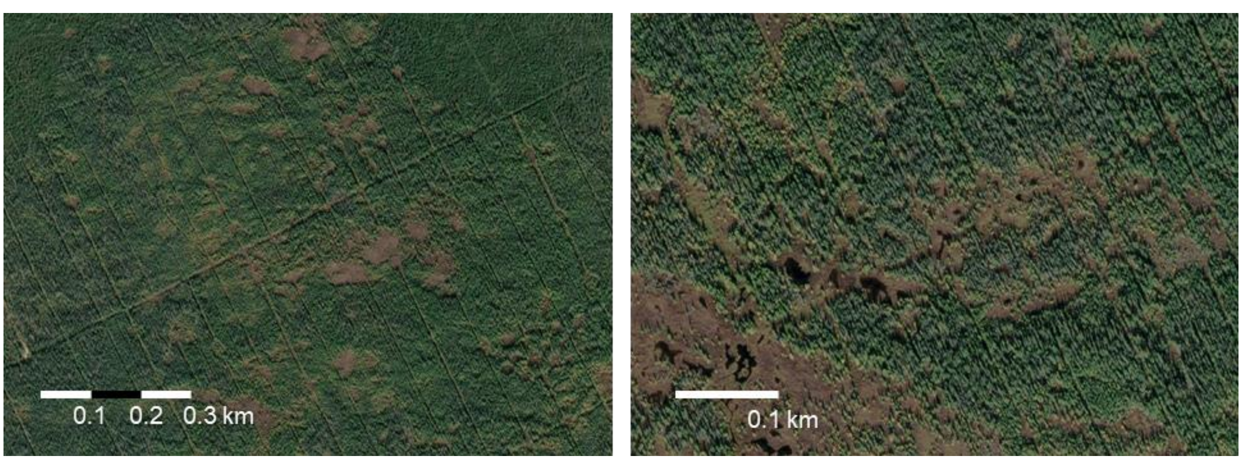

Figure 17. Examples of land clearing for seismic line surveys near Pine Point mine site (Buffalo River basin). Clearings now more closely resemble wetland cover (left: -114.760°, 60.796°) and coalesce with the wetland drainage network (right: -114.762°, 60.790°). ESRI Canada.

Longer-term studies (since the 1980s) of the impact of buried pipelines on permafrost thaw have been conducted for the Norman Wells to Zama pipeline corridor (e.g., Burgess & Smith, 2003; Smith et al., 2008; Smith & Riseborough, 2010). Along the Norman Wells corridor, ground temperatures are higher beneath land clearings than in undisturbed terrain. As a result, beneath the clearing, permafrost thaw exceeded 5 m, the ground surface subsided >2 m, and surface ponding occurred (Smith et al., 2008). Simulations by Smith & Riseborough (2010) indicate that for areas with warm and thin permafrost (MAGT >-1; 20m thick), the combined effect of land disturbances from buried pipelines and climate warming is predicted to completely degrade permafrost beneath linear disturbances in the next 20–40 years, with effects possibly extending beyond the clearing. The authors identified these disturbances as the primary driver of local permafrost thaw in the short-term (10–15 years), with climate change becoming more important over longer time scales.

6 Impacts of Thaw on Landcover and Hydrology

Permafrost degradation resulting from climate change, wildfire, or land disturbance can alter the thermo-hydrologic regime, which alters ecosystems and vegetative communities. Changes in landcover directly impact the hydrologic functioning of an area, leading to changes in the routing, storage, and connectivity of surface and subsurface waters (Quinton et al., 2011b). Considerable landcover changes have been observed in the peat-plateau and thermokarst bog landscapes common to the Taiga Plains (Gibson et al., 2021). The resulting hydrologic changes from this altered landcover have been investigated at length at Scotty Creek, NT, in the Liard River basin. Although much of this research has been conducted in the lower Liard River valley, concepts apply to the plateau-wetland complexes common throughout the Taiga Plains in southern NT (Gibson et al., 2021) and northern AB (Heffernan et al., 2020). As such, the Taiga Plains will be a large part of the discussion on the impacts of thaw on landcover and hydrology. Thaw-induced landcover and hydrologic changes to the Taiga Shield ecoregion remain poorly understood and are primarily hypothesized here based on similar environments.

6.1 Thaw-Induced Landcover Change

The presence of permafrost can support certain ecosystems by controlling soil temperature and moisture, rooting zones, and subsurface hydrology (Woo, 2012). Permafrost degradation results in changes to hydrothermal regimes (Jin et al., 2020), ground settlement or collapse, and inundation (Sannel and Kuhry, 2011; Vallée and Payette, 2007; Vitt et al., 1994). These changes impact the ability of vegetation to survive and can lead to the demise of one plant community and the emergence of another. For example, the black spruce forests in the Taiga Plains peatlands require relatively dry conditions for growth and will die when roots become waterlogged, which dramatically alters forested landcover to wetland (Quinton et al., 2011b). Widespread bedrock in the Taiga Shield likely means there will be relatively less dramatic landcover changes in this region. However, due to the relatively high abundance of lakes in this area, thaw-induced changes to lake levels may have implications for landcover. Where lakes expand in size, the coverage of certain vegetation can decline as tree roots become waterlogged (Quinton et al., 2019), or wetland vegetation can increase where lakes are shrinking (Sannel and Kuhry, 2011).

Permafrost thaw-induced landcover change and disturbances occur at a scale that can be seen in aerial photographs and satellite imagery. Remote sensing techniques have advanced significantly for estimating the occurrence of permafrost and rates of degradation (e.g., Nguyen et al., 2009; Nitze et al., 2018; Panda et al., 2010). A detailed discussion of such techniques is beyond the scope of this report; however, many of the thaw-induced landcover changes observed in the transboundary study area have been identified using remote sensing techniques. These include mapping thermokarst features associated with permafrost degradation in the peatlands of the Taiga Plains (Gibson et al., 2020; Gibson et al., 2021) and lake expansion or decline in the Taiga Shield (Carroll et al., 2011).

6.1.1 Peat Plateau Wetlands

In the Taiga Plains, permafrost degradation results in a transition from a landscape dominated by forested plateaus to one dominated by permafrost-free bogs and fens (Gibson et al., 2020; Quinton et al., 2011a). In the first stage of landscape transformation (Figure 18), increased surface warming results in forested plateaus with small supra-permafrost taliks (Carpino et al., 2021; Connon et al., 2018). Where there is a thinning of tree cover or a land disturbance in a forested plateau, a depression in the permafrost table can begin to form (Figure 18 II). Subsurface water will be driven toward these depressions, which increases heat transfer from the surface to the permafrost table and talik extent. The development of supra-permafrost taliks may also supply advective heat from adjacent surface waters (Connon et al., 2018; Kurylyk et al., 2016; Sjöberg et al., 2016). As this feedback continues, surface and subsurface heat transfer deepen the depression, further driving subsurface drainage and thinning tree cover. The result is a complete loss of permafrost and the formation of a collapsed bog (Figure 18 III; Chasmer et al., 2011b; Quinton et al., 2011). Supra-permafrost talik expansion along plateau margins (Baltzer et al., 2014; Connon et al., 2018) and lateral heat transfer from neighboring wetlands (Kurylyk et al., 2016) enhances degradation at the sides of permafrost landforms (Figure 11b). This heat transfer results in further collapse of plateau edges until surrounding isolated bogs coalesce, forming an interconnected network of bogs with peat plateau islands (Figure 18 IV; Chasmer & Hopkinson, 2017; Connon et al., 2015; Hayashi et al., 2011).

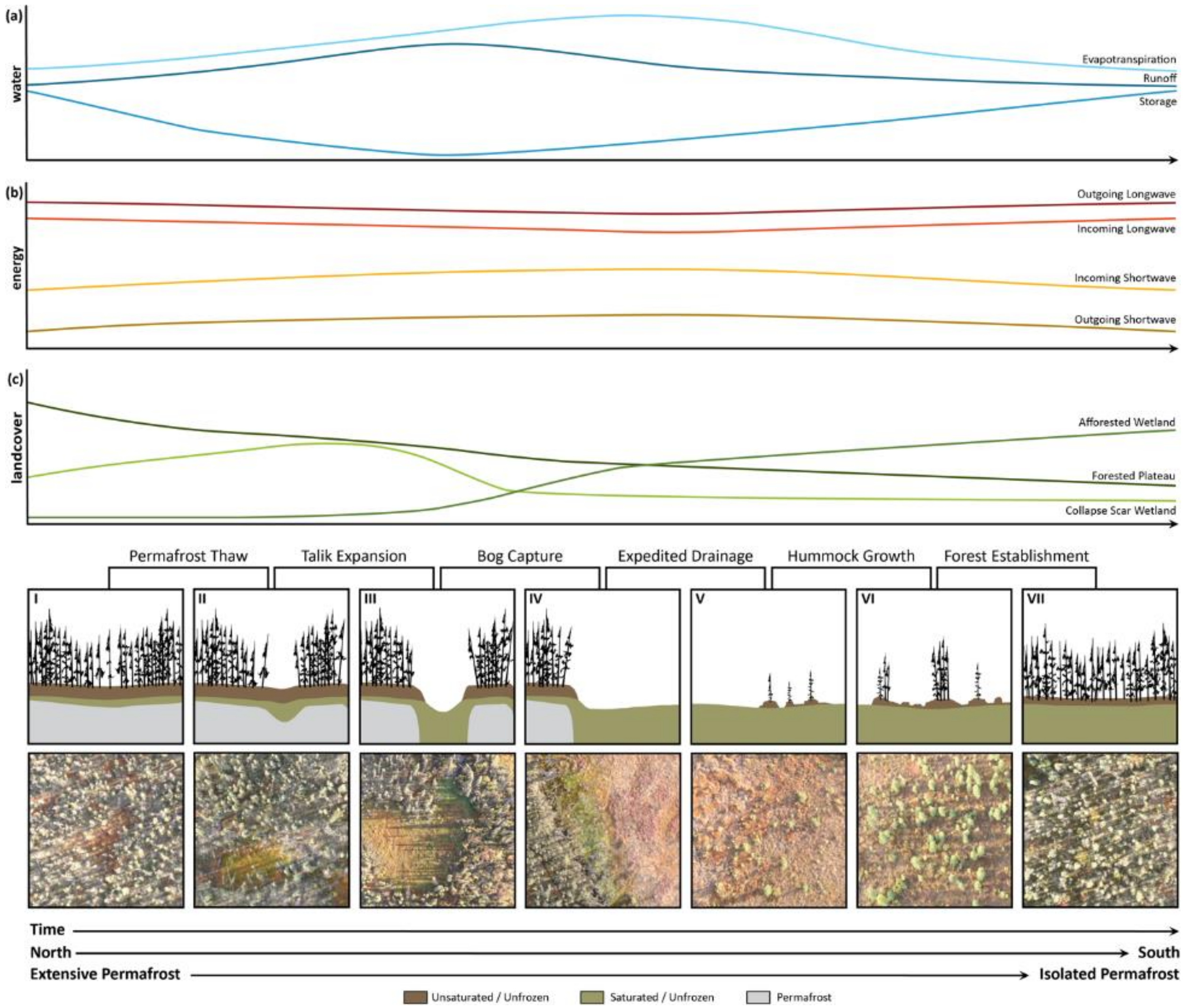

Figure 18. Conceptual framework by Carpino et al. (2021) of landscape trajectory (bottom) and associated relative changes in local water balances (a), local energy balances, (b) and landcover (c). Satellite images at different locations in the Scotty Creek basin, NT, are used as a proxy for changes in time.

Permafrost plateaus act as hydrologic barriers, where subsurface flow and connectivity are restricted. Upon removing these subsurface "dams" due to permafrost thaw, bogs that were once bound by permafrost become more connected to the drainage network (Connon et al., 2014). This interconnection promotes the drying of wetlands (Haynes et al., 2018), allowing hummock micro-topography to develop and the regeneration of trees (Figure 18 V; Haynes et al., 2020). Progressive drainage of wetlands supports further hummock growth and forest regeneration (Figure 18 VI) until the landscape converts back to extensive forest cover (Figure 18 VII; Carpino et al., 2021). Most recently, in the Taiga Plains, Dearborn and Baltzer (2021) found that despite black spruce forests declining from permafrost thaw, forest productivity is still increasing due to the new growth of tamarack trees (*Larix laricina*) despite being a non-dominant species.

The cycle of peat plateau and palsa collapse followed by forest regeneration has previously been described by Zoltai (1993) and occurs over approximately a 600-year period under a stable climate. In this model, forest regeneration is associated with the redevelopment of permafrost that provides conditions dry enough for tree growth. However, the unstable conditions of rising surface temperatures in the Taiga Plains (Figure 14) have likely resulted in the disruption of this cycle (Camill, 1999), where far greater permafrost degradation occurs than aggradation (Quinton et al., 2011a). Thus, Carpino et al. (2021) have suggested a conceptual model where the transition to forest cover is absent of underlying permafrost. The increases in forest cover observed in the southern extent of the sporadic-discontinuous zone (Carpino et al., 2018) further support this, in conjunction with the migration of the southern extent of permafrost (Holloway and Lewkowicz, 2020; Kwong and Gan, 1994). Since the timeframe of forest recovery does not depend on the relatively slow process of permafrost aggradation, the trajectory of forest regeneration following permafrost thaw may be on the scale of decades rather than centuries (Carpino et al., 2021).

Forest fires will likely accelerate this landscape transformation, as observed in the Liard River valley (Gibson et al., 2018). Land disturbances, such as land clearing for seismic line surveys and community infrastructure, also accelerate this transformation (Haynes et al., 2019). For example, the clearing of landcover for seismic line surveys and winter roads at Scotty Creek, NT, has led to thaw-induced ground subsidence, surface ponding, talik expansion, and the alteration of landcover to more closely resemble wetland features (Braverman and Quinton, 2016; Williams et al., 2013). Landcover alteration can also be seen near seismic lines and access roads for mineral exploration near Pine Point mine, NT (Figure 17).

6.1.2 Lake Environments

Drainage of thaw lakes has been recorded in Alaska, with surface water declines of ~30% since the 1950s (Hinkel et al., 2001; Riordan et al., 2006) and Central Siberia, with lakes >40 ha declining by ~10% (Smith et al., 2005). Decadal timeframes for drainage have been recorded in High Arctic ponds due to increased evaporation and warmer temperatures (Smol and Douglas, 2007), in contrast to so-called “catastrophic drainage” over 24-hour periods observed elsewhere. Catastrophic drainage has been attributed to high rainfall and snowmelt in early summer that degrades permafrost in lake shorelines and promotes ice-wedge thermo-erosion (Jones and Arp, 2015). In Western Siberia and Alaska, a mechanism has been described where large lakes act as a collecting funnel of water from surrounding smaller thermokarst lakes on a higher elevation gradient. Once the large lake acquires a critical mass of water, the lake bottom subsides due to widespread talik development, which triggers the drainage of the smaller adjacent lakes (Kirpotin et al., 2008; Yoshikawa and Hinzman, 2003).

Lake drainage and expansion can occur in tandem in the landscape. A study of peatland lakes in the Hudson Bay Lowlands, northern Sweden, and northeastern Russia found minimal changes in lake area at continuous permafrost sites (Sannel and Kuhry, 2011). However, they observed lake drainage, paludification, and expansion of small lakes in the sporadic permafrost sites. A decrease in lake extent was suggested to be driven by increased evapotranspiration, infilling with vegetation, or lateral drainage in surface channels. An increase in lake extent was connected to increased precipitation, frost heave resulting in damming, or shoreline erosion. When compared to catastrophic drainage described elsewhere, they suggested that drainage processes may be slower in peatlands (Sannel and Kuhry, 2011).

Using MODIS data, Carroll et al. (2011) estimated changes in surface water storage across northern Canada from 2000–2009. They found surface water gains in the Hay-Zama lakes area and a small reduction in the Kakisa basin (Figure 16). In the Mackenzie Wood Bison Sanctuary north of the transboundary region, remote sensing coupled with paleo-reconstruction showed lake expansion since the 1980s represented a net positive change in the water balance and resulted in flooding of essential bison habitat (Korosi et al., 2017). The observed lake expansion aligns with results from Caroll et al. (2011) (Figure 16). The primary factors leading to lake expansion were increased temperature and precipitation, while increased groundwater inputs from permafrost thaw were present, but not a predominant mechanism (Korosi et al., 2017).

No evidence of lake expansion (1950s–2012) was observed in remote sensing and paleo-reconstruction of two lakes in the Kakisa basin, although fen cover had significantly increased (Coleman et al., 2015). This long-term stability contrasts with lake area declines in the Kakisa basin observed by Caroll et al. (2011). As Kokelj and Jorgenson (2013) noted, fen infilling can be a major factor in lake shrinkage and complicate directional detection, which may be a driver for the lakes in the Kakisa basin. A mechanism for the expansion of lakes in the Hay-Zama lakes area was not described by Caroll et al. (2011), but Hay River inflow greatly influences the lake area and could be a driver of observed increases (Alberta Environment and Parks, 2007). Gains were particularly high for Zama Lake in 2007–2009 relative to 2000–2006 (Carroll et al., 2011), which were years of high water level for Hay River relative to historical averages (Environment Canada Historical Data).

Remote sensing analysis of net changes in surface water area across Canada between 2000–2009 shows net losses in the Taiga Shield (Figure 19; Carroll et al., 2011). Recent studies of lithalsa permafrost features in the Taiga Shield suggest that lithalsa thaw will expand the surface area of thermokarst ponds (Morse et al., 2019). An inventory of thermokarst ponds in the North Slave Upland and Lowland found that between 1945–2005, 3138 ponds expanded or developed (Morse et al., 2017). However, surface water area increased in only 3.75 km^2 of the 4348 km^2 study area due to the thermokarst pond's small size. Ponding was most common in the low elevation glaciolacustrine deposits within the North Slave Lowland (Morse et al., 2017). Observed lake declines in the Taiga Shield Low Subarctic ecoregion (Figure 19; Carroll et al., 2011) may relate to peatlands that cover 5-10% of the landscape (Ecosystem Classification Group, 2008b), or potential changes in lithalsas that may be present in glaciolacustrine sediments. A knowledge gap is thus present for the Taltson basin landscape trajectory.

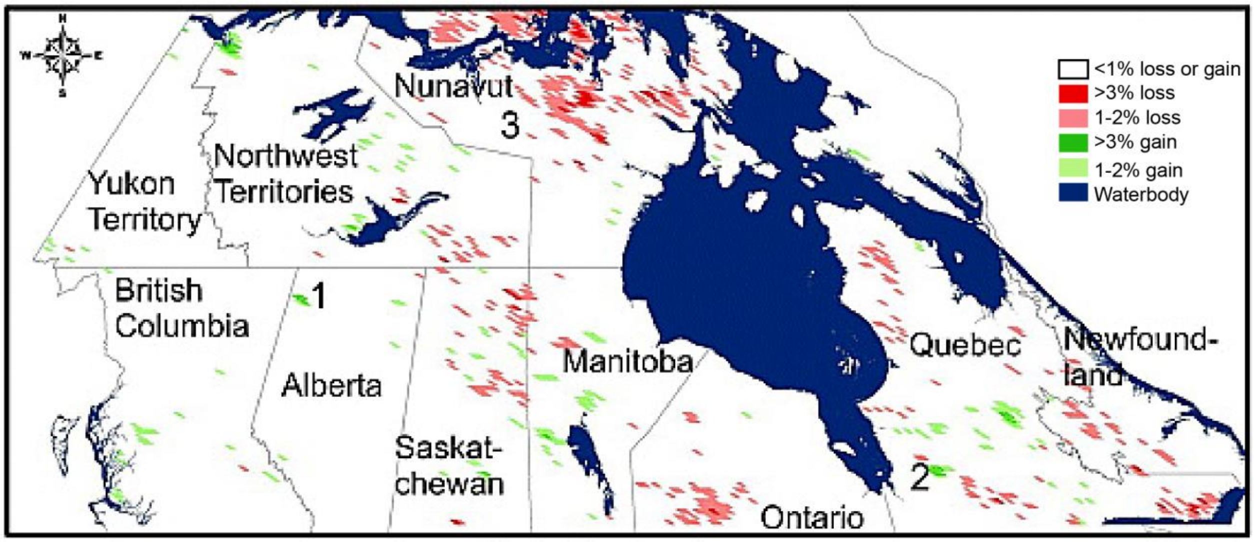

Figure 19. Net change in surface water per 23 km grid cell for Canada from 2000 to 2009. Area 1 shows net gain for Hay Lake, Area 2 shows net gain for man-made reservoir (LaGrande reservoir), Area 3 shows large areas of net loss in Nunavut (Carroll et al., 2011).

6.2 Thaw-Induced Changes to Hydrology

The thaw-induced landcover changes discussed have implications on the routing, storage, and connectivity of surface and subsurface water. Each landcover serves a particular hydrologic function, so when there is a shift away from one cover to another, there is a concurrent change in the hydrologic behavior of a basin. A recent review of thaw-induced hydrologic changes has been conducted by Walvoord & Kurylyk (2016). Permafrost thaw can result in changes to ALT, soil moisture, surface water-groundwater connectivity, streamflow discharge and seasonality, and surface and subsurface water storage. Many thaw-induced hydrologic changes have been observed over recent decades (full summary in Table B.3 in appendices). However, inadequate baseline and historical data continue to be a challenge in the study region and across the globe. There is a general lack of understanding of large-scale and long-term impacts, particularly in peatlands outside of the Liard River basin in western NT.

6.2.1 Active Layer Thickness

ALTs have been increasing in some regions of the circumpolar north and decreasing in others. For example, ALT has been increasing in subarctic Sweden (Åkerman and Johansson, 2008), Arctic Russia (Mazhitova et al., 2008), and eastern Siberia (Brutsaert and Hiyama, 2012). ALT in the Lower Mackenzie Valley increased between 1948–1995 but decreased between 1995–2006 due to declining snow cover (Park et al., 2013). As noted, ALT changes are highly dependent on the physical properties of the subsurface, short-term, local climate variations, and land disturbances, which make it challenging to make broad conclusions about ALT in a region.

The Circumpolar Active Layer Monitoring Network (CALM) is a program developed to observe changes in near-surface permafrost and active layers over multi-decadal time scales (Smith et al., 2009; Tarnocai et al., 2004). Data are available for the Mackenzie Valley but only extend as far south as Fort Simpson, NT.

Annual end-of-season thaw depths for Fort Simpson significantly increased between 1999–2015 (R=0.8, p<0.001) at a rate of 1.6 cm/year (Figure 20). At Scotty Creek, ALTs have increased over the past two decades (Quinton et al., 2019). Between 1993–2000, thaw depths along the banks of Manners Creek (61°46’N 121°12’W) also increased by up to 0.3 m (Nixon, 2000; Nixon et al., 2003).

