Thaw-induced impacts on land and water in discontinuous permafrost: A review of the Taiga Plains and Taiga Shield, northwestern Canada

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Abstract

Rising air temperatures, intensifying wildfire activity, and human disturbance are driving rapid permafrost thaw across the subarctic, particularly for thaw-sensitive discontinuous permafrost. The Taiga Plains and Taiga Shield ecozones of northwestern Canada have experienced rapid and widespread permafrost thaw over recent decades, creating significant community concerns and knowledge gaps. In direct response, this review: (1) outlines the observed thaw-induced changes in landcover, hydrology, and water quality; (2) discusses the underlying drivers and mechanisms of these changes; and (3) identifies knowledge gaps to guide future research in the discontinuous permafrost zone of the Taiga Plains and Shield (study region). In the Taiga Plains, permafrost is mainly associated with peatlands where its thaw increases the extent of thermokarst wetlands at the expense of treed peatlands underlain by permafrost. This thaw-induced landcover change enhances the hydrological connectivity of the landscape, which increases basin-scale runoff and annual streamflow, and enables wetland drainage such that permafrost-free treed wetlands develop. Thaw-induced landcover changes in the lake- and bedrock-dominated Taiga Shield are not well known but are expected to occur as limited or minor thermokarst pond development and changing lake extent due to the low (<5%) peatland coverage of this ecozone. Permafrost thaw also increases the connectivity between surface water and groundwater, leading to increasing winter baseflows and possibly icing (aufeis) development. Such increases in hydrologic connectivity can enhance the mobilization of parameters of concern for water quality, both in the Taiga Plains and Shield. The thawing of peatlands will likely increase the transport and concentrations of dissolved organic carbon and metals bound to organic compounds, including methylmercury. Further work is needed to fully understand the biogeochemical processes operating in these systems and the degree to which thawing peatlands will impact water quality and quantity at the larger basin scale. The greatest knowledge gaps across the study region surround the evolution of thaw-activated groundwater flow systems and the consequences for wetland biogeochemistry, the rates and patterns of permafrost thaw, contaminant transport, and streamflow of larger river systems. This synthesis not only informs future research directions in the study region but extends to similar subarctic peatland and Shield environments common throughout the circumpolar north.

Key words: Permafrost; Peatlands; Hydrologic Connectivity; Hydrology; Water Quality; Landcover Change

1 Introduction

Northwestern Canada is warming at nearly twice the global rate (Box et al., 2019; Vincent et al., 2015), leading to widespread permafrost thaw (Gibson et al., 2021). Discontinuous permafrost is highly vulnerable to thaw (Spence et al., 2020) since fragmented permafrost bodies receive vertical and lateral conduction (Devoie et al., 2021). It is also relatively thin and warm (isothermal at the freezing point), so even slight increases in temperature or changes in the surface energy balance from anthropogenic or natural disturbance can lead to permafrost thaw (Quinton et al., 2009). As such, the southern fringe of the discontinuous permafrost zone is experiencing some of the highest rates of areal permafrost thaw (Helbig et al., 2016). Here, permafrost extent has decreased between ~10–50% over the last 50–60 years (Beilman and Robinson, 2003; Chasmer and Hopkinson, 2017; Holloway and Lewkowicz, 2020; Quinton et al., 2011; Zhang et al., 2014), with evidence suggesting the southern permafrost boundary is migrating northward (Kwong and Gan, 1994). In addition, wildfires in the northern hemisphere are increasing in frequency, severity, and quantity (Hanes et al., 2019; Jafarov et al., 2013; Wotton et al., 2017; Zhang et al., 2015) which is further accelerating rates of permafrost thaw (Gibson et al., 2018).