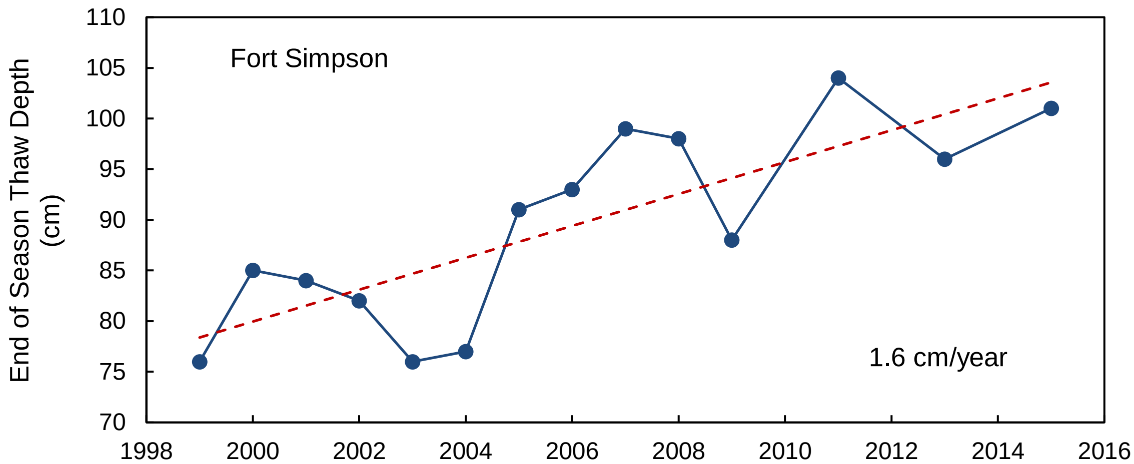

Figure 20. Monitoring of annual end-of-season thaw depth for Fort Simpson from 1999-2015 (CALM, 2020).

In contrast to the ALTs in the northeastern Liard basin, ALT in a peat plateau at Petitot River (59°45’N 119°31’W) exhibited no trend between 1988–2000 (Nixon et al., 2003). During this period, ALT fluctuated between 0.67–0.78 m with a mean of 0.71 m. The authors attributed this relative stability to insulation from the surface organic layer and forest cover. Along the Mackenzie Highway in the Hay River basin, ALT from 1962 to 2017/2018 exhibited little change except at some locations that had experienced fire (Holloway and Lewkowicz, 2020). Here, organic matter layers greater than 50 cm had maintained consistent ALTs at most revisited sites.

In the Taiga Shield, surface water inputs govern seasonal thaw depths of soils in bedrock basins (Guan et al., 2010a, 2010b). Wetter soils found in wetlands enhance conduction from surface and stream inflows, and runoff provides additional advective heat. Wetter areas also freeze more slowly in winter (Karunaratne et al., 2008), leading to warmer soil that is more susceptible to thaw. For drier soil-filled valleys, thaw depth is generally driven by surface conduction alone. There is a lack of knowledge regarding the trends in ALT for the Taiga Shield, especially where permafrost exists in bedrock. It is possible that where thick organic cover coincides with a fine-grained substrate, ALT has remained relatively stable over the past several decades, as observed in the Hay River basin (Holloway and Lewkowicz, 2020). Further investigation is required to assess changes in ALT in the Taiga Shield region.

6.2.2 Groundwater

Increases in ALT lead to the development of supra-permafrost taliks, a layer directly above permafrost that remains unfrozen year-round and permits supra-permafrost groundwater flow and storage (Figure 21; Walvoord & Kurylyk, 2016). As permafrost degrades, taliks expand and become increasingly coupled, creating effective heat and mass transfer pathways for warmer subsurface recharge and surface waters

(Figure 21b; Kurylyk et al., 2016). As noted in Section 5.1.2, late summer rainfall may enhance the development of near-surface taliks and increase hydrologic connectivity between terrestrial and aquatic environments (Beel et al., 2021; Douglas et al., 2020). At Scotty Creek, NT, permafrost underlying a talik has been found to degrade five times faster than permafrost without a talik, as it limits permafrost cooling in the winter (Connon et al., 2018). Wildfire or land disturbance generally enhances talik development and permafrost degradation (Gibson et al., 2018). Supra-permafrost groundwater flow can irreversibly thaw underlying permafrost (Devoie et al., 2019), leading to a positive feedback loop that intensifies summer thaw rates and increases winter groundwater contributions to rivers and streams (Connon et al., 2014).

Sub-permafrost groundwater flow can also occur in these environments (Figure 21). The thin (typically <10 m) and discontinuous nature of permafrost in the Taiga Plains (Section 4) results in numerous open taliks beneath water bodies and wetland features (bogs and fens) that allow for the exchange of supra- and sub-permafrost waters. Since much of the transboundary Taiga Plains is expected to be underlain by low permeability silts and clays with low vertical hydraulic gradients, sub-permafrost groundwater contributions through the mineral soil are anticipated to be relatively low (Hayashi et al., 2004a). Sub-permafrost groundwater flow can still occur within the shallow peat layers and in areas of higher permeability mineral soils, but further research is needed in this area to understand its impact on changing hydrologic systems. Similarly, in the Taiga Shield, the relatively shallow permafrost (<50 m) and abundance of lakes and permafrost-free bedrock outcrops likely result in a highly connected subsurface system. However, direct evidence of this is lacking.

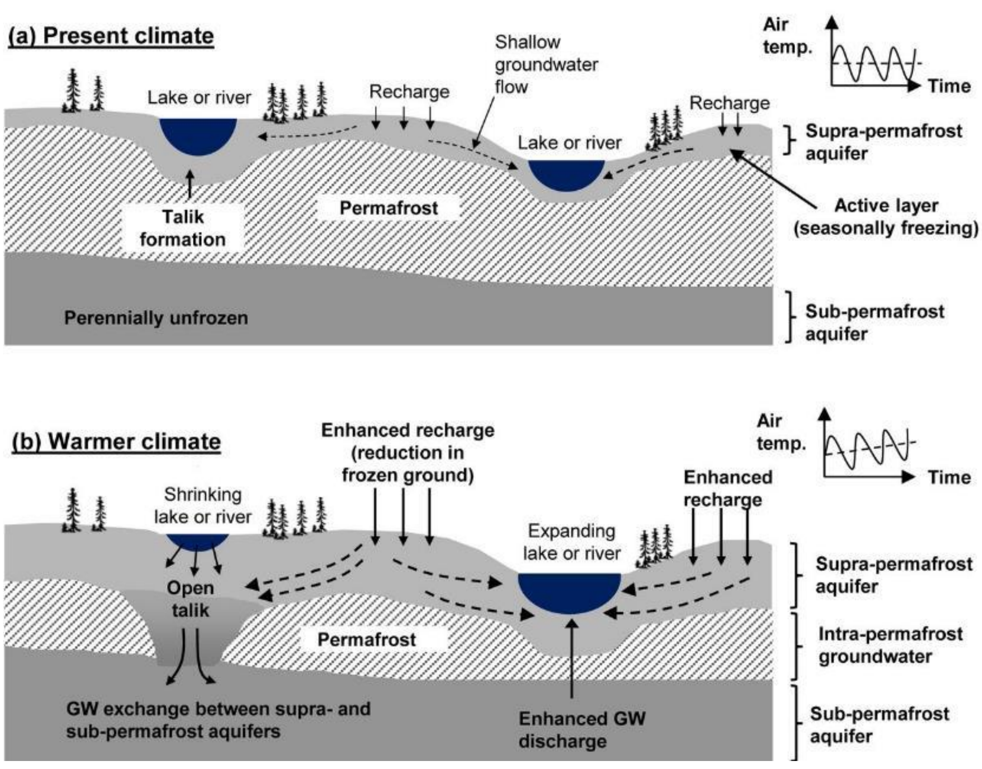

Figure 21. Changes in hydrogeologic conditions due to thaw displaying lake expansion and lake drainage trajectories (Walvoord and Kurylyk, 2016).

Permafrost thaw and changing landcover type can reduce shallow sub-surface runoff and increase groundwater recharge and storage (Figure 21; Lamontagne-Hallé et al., 2018; Walvoord & Kurylyk, 2016). However, the impacts of permafrost thaw and landcover changes on larger-scale groundwater systems throughout the transboundary region are not well understood. In the discontinuous permafrost zone in northern Quebec, complete loss of low-vegetation "permafrost mounds" result in increased vegetative landcover with time and a transition from grass and lichen to forest cover (Young et al., 2020). As a result of this landscape transition, shallow (<5 m) groundwater recharge increased beneath permafrost-free forested areas due to greater snow capture. Altered evapotranspiration rates from landcover changes can impact groundwater levels as well. For example, as temperatures increase and growing seasons become longer, it is expected that evapotranspiration rates will also increase for both the Taiga Plains and Shield (Bring et al., 2016), which could impact groundwater levels.

The presence of permafrost and associated interaction with groundwater is a considerable knowledge gap for most transboundary areas. In the Mackenzie Valley north of Fort Simpson, permafrost considerably impacts groundwater recharge but does not appear to influence where groundwater discharge occurs (Michel, 1986). In the Liard and Petitot River basins, groundwater monitoring is limited, and no longer-term records are available (Golder Associates, 2017). There are two longer-term groundwater monitoring locations in the Hay River basin which include a shallow (5.8 m) and deep (48.8 m) well near Zama and a deep (48.7 m) well near Meander River (Figure 22; Stantec, 2016). In the shallow aquifer near Zama City, groundwater levels between 1989 and 2005 are generally lower than between 2005 and 2019 (Figure 22a). The deeper Zama well has more data gaps but shows similar trends as the shallow well (not shown here), indicating changes are likely to propagate to deeper horizons. Although there are considerable gaps in the data, deep groundwater levels near Meander River generally exhibit little change from 1989–2019 (Figure 22b). Temporal variation near Zama may reflect changes in local permafrost extent, precipitation, or landcover, but records of change in this area are limited and require further investigation to determine the primary driver of groundwater changes.

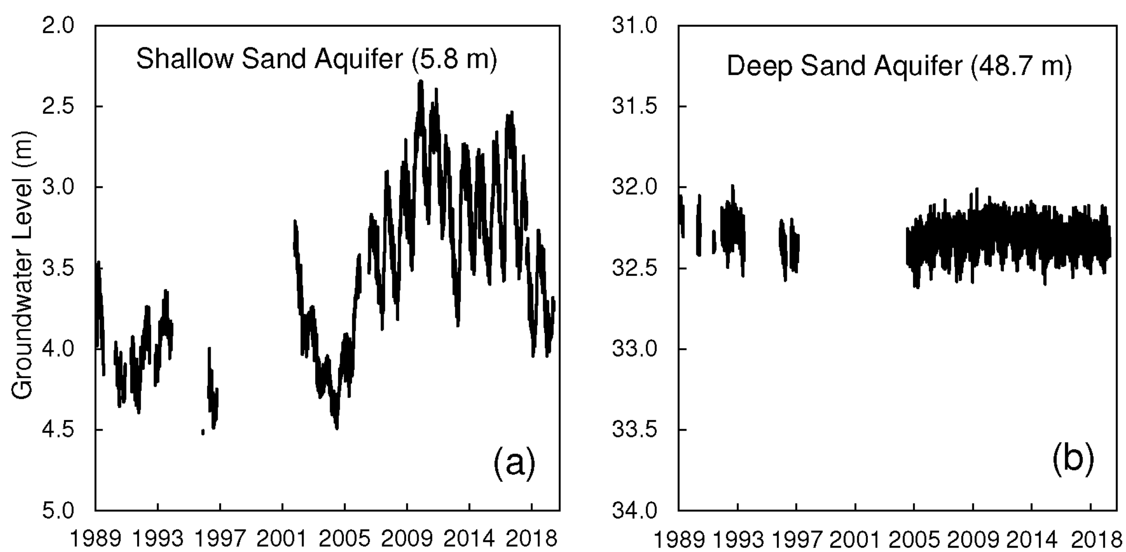

Figure 22. Groundwater levels in the Hay River basin from 1989 to 2019 for (a) a shallow (5.8 m) sand aquifer near Zama City, AB and (b) a deep (48.7 m) sand aquifer near Meander River, AB. Data from the Alberta Groundwater Observation Well Network (Government of Alberta, 2021a).

The role of permafrost on the hydrology and hydrogeology of the southern Taiga Shield is largely unknown due to the absence of both permafrost and groundwater monitoring in this region. Thus, thaw-induced impacts to the groundwater system are not well understood. However, permafrost hydrology and resulting impacts from permafrost thaw have been hypothesized by Morse & Spence (2017) for the Taiga Shield. The authors suggest that permafrost in the soil-filled bedrock valleys likely reduces groundwater storage capacity and promotes runoff. As permafrost thaws in valleys under warming conditions, groundwater recharge and storage will likely increase. Runoff from upland bedrock hillslopes may carry additional heat, further accelerating permafrost thaw (Guan et al., 2010).

In the Precambrian Shield, localized groundwater flow systems can occur through fracture networks and highly conductive fault zones that commonly underlie lakes (Woo, 2012). Morse & Spence (2017) suggest flow can also occur through taliks below lakes, but the configuration of these taliks is not well documented. Persistent permafrost thawing beneath soil-filled valleys and lakes may extend thaw into deeper bedrock permafrost. Thawing would lead to groundwater flow reactivation through deep fracture networks and fault zones (Morse & Spence, 2017; Rouse, 2000). However, evidence for this is lacking, and the resulting changes to larger-scale basin behaviour are unknown. Regional water tables in the surficial material and underlying bedrock are likely linked; however, they remain highly uncertain in this environment.

Hydrologic changes from climate-driven thaw in the Taiga Shield may be similar to the hydrologic effects of wildfires investigated in two Shield basins by Spence et al. (2020). Differences in annual streamflow between unburned and burned basins were insignificant. However, winter baseflow was higher in the previously burned basin, as evidenced by considerable icing (sheetlike masses of layered ice) at the stream outlet. Since icings form from groundwater discharge, these results suggested that the forest fire promoted talik development and increased hydrologic connectivity (Figure 23). Further investigation is needed to understand the thaw-induced hydrologic changes in the Taiga Shield transboundary region.

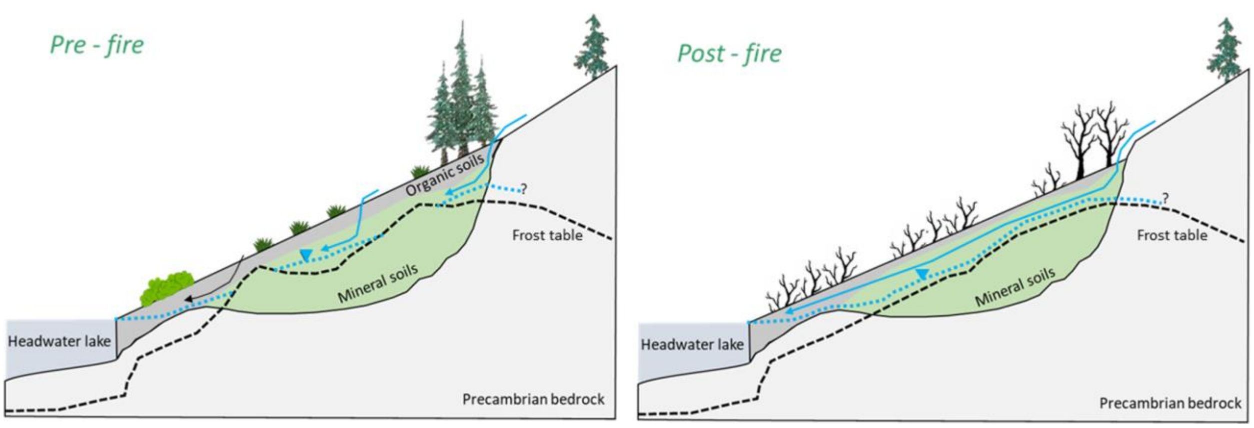

Figure 23. Conceptual illustration of the increased surface-subsurface water connectivity in a bedrock basin as a result of wildfire-driven permafrost thaw (Spence et al., 2020).

6.2.3 Icings

Groundwater discharging through taliks along river and stream banks in winter can result in riverine icings (Woo, 2012), altering the seasonal water balance of a basin (Reedyk et al., 2011). Since river baseflow is the primary source of water for riverine icings (Crites et al., 2020), increasing baseflow may increase riverine icing occurrence in areas where permafrost previously inhibited groundwater flow and discharge over the winter months. However, icing occurrence is closely related to low winter air temperatures and the presence of frozen ground (Crites et al., 2020; Ensom et al., 2020). Thus, as winter air temperatures continue to increase and permafrost further degrades, icing may also decline. Icing investigations in the Taiga Plains have been limited to north of Fort Simpson with a limited assessment of icing trends (Crites et al., 2020; Glass et al., 2021; Reedyk et al., 2011). The influence of changing baseflows on riverine icing development remains a knowledge gap for the Taiga Plains transboundary region.

In the subarctic Canadian Shield, icing development is related to high autumn rainfall and frequent mid-winter warming events (Morse and Wolfe, 2015; Sladen, 2017). Continued increases in autumn rainfall (1943–2013) may promote icing development in the Taiga Shield transboundary region, but this could be counteracted by rising air temperatures and continued decreases in mid-winter warming events (≥5℃) (Morse and Wolfe, 2017). At present, the highest icing density is associated with highly fractured bedrock in the Shield that is likely permafrost free (Morse and Wolfe, 2015), suggesting icing occurrence could increase as permafrost thaws and basins become more hydrologically connected (Spence et al., 2020; Spence et al., 2014). Long-term changes of icings in the Taiga Shield are highly uncertain (Morse and Wolfe, 2017, 2015).

6.2.4 Peat Plateau Wetlands

The hydrology of peat plateau wetlands has been thoroughly investigated at Scotty Creek, NT (61.3°N, 121.3°W), approximately 50 km south of Fort Simpson. Permafrost generally restricts lateral flow at a basin scale, forcing water to flow around plateaus (Quinton et al., 2019). The primary hydrologic function of channel fens is to transfer water toward the basin outlet laterally, whereas thermokarst bogs and poor fens (i.e., weakly minerotrophic peatlands) primarily store water (Hayashi et al., 2004; Quinton et al., 2003). These distinct functions have implications for the basin outflow hydrograph. Quinton et al. (2003) demonstrated that as the areal coverage of fens in a basin increases, so does runoff. In contrast, greater proportions of captured bogs resulted in decreased basin runoff. Stream hydrographs for these regions are characterized by peak flows in April-May in response to spring freshet, but a similar magnitude response can also result from large summer storms (Quinton et al., 2003).

Peat plateaus and palsas generate runoff due to their elevation above surrounding wetlands and relatively impermeable permafrost core that restricts infiltration (Quinton et al., 2009; Woo, 2012). Greater surface runoff occurs in spring when the active layer is frozen, and the freshet generates large volumes of snowmelt (Woo, 2012; Wright et al., 2009). Once the active layer begins to thaw, infiltrated snowmelt contributes to subsurface runoff from the plateau. The frost table position in spring confines lateral flow to the highly conductive upper peat layer, which promotes higher subsurface flows (Quinton et al., 2008; Wright et al., 2008). The water table in the peat plateaus can range from 0 to 0.5 m below the ground surface in late summer (Quinton et al., 2009). The water table in flat bogs and channel fens is near-surface (<0.1 m), except in early spring, where snowmelt runoff raises water levels above the peat mats (Quinton et al., 2009).

Snowmelt surface and subsurface runoff are primarily directed toward adjacent fens along sloped margins (Figure 24a; Connon et al., 2014). Secondary runoff occurs within the plateau, where water is stored in isolated bogs and depressions. Water that is added to isolated bogs from surface/subsurface runoff and precipitation is primarily removed through evaporation or possibly groundwater recharge because surrounding permafrost plateaus act as hydrologic dams (Quinton et al., 2009). Under periods of high water availability (e.g., during spring snowmelt), isolated bogs can become hydrologically connected to form a network of cascading wetlands (Connon et al., 2015). Cascading wetlands roughly follow the fill-and-spill process, whereby the wetland storage capacity must be exceeded to activate hydrologic connectivity to adjacent collapsed bogs and channel fens.

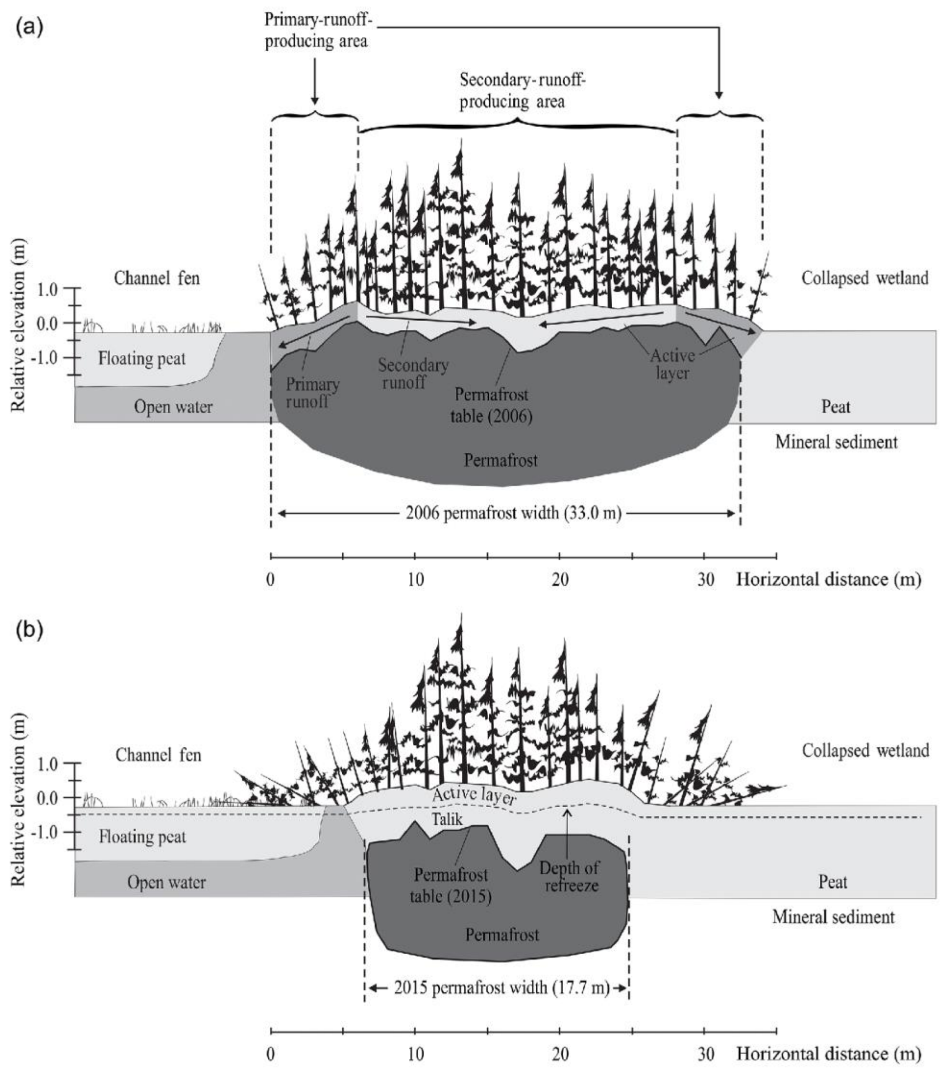

Figure 24. (a) Cross-section of a peat plateau showing primary and secondary runoff areas and (b) shrinking of the permafrost plateau and talik development at Scotty Creek (Quinton et al., 2019).