There are growing concerns from Indigenous groups in this region who have occupied their lands since time immemorial and are directly impacted by climate change (Mackenzie River Basin Board, 2021). Permafrost thaw is rapidly transforming terrestrial and aquatic ecosystems and changing water quantity and quality, which impact wildlife and fish, and threaten to change traditional access routes. These changes, combined with expanding resource development projects and increasing road access, have stimulated new research within the region, including Indigenous-led land monitoring (e.g., Dene Tha' First Nation, 2021; Government of the Northwest Territories, 2020; Indigenous Leadership Initiative, 2021) and initiatives that document climate-driven changes (e.g., Christensen, 2015; Guyot et al., 2006; Parlee & Maloney, 2017). Several recent reviews have focussed on broad-scale thaw-induced terrestrial impacts (Jin et al., 2020; Quinton et al., 2009), hydrology (e.g., Bring et al., 2016; Kokelj and Jorgenson, 2013; McKenzie et al., 2021; Walvoord and Kurylyk, 2016; Woo et al., 2008), and water quality (Cochand et al., 2019; Frey and

McClelland, 2009; Miner et al., 2021a; Tank et al., 2020; Vonk et al., 2015, 2019), all of which note that region-specific characteristics control landscape response to permafrost thaw. However, due to interdisciplinary barriers, how changes in landcover, hydrology, and water quality affect each other is rarely discussed. Considering this region is one of the most rapidly warming (Vincent et al., 2015) and hydrologically evolving on Earth (Mack et al., 2021), an in-depth and region-specific review for the southern Taiga Plains and Taiga Shield is necessary to identify knowledge gaps and guide future research in the region. Here, we provide a detailed overview of permafrost thaw impacts that account for feedback and linkages among landcover, hydrology, and water quality components.

2 Study Region

This review focuses on the southern portion of the discontinuous permafrost zone of the Taiga Plains and Taiga Shield ecozones of western Canada (Figure 1). The study region lies within the traditional lands of many Indigenous groups and Nations including the Denendeh (Dënësųłıné Nëné), Dene Tha', Michif Piyii (Métis), Northwest Territory Métis Nation, Dehcho Dene, Acho Dene Koe, Akaitcho Dene, Kátł’odeeche First Nation, Salt River First Nation, and Kaska Dena Kayeh, Sahtu Dene and Métis, Tłı̨chǫ Nation, Dahlu T’ua, Tes-He-Olie Twe, Kisipakamak, and Athabascan Chipewyan First Nations. Permafrost extent (Figure 1a) generally follows mean annual air temperature (MAAT) trends (Brown et al., 1997), with increased extent at higher elevations (Gruber, 2012). For example, the Horn Plateau (Figure 1a-i) and the Caribou Mountains (Figure 1a-ii) have greater predicted permafrost extents than surrounding areas. Permafrost maps for the northern hemisphere were also developed by Obu et al. (2019), but the sporadic permafrost zone of the Canadian subarctic had the lowest model accuracies for Canada and predicted mean annual ground temperatures (MAGT) overestimated borehole measurements. Higher resolution (e.g., 15 m) permafrost probability models have been generated for northern Alberta (Pawley and Utting, 2018) but are lacking for the rest of the study area. Excess ice (i.e., segregated ice and wedge ice) abundance in the top 5 m of permafrost is generally low (<15%) or absent (Brown et al., 1997; O'Neill et al., 2019), particularly in the bedrock of the Taiga Shield. Relatively high excess ice abundance (5–10%) is predicted in the eastern portion of the Taiga Plains south of Great Bear Lake (O'Neill et al., 2019). Due to the distinct characteristics of the Taiga Shield and Taiga Plains, separate detailed descriptions of the ecoregions are discussed below.