The thaw-induced landcover changes observed in the peatlands of the study region have considerable impacts on the hydrology of the basin. In the early stages of peat plateau permafrost degradation (Figure 18 I, II), there is a higher areal coverage of collapse bogs disconnected from the hydrologic network by relatively impermeable permafrost (Carpino et al., 2021; Connon et al., 2014). Thus, a higher proportion of atmospheric water inputs are being stored within the basin (Haynes et al., 2018). With black spruce dominating the landcover, evapotranspiration rates are relatively low due to its low transpiration rates (Warren et al., 2018), making understory vegetation the primary contributor to evapotranspiration (Chasmer et al., 2011b).

On peat plateaus, unfrozen groundwater is stored in shallow supra-permafrost taliks that deepen under continued warming and land disturbances (Figure 24a; Quinton et al., 2019). The deepening of supra-permafrost taliks in permafrost plateaus results in increased hydrologic connectivity between the land cover in peat plateau-wetland complexes (Connon et al., 2014). Permafrost that previously acted as a subsurface hydrogeological barrier enables drainage of isolated collapsed bogs upon thawing (Haynes et al., 2018). Thus, groundwater storage temporarily increasing under bog expansion, but as the plateau continues to shrink and the land is converted to runoff-producing wetland, groundwater, and basin storage decline (Haynes et al., 2018).

As a result of bog expansion, the basin is covered by a greater proportion of standing/open water and saturated wetland vegetation (including *Sphagnum* mosses), increasing evaporation rates (Figure 18 IV, V; Carpino et al., 2021). The hydrologic changes resulting from a full transition to permafrost-free, treed-wetlands remain uncertain and require further investigation. However, under dryer surface conditions and increases in black spruce growth, evapotranspiration rates are likely to decline.

In this landscape, the impacts of permafrost thaw from linear disturbances (e.g., seismic lines and winter roads) on the drainage network's hydrologic functioning have also been investigated at Scotty Creek, NT (Braverman and Quinton, 2016; Williams et al., 2013). When water availability and frost tables are high during the snowmelt period, the linear disturbances become filled with water and behave similarly to isolated bogs on peat plateaus (Williams et al., 2013). The ability for this surface water to be transmitted to adjacent fens is suggested to follow a fill-and-spill drainage pattern. Although Williams et al. (2013) had not observed increases in hydrologic connectivity between linear disturbances and drainage networks, it was hypothesized that linear disturbances might begin to function more like channel fens and increase basin with progressive permafrost degradation drainage. Similarly, the subsurface flow could become increasingly important with the development of supra-permafrost taliks, but the low hydraulic conductivity of the catotelmic peat makes this unlikely (Braverman and Quinton, 2016).

6.2.5 Lake Environments

Lake areas can fluctuate with summer precipitation and water levels in adjacent areas (Kokelj & Jorgenson, 2013; Plug et al., 2008; Vallée & Payette, 2007). Lateral lake expansion can contribute to the toppling of trees, vegetation, and soil erosion on shorelines, impacting water quality, and lateral subsurface thaw beneath the shoreline can accelerate shoreline collapse and permafrost degradation (Kokelj et al., 2009). Thermokarst lake decline or lake expansion impacts water storage, routing, and landscape connectivity (Figure 21). Lake drainage has been associated with decreased surface water storage, where subsurface flow paths are enhanced at the expense of surface waters (Karlsson et al., 2012). In contrast, lake expansion may increase surface water storage and reflect enhanced groundwater recharge (Walvoord and Kurylyk, 2016). Permafrost thaw in boreal Alberta was shown to influence lake runoff (Gibson et al., 2015). Higher runoff was generated from permafrost thaw-influenced lakes in the Caribou Mountains relative to lower elevation sites with lesser peatland/permafrost influence. However, this response may wane as permafrost becomes extensively thawed.

The Taltson River basin in the Taiga Shield has the highest proportion of lakes in the study area. The high population of lakes in this network can attenuate surface runoff, such that streamflow responses from spring freshet or storm events are delayed (Morse & Spence, 2017). Due to the fill-spill process that controls basin runoff, increases in the storage capacity of soil-filled bedrock valleys could mean less water contributes to basin runoff and, therefore, lake inflow (Morse & Spence, 2017). The volume of water from melting ice in permafrost is unlikely to dramatically affect lake levels due to the relatively low ice content in the Taiga Shield (Spence et al., 2014). However, water routing and storage changes resulting from permafrost thaw may affect the network of lakes in the Taltson River basin. As open taliks develop beneath lakes, lake levels may decline, connecting surface water to deeper flow systems (Figure 21; Walvoord and Kurylyk, 2016). Thaw-enhanced subsurface water flow beneath lakes in the Taiga Shield could explain the declines in lake levels observed by Carroll et al. (2011), but the configuration of taliks in this area is unknown. Contrastingly, decadal atmospheric circulation patterns such as the El Nino/Southern Oscillation and Pacific Decadal Oscillation (Bonsal and Shabbar, 2011) may explain increases or decreases in surface water extent on shorter (i.e., multi-year to decadal) timescales.

6.2.6 Streamflow and Winter Baseflow

Stream discharge has been increasing in permafrost terrain across the circumpolar north at varying basin scales (e.g., Connon et al., 2014; McClelland et al., 2004; Peterson et al., 2002; St. Jacques & Sauchyn, 2009; Walvoord & Striegl, 2007b). Increases in streamflow have also been observed throughout the transboundary region (Table 7). The drivers of increased streamflow vary by region and landcover but have been correlated to increasing air temperatures (Peterson et al., 2002). Three explanations for increasing streamflow in discontinuous permafrost terrain under climate warming have been proposed in the literature and will be further discussed below: (i) thawing permafrost; (ii) reactivation of subsurface flow paths; and (iii) thaw-induced land cover changes.

An early explanation for rising streamflow was that permafrost thaw supplied additional water inputs to streams from the conversion of ice to liquid water (St. Jacques and Sauchyn, 2009; Walvoord and Striegl, 2007a). However, studies have shown that the estimated volume of water sourced from thawing permafrost, particularly in low ice content terrain, is insufficient to account for all or most observed increases in river discharge (McClelland et al., 2004). This trend has been noted in literature from the Taiga Plains (Connon et al., 2014) and Taiga Shield (Spence et al., 2014). Although some components of streamflow can stem from the thawing of ice-rich peat plateaus in the Taiga Plains, it is a small percentage (<5%) of total annual runoff (Connon et al., 2014).

Thaw-induced reactivation of groundwater flow paths that increase groundwater discharge to rivers is the second explanation for rising streamflow (Crites et al., 2020; Smith et al., 2007; St. Jacques & Sauchyn, 2009; Walvoord & Striegl, 2007b). Much of the increases to streamflow are occurring in low-flow winter months (Peterson et al., 2002), including the Liard River valley where winter baseflow has increased between 1964–2012 (Table 7; Connon et al., 2014; Shrestha et al., 2019; St. Jacques & Sauchyn, 2009). This would indicate that thaw-induced talik development enables winter-time groundwater discharge. Sources of groundwater discharge may be from deeper flow systems or reopened flow paths that enable drainage of wetlands and lakes to occur year-round (Smith et al., 2007; Walvoord & Kurylyk, 2016; Yoshikawa & Hinzman, 2003). Although increased talik development has been observed in the plateau-wetland complexes in the Taiga Plains (Connon et al., 2018; Gibson et al., 2018), baseflow was found to be a relatively small (<7%) component of annual streamflow, insufficient to explain the observed increases to streamflow (Connon et al., 2014).

The third explanation for rising streamflow is that thaw-induced landcover changes are altering the basin runoff dynamics. For the lower Liard River Valley, liquid water inputs from thawing permafrost and subsurface reactivation could not fully explain the increases in runoff (Connon et al., 2014). Precipitation also did not increase during periods of increased runoff. Instead, permafrost thaw results in a landscape transition to a higher runoff producing landcover (Connon et al., 2014), which is accelerated by supra-permafrost talik development (Connon et al., 2018). The low permeability of the underlying mineral soil may be why increased subsurface connectivity was not a dominating factor in streamflow rises in this environment compared to others (Kurylyk and Walvoord, 2021). However, the cumulative effects of landcover change and subsurface reactivation on streamflow and how this varies across landscapes require additional investigation to predict hydrologic change across the region.

Evidence for landcover change driving rises in streamflow is supported by runoff ratios in the Liard River valley increasing between 1996–2012 (Table 7; Connon et al., 2014). Figure 25 illustrates that, despite non-significant changes in annual precipitation between 1978 and 2017, annual runoff significantly increased for basins in the Taiga Plains underlain by permafrost. However, changes in annual runoff were not observed for basins in the Taiga Shield with similar proportions of permafrost, likely due to limited thaw-induced landcover changes associated with the bedrock-dominated terrain.

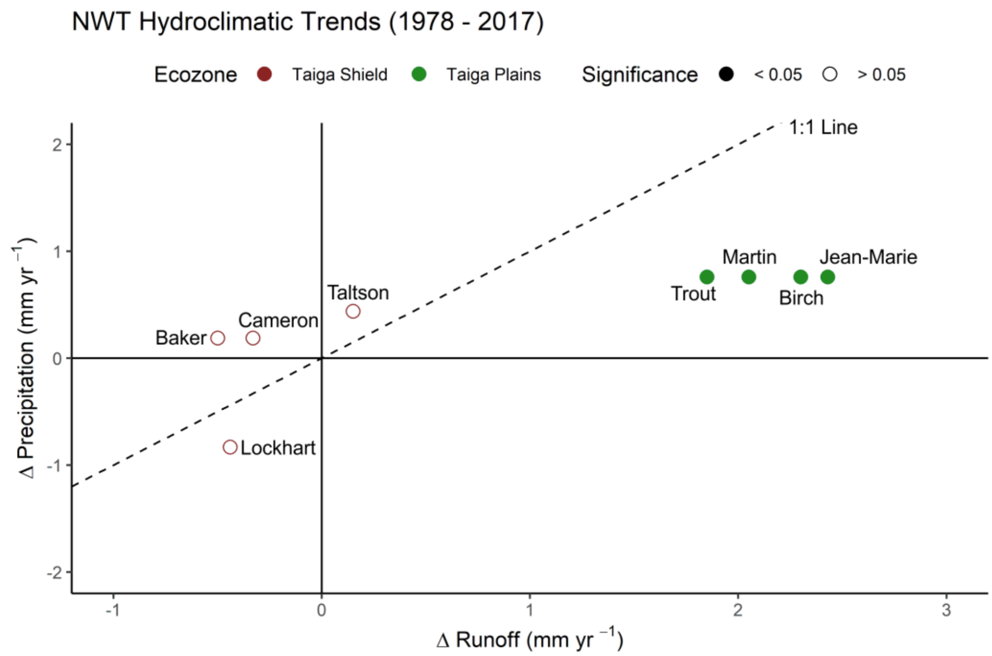

Figure 25. Changes in annual precipitation versus changes in runoff between 1978 and 2017 for basins in the Taiga Plains and Taiga Shield with similar proportions of permafrost coverage. The 1:1 line indicates where a unit change in precipitation will result in an equal unit change in runoff. Plotting off the line, like the basins shown in the Taiga Plains, suggest other factors like thaw-induced landcover change are altering runoff patterns. Significance and magnitude of change were determined from a Mann Kendall test. Runoff data was obtained from gauges operated by the Water Survey of Canada within the transboundary region. Precipitation records were obtained from the closest community with a long-term record. No change in precipitation was statistically significant.

Annual flows in the Hay River have been stable since the 1960s (Shrestha et al., 2019; Stantec, 2016; Tank et al., 2016). However, annual minimum daily flows increased in the Lower Hay sub-basin from 1964–2012, suggesting winter baseflow is increasing (Stantec, 2016) with potential influence from groundwater contributions. Shrestha et al. (2019) observed a similarly increasing winter runoff trend in the Hay River, but it was not statistically significant.

The Slave River is influenced by the W.A.C. Bennett Dam on the Peace River, making it challenging to disentangle changes in water quantity to climate change effects or dam operations. The dam has dampened the hydrograph and altered the seasonality of flow, such that spring peaks have reduced by 20% and low flows have increased by 75% (Sanderson et al., 2012). An earlier spring freshet has been observed, which may be climate change-related or due to dam construction (Sanderson et al., 2012). A significant decline in annual stream discharge for the Slave River (1960–2012) may stem from hydroelectric production (Tank et al., 2016); however, non-significant decreasing trends were found from 1971–2010 (Sanderson et al., 2012). Significant decreasing summer and fall trends were detected (1971–2010) with an increasing winter flow trend (Sanderson et al., 2012), mirroring trends in the Peace River (Schindler and Donahue, 2006; Seneka and Faria, 2011). Further investigation is needed to unravel the impacts of permafrost thaw on this transboundary basin.

In the discontinuous permafrost region of the Taiga Shield, winter streamflow at Baker Creek (62 30.8°N, 114 24.25°W) has been increasing since 1997–2011 (Spence et al., 2014). Unlike other regions that have experienced rising winter streamflow, the source of this increase is unrelated to permafrost thaw due to the low ground ice abundance of the Taiga Shield. At Baker Creek, rising winter streamflow is associated with increased autumn rainfall that raises lake levels above basin outlets, supporting higher winter runoff (Spence et al., 2014). As such, the lack of trend in streamflow for Taltson River in the Taiga Shield (St. Jacques and Sauchyn, 2009) may be a result of low ice content, bedrock outcrops limiting permafrost extent, and/or stable local precipitation, but further investigation is needed.

It is hypothesized that declines in permafrost extent in soil-filled bedrock valleys will increase subsurface storage (Morse & Spence, 2017). Due to the fill-and-spill drainage pattern of the Shield environment (Spence & Woo, 2003), higher storage capacity would need to be met before downstream flow and connectivity could occur (Morse & Spence, 2017). Peak flows of rivers in the Taiga Shield typically occur in early spring during snowmelt, but similar flows can result from large summer rainfall events (Kokelj, 2003). Generally, runoff is limited in the summer months due to high evapotranspiration-precipitation ratios (Morse & Spence, 2017). Increased subsurface storage may lead to more intermittent flows and delayed streamflow responses to nival freshet or summer rainfall events.

6.3 Summary of thaw-induced changes to landcover and hydrology

An assessment of the landcover and hydrology shifts in the Taiga Plains and Taiga Shield is summarized by Table 7, where the key thaw-induced changes are detailed per basin concerning the direction of change and the potential stressors/factors that contribute to the changes.

The landscape of the Taiga Plains has undergone important changes due to the cumulative impacts of rapid air temperature increases, wildfire, and human disturbance. Permafrost-underlain, forested peat plateaus have collapsed into waterlogged bogs, channel fens, or thermokarst lakes, with some regions now experiencing afforestation without the regeneration of permafrost. Key thaw-induced hydrological shifts include the expansion of taliks, increased subsurface connections, and enhanced streamflow regimes.

While the Taiga Shield has experienced similar temperature increases and enhanced wildfire regimes, the characterization of permafrost and cryohydrogeology in the region is greatly lacking. Likely, the pre-Cambrian bedrock that underlies the region lends to less dramatic landscape changes that are limited to fragmented peat plateaus or expansion/reduction of the small lakes that dominate the region.

Table 7. Thaw-induced changes to landcover and hydrology observed in the transboundary area.

Thaw-induced change	Location in study area	Direction of change & time frame	Stressors/Factors	References
Landcover				
Forest cover	Liard River Basin, BC portion of Petitot River basin	Net loss 1970-2010, with forest gains in Petitot river limiting net loss in this area	Warming climate, changing winter precipitation (e.g., rain-on-snow, snowpack declines, mid-winter melts)	Carpino et al. (2018)
Wetland area	Scotty Creek	Increase (1970–2008); (1955–2015)	Warming climate, wildfire, changing precipitation, land disturbance	Quinton et al., (2011); Gibson et al. (2018)
Lake Area	Taiga Shield	Decrease (2000–2009)	Changing precipitation, increased temperature, permafrost thaw	Carroll et al., (2011)
	Kakisa Basin	Decrease (2000-2009), Stable (1947–2012)	Changing precipitation, increased temperature, permafrost thaw	Carroll et al., (2011); Coleman et al., (2015)
	Hay-Zama Lakes	Increase (2000–2009)	Precipitation, temperature, river inflow	Carroll et al., (2011)
Hydrology				
Active layer thickness	Hay River	Stable in most locations, increase under burn sites (1963–2017)	Warming climate, wildfire, changing precipitation, human disturbance	Holloway & Lewkowicz (2020)
	Petitot River	No SS trend (1988–2000)	Organic layer and fire	Nixon et al. (2003)
	Scotty Creek	Increase (1998–2018); (1955–2015)	Warming climate, talik development	Quinton et al. (2011); Gibson et al. (2018)
Spatial distribution of Taliks	Scotty Creek	Increase (2011–2015)	Climate warming, changes in precipitation, human disturbance	Connon et al. (2018)
	Scotty Creek	Increase (1955–2015)	Increasing air temperatures, wildfire formation	Gibson et al. (2018)
Surface-subsurface connectivity	Scotty Creek	Increase at local-scale (1996–2012)	Climate warming	Connon et al. (2014)
Icings (Aufeis)	North Slave Region (Taiga Shield)	Variable (1985–2014)	Climate change (rising autumn rainfall, decreasing mid-winter warming).	(Morse and Wolfe, 2015)

Wetland Storage	Scotty Creek	Decrease (2003–2017)	Climate warming	Haynes et al. (2018)

Thaw-induced change	**Location in study area**	**Direction of change & time frame**	**Stressors/Factors**	**References**
Lake Runoff	Caribou Mountains	Increase (2015)	Changing precipitation, increased temperature, permafrost thaw	Gibson et al., (2015)
Winter baseflow (annual low flow)	Liard River valley	Increases (1964-2012)	Warming climate, wildfire, changing precipitation	St. Jacques & Sauchyn, 2009; Connon et al. (2014); Shrestha et al. (2019); (Stantec, 2016)
	Hay River	No SS trend (1988-2012), Increase min flows (1964–2012)	Warming climate, wildfire, changing precipitation	Shrestha et al., (2019); (Stantec, 2016); St. Jacques & Sauchyn, 2009;
	Slave River	Increase (1971-2010)	Bennett Dam, changing precipitation	Sanderson et al., (2012)
	Baker Creek, North Slave Region	Increase (1996–2011)	Increasing autumn rainfall	Spence et al. (2014)
	Taltson River	No SS trend (1963–1997)	Thin overburden, low ice content	Jacques & Sauchyn (2009)
Annual Streamflow	Liard River	Increase (1966–2007)	Warming climate, wildfire, changing precipitation	Jacques & Sauchyn (2009)
	Lower Liard River Valley	Increase (1996–2012)	Climate change, landcover transition to higher runoff producing landscape.	Connon et al. (2014)
	Hay River	No SS trend (1964–2012)		St. Jacques & Sauchyn (2009); Tank et al. (2016); Stantec, (2016); (Shrestha et al., 2019)
	Slave River	Decrease (1960–2012), No SS trend (1971-2011)	Bennett Dam, changing precipitation	Tank et al., (2016); Sanderson et al., (2012)
	Taltson River	No SS trend (1966–2007)	Thin overburden, low ice content	St. Jacques & Sauchyn (2009)
Streamflow seasonality	Mackenzie River	Decrease in max/min discharge ratio and earlier spring melt (1973–2011)	Climate warming, changing precipitation	(Yang et al., 2015)

SS=Statistically Significant

7 Impacts of Permafrost Thaw on Water Quality and Biogeochemistry

The impacts of permafrost thaw on landcover and hydrology can cascade into water quality and biogeochemical cycling, potentially affecting the health of ecosystems, aquatic and terrestrial biota, and people (Frey and McClelland, 2009; Vonk et al., 2015). Here, the water quality of transboundary waters is discussed regarding long-term monitoring of the Liard, Slave, and Hay rivers, in addition to synthesizing studies that examine the effects of permafrost thaw on water quality parameters. As indicated in previous sections, thaw in peatlands is most relevant to landcover and hydrologic shifts in the transboundary region. Therefore, literature is drawn upon that directly examines transboundary waters and representative external regions, including Fennoscandia and the West Siberian Lowlands.

7.1 Overview of the AB-NT Transboundary Water Quality

The major transboundary rivers each have unique characteristics that influence their water quality. The Liard River has mountainous headwaters, high seasonal runoff, and surficial geology that leads to high suspended sediment loads (median total suspended solids (TSS) 31 mg L^{-1}), high pH (7.5-8.5), and moderate conductivity (100-500 µS cm^{-1}) with data reported from 1968 to 2015 (Golder Associates, 2017). The Hay River is influenced by widespread peatlands and region of uplands, with lower suspended sediment (median TSS 12.5 mg L^{-1}), slightly alkaline pH (6.9-8.3), and moderate conductivity (123 to 860 µS cm^{-1}), with data reported from 1989-2010 (Environ EC (Canada) Inc., 2012; HDR Corporation, 2015; Stantec, 2016). The Slave River is influenced by the easily eroded sedimentary rock in the Athabasca and Peace sub-basins, leading to high suspended sediment loads (median TSS 108 mg L^{-1}), slightly alkaline pH (6.8-8.7), and moderate conductivity (138 to 364 µS cm^{-1}), with data reported from 1972-2010 (Sanderson et al., 2012). Water quality parameters for the rivers varied seasonally, with suspended sediments peaking during spring freshet and conductivity increasing in winter as groundwater contributions increased (Golder Associates, 2017; Sanderson et al., 2012; Stantec, 2016).

Long-term monitoring of DOC in the Hay River shows higher concentrations (2.6-7.3 mg L^{-1}) compared to the Slave River (1.5-40.4 mg L^{-1}) and Liard River (0.1-33 mg L^{-1}); high concentrations in the Hay River are likely due to peatland influence (Golder Associates, 2017), while lower DOC in the Slave River may relate to photo- or bio-degradation in Lake Athabasca (Sankar et al., 2019) or retention in the Bennett Dam reservoir (Maavara et al., 2017). The rivers had moderate to high nutrient (nitrogen and phosphorus) concentrations as the Hay River was classified as mesotrophic-eutrophic (Golder Associates, 2017), Slave River was classified as eutrophic (Sanderson et al., 2012), and Liard River indicated oligotrophic conditions in the upstream reaches, and potential for eutrophic conditions in downstream reaches (Golder Associates, 2017). Phosphorus and metals in the Hay, Slave, and Liard rivers were predominantly in the particulate, less bioavailable form, and correlated with suspended sediment loads. Some metals frequently exceeded water quality guidelines (Golder Associates, 2017; Sanderson et al., 2012; Stantec, 2016).

Based on long-term monitoring of transboundary rivers, the water quality is good to fair and highly influenced by the natural conditions of the basins; in cases where water quality guidelines were exceeded, the driver was typically high sediment loads. The current water quality monitoring programs in the transboundary region are summarized in Table B.4, while water quality data repositories are summarized in Table B.5, enabling further temporal analysis of water quality trends.

7.2 Effects of Permafrost Thaw on Water Quality

The alteration of landcover and hydrology through permafrost thaw can impact downstream water quality. Stores of organic matter, nutrients, metals, and persistent organic pollutants previously locked in permafrost may become mobilized due to thaw (Arctic Monitoring and Assessment Programme, 2015; Frey and McClelland, 2009; Vonk et al., 2015), with implications ranging from ecosystem health to drinking water quality to the toxicity of country foods.

7.2.1 Physical Parameters

Physical parameters, including pH, specific conductance, total dissolved solids (TDS), and total suspended solids (TSS), provide basic information on the water quality of rivers (Sanderson et al., 2012). Organisms in surface waters are typically adapted to a specific range of pH, light visibility, and level of suspended materials (Hassan Omer, 2020). These parameters can influence the biogeochemical cycling discussed later in this report. For example, suspended particles provide adsorption media for metals, and metal dissolution is promoted in highly acidic water (Hassan Omer, 2020).

The acidic or basic properties of water are measured through pH. Pure water has a neutral pH of 7, with lower values for acidic waters and higher for basic. pH influences the solubility and uptake by organisms (bioavailability) of chemical constituents such as nutrients and metals (Hassan Omer, 2020). Permafrost thaw and increased connection to groundwater may influence pH trends in transboundary waters to become less acidic. Permafrost-influenced streams in the Western Siberian Lowlands were found to have a lower pH than streams where permafrost was absent, attributed to buffering by groundwater in southern streams or carbonate dissolution in mineral soils (Frey et al., 2007), and later sampling in West Siberian Lowland streams confirmed a decreasing pH trend with increasing latitude (Pokrovsky et al., 2015). A latitudinal decrease in pH was also observed in lakes and streams of the Taiga Plains (Figure 26). No pH trend was observed in the Liard River (Golder Associates, 2017), while the Slave River and Hay River had increasing trends (Environ EC (Canada) Inc., 2012; Glozier et al., 2009; HDR Corporation, 2015; Sanderson et al., 2012; Stantec, 2016). Increased biological activity was suggested to drive pH increase in the Slave River (Sanderson et al., 2012), while a causal driver for Hay River was not identified (HDR Corporation, 2015; Stantec, 2016).

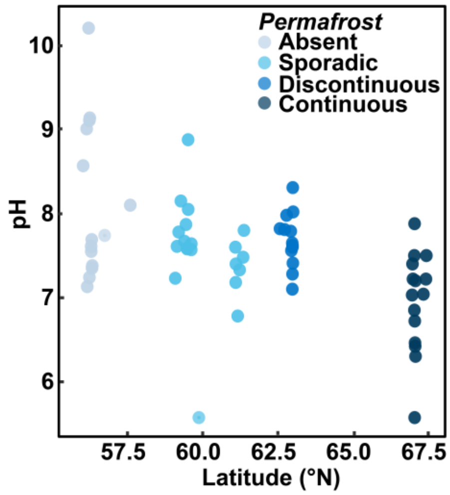

Figure 26. pH as a function of latitude for lakes and streams within the Boreal Plains and Taiga Plains of Alberta and the Northwest Territories (data from Thompson & Olefeldt, 2020).

Specific conductance measures the ability of electricity to be conducted through water. Dissolved salts sourced primarily from weathering processes, including calcium, magnesium, sodium, and potassium, contribute to the specific conductivity. Lakes and rivers typically range 50 to about 1500 µS cm^{-1} (McNeely et al., 1979). Closely linked to conductance, TDS is a measurement of dissolved solids per volume of water. Solids are quantified from a filtered water sample and include inorganic ions and organic matter (Hassan Omer, 2020). As conductivity is influenced by connection with mineral sediment, groundwater connectivity can be indicated by conductance. Minerotrophic land covers and those that convey water, like channel fens, have higher conductivity (Hayashi et al., 2004b; Olefeldt and Roulet, 2012). It is possible that as basins become more hydrologically connected and groundwater contributions increase with permafrost thaw, conductivity will also increase (Frey and McClelland, 2009). The Liard and Hay rivers had no temporal trend in TDS or conductivity (Golder Associates, 2017; Stantec, 2016), while the Slave River had no temporal trend in conductivity and a significant decreasing trend in TDS with no causal driver identified (Sanderson et al., 2012).

TSS is a measurement of solid material per volume of waters, an important parameter influenced by erosion, either natural or driven by human activities (CCME, 1999). Phosphorus, metals, and organic matter can adsorb to suspended solids; thus, higher TSS concentrations may correspond to higher concentrations of those parameters. However, parameters adsorbed to particulates are typically less bioavailable. High quantities of suspended materials increase water treatment costs and can damage fish gills, with decreased resistance to diseases and reduced growth rates (Hassan Omer, 2020). TSS generally increases with river size and river flow. Higher flows allow for greater river sediment suspension and erosion, but TSS concentrations further vary between basins based on landscape characteristics such as slope and landcover (Meybeck et al., 2003). In regions affected by permafrost thaw slumps (e.g., the Peel Plateau), the debris that flows from thawed hillslopes can increase downstream suspended sediment loads by several orders of magnitude (Kokelj et al., 2013). As hillslope thermokarst coverage is minimal in the transboundary region (Olefeldt et al., 2016), and permafrost thaw in peatlands has not been associated with increased particulate loads (Krickov et al., 2020), it is unlikely that permafrost thaw will increase suspended sediment loads in the transboundary waters. No temporal trends in TSS have been observed in the major transboundary rivers (Environ EC (Canada) Inc., 2012; Golder Associates, 2017; HDR Corporation, 2015; Sanderson et al., 2012; Stantec, 2016).

7.2.2 Organic Matter

Dissolved organic matter (DOM) is a complex mixture of organic compounds produced both external to surface waters in soil organic layers, vegetation canopy, and litter (Moore, 2013) and internally within rivers and lakes through primary productivity (Rautio et al., 2011). DOM contains carbon (dissolved organic carbon or DOC) but also dissolved organic nitrogen (DON) and phosphorus (DOP) (Moore, 2013).

Peatlands are major sources of DOC to boreal streams (Moore, 2013). Globally, the magnitude of annual DOC export in the Mackenzie River is amongst the highest (Li et al., 2017). DOC is a substrate for microbial activity and plays an important role in water quality. DOM controls light penetration into water bodies, with implications for phototransformations of neurotoxic methylmercury (Klapstein and O'Driscoll, 2018) and light conditions that control fish growth, predation, and reproduction (Solomon et al., 2015). Metals such as mercury can bind to DOM, and DOM can alter drinking water color, taste, and odor. During water treatment processes, DOC can interact with chlorine to produce potentially carcinogenic disinfection by-products and interfere with the effectiveness of disinfection (Teixeira and Nunes, 2011). As such, there is interest in predicting how DOC levels in northern streams may be affected through permafrost thaw.

Permafrost presence and peatland cover are important controls on DOC concentrations. A survey of rivers in northern Alberta and southern Northwest Territories, including the transboundary basins of Hay River, Kakisa River, and Buffalo River, found DOC concentrations increased with basin peatland cover but were consistently lower north of the permafrost boundary (

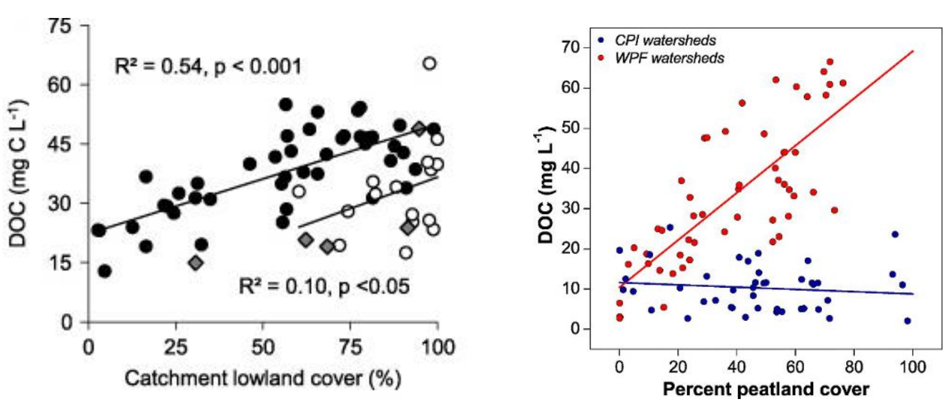

Figure 27; Olefeldt et al., 2014). Similar patterns have been observed in the Western Siberian Lowlands, the largest expanse of northern peatlands (Frey and Smith, 2005). Permafrost-influenced rivers had low DOC concentrations, and permafrost-free basins had significantly higher DOC concentrations, rising with peatland cover.

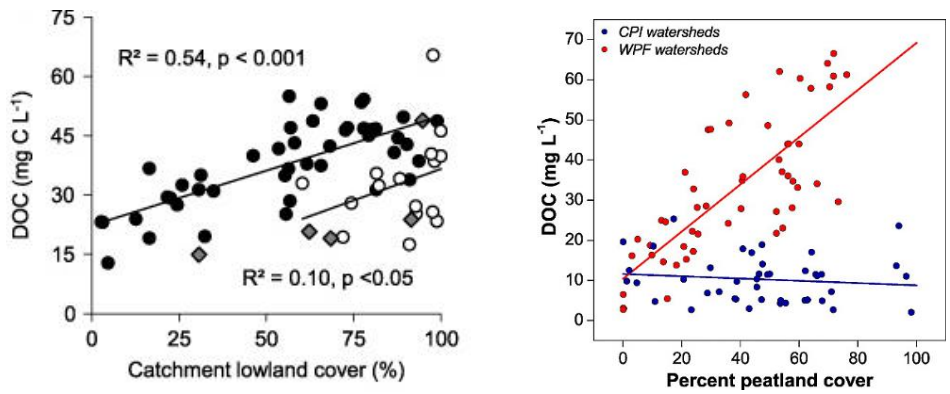

Figure 27; Frey and Smith, 2005). In a Swedish study, DOC export likewise increased with basin peatland cover (Olefeldt et al., 2013). Patterns of DOC concentrations within peatland lakes across the Taiga Plains were highest in the sporadic permafrost region (Figure 28; Kuhn, 2021).

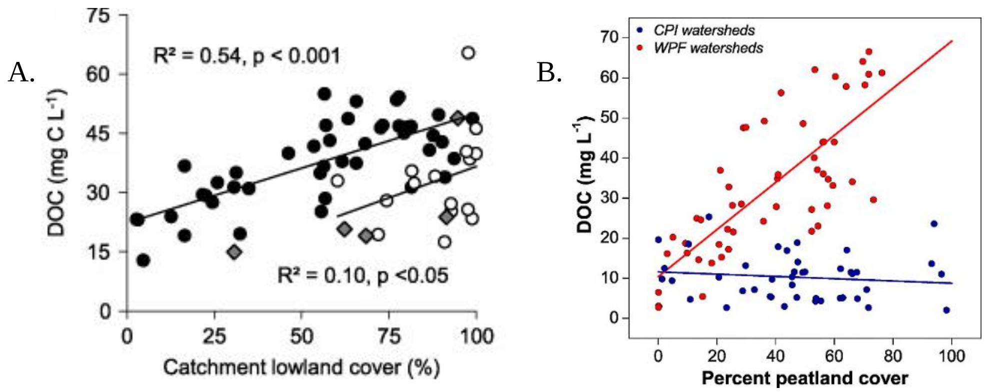

Figure 27. A) Scatterplots between basin lowland cover and river DOC concentrations within the Boreal Plains and Taiga Plains of Alberta and the Northwest Territories. Fitted lines are significant ($p < 0.05$) linear regression. Black circles indicate basins south of the permafrost boundary, open circles indicate basins north of the permafrost boundary, and grey diamonds indicate lake basins (Olefeldt et al., 2014). B) Dependence of DOC concentration on the percent peatland cover within the sampled basin in the Western Siberian Lowlands. CPI = cold permafrost-influenced basins, WPF = warm permafrost-free basins (Frey and Smith, 2005).

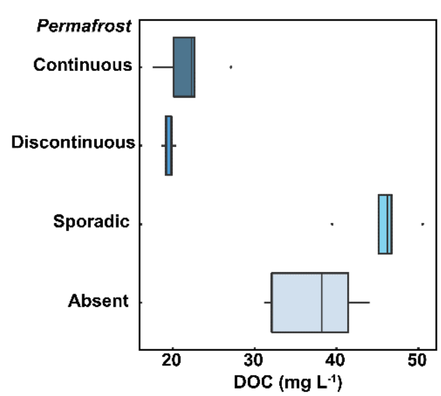

Figure 28. DOC concentrations of lakes within the Boreal Plains and Taiga Plains of Alberta and the Northwest Territories, displayed as box plots of the median, first and third quartiles, whiskers of 1.5 times the interquartile range, and outliers by permafrost zone (data from Kuhn, 2021).

Particulate organic carbon (POC) may also be influenced by permafrost thaw. For example, in rivers across the Western Siberian Lowlands, the highest flux and concentrations of POC were measured at the active thawing front (sporadic and discontinuous permafrost zones). Sources of POC were likely overland flow from surficial peat horizons, and both riverbank abrasion and supra-permafrost flow from deeper peat stores (Krickov et al., 2018). These studies suggest that ongoing permafrost thaw may increase carbon concentrations in permafrost peatland basins. Furthermore, the export of DOC is jointly controlled by solute concentrations and the hydrologic regimes of rivers. Therefore, increasing runoff regimes as described above could result in higher DOC export, but further research is needed.

Although DOC increases are predicted with permafrost thaw in peatland environments, two peat-focused studies found contradictory results. In the Western Siberian Lowlands, marginal decreases in DOC were predicted due to shorter water residence times as active layer deepening and hydrological connections increased in thawing peatlands (Raudina et al., 2017). Similar conclusions were reached regarding active layer deepening in the Qinghai-Tibetan Plateau’s organic soils, where DOC concentration and biodegradability decreased with thaw depth (Mu et al., 2017).

In non-peatland environments, deepened groundwater flow paths from thaw have resulted in decreases of DOC in basins in Alaska (Douglas et al., 2013; Petrone et al., 2006) and Yukon (Shatilla and Carey, 2019) as mineral soil can readily adsorb DOC (Kothawala et al., 2012). Groundwater influence (inferred from electrical conductivity) in northern Sweden was related to lower DOC concentrations and aromatic quality relative to peatland sources, where groundwater contributions increased in wetter years (Olefeldt & Roulet, 2012). While long-term carbon export has increased in the peatland-influenced Mackenzie River (Tank et al., 2016), carbon export has decreased in the Yukon River, attributed to increasing groundwater connections that deliver less DOC (Walvoord and Striegl, 2007a).

To track indication of permafrost thaw and mobilization of organic matter, dating the age of DOC through radiocarbon analysis determines whether the source of carbon is from the decomposition of relatively young plant or peat matter (modern carbon), or the decomposition of plant or peat matter previously frozen in permafrost (aged carbon). Currently, DOC in Taiga Plains streams is relatively modern, sourced from recent microbial activity (Burd et al., 2018; Tanentzap et al., 2021). However, an abrupt DOC aging event in 2018 was detected in the Mackenzie River’s northern reaches (Schwab et al., 2020) and the Peace and Liard Rivers, attributed to petrogenic organic carbon stores and the mobilization of permafrost peat. In contrast, more modern DOC was detected in the Taiga Shield rivers and attributed to aquatic biomass, thinner organic soils, and a low presence of sedimentary rock (Campeau et al., 2020). As noted in a recent synthesis of radiocarbon DOC and POC across the pan-Arctic, it is difficult to conclude whether the organic matter released from deep soils is generated because of landscape disturbance or regular terrestrial permafrost carbon cycling (Estop-Aragonés et al., 2020). Data are too sparse in the study region to make conclusive attribution to permafrost thaw.

Models suggest that carbon export in the Mackenzie River’s northern reaches has increased in recent decades, while no trends were found in the Hay River and Slave River. Temporal analysis showed that DOC flux has increased by ~40% at the mouth of the Mackenzie River since the early 1970s, attributed to increasing DOC concentrations from permafrost thaw in northern sub-basins. Liard River (1973–2012) had a significantly increasing DOC trend; however, no trend was detected in Hay River (1988–2012) or the Slave River (1960–2012), excluding two years of large water release from the Bennet Dam (Figure 29; Tank et al., 2016). Another study of long-term DOC flux, including Liard River (1972–2012) and Hay River (1988–2012), found non-significant but slightly increasing trends in DOC fluxes. Differences in the two studies may be attributed to different bias-correction methods (Shrestha et al., 2019). DOC concentrations have remained stable in the transboundary rivers from the 1970s to early 2010s (Table 8).

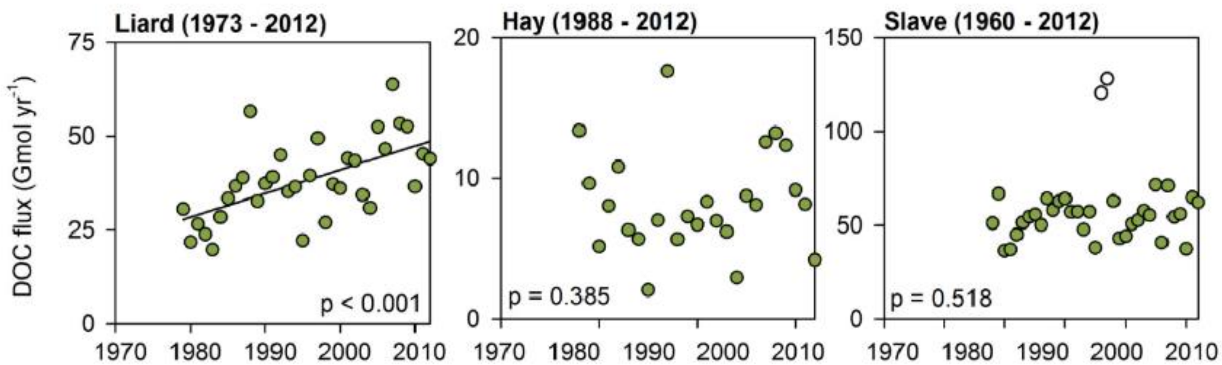

Figure 29. LOADEST-modeled yearly fluxes of dissolved organic carbon (Tank et al., 2016).

7.2.3 Nutrients

Terrestrial disturbances due to permafrost thaw, wildfire, and increasing human influence (agriculture, wastewater) may enhance nutrient fluxes in the Taiga Plains and Shield ecoregions. Nutrients are essential for organisms' functioning, but excess nutrients in water bodies can trigger algal growth, oxygen depletion, and fish die-offs. Primary nutrients include phosphorus and nitrogen, which can exist in different chemical forms. Dissolved forms are most bioavailable, and particulate forms are considered less bioavailable. Phosphorus is a key element for the growth of aquatic plants and is often a limiting nutrient to aquatic primary productivity. Phosphorous is naturally sourced from the weathering of phosphorus-bearing rock. Orthophosphate/phosphate is the inorganic form of phosphorus and is most available for plant uptake. Nitrogen is another limiting nutrient, naturally sourced from soil erosion, atmospheric fixation, and plant matter, with the dissolved inorganic forms nitrate, nitrite, and ammonium most available for organisms (Schlesinger and Bernhardt, 2013).

Permafrost has been shown to influence nutrient concentrations. For example, a dataset of peatland-influenced lakes and rivers ranging from 56°N to 67°N in the Taiga Plains showed the highest dissolved nitrogen and phosphate in permafrost-free and sporadic permafrost zones relative to discontinuous and continuous permafrost (Figure 30; Thompson & Olefeldt, 2020). Likewise, particulate nitrogen in the Western Siberian Lowlands rivers had the highest concentrations and fluxes in the sporadic and discontinuous permafrost, attributed to thawing, deeper peat soils (Krickov et al., 2018). Extractions from sporadic permafrost region peatlands in northern Sweden showed that thawing peatlands mobilized high quantities of nitrogen. However, it was suggested to be preferentially taken up by plants rather than delivered to downstream environments (Keuper et al., 2012).

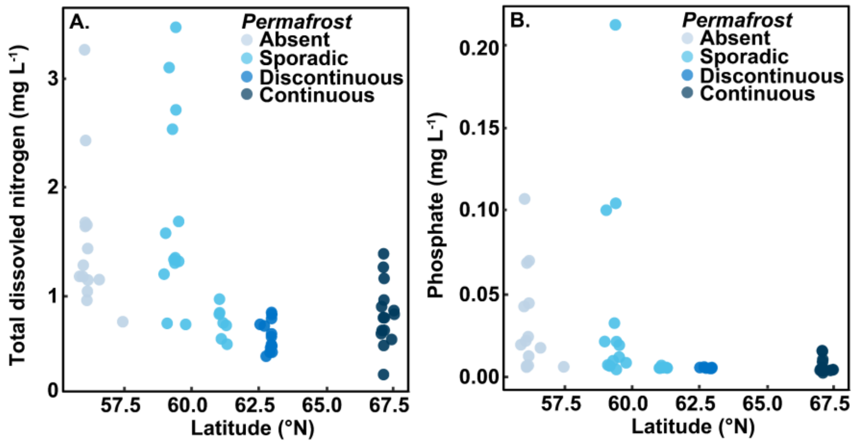

Figure 30. A) Total dissolved nitrogen and B) phosphate as a function of latitude for lakes and streams within the Boreal Plains and Taiga Plains of Alberta and the Northwest Territories (data from Thompson & Olefeldt, 2020).

Wildfires may also expose and mobilize nutrients from peatland basins. For example, a comparison of burned and unburned sub-basins of the Liard River found higher phosphorus yields from the burned Notawohka Creek than the unburned Scotty Creek, with limited effects on nitrogen forms (Burd et al., 2018). A larger survey of water quality in streams across the Taiga Plains and Taiga Shield showed that the influence of wildfire on both phosphorous and nitrogen was only detected for smaller headwater basins, while no effect for larger rivers (Tank et al., 2018).