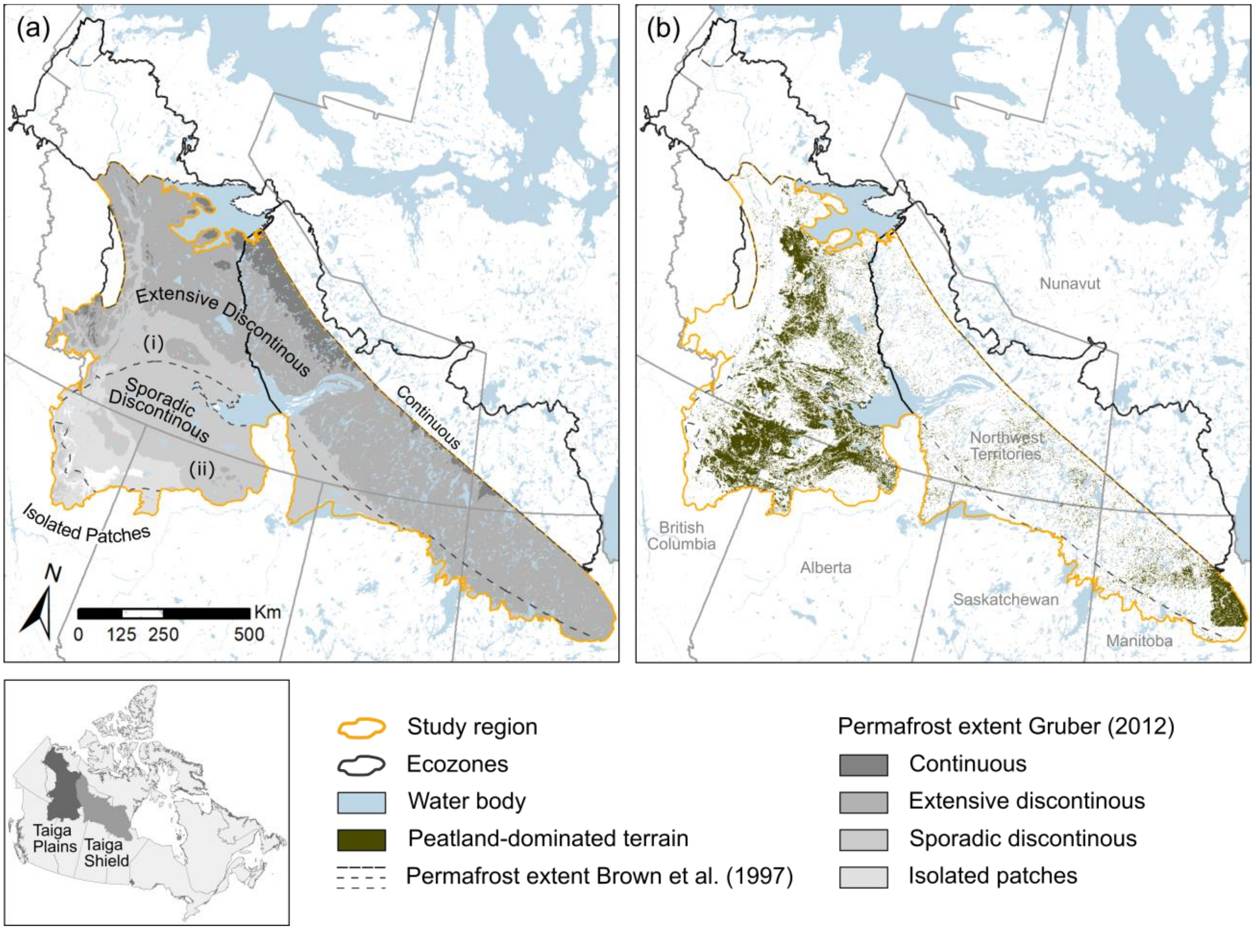

Figure 1. (a) Permafrost extent within the Taiga Plains and Taiga Shield ecozones after Gruber (2012) and compared to Brown et al. (1997). The study region excludes the continuous permafrost zone based on the extent from Brown et al. (1997), but includes sporadic (<10% areal coverage), isolated (10-50% areal coverage), and extensive discontinuous permafrost (50-90% areal coverage). The influence of topography on permafrost extent can be seen over the (i) Horn Plateau and (ii) Caribou Mountains. (b) Predicted distribution of peatland-dominated terrain in the Taiga Plains and Taiga Shield. Peatland-dominated terrain was mapped using a saturated soils dataset (Natural Resources Canada, 2017) following methods described in Carpino et al. (2021). Note that ecozone boundaries are based on the National Ecological Framework for Canada, where the Slave River corridor falls within the Boreal Plains Ecoregion (Ecological Stratification Working Group, 1995).