Long-term analyses of phosphorus in the transboundary rivers show increasing trends in some cases. Small, non-significant annual increases in total phosphorus fluxes were observed in the Hay River (1988–2012) and Liard Rivers (1979–2012), with significant increases in winter fluxes for the Liard River (Shrestha et al., 2019). Increasing winter phosphorus flux in the Liard River was likely connected to increased winter streamflow (Shrestha et al., 2019), as no trend in phosphorus concentrations was observed from 1974–2016 (Golder Associates, 2017). As increased winter streamflow in the Liard River has been linked to permafrost thaw (see section 6.2.6; 6.3), increased winter phosphorus fluxes may be a cascading effect of thaw. Trends of total phosphorus concentrations in the Hay River are inconclusive, as one report found significant increases over time (Environ EC (Canada) Inc., 2012), and another found no significant trend (HDR Corporation, 2015; Stantec, 2016). Increasing total phosphorus concentrations have been reported for the Slave River (Glozier et al., 2009; Sanderson et al., 2012) but were linked to the potential influence of agricultural activities in the Peace River basin (Sanderson et al., 2012).

Nitrogen forms did not follow a temporal trend in the Liard River (Golder Associates, 2017) or Slave River (Glozier et al., 2009). However, in the Hay River, particulate nitrogen concentrations significantly increased from 1989 to 2014 (HDR Corporation, 2015; Stantec, 2016). Dissolved nitrogen decreased during the open water and ice-covered seasons but not annually (HDR Corporation, 2015; Stantec, 2016). Due to different statistical methods, temporal trends of inorganic nitrogen are inconclusive, with one report finding significant temporal increases (Environ EC (Canada) Inc., 2012) and another found no significant trends for the same period (HDR Corporation, 2015; Stantec, 2016).

7.2.4 Mercury

Mercury is a listed concern in the 2030 NT Climate Change Strategic Framework, within goals to understand how country foods and food safety may be impacted by climate change (Government of the Northwest Territories, 2019). Atmospheric deposition of mercury from distant sources becomes bound to organic matter and thus accumulates in soils, especially organic-rich peatland soils (Grigal, 2003). Permafrost inhibits any further cycling of mercury, but mercury release has been detected in Swedish thaw ponds (Klaminder et al., 2008; Rydberg et al., 2010) and downstream of thawing peatlands in the Western Siberian Lowlands (Lim et al., 2019). The transition of dry peat plateaus into water-logged fens and bogs may enhance the microbial transformation of mercury's most toxic form, methylmercury.

Methylmercury is a neurotoxin that biomagnifies in concentrations as it travels from primary producers and consumers to higher trophic level organisms and bioaccumulates in tissues over the lifetime of aquatic biota (Mcintyre & Beauchamp, 2007). Human intake of MeHg may impact the central nervous system, the cardiovascular system, reduce reproductive outcomes, suppress immune function, and during gestation, can pass across the placenta to the fetus (Mergler et al., 2007). However, current monitoring programs do not include methylmercury as a regularly sampled parameter.

Fish consumption advisories have been enacted due to mercury in Northwest Territories lakes. Numerous advisories in the peatland-rich Dehcho region are related to unsafe mercury levels, particularly in predatory species, e.g., northern pike and walleye (Laird et al., 2018). Elevated mercury in fish has been detected in Mackenzie basin lakes with low mercury water concentrations, which was attributed to old, slow-growing fish with high mercury burdens (Evans et al., 2005). Longer-term trends (the 1990s to 2012) in Great Slave Lake showed significant mercury increases in lake trout and burbot, but not northern pike, and mercury trends were not linked to increasing lake temperature and productivity (Evans et al., 2013). Levels of mercury in fish depended both on fish species, fish age, and lake characteristics. Evidence suggested that mercury of some species was associated with the terrestrial delivery of DOC to the lake, implying that permafrost thaw may influence mercury levels, but that the response will not be uniform and needs further studies (Swanson and Low, 2017). In contrast, fish in Yukon and Nunavut do not have increasing mercury bioaccumulation (Chételat et al., 2015), potentially relating to the lesser influence of permafrost peatlands in those regions. There is potential for increasing mercury burdens in fish with mercury release from permafrost in the transboundary region, as basin mercury inputs can influence biotic mercury concentrations (Evans et al., 2005).

Permafrost thaw and the development of thermokarst wetlands have been shown to create hotspots of methylmercury production. However, it is unclear whether these hotspots can influence concentrations and fluxes at the basin level. The production of methylmercury (methylation) is tied to the microbial community structure, dissolved organic matter quantity and quality, mercury bioavailability, and the abundance of electron receptors (Bravo and Cosio, 2020). The nutrient-rich environment of thaw fens was more productive for methylation than nutrient-poor thaw bogs in Sweden (Fahnestock et al., 2019), Alaska (Poulin et al., 2019), Scotty Creek research site in the Liard basin (Figure 31; Gordon et al., 2016), and peatlands draining to the Hay River (L. Thompson, unpublished data). Methylmercury and total mercury concentrations were not elevated in the rapidly thawing sporadic and discontinuous permafrost regions in a survey of Taiga Plains rivers and lakes relative to other permafrost zones. However, peatlands and DOC were key drivers for methylmercury concentrations (Thompson et al., In Prep.).

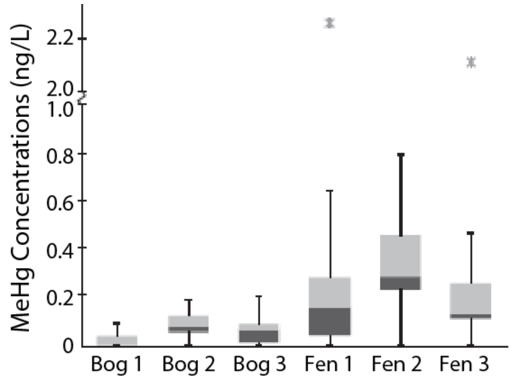

Figure 31. Box plot displaying median and quartile ranges for methylmercury (MeHg) concentrations in different wetlands in the Scotty Creek research site from Gordon et al., 2016.

Thermokarst peatland lakes release mercury and carbon (Klaminder et al., 2008; Korosi et al., 2015), and organic-rich ponds have been recognized as sites with high sediment mercury methylation in High Arctic (Lehnherr et al., 2012; MacMillan et al., 2015; St. Louis et al., 2005). In the Northwest Territories, small lakes in peat-rich areas had high DOM and methylmercury concentrations (Evans et al., 2005), suggesting higher methylmercury production within the lake sediments. However, DOM may be a primary vector of methylmercury from external sources such as wetlands to lakes (Branfireun et al., 2020; Bravo et al., 2017). This model was observed in small peatland lakes across the Taiga Plains, where trends in water chemistry suggested that methylmercury was predominantly sourced from surrounding fens (Thompson et al., In Prep.). While peatland lakes may not be sites of high methylmercury production, they will likely receive increased inputs of mercury forms as permafrost thaw advances and landscapes shift to thermokarst wetlands.

Mercury concentrations in the transboundary region were too inconsistently sampled to assess trends but revealed frequent exceedance of water quality guidelines, attributed to particle-bound mercury, a less bioavailable form (Golder Associates, 2017). In the Slave River, mercury was measured sporadically starting in the 1980s, and older measurements are considered unreliable, with regular sampling instated in 2011. Although temporal trends could not be examined, ~50% of measured samples in the period before 2011 exceeded the mercury concentration guideline of 0.02 $\mu g\ L^{-1}$, which high geogenic sources may explain (Grey et al., 1995; Sanderson et al., 2012). No trend in Hay River was observed for mercury in sediments separated from water by centrifuge (suspended sediment) between 1995–2012, with no data points greater than recommended values (Environ, 2012; Stantec, 2016). More recent mercury trends in Slave and Hay rivers (2014-2020) show only two occasions where the CCME guideline was exceeded out of 145 observations in the Hay River and 11 occasions where guidelines were exceeded out of 125 observations in the Slave River, reaching up to ~100 ng Hg L^{-1} in two instances that corresponded with peak flows (Figure 32).

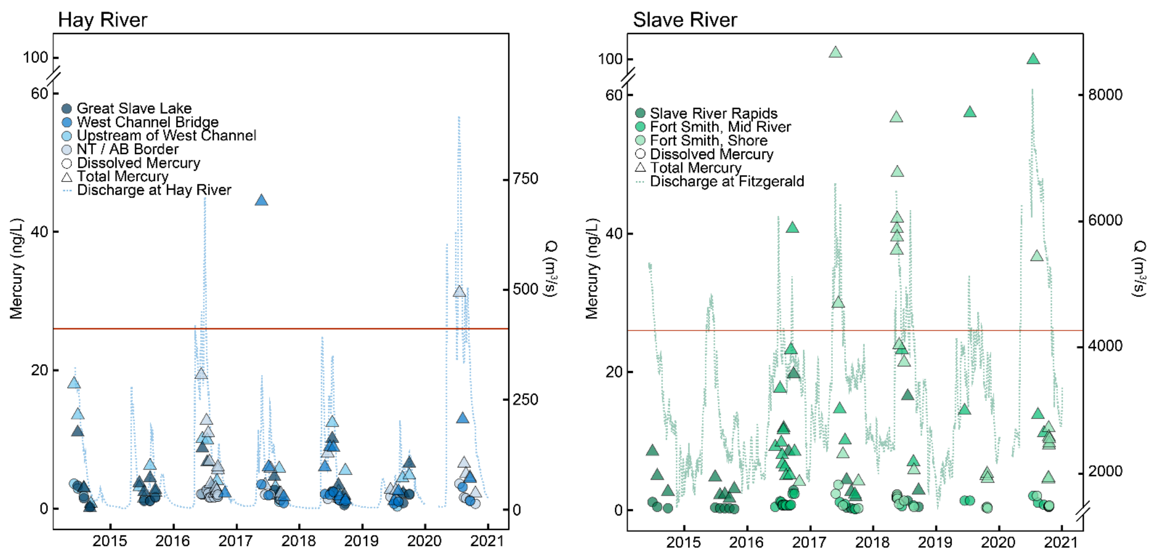

Figure 32. Mercury concentrations in the Hay River (n = 145) and Slave River (n = 125) from 2014 to 2020 (Government of the Northwest Territories, 2021), compared to water quality guideline of 26 ng Hg L^{-1} (red line). Triangles indicate total mercury concentrations, circles indicate dissolved mercury concentrations, and color indicates sampling site. Discharge is indicated by the dotted line (Environment and Climate Change Canada, n.d., n.d.).

7.2.5 Other Metals

Some evidence from other regions shows that peatland permafrost thaw can lead to increased mobilization and downstream transport of metals complexed to DOM, such as lead, iron, and selenium. In northern Sweden, peatland thermokarst development led to an increased flux of lead into the sediment of adjacent lakes (Klaminder et al., 2010). A study of iron release through permafrost thaw in Sweden found that large quantities of organic matter are bound to reactive iron; with waterlogging and oxygen limitation after permafrost thaw, iron-reducing bacteria begin mobilizing both iron and carbon (Patzner et al., 2020). In thaw lakes and rivers of the Western Siberian Lowlands, selenium concentrations were highest in the discontinuous permafrost zone and attributed to peat thawing, although concentrations did not exceed toxic thresholds. Substances that readily bind with selenium, including DOC and iron, were shown to be linearly correlated with selenium concentrations (Pokrovsky et al., 2018). Since the primary driver of increased mobilization of these metals is the shift in anoxic conditions associated with thermokarst wetland development, similar trends may occur within the transboundary region.

A low-frequency sampling of metals in the transboundary rivers confounded temporal trend assessment. Nevertheless, some temporal trends were detected; significant decreases of chromium and molybdenum in the Slave River (Sanderson et al., 2012), decreasing trends of total iron and total lithium in the Hay River (HDR Corporation, 2015) in addition to an increasing trend of total vanadium (Environ, 2012; HDR Corporation, 2015; Stantec, 2016). No temporal trends for metals in the Liard River were identified (Golder Associates, 2017).

7.2.6 Persistent Organic Pollutants

Persistent organic pollutants (PoPs) are toxic chemicals known to bioaccumulate and biomagnify in food webs. PoPs have been detected in northern environments in air, biota water, ice, snow, and sediments and can originate from natural or industrial sources, delivered locally or from long-distant atmospheric transport. PoPs that have been banned for 20–30 years, including DDT (dichloro-diphenyl-trichloroethane) and PCBs (polychlorinated biphenyls), are showing reduced levels in air and biota. In contrast, newer or more recently regulated PoPs have mixed trends (Arctic Monitoring and Assessment Programme, 2015). AMAP identified a knowledge gap in freshwater cycling of PoPs, and mobilization of PoPs with permafrost thaw is a concern (Vonk et al., 2015). While studies are limited, PoPs have been found to revolatilize from permafrost soils to the atmosphere (Cabrerizo et al., 2018; Ren et al., 2019), and permafrost thaw is expected to release PoPs into aquatic systems (Ma et al., 2016) as has been observed from glacial meltwater (Pawlak et al., 2021).

In the Slave River, PoPs, including chlorinated phenolics, organochlorine pesticides, have been detected in water samples but not above CCME guidelines, while PCBs were not detected (1990–1995, 2000–2010). However, detection limits in some PoPs were greater than the CCME guidelines; thus, analytical methods with lower detection limits were recommended (Sanderson et al., 2012).

Water sampling of the Hay River detected the presence of polycyclic aromatic hydrocarbons (PAHs), but concentrations were well below guidelines (1994–2010, 2012–2014). The PAH source was attributed to petroleum rather than combustion sources (more alkylated than parent PAHs) and could have arisen from known oil reserves in the Hay-Zama Lakes. PAHs in suspended sediment were predominantly below detection limits from 1998 to 2005, but lower detection limits post 2011 led to more PAHs detected. Similarly, higher proportions of alkylated than parent PAHs were measured. While there are no CCME guidelines for suspended sediment, a few measured concentrations exceeded recommendations for parent PAHs in benthic sediments. Passive hydrocarbon samplers have been used in the Hay River for 2012–2014, but it was noted that cross-contamination is a concern for field installation (Stantec, 2016).

In the Liard River, suspended sediment sampling detected PCBs, but concentrations did not exceed quality guidelines, while PAHs exceeded guidelines on some occasions. Temporal trends were not detected; however, low-frequency sampling reduced the robustness of the temporal analysis. Sources of the PAHs were attributed to shale gas deposits in the environment, occasional contributions from forest fires, and not linked to permafrost thaw (Golder Associates, 2017).

7.2.7 Tritium

Tritium, a radioactive form of hydrogen sourced from nuclear weapons testing in the 1950s, was elevated in the transboundary region's thawing peatlands (Bond and Carr, 2018). However, the levels of tritium were not likely to be harmful to humans or aquatic life, and instead, the interest in tritium is to understand the impacts of thaw on hydrology (Bond and Carr, 2018; IRSN, 2010). Hence, elevated tritium concentrations in the discontinuous permafrost zone indicate new hydrological connectivity of peatlands to the stream network (Bond and Carr, 2018).

In Alberta, overall low levels of tritium were detected in the Athabasca Basin with relatively higher concentrations in thaw lakes and wetlands (Gibson et al., 2016). A later survey of lakes across Canada found the highest tritium concentrations in the sporadic and discontinuous permafrost regions of the Northwest Territories relative to Manitoba, Newfoundland (Figure 33; Bond & Carr, 2018), and Alberta (Gibson et al., 2016). Of the Northwest Territories sites, lakes near Jean Marie River, Kakisa, Behchoko, and Yellowknife were sampled (Bond and Carr, 2018). The elevated concentrations in NT lakes were attributed to permafrost thaw, as tritium concentrations in permafrost are controlled by radioactive decay determined by its half-life (12.5 years). In contrast, tritium concentrations in unfrozen waters are reduced by radioactive decay and hydrodynamic dispersion, likely explaining the lower tritium concentrations observed at the AB sites in sporadic permafrost (Bond and Carr, 2018). Mobilization of radionuclides may increase as permafrost thaw continues, as Arctic and sub-Arctic regions are the largest terrestrial sink for radioactive contaminants (AMAP, 2011).

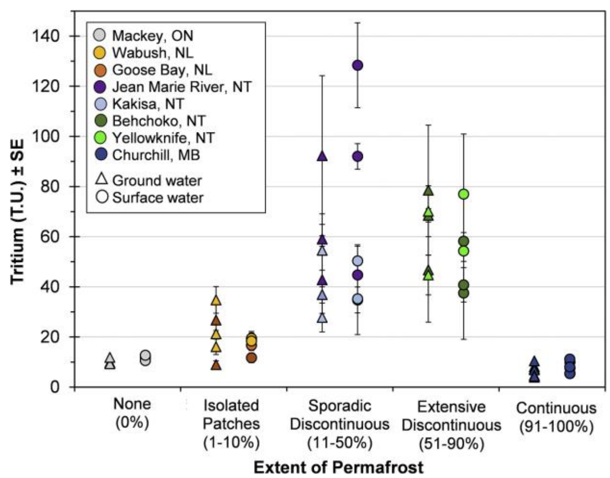

Figure 33. Tritium concentrations in groundwater discharge and surface waters in lakes located in various permafrost zones across Canada from Bond & Carr (2018). Each sample lake is represented as a data point (surface waters = circles, groundwaters = triangles).

7.2.8 Groundwater Biogeochemistry

The activation of groundwater systems as permafrost thaws poses new risks to high latitude water quantity and quality (McKenzie et al., 2021). Our understanding of Arctic and sub-Arctic hydrology is almost entirely based on surface water observations, but new subsurface pathways activated through thaw often drive surface processes (IPCC, 2019; McKenzie et al., 2021). Groundwater knowledge in the transboundary region is largely deficient, as discussed in Sections 6.2.2 (Golder Associates, 2017; VanGluck, 2016). Few studies in the transboundary region directly measure groundwater biogeochemistry and instead make inferences based on surface water. For example, high ion concentrations in lakes and rivers of the Taiga Plains (Figure 34, Thompson & Olefeldt, 2020) indicate that surface-groundwater connectivity may be currently high in sporadic and discontinuous permafrost regions.

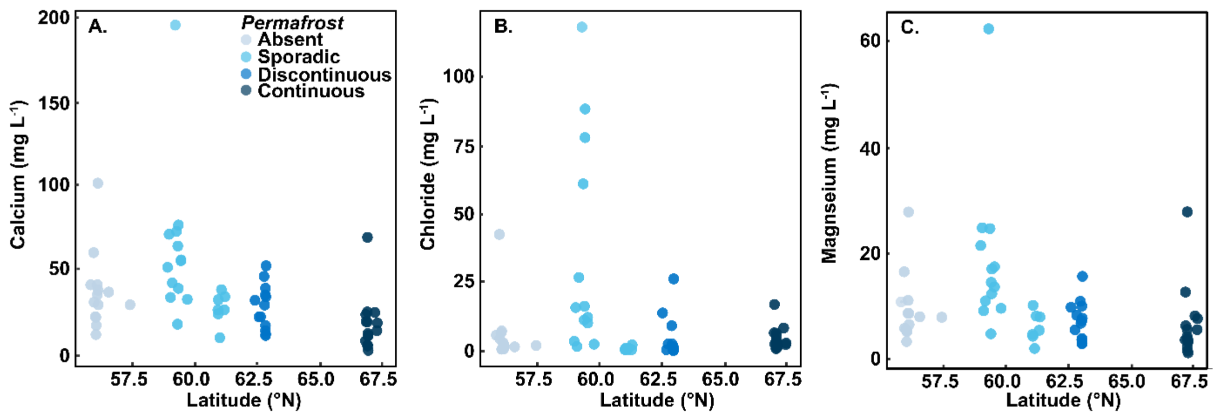

Figure 34. A) Calcium, B) Chloride, and C) Magnesium as a function of latitude for lakes and streams within the Boreal Plains and Taiga Plains of Alberta and the Northwest Territories (data from Thompson and Olefeldt, 2020).

Monitoring in the Liard/Petitot basins indicated that TDS were generally greater than in groundwater than surface water due to longer residence times and mineral dissolution, and calcium-bicarbonate enrichment showed a relatively short residence time for groundwater flow paths. The only available groundwater data were from five wells encompassing seven samples from 1995 and 2009. A comparison of major ions in surface waters for the Petitot River and Liard River with a Piper plot and found more groundwater input in the Petitot than the Liard River, attributed to differing bedrock (Figure 35). For both rivers, groundwater influence was most substantial in fall and winter and weakest during freshet. The groundwater quality data was a notable knowledge gap in the Liard/Petitot basins, and expanded permafrost mapping was suggested (Golder Associates, 2017).

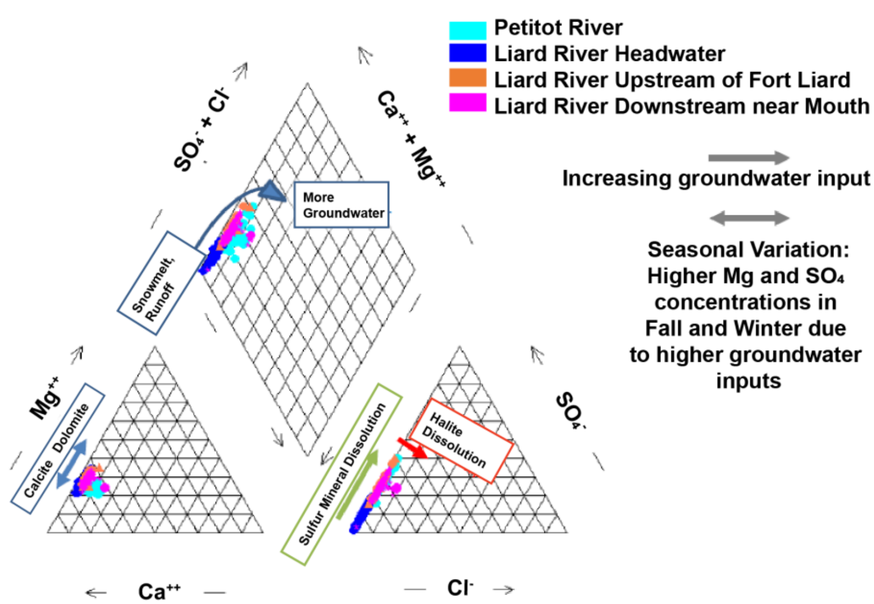

Figure 35. Piper plot of major ion chemistry in Liard River and Petitot River. Aqueous cations (calcium, magnesium, and sodium plus potassium cations) and anions (sulfate, chloride, and carbonate plus hydrogen carbonate) are plotted (Golder Associates, 2017).

Groundwater quality data as a knowledge gap is not limited to the Liard basin. In 2016, there were 1238 registered water wells in the Hay River basin and three wells maintained by Alberta Environment and Parks for the Groundwater Observation Well Network (GOWN). Water quality monitoring in the GOWN wells began in 1989, with some significant data record gaps to date, but the groundwater quality was not available for the 2016 report by Stantec. Two days of water quality sampling are available for the GOWN wells (6/9/1988, Well #376427; 8/28/1987, Well #376428) in the Alberta Water Well Information Database (Government of Alberta, 2021b). While groundwater quality data may have been recorded in some registered wells, the lack of publicly available data and incomplete public records for the GOWN wells preclude long-term water quality assessment. To assess the impacts of community waste on groundwater water quality, the Department of Municipal and Community Affairs, Government of NT has installed monitoring wells in 22 communities across the NT, including Enterprise, Fort Liard, Fort Providence, Fort Resolution, Fort Simpson, Jean Marie, River, and Kakisa. Although the results of this study are not yet publicly available, these wells could form the basis of a groundwater quantity and quality network that integrates impacts from permafrost thaw.

Predicted impacts of permafrost thaw include increased groundwater recharge from runoff, increased area and flow of groundwater discharge to surface waters, and increased surface water-groundwater mixing (Golder Associates, 2017). Increased groundwater discharge and mixing with surface waters may increase TDS concentrations, conductivity, and ion concentrations (Frey and McClelland, 2009). In addition, as the delivery of electron receptors such as iron and sulfate increase with groundwater connectivity, a consequence may be the enhanced methylmercury production (e.g., through iron- and sulfate-reducing bacteria) and thus increased concentrations of methylmercury (Gordon et al., 2016).

McKenzie et al. (2021) noted that northern field programs that address subsurface knowledge gaps are required. Future-facing water management strategies must see groundwater as a potential water resource, an accelerator of landscape change, and a driver of infrastructure damage and water pollution (Figure 36; McKenzie et al., 2021). In areas where groundwater quality is at risk, baseline knowledge of groundwater quality is critical. Many groundwater quality studies are concentrated in the western Canadian Arctic and Alaska and are lacking in peatland-dominated basins (Cochand et al., 2019).

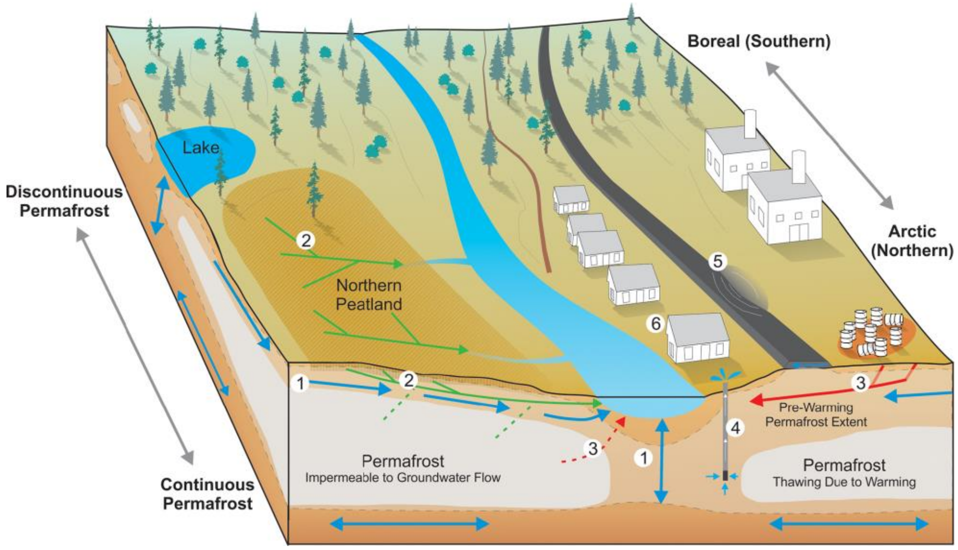

Figure 36. Pathways for groundwater to catalyse environmental change in the Arctic (McKenzie et al., 2021).

7.3 Anticipated Water Quality Trends in the AB-NT Transboundary Region

While the $CWRVI_{PT}$ developed by Spence et al. (2020) shows high vulnerability to thaw in the transboundary region, there are relatively low risks of impairment in the region when also considering other stressor variables to water quality such as roads, pipelines, agriculture, and population pressures (Figure 37; Environment and Climate Change Canada, 2017). However, detecting impacts of permafrost thaw on water quality may be confounded by generally low runoff characteristic of Taiga ecoregions (Ecosystem Classification Group, 2007; Ecosystem Classification Group, 2008b). Small changes in precipitation can trigger variability in runoff, and the region is influenced by decadal atmospheric circulation patterns such as the El Nino/Southern Oscillation and Pacific Decadal Oscillation (Bonsal and Shabbar, 2011) that in turn can impact runoff. Thus, caution must be taken in interpreting changes to water quality as permafrost thaw-driven changes.

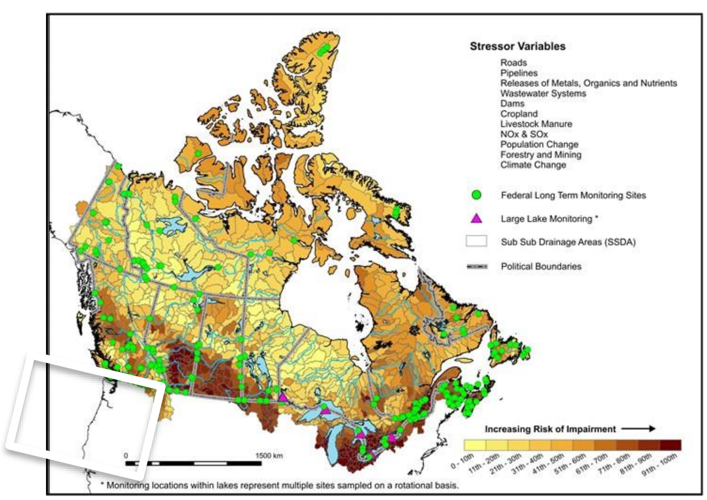

Figure 37. Visualization of the risk-based basin analysis (RBBA) used to quantify the relative risk to water quality in Canada's drainage areas, which aggregates stress from 16 human activities and classifies basins on a relative risk scale. The transboundary region is highlighted by a white box (Environment and Climate Change Canada, 2017).

Potential shifts in physical parameters as thaw advances may include increasing pH and conductivity, while TSS load is unlikely to change because of thaw. A causal driver was not identified for increasing pH trends in the Hay River (Stantec, 2016), which could potentially be linked to thaw due to increased groundwater connection; this attribution is not conclusive as no corresponding trends in electrical conductivity or TDS as groundwater indicators were observed in the Hay River.

While DOC concentrations have remained stable in the major transboundary rivers and increased DOC export in the Liard River was attributed to streamflow, concentrations of DOC are expected to increase as permafrost thaws in peatland-dominated basins, and some pulses of aged carbon have been observed in the Taiga Plains. Likewise, increased concentrations of nutrients may be expected as permafrost thaws and wildfire incidence increases. However, latitudinal observations of DOC and nutrients (Figure 28; Figure 30) show peak concentrations in the permafrost-free and sporadic permafrost zones; greater increases may be expected in the discontinuous and continuous permafrost zones.

Mobilization of mercury from permafrost thaw has been detected outside of the transboundary region, but inconsistent sampling data precludes long-term trend assessment in the transboundary rivers. From available data, exceedances of water quality guidelines have been associated with particle-bound mercury during high discharge periods. Permafrost thaw has additionally been shown to increase production of methylmercury in wetlands within and external to the transboundary region, although elevated concentrations have not been detected in downstream lakes and streams at the permafrost thawing front of the Taiga Plains. Still, increased methylmercury concentrations may be expected as thaw continues. Including methylmercury as a parameter in transboundary monitoring programs is highly recommended.

It is unlikely that peatland permafrost thaw is responsible for the observed trends in metals over the last few decades in the large transboundary rivers. Due to particulate transport association, future changes in total metal concentrations are likely to be primarily influenced by the frequency and magnitude of high-flow periods. For example, in 2020, record high water levels in the Slave and Hay rivers corresponded with record high concentrations of particulate metals, including arsenic, lead, iron, and aluminum (Hinchey, 2020). Any potential increased release of metal from thawing peatlands is likely to be difficult to detect in the main stems of the transboundary rivers but may influence smaller peatland-rich headwater basins.

While the relationship between PoPs and permafrost thaw is a knowledge gap in the literature, some studies have pointed to the release of PoPs from glacial melt as an indicator that permafrost thaw may release PoPs. Available data from the transboundary region indicate detection of PoPs with a few exceedances of water quality guidelines and no connections drawn to permafrost. However, continued monitoring of PoPs is recommended.

Expanded monitoring of groundwater quality in the transboundary region should be implemented as data availability was severely limited. However, the most significant impacts on groundwater are likely to occur further north than the transboundary rivers, within regions transitioning from continuous to discontinuous permafrost. Although analysis of tritium in the transboundary region showed enhanced subsurface water contributions, it is likely that some groundwater connections are already established in the sporadic and discontinuous permafrost zone and further permafrost thaw is less likely to have large impacts on surface water quality.

The observed shifts to water quality and biogeochemistry that can be attributed to permafrost thaw are described in Table 8, where the key thaw-induced changes are detailed per basin in relation to the direction of change and the potential stressors/factors that contribute to the changes.

Table 8: Summary of thaw-induced changes to water quality and biogeochemistry observed in the transboundary area.

Thaw-induced change	**Location in study area**	**Direction of change & time frame**	**Stressors/Factors**	**References**
DOC concentrations	Hay River, Buffalo River	Highest in non-permafrost basins (2011)	Presence of permafrost dampened DOC while peatlands increased DOC	Olefeldt et al. (2014)
Phosphorus flux	Liard River	Increasing (seasonal, 1970s-2010s)	Winter trend - Follows streamflow trends, potentially driven by permafrost thaw	Shrestha et al. (2019)
Phosphorus concentrations	Notawhoka Creek (near Liard sub-basin)	Increasing (2016)	Permafrost thaw, wildfire	Burd et al. (2018)
Methylmercury concentrations	Scotty Creek basin (Liard sub-basin), Hay River basin	Increasing (2013); (2019)	Elevated methylmercury concentrations in permafrost-free fens that are expanding on landscape	Gordon et al. (2016); L. Thompson (unpublished data)
Tritium	Kakisa, Slave River	Increasing (2016, 2018)	Sourced from nuclear weapons testing in 1950s, mobilized by permafrost thaw	Bond & Carr (2018); Gibson et al. (2016)

8 Conclusions, knowledge gaps, and recommendations

The current and anticipated thaw-induced changes to the landcover, hydrology, and water quality of the transboundary regions that are detailed in this report are summarized in Figure 38 and Table i. A summary of identified knowledge and data gaps for the region, along with recommendations, is included in Table 9. Figure 38 is divided into ecoregions due to the distinct differences amongst the Taiga Shield and Taiga Plains, where the front-right portion of the figure visualizes the Taiga Shield, and the remainder visualizes the Taiga Plains. The figure represents summer conditions at the maximum annual thaw depth.

In the Taiga Shield, the ice-poor permafrost in the fractured Precambrian bedrock is likely to be present under depressions that are filled with fine-grained soils (silts and clays) or peatland. As permafrost thaws, the landscape changes may be limited to the peat plateaus that cover 5–10% of the region or altered lake extent. Thaw may result in enhanced groundwater flow pathways that deliver DOC and mercury from thawing peatlands to lakes, but research on the topic is inadequate. More research is needed on the impact of thaw on groundwater flow and biogeochemistry throughout the transboundary region.

In the Taiga Plains, the predominant permafrost landform is forested peat plateaus, under which ice-rich permafrost is present. Tamarack and black spruce uplands with insulating forest mosses may also be underlain with permafrost. Wildfire, human development, and increasing air temperatures are triggers for permafrost thaw. As ice-rich permafrost thaws, the land surface subsides, and the dry plateaus are replaced with waterlogged collapse bogs and fens. While the collapse bogs may initially be disconnected from other wetlands and temporarily increase groundwater storage, continued development of collapse wetlands and the expansion of channel fens that act as conduits for flow results in a higher runoff-producing landcover. Subsurface connectivity and groundwater flow likely increase and may contribute to increased annual and winter flows in rivers. Over time, collapse bogs may develop elevated hummocks with dry enough conditions to support the re-growth of black spruce, but this afforestation will most likely not support the regeneration of permafrost.

As permafrost thaws, the release of DOC, metals, and tritium from peat may increase, while wildfire may enhance the aquatic release of phosphorus. Waterlogged bogs and fens are environments that are more suited for the microbial production of methylmercury than dry peat plateaus; thus, lakes and rivers may see increased concentrations of methylmercury. Groundwater quality is a key knowledge gap in the transboundary region, and expanded monitoring is recommended. Continued monitoring of transboundary waters is required given the risks of parameters such as mercury to the health of people and wildlife.

Table 9. Identified knowledge and data gaps in the transboundary region and associated recommendations.

Knowledge/Data Gap	Recommendation
Taiga Shield – Limited studies in general have been conducted in the transboundary Taiga Shield. Detailed permafrost extent and probability mapping is absent. Lack of active layer thickness measurements precludes trend assessment. As such, little it known about the impacts of permafrost thaw on water quantity in this region.	Apply similar mapping approaches as Gibson et al. (2020) and Zhang et al. (2014) to the Taltson River basin in the Taiga Shield. Assess the reliability of applying research from the North Slave to the more remote Taltson River basin.
Ground Temperature – Long-term ground temperature measurements are largely absent outside the Mackenzie River Valley, which limits the accuracy of available permafrost maps.	Establish ground temperature monitoring networks and/or compile information from non-public databases. Ground truthing should be attempted in alignment with mapping efforts.
Lithalsas – The presence of lithalsas and other landforms in the transboundary Shield is possible but unconfirmed.	Mapping of permafrost landforms in the Taltson River basin should be conducted.
Permafrost Degradation in the Taiga Shield – Degradation rates in the transboundary Taiga Shield have not been determined.	Region-specific estimates of permafrost thaw rates should be made.
Groundwater Monitoring – Assessment is limited by the lack of groundwater monitoring wells.	Integrated water level monitoring from existing wells in the transboundary region should be implemented (e.g., AB Groundwater Observation Well Network, and Municipal and Community Affairs wells for waste management). A groundwater monitoring network within a set of regionally representative landscapes should be established to monitor change.

Knowledge/Data Gap	Recommendation
Streamflow and Baseflow – The cumulative effects of landcover change and subsurface reactivation on streamflow across the region are uncertain. Groundwater contributions to streamflow are often inferred, not physically measured.	Additional groundwater-surface water investigations that span diverse landscapes should be undertaken. Wherever possible, direct measurements/monitoring of groundwater discharge should be conducted.
Lake Extent – The long-term trajectory of lake extent in the Taiga Shield is poorly understood.	Assessment of multi-decadal changes in lake extent should be conducted to understand the trajectory of landscape change in the Taltson River basin. Such information could also help infer changes in sub-permafrost groundwater systems.
Icings – The influence of changing baseflows on riverine icing development remains a knowledge gap for the Taiga Plains transboundary region	Spatial and temporal areal mapping of riverine icings in the Taiga Plains may aid in revealing the rate of change in hydrologic connectivity at a basin-scale.
Water Quality Trend Assessment – Evaluations of long-term water quality trends in transboundary waters are available up until the early 2010s.	Reassessment of long-term water quality parameters for annual trends with most recent data; see Table B.4 and Table B.5 for monitoring programs and data repositories.
Methylmercury – Parameter of concern for health risks is not included in transboundary monitoring programs, and its production is predicted to increase with permafrost thaw in peatlands.	Addition of methylmercury as regularly sampled parameter for water quality monitoring programs.
Persistent Organic Pollutants – The impacts of permafrost thaw on persistent organic pollutants are uncertain, with potential increases projected downstream of thawing permafrost.	Continued monitoring of persistent organic pollutants, studies in the transboundary region that examine linkages between permafrost thaw and persistent organic pollutants.
Groundwater Quality – Despite projected increases of groundwater discharge and mixing with surface waters as thaw progresses, transboundary groundwater quality data are not publicly available, and analyses of long-term trends have not been conducted.	Analysis of groundwater quality sampled from Hay River GOWN wells is recommended. Monitoring of existing wells in the transboundary region should be implemented for water quality parameters to determine baseline quality and maintained long-term.

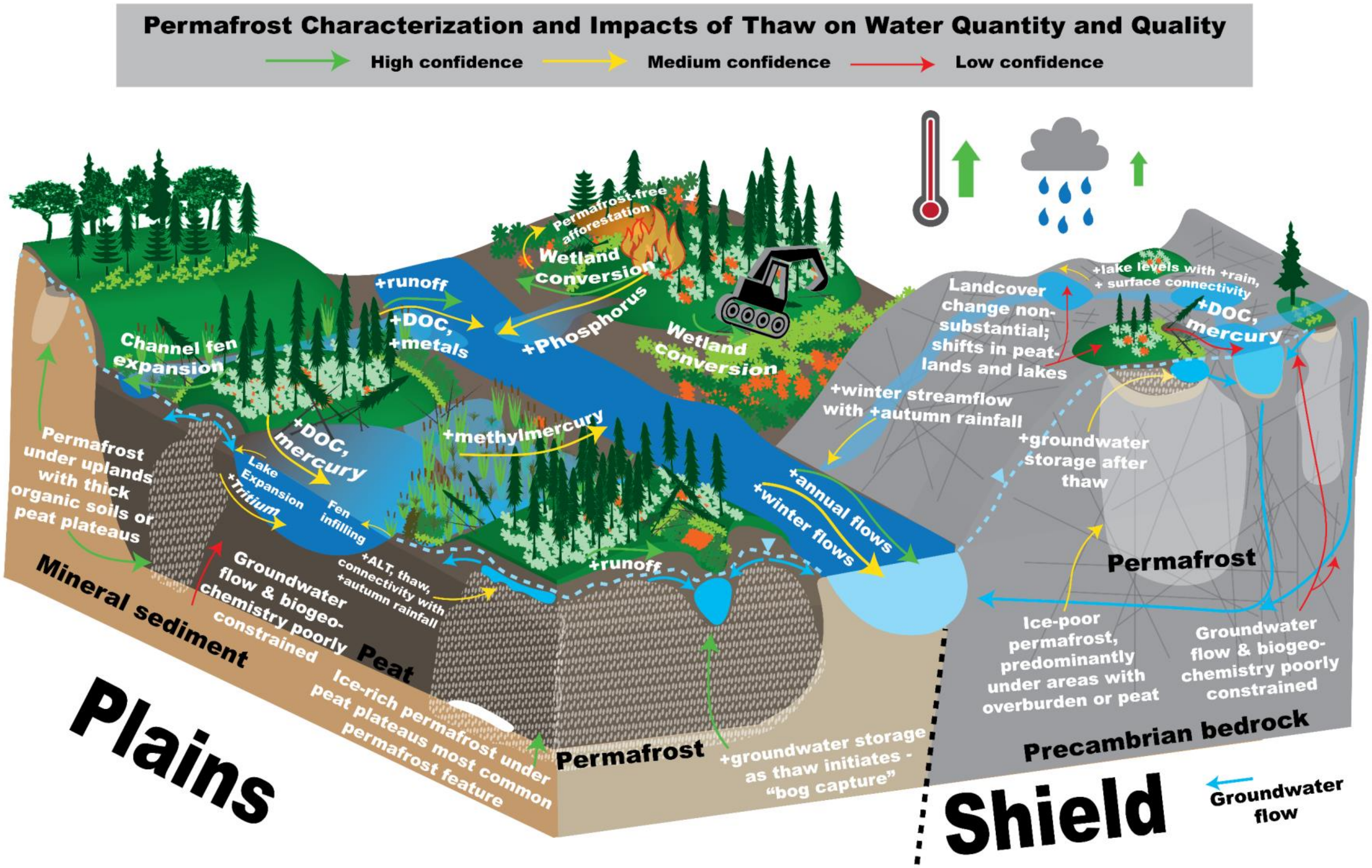

Figure 38. Permafrost characterization and impacts of thaw on water quantity and quality of the AB-NT transboundary region. Arrows correspond to confidence levels of thaw-induced changes where green indicates high confidence (data and studies available to support findings), yellow indicates medium confidence (data is available at select locations but more studies or data is required to better support findings), and red indicates low confidence (data is unavailable or not publicly reported across the transboundary region).

List of Figures

List of Tables

List of Abbreviations

AB	Alberta
ALT	Active layer thickness
AMAP	Arctic Monitoring & and Assessment Programme
BWMA	Bilateral Water Management Agreement
CALM	Circumpolar Active Layer Monitoring Network
$CWRVI_{PT}$	Canadian Water Resource Vulnerability Index to Permafrost Thaw
DDT	Dichloro-diphenyl-trichloroethane
DOC	Dissolved organic carbon
DOM	Dissolved organic matter
DZAA	Depth of zero annual amplitude
MAAT	Mean annual air temperature
MAGT	Mean annual ground temperature
NT	Northwest Territories
TDS	Total dissolved solids
TTOP	Temperature of the top of permafrost
TSS	Total suspended solids
PoPs	Persistent organic pollutants
PAHs	Polycyclic aromatic hydrocarbons
PCBs	Polychlorinated biphenyls

POC	Particulate organic carbon
RBBA	Risk-based basin analysis
ROW	Right-of-way
TOC	Total organic carbon

List of Terms

Definitions of the following terms have been sourced from the text Permafrost Hydrology by Woo (2012), The Canadian Wetland Classification System (Canada Committee on Ecological (Biophysical) Land Classification et al., 1997), or have been summarized from relevant literature cited within this report.

Active layer	is the surface zone lying above the permafrost that thaws and freezes seasonally.
Active layer thickness	is the maximum depth of seasonal thaw.
Advection	is horizontal or vertical transport of mass or energy by a fluid.
Aggradation	is the build up of permafrost through a drop of ground temperature below 0°C.
Albedo	is the fraction of the incoming short-wave radiation reflected by a surface.
Aquifer	is any water-saturated body of geological material from which enough water can be drawn at a reasonable cost for the purpose required.
Baseflow	is the streamflow component that is supported by groundwater sources. Separation of baseflow from direct runoff in a hydrograph is arbitrary as groundwater contribution can rarely be isolated on physical grounds.
Basin	is a hydrological unit that integrates hydrologic activities occurring spatially within its domain, guided by topography. Synonymous with *watershed, catchment*.
Bioaccumulation	is the net accumulation of a substance in an organism such that the substance is taken up at a rate greater than it is eliminated.
Bioavailable	describes availability for use or storage by an organism (bioavailability).
Biomagnification	is the process by which the concentration of a substance increases with increasing trophic level of a food-web.
Bog	is a wetland that receives its water primarily from atmospheric sources. Peat accumulation results in disconnection from groundwater and conditions tend to be acidic and nutrient-poor.
Collapse Scar (or collapse bog)	is a bog that develops within or adjacent to palsas or peat plateaus due to thaw-induced ground subsidence. When internal to peat plateaus, collapse scars are nearly circular to oval-shaped and expand outward as thaw persists.
Connectivity	in a strict sense, describes the topologic linkage among objects; it is liberally interpreted in hydrologic literature to describe the flow linkage in a drainage network in terms of its pattern (nodes and segments, sequencing), mode (surface or subsurface), and degree (continuous or ephemeral).
Cryopeg	is a zone that is perennially cryotic but remains unfrozen due to freezing point depression.
Cryotic	refers to the condition of materials at or below 0°C.
Depth of zero annual amplitude	is the distance from the ground surface downward to the level beneath which there is practically no annual fluctuation in ground temperature (for practical

	purposes, it is taken where the fluctuation is less than 0.1℃).
Discharge	is (1) the flow of water passing the cross-section of a conduit, such as a pipe or a channel, per unit time; (2) issuance of water from groundwater storage.
Dissolved	describes solutes that are able to pass through a filter (generally 0.7 – 0.22 µm).
Fen	is a wetland that receives its water supply from vertical as well as lateral sources and are richer in minerals due to groundwater connectivity relative to bogs.
Fen, floating	is a fen situated adjacent to ponds or lakes and are underlain by water or mixed water and peat. The peat surface is generally less than 0.5 m above the lake level, and the rooting zone may be in contact with the lake water.
Fen, horizontal	occupies broad, ill-defined depressions and occur on gentle slopes, characterized by featureless surfaces.
Fen, ribbed	develops on sloping terrain and are characterized by narrow, peaty ridges ("strings") that enclose open water pools or depressions of open water ("flarks") or wet fen surfaces. Synonymous with *string fen*.
Fen, shore	is a fen situated adjacent to lakes or ponds where peat forms the shore. The surface peat does not float and is firmly anchored.
Fill-and-spill concept	postulates that water has to accumulate to a particular level representing the threshold of flow blockage before it can spill over to an adjacent zone with a lower water level.
Frost mound	is a domed feature up to several meters high, with sediments covering a core composed mainly of injection ice.
Frost table	is the top of the frozen zone in the active layer; at its maximum depth, the frost table is the permafrost table.
Groundwater, intra-permafrost	groundwater that is found within the permafrost.
Groundwater, sub-permafrost	groundwater that is present beneath the permafrost.
Groundwater, supra-permafrost	groundwater that occurs above the permafrost.
Heat	is the energy transferred from a system of high temperature in contact with one of low temperature.
Heat Capacity	is a measure of the capacity of a substance to store heat.
Specific heat capacity	is the heat required to raise unit mass (or unit volume) of a substance by one degree of temperature.
Hummock (peat)	is a microtopographic, raised mound of peat and moss that can develop adjacent to a depression (hollow).
Hummock, earth	is a mound developed on cryoturbated ground. Synonymous with *thufa*.
Hydraulic conductivity	is a measure of the rate at which water can pass through a porous medium.

Hydrograph is a plot of discharge or other properties of flow against time.

Hydrophyte is a plant that grows in water or saturated soils.

Ice, excess is the volume of ice-melt water that exceeds the pore space available in the host material under natural unfrozen conditions.

Ice, pore is the ice occurring in the pores of soils and rocks, and is produced when soil water freezes in situ.

Ice, segregated forms discrete ice layers or lenses in freezing mineral or organic soils, as a result of the migration (and subsequent freezing) of pore water.

Ice wedge is formed of foliated or vertically banded ice. It has a wedge-shaped cross-section; and in plan form, it underlies the rims of large polygons.

Ice, vein is formed by water freezing in soil cracks and rock fissures, and pre-existing ice.

Icing (Aufeis) is layered or laminated ice formed by the freezing of water that seeps from the ground, flows from a spring or emerges from below a river bed or through fractures in river ice.

Linear disturbance describes human-induced land disturbances, including pipelines, roads, seismic lines that create networks of linear (straight) lines.

Lithalsa is a permafrost mound or ridge that forms in mineral-rich soils in warm discontinuous permafrost.

Marsh is a wetland that has shallow water, and has levels that usually fluctuate daily, seasonally or annually due to tides, flooding, evapotranspiration, groundwater recharge, or seepage losses.

Mass wasting is downward movement of slope materials under the influence of gravity.

Mercury is an element that occurs naturally in the earth's crust and can be released by rock weathering, volcanic activity, or human activity including fossil fuel combustion and artisanal gold mining. Mercury exposure, primarily through consuming fish and shellfish, can result in adverse health impacts.

Methylmercury is an organic, neurotoxic form of mercury (CH_3Hg^+) produced by microbes in anoxic environments that can bioaccumulate and biomagnify in food webs.

Nitrogen is a limiting nutrient, naturally sourced from soil erosion, atmospheric fixation, and plant matter, with the dissolved inorganic forms of nitrate, nitrite, and ammonium most bioavailable for organisms.

Organic carbon, dissolved is a complex mixture of dissolved organic compounds containing carbon that are produced in soil organic layers, vegetation canopy, and litter. Sometimes used interchangeably with *dissolved organic matter*, although dissolved organic carbon specifically to the mass of carbon in the dissolved organic material.

Organic carbon, particulate is a complex mixture of particulate-bound organic compounds containing carbon that are produced in soil organic layers, vegetation canopy, and litter.

Organic matter, dissolved a complex mixture of dissolved organic compounds that are produced in soil organic layers, vegetation canopy, and litter. Sometimes used interchangeably with *dissolved organic carbon*, although dissolved organic matter may be

	comprised of other elements including phosphorus, nitrogen, oxygen, and hydrogen.
Outcrop	is that part of the bedrock that is exposed at the ground surface (though it can be veneered by a thin layer of sediments and vegetation).
Overburden	is soil and rock materials that overlie a substratum of concern.
Palsa	is a peaty frost mound 1–7 m in height and 1–100 m in diameter. It is considered to grow by the build-up of segregated ice in the underlying mineral soil.
Paludification	is the process of peat formation, generally under anoxic, waterlogged conditions.
Particulate	describes solutes that are not able to pass through a filter (generally 0.7 – 0.22 µm).
Patterned ground	is a ground surface, mainly in permafrost areas, that exhibits some regular pattern due to an orderly arrangement of fissures, coarse materials or vegetation.
Peat	is an organic soil formed under waterlogged conditions. The dead plant materials are incompletely decomposed due to the prevalent anoxic conditions. The organic matter content should be no less than 20% of the dry weight.
Peat plateau	is a flat-topped expanse of frozen peat, elevated above (>1 m) the general surface of a wetland. Segregated ice lenses may, or may not, extend into the underlying mineral soil.
Permafrost	is bedrock, organic or earth material that has temperatures at or below 0℃ persisting over at least two consecutive summers.
Permafrost, continuous	90–100% areal coverage
Permafrost, discontinuous	50–90% areal coverage
Permafrost, isolated	10–50% areal coverage
Permafrost, sporadic	0–10% areal coverage
Permafrost table	is the top of the permafrost, normally being the maximum depth of the seasonal frost table.
Persistent organic pollutants	are organic compounds that are resistant to environmental degradation, known to bioaccumulate and biomagnify in food webs.
pH	describes how acidic or basic a solution is based on hydrogen ion activity, measured on a scale of 0-14 pH units where a pH of 7 is neutral, less than 7 is acidic, and greater than 7 is basic.
Phosphorus	is a key element for the growth of aquatic plants and is often a limiting nutrient to plant growth, naturally sourced from the weathering of phosphorus-bearing rock. Orthophosphate/phosphate is the inorganic form of phosphorus and most bioavailable for plant uptake.
Polychlorinated biphenyls	are persistent organic pollutants belonging to a group of human-produced organic chemicals consisting of carbon, hydrogen, and chlorine atoms. Manufacturing has

declined since the 1960s.

Polycyclic aromatic hydrocarbons are persistent organic pollutants that are comprised of at least two fused aromatic rings and are produced from natural and anthropogenic sources including coal, petroleum, vehicle emissions, forest fires, and volcanic eruptions.

Polygons are macro-scale patterned ground delineated by cracks measuring 10^1–10^2 m in length, that may be perpendicular to each other or show no preferred orientation.

Recharge is the addition of water to the groundwater reservoir.

Runnels refers to a surface flow network that conveys water.

Runoff is water (from rain, snowmelt, irrigation etc.) that flows horizontally through the surface or subsurface towards a stream or surface waterbody. It includes overland flow, return flow, interflow, and baseflow.

Specific conductance is a measurement of the ability of a solution to conduct electrical current as an indicator of the quantity of salts.

Streamflow is discharge that occurs in a natural channel.

Sub-permafrost water is water that occurrs in the unfrozen (>0°C) ground below the permafrost.

Supra-permafrost water is water that occurrs in the unfrozen (>0°C) ground above the permafrost. It occurs in the active layer, between the active layer and the permafrost table, and in taliks below rivers and lakes.

Suspended sediment is primarily fine inorganic particles of clay and silt (typically < 0.063 mm) suspended in the water column. It also may include fine sand (0.63-0.250 mm) and particulate organic matter.

Talik is unfrozen zone in a permafrost area. Synonymous with *thaw bulb*.

Talik, Closed A layer or body of unfrozen ground occupying a depression in the permafrost table below a lake or river.

Talik, Isolated A layer or body of unfrozen ground entirely surrounded by perennially frozen ground.

Talik, Open A body of unfrozen ground that penetrates the permafrost completely, connecting suprapermafrost and subpermafrost water.

Thawing front is the leading edge of a soil zone that undergoes thawing.

Thermal conductivity is a measure of the ability of a material to conduct heat.

Thermokarst refers to the karst-like topography that is produced as thawing occurs in ice-rich permafrost.

Total dissolved solids is a measurement of dissolved solids per volume of water. Solids are quantified from a filtered water sample.

Total suspended solids is a measurement of solid material per volume of water; all suspended solids by mass.

Tritium is a radioactive form of hydrogen that was released in Northern Canada from nuclear weapons testing in the 1950s.

Water table is the upper limit of the saturated zone in an unconfined aquifer.

Wetland is land saturated long enough during the growing season to develop hydric soil, support hydrophytes, or allow prolonged flooding.

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Appendix A: Maps

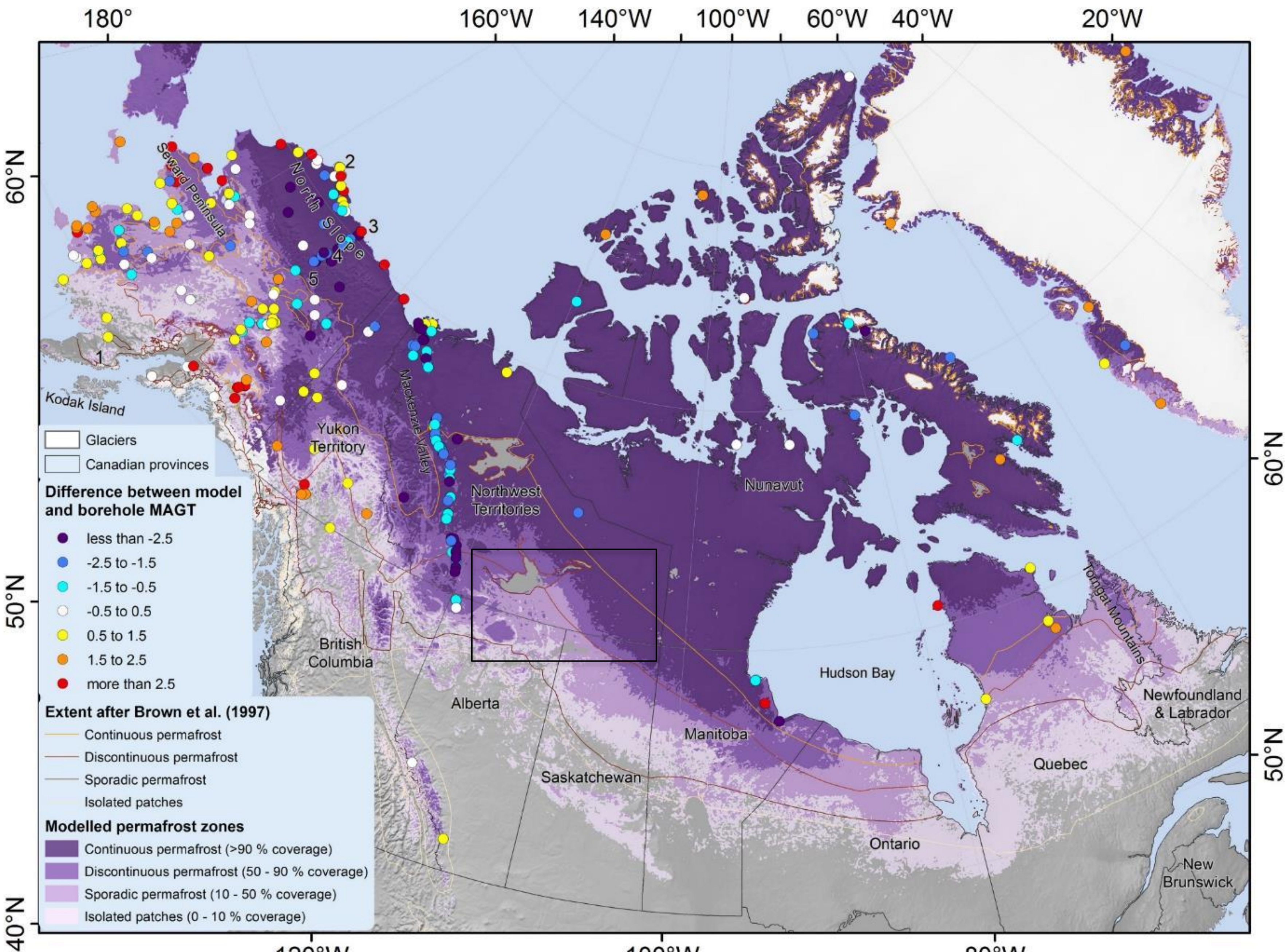

Figure A.1. Permafrost distribution across Canada from Obu et al. (2019) with comparison between model predictions, borehole data and Brown et al. (1997).

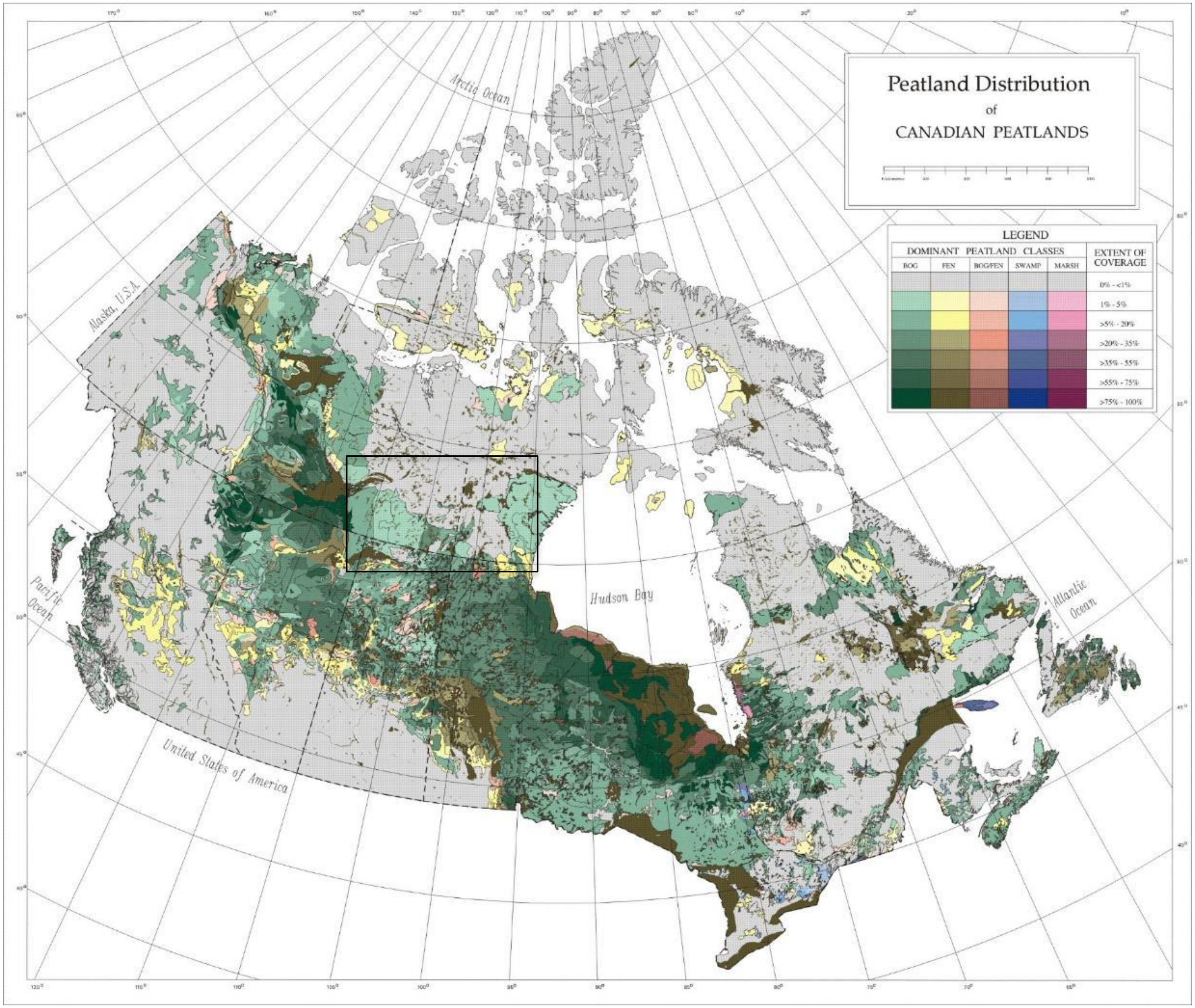

Figure A.2. Map of peatland distribution in Canada (Tarnocai et al., 2011).

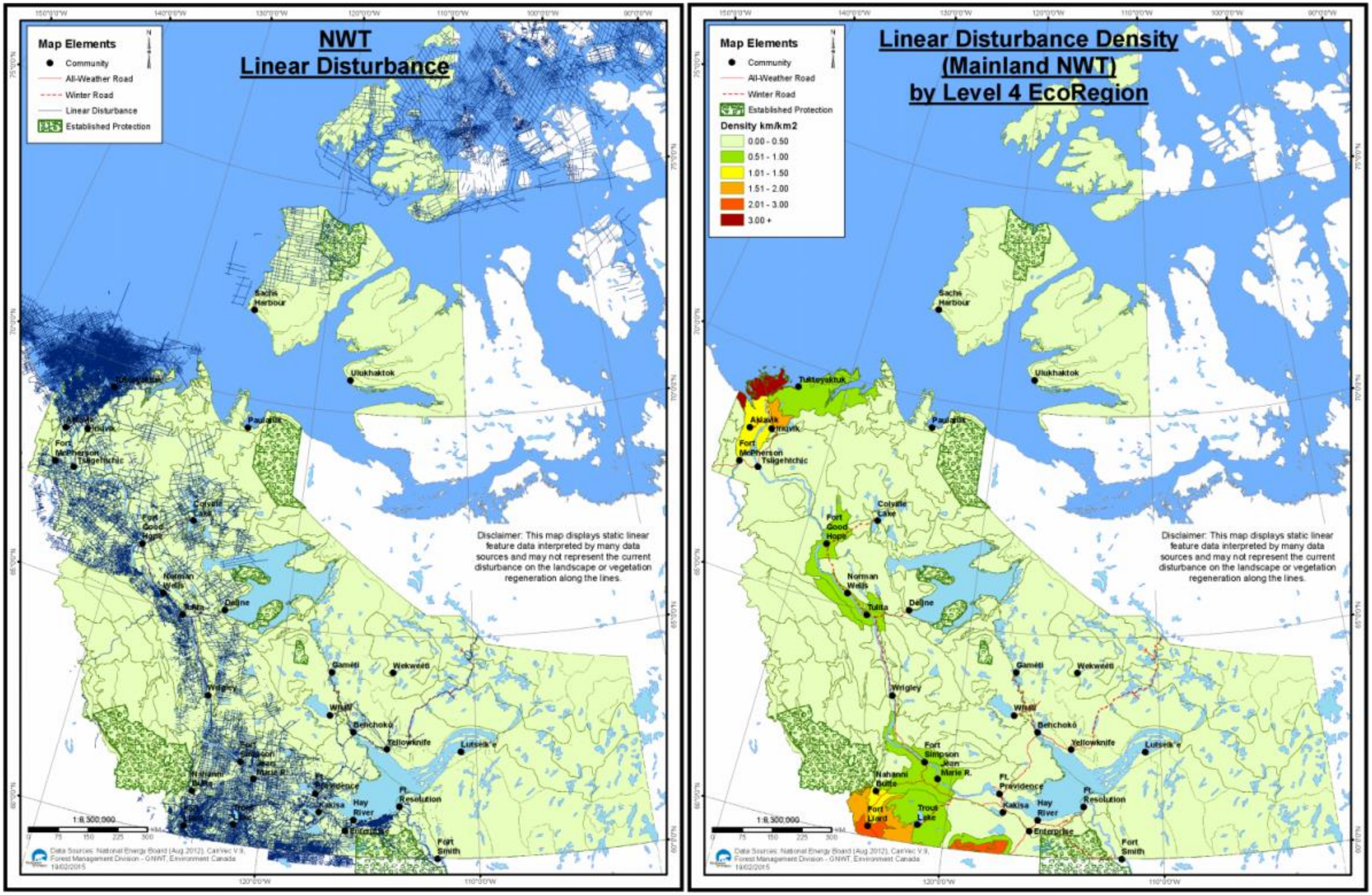

Figure A.3. Map of linear disturbances in the NT (left) and density of linear disturbances by level 4 ecoregion in NT (right) from Environment and Natural Resources (2016).

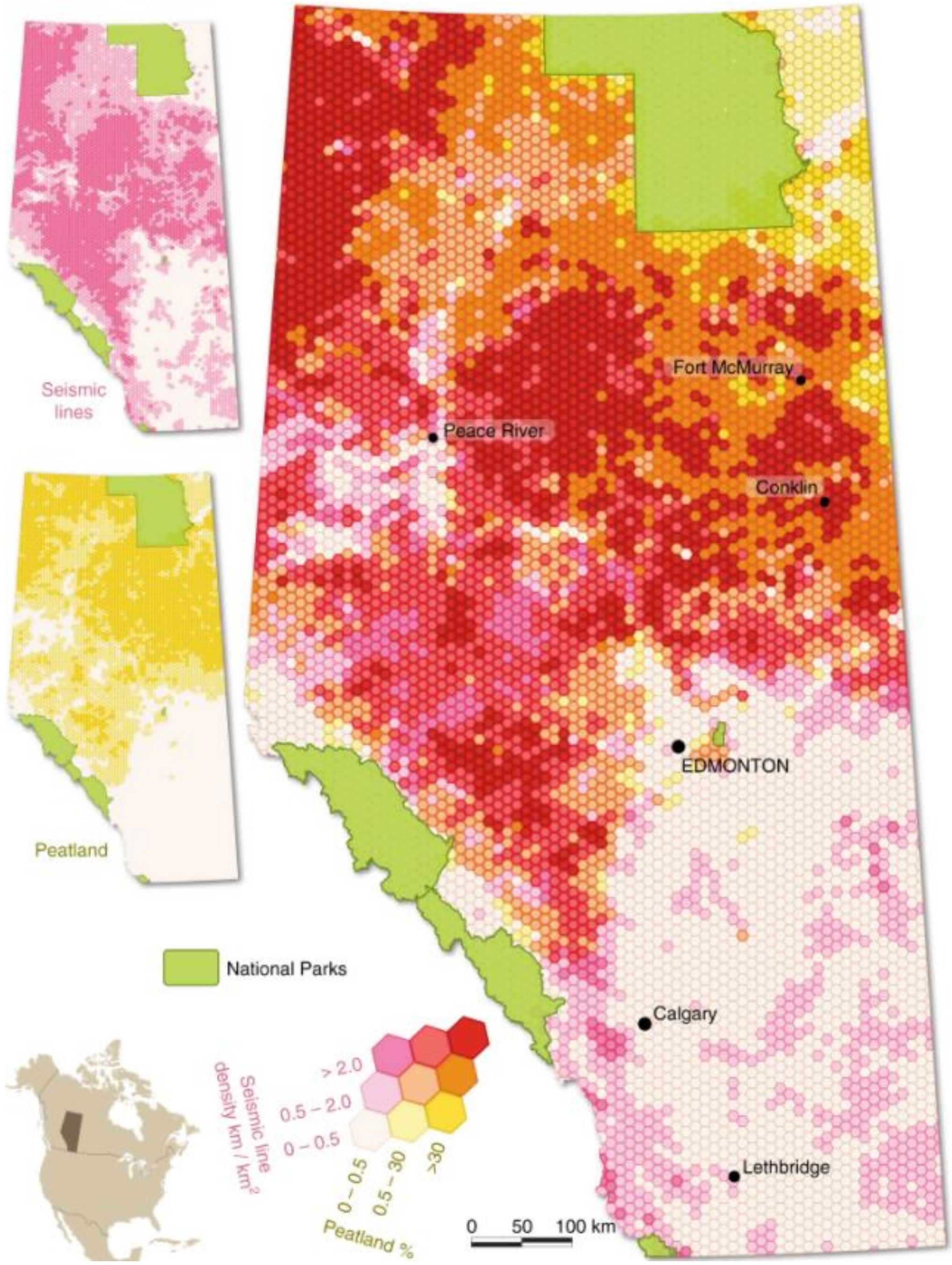

Figure A.4. The spatial overlap of peatlands and seismic lines in Alberta, Canada (Strack et al., 2019).

Appendix B: Tables

Table B.1. Summary of permafrost data along the Liard/Petitot River basin from Smith et al. (2013), retrieved from GTN-P (2016).

Site Name	Lat	Long	Permafrost Thickness (m)	MAGT (°C)	MAGT depth (m)	Date/period	Organic Layer Thickness (m)	Soil Type	Vegetation
Fort Simpson FS deep	61.838	-121.330	12	-0.3	6	Jan-Dec 2008	1.5	Sand	Boreal, spruce with hardwoods, Coniferous Forest
Manner's Ck. A-T4-85-8A	61.605	-121.093	12	-0.2	6	Jan-Dec 2007	0.5	Ice rich, massive ice lenses, silty clay	Coniferous Forest
Manner's Creek B-T4-85-8B	61.603	-121.091	4	-	-	-	2.4	Low ice content, silt, clay	Deciduous Forest
Liard spruce 97TC4	61.545	-121.392	8	-0.1	5	Sept 2007-08		Fine sand	Coniferous Forest
Petitot River N. A-T4-84-5A	59.758	-119.516	17	-0.2	6	Sept 2008-09	3.8	Ice rich, clay	Collapsing peat plateau, Coniferous Foreset
Petitot River N. B-T4-84-5B	59.757	-119.513	13.5	-0.1	4	Sept 2008-09	6.9	Ice rich, clay	Peat plateau, Coniferous forest
Petitot River S-T4-84-6	59.461	-119.246	6	-0.4	4	Sept 2007-08	5.6	Ice rich, clay	Peat plateau adjacent to fen depression, Coniferous Forest

Table B.2. Summary of permafrost characteristics for sites in the Hay River basin investigated by Holloway and Lewkowicz (2020)

Site	Lat	Long	Median Permafrost Table Depth (m)	Permafrost Thickness (m)	Organic Layer Thickness (m)	Soil Type	Canopy and Surface
3	60.75907	-115.8616	0.44	8	> 0.85	Clay, silt, with some stones	Spruce; moss, lab tea, willow, birch.
39	60.03948	-116.87433	0.61	5 to 8	1.2	Clay, silt	Spruce, tamarack, jack pine; hummocky sphagnum, lichen, lab tea
43	59.94423	-117.02242	0.51	5 to 8	> 0.48	-	Spruce, tamarack; sphagnum, moss, lichen, lab tea
54	59.87871	-117.04252	0.52	5	0.4	Clay	Spruce; hummocky sphagnum and moss, lichen, lab tea
63	59.61908	-117.17265	0.64	5	0.55	Organic, silt, sand	Spruce, hummocky sphagnum, moss, lab tea, lichen
72	59.37919	-117.30682	1.02	5	> 0.50	-	Spruce, birch; hummocky sphagnum, lab tea
75	59.19257	-117.54987	0.61	5	> 0.50	Silt, sand, gravel	Spruce; sphagnum, moss

Table B.3. Observed changes to permafrost, hydrologic and ecosystem variables in pan-Arctic regions for selected studies between 2000 and 2016. "Data gap" in last column denotes a lack of observational data to determine change in the attribute. Bolded locations and citations indicate observations occurred in the transboundary study area. Table reproduced from Walvoord & Kurylyk (2016).

Observed attribute	**Trajectory**	**Geographic location**	**Time frame**	**Selected references**
Permafrost distribution				
ALT	increase (1,2,6); variable (3,4); high inter-annual variability (5)	Subartic Sweden (1); Arctic Russia (2); Alaska, USA (3); Pan-Arctic (4); N Europe (5), E Siberia (6)	varies	(1) Åkerman & Johansson, (2008); (2) Mazhitova et al., (2008); (3) Osterkamp, (2005); (4) Hinzman et al., (2013); (5) Harris et al., (2009); (6) Brutsaert & Hiyama, (2012)
Spatial extent	8% (1); decrease by 38% (2)	Tanana Flats, Alaska, USA(1); **NW Territories, Canada (2)**	1949–1995 (1); 1947– 2008 (2)	(1) Jorgenson et al., (2001); **(2) Quinton et al., (2011)**
Open vertical taliks	inferred increase in abundance	Siberia	1973–2004	Smith et al., (2005); data gap
Lateral taliks	inferred increase† in abundance	Yukon Flats, Interior Alaska	1979–2009	Jepsen et al., (2013); data gap
Water flux				
Supra-PF flow	increase‡ (1); variable‡ (2)	Yukon River Basin, USA/Canada (1); N Sweden (2)	1950–2004 (1); 1910–2010 (2)	(1) Lyon & Destouni, (2010); (2) Sjöberg et al., (2013)
Lake/GW exchange	episodic localized increase (1); increased lake size due partly to PF thaw (2)	Seward Pennisula, Alaska, USA (1); E Siberia (2)	1950–2002 (1); 1992–2008 (2)	(1) Yoshikawa & Hinzman, (2003); (2) Fedorov et al., (2014)
Soil drainage	expected increase			data gap; expectations derived from modeling studies
Sub-PF flow	expected increase	discontinuous PF regions		data gap; limitations on measurement capability; indirect evidence from baseflow increases (see below)
Baseflow	increase	Yukon River Basin, USA/Canada (1); N Eurasia (2); **NW Territories, Canada** (3); pan-Arctic region (4)	past 3–7 decades	(1) Walvoord & Striegl, (2007); (2) Smith et al., (2007); **(3) St. Jacques & Sauchyn, (2009)**; (4) Rennermalm et al., (2010)
Water distribution				

Soil moisture	variable; depends on landscape position and other factors (1,2); increase (3)	Interior Alaska, USA (1,2); Abisko region Sweden (3)		(1) (Jorgenson et al., 2001); (2) O'Donnell et al., 2012; (3) Christensen, (2004)
Lake and wetland distribution	decrease (1); slight decrease in net area (2, 3)	Siberia (1); Old Crow Basin, Canada (2); Yukon Flats, Alaska, USA (3)	1973–2004 (1); 1951–2001 (2); 1979–2009 (3)	(1) Smith et al., (2005); (2) Labrecque et al., (2009) and references therein; (3) Rover et al., (2012)
GW storage	variable (1); increase (2)	Arctic (1); Lena River Basin, Eurasia (2)	2002–2008 (1); 2002–2010 (2)	(1) Muskett & Romanovsky, (2011); (2) Velicogna et al., (2012)
Aufeis	no change in spatial distribution; volume change unknown	Brooks Range, Alaska, USA	past 100+ yr	Yoshikawa et al., (2007)
River ice thickness	decrease, with variability in max. thickness reduction	northern latitude synthesis	records spanning 1912 to 2006	**Beltaos and Prowse, 2008 (a review)**
Ecosystem variables				
Shifts in vegetation structure and composition	overall increase in shifts: forest and plateau loss (1); birch forest shift to fens and bogs (2); shrub to graminoid dominance (3)	**NW Territories, Canada** (1); Alaska, USA(2); Abisko region, Sweden (3)	1947–2008 (1); 1949–1995 (2); 1970–2000 (3)	**(1) Chasmer et al., (2010); Baltzer et al., (2014);** (2) Jorgenson et al., (2001); (3) Christensen, (2004)
SW hydrologic connectivity	increase at local scale	**Scotty Creek, NW Territories, Canada**	1996–2012	**Connon et al., (2014)**
Subsurface hydrologic connectivity	expected increase			data gap
Seasonality of streamflow	decrease in max/min discharge ratio (1, 2); earlier spring melt (2)	Siberia (1); **NW Territories, Canada (2)**	1942–1998 (1); 1973–2011 (2)	(1) Ye et al., (2009); **(2) Yang et al., (2015)**
Seasonality of stream temperature	decrease: warming (cooling) trends in early (late) open-water season	Siberia	1950–1992	Liu et al., (2005)

† Includes supra-permafrost and intrapermafrost taliks.
‡ Using streamflow recession intercept as a proxy for assessing supra-permafrost flow.
ALT = active layer thickness; PF = permafrost; SW = surface water; GW = groundwater.

Various programs have been in place to monitor and archive water quality in the AB-NT transboundary watersheds undertaken by a combination of federal, provincial/territorial, or public programs (Table B.4). Eight databases have been identified that contain collected water quality data (Table B.5) where four databases are openly available, two databases have data potentially available upon request, and one database is accessible upon successful training (CABIN). Future analysis of water quality parameters could utilize these data to provide up-to-date long-term trends.

Table B.4. Current water quality monitoring programs in the AB-NT Transboundary Watersheds

Program Name	**Administration**	**Description**	**Scope**	**Water quality parameters**	**Archiving**
Transboundary Rivers Monitoring Program	GNWT: Environment and Natural Resources, Water Resources	The transboundary water quality sampling sites were established to characterize the water quality in the major transboundary rivers flowing into the NWT.	The transboundary rivers monitored include the Slave (est. 1990), Hay (est. 2004), Liard (est. 1991).	Temperature, pH, conductivity, dissolved oxygen, turbidity, alkalinity, sediment and water: phosphorus, nitrogen, major ions, metals, total suspended solids, benthic macroinvertebrates	Partially available in the Lodestar database
Canadian Aquatic Biomonitoring Network (CABIN)	Environment and Climate Change Canada	Aquatic biomonitoring program for assessing the health of freshwater ecosystems in Canada.	> 100 NWT sites sampled by various organizations. Sites are generally sampled once or twice annually. The number of new sites added varies yearly.	Temperature, pH, conductivity, dissolved oxygen, turbidity, alkalinity, phosphorus, nitrogen, major ions, metals, total suspended solids, benthic macroinvertebrates	CABIN database
Community-Based Water Quality Monitoring	GNWT: Environment and Natural Resources, Indigenous governments and communities, Aboriginal Aquatic Resource and Oceans Management (AAROM) Community-based Monitoring	Aquatic monitoring program partnership to support community development and implementation.	Monitoring began in 2012 where stations are visited monthly during ice-free season to change equipment and collect grab samples. Stations include Slave River, Hay River, Liard River, Mackenzie River, Kakisa River, Great Slave Lake	Grab samples: Temperature, pH, conductivity, dissolved oxygen, nutrients, ions, metals, mercury, bacteriology, chlorophyll-a. Continuous monitoring: temperature, conductivity, pH, oxidation/reduction potential, dissolved oxygen, turbidity, chlorophyll. Passive sampling: dissolved polycyclic aromatic hydrocarbons, dissolved metals, methylmercury, vanadium.	Mackenzie DataStream, Lodestar database, NWT Discovery Portal

Cumulative Impacts Monitoring Program (CIMP)	GNWT: Environment and Natural Resources, Conservation, Assessment and Monitoring, Indigenous governments	Collection, analysis and reporting of information related to environmental conditions in the NWT.	CIMP was initiated in 1999. Three priority valued components are caribou, water, and fish; over 50 funded projects listed water as a valued component.	Various parameters depending on the project.	NWT Discovery Portal, Mackenzie DataStream
Nahanni National Park Reserve Water Monitoring Program	Environment and Climate Change Canada, Parks Canada	A joint, ongoing program to monitor ecological integrity of Nahanni National Park National Park	Water samples have been collected since 1988 and expanded subsequently to sites on Flat River, South Nahanni River, and Prairie Creek.	Total and dissolved metals, major ions, physical parameters, nutrients, organics, cyanide	Aquatic Chemistry and Biology Information System /National Long-term Water Quality Monitoring Data
Northern Water Quality Monitoring Network	Environment and Climate Change Canada	Collection of baseline data and reference conditions for northern rivers.	The program began in the 1960s and includes Liard River and the Great Bear River, and samples are collected 3-6 times per year.	Physical parameters, total and dissolved metals, major ions, nutrients, organics	Aquatic Chemistry and Biology Information System /National Long-term Water Quality Monitoring Data
NWT Drinking Water Quality Monitoring	GNWT: Health and Social Services, Municipal and Community Affairs, and Public Works and Services, Stanton Health Authority	Monitoring program to ensure Water Treatment Plant infrastructure is in good condition, and is being operated and maintained safely.	Initiated between 1994 and 2007, depending on the community, water quality parameters are tested at various intervals. Includes Fort Liard, Fort Simpson, Kakisa, Fort Smith, Hay River	*E. coli* and total coliforms (weekly on treated water sample), chlorine (daily on treated water sample), turbidity (daily on untreated water sample), trihalomethanes (quarterly on treated water sample), full suite of chemical and physical parameters (annually on treated sample)	Online Drinking Water Quality Monitoring Database
NWT-Alberta Inter-Jurisdictional Rivers Program	Environment and Climate Change Canada and Alberta Environment and Parks	This partnership monitors the water quality of rivers flowing from Alberta to the NWT in the Mackenzie River Basin.	Hay River has sampled six times per year at the NWT/Alberta border since 1988 and Slave River has been sampled eight times per year near Fort Fitzgerald since 1960.	Physical parameters, major ions, total and dissolved metals, bacteriological, nutrients, PAHs, ammonia (since summer 2011), organochlorines (1 time/yr)	Aquatic Chemistry and Biology Information System /National Long-term Water Quality Monitoring Data

Oil Sands Water Quality Monitoring	Environment and Climate Change Canada and Alberta Environment and Parks	This partnership evaluates pollutants in watersheds of the Alberta oil sands region and coincides with the Wood Buffalo National Park monitoring program in some locations.	A portion of this monitoring program take place in Slave, Athabasca and Peace River watersheds at 12 locations in the NWT and Northern Alberta, initiated in 2010. Water quality is sampled 2 to 10 times annually.	Grab samples: Physical parameters, major ions, nutrients, bacteriological, organics, total and dissolved metals, phenol, petroleum hydrocarbons, BTEX, ammonia. Passive sampling: PAHs, dioxins, furans, pesticides	Aquatic Chemistry and Biology Information System /National Long-term Water Quality Monitoring Data
Surveillance Network Program	Mackenzie Valley Land and Water Board	Water quality is monitored at the outflow of sewage lagoons and at the landfill, or other locations under a type A or B water license.	Between 1970s and current depending on community: includes Fort Smith, Fort Simpson, and Hay River (Type A), and Fort Liard and Enterprise (Type B).	Physical parameters, major ions, nutrients, total and dissolved metals (including mercury), solids, organics, bacteriological, phenols, petroleum hydrocarbons, BTEX, ammonia	Annual reports and SNP reports are posted on the Mackenzie Valley Land and Water Board public registry.
Wood Buffalo National Park Water Monitoring Program	Environment and Climate Change Canada, Parks Canada	A joint, ongoing program to monitor ecological integrity of Wood Buffalo National Park	Water samples have been collected at sites on Athabasca River, Peace River, and Birch River since 1988 on the Alberta side of the park and coincide with the Oil Sands Water Quality Monitoring program	Grab samples: Physical parameters, major ions, nutrients, bacteriological, organics, total and dissolved metals, phenol, petroleum hydrocarbons, BTEX, ammonia. Passive sampling: PAHs, dioxins, furans, pesticides	Aquatic Chemistry and Biology Information System /National Long-term Water Quality Monitoring Data

Table B.5. Data repositories for water quality in the AB-NT Transboundary Watersheds.

Database Name	**Administration**	**Description**	**Availability**	**Water quality parameters**	**Access link**
Aquatic Chemistry and Biology Information System (ACBIS)/National Long-term Water Quality Monitoring Data	Environment and Climate Change Canada	Data management system to store, track, verify, and distribute data to clients. Users include project managers, field personnel, and internal staff. Data from monitoring of the Lower Mackenzie River Basin and the Peace – Athabasca River Basin has been recorded for >15 years.	To access the database, users need an approved SQL Server account. Common water quality variables by watershed are uploaded to the open access National Long-term Water Quality Monitoring Data, and special data requests of provisional or raw data may be accommodated.	>1900 potential parameters including water temperature, pH, conductivity, dissolved oxygen, turbidity, alkalinity, chlorophyll-a, total suspended solids, total dissolved solids, nutrients, major ions, dissolved and total metals; Sediment parameters include dioxins and furans, herbicides, napthenic acids, PAHs, PCBs, pesticides	Lower Mackenzie River Basin Long-term Water Quality Monitoring Data; Peace-Athabasca River Basin Long-term Water Quality Monitoring Data

Canadian Aquatic Biomonitoring Network (CABIN)	Environment and Climate Change Canada	Aquatic biomonitoring program for assessing the health of freshwater ecosystems in Canada.	Federally collected data is available per drainage area on the Open Government Portal - Canada.ca; Access is granted to full CABIN database after completing training modules	Temperature, pH, conductivity, dissolved oxygen, turbidity, alkalinity, phosphorus, nitrogen, major ions, metals, total suspended solids, benthic macroinvertebrates	Water: CABIN
Mackenzie DataStream	The Gordon Foundation	Mackenzie DataStream is an open access platform for sharing water quality information in the Mackenzie Basin. Data Stewards (contributors) upload standardized data from estuaries, lakes/ponds, ocean, rivers/streams, or wetlands.	Open data is available on the Mackenzie DataStream, a searchable map-based interface. Potential contributors from research institutions, government, or communities contact the foundation (datastream@gordonfn.org) to receive data upload templates and access to the website as a Data Steward.	>6300 potential parameters including temperature, pH, conductivity, dissolved oxygen, turbidity, alkalinity, chlorophyll-a, major ions, metals, fecal coliforms, E. Coli, cyanide, total dissolved solids	Mackenzie DataStream
Mackenzie Valley Land and Water Board Resources	Mackenzie Valley Land and Water Board	Regulatory authority that originates from Mackenzie Valley Resource Management Act.	Reports and studies from the Surveillance Network Program are available on the public registry. Search document sub type with keyword "SNP Reports" with options to filter by location.	Physical parameters, major ions, nutrients, total and dissolved metals (including mercury), solids, organics, bacteriological, phenols, petroleum hydrocarbons, BTEX, ammonia	MVLWB
NWT Discovery Portal	GNWT, Centre for Geomatics and NWT Cumulative Impacts Monitoring Program (CIMP)	The portal includes information, traditional knowledge, baseline studies, monitoring, and scientific research. Contributors include communities, industry, NGOs, academics, and government departments and agencies.	Open data is available on the Discovery Portal. To access water quality data, filter using keywords "Cumulative Impact Monitoring Program (CIMP)", "Water Quality", and "Water and Sediment Quality"	Data upload can be in a variety of formats with a variety of water quality parameters. Metadata standards are enforced.	NWT Discovery Portal

NWT Drinking Water Quality Database	Government of the Northwest Territories: Health and Social Services, Municipal and Community Affairs, and Public Works and Services, Stanton Health Authority	Monitoring program to ensure Water Treatment Plant infrastructure is in good condition, and is being operated and maintained safely.	Open data is available on the Municipal and Community Affairs website.	*E. coli*. total coliforms, chlorine, turbidity, trihalomethanes, alkalinity, metals, nutrients, pH, total dissolved ions, total suspended solids	Online Drinking Water Quality Monitoring Database
NWT Lodestar	Government of the Northwest Territories Environment and Natural Resources, Indigenous and Northern Affairs Canada	Lodestar is an online database for archiving environmental data across the Northwest Territories from site investigations, remediation projects, and long-term monitoring programs.	Data are available on request from the database managers.	>1100 potential parameters including water temperature, pH, conductivity, dissolved oxygen, turbidity, alkalinity, chlorophyll-a, total suspended solids, total dissolved solids, nutrients, major ions, dissolved and total metals; Sediment parameters include dioxins and furans, herbicides, napthenic acids, PAHs, PCBs, pesticides	Contact nwtwaterstrategy@gov.nt.ca
Water Quality Data Portal	Alberta Environment and Parks	Alberta Environment and Parks, and its partners, collect surface water quality samples in rivers, lakes and other water bodies across the province of Alberta.	Open data is available on the Water Quality Data Portal, a map-based tool to search for stations in Alberta. Contains Lake Water Quality Data, Long Term River Station Data, Station Inventory, Trophic Condition of Alberta Lakes	Temperature, pH, conductivity, dissolved oxygen, turbidity, alkalinity, chlorophyll-a, Secchi disk transparency, true colour, major ions, metals, fecal coliforms, E. Coli, cyanide, total dissolved solids	WQP