2.1 Taiga Plains

The Taiga Plains is characterized by low relief, poor drainage, and thick organic deposits (up to 8 m) with a peatland extent that covers nearly half the total area (Ecosystem Classification Group, 2009; McClymont et al., 2013; Tarnocai et al., 2011). The Taiga Plains developed with the recession of the Laurentide Ice Sheet, as evidenced by the till plains in uplands and widespread lacustrine deposits remnant of the vast postglacial Lake McConnell (Lemmen et al., 1994). MAAT and average annual precipitation (1981–2010) generally decreases with increasing latitude ranging from -1.0℃ to -5.1℃ and 294 mm/yr to 451 mm/yr (ECCC, 2021).

Permafrost in the Taiga Plains study area is relatively thin (1.5 m to 17 m) and warm (-2ºC to -0.2ºC) with permafrost temperature decreasing and thickness increasing with latitude (Brown, 1964; Burgess and Smith, 2000; GTN-P, 2016; Holloway and Lewkowicz, 2020; Smith et al., 2013, 2010). Here, permafrost is strongly linked to peatlands with dry ground surfaces (e.g., peat plateaus, palsas), particularly in warmer regions, due to the thermal buffering provided by unsaturated peat (hereafter, permafrost peatlands). The low thermal conductivity of dry peat (~0.06 W/m·K) insulates against ground heating in the summer, and the high thermal conductivity of saturated/icy peat (~1.9 W/m·K) facilitates ground cooling in the winter (Woo, 2012). The highest concentration of permafrost peatlands within the study region (Figure 1b) occurs along the central corridor of the Taiga Plains (Gibson et al., 2021; Hugelius et al., 2020; Tarnocai et al., 2011). The region has epigenetic permafrost conditions where peatland development began ~8,500 years ago while permafrost aggradation occurred 1,200–4,500 years ago (Heffernan et al., 2020; Pelletier et al., 2017).

Tree-covered peat plateaus are the predominant permafrost landform in the Taiga Plains, followed by palsas and polygonal peat plateaus (definitions in Table 1). Peat plateaus are commonly found in wetland environments covered by black spruce trees because the ground surface is raised 1–3 m above surrounding wetlands (Figure 2a,c; Quinton et al., 2003; Zoltai and Tarnocai, 1974) and therefore provide sufficiently dry conditions to support the shallow (0.2 m) root system of black spruce trees (Viereck and Johnston, 1990). Permafrost in the Taiga Plains also occurs in mixed-forest uplands with fine-grained mineral sediment (silts and clays) overlain by >0.3 m of organic cover (Holloway and Lewkowicz, 2020). Organic layers of sufficient thickness are the primary control on permafrost occurrence, followed by fine-grained substrate (Burgess and Smith, 2000).

Common permafrost thaw features in the Taiga Plains include collapse scar wetlands (bogs and poor fens; Figure 2a,d) and lakes that develop as ice-rich permafrost thaws and the overlying ground surface subsides, causing peat plateaus to collapse internally and along plateau margins (Zoltai, 1993). This thaw-induced ground surface subsidence/inundation and land-cover change is also referred to as thermokarst (Harris et al., 1988). Thermokarst wetlands can either be relatively small (tens of meters) and isolated within a peat plateau (i.e., isolated bog; Figure 2d) or interconnected (i.e., poor fens) and eventually drain to broad, linear channel fens (Figure 2a,e) that route water to the basin outlet (Connon et al., 2014; Quinton et al., 2009b; Vitt et al., 1994). At the larger scale, these major landcovers form plateau-wetland complexes comprised of peat plateaus with internal thermokarst wetlands that are separated by channel fens (Figure 2a). Most plateau-wetland complexes in the study region south of 62° latitude exhibit a high (67–100%) degree of thaw based on the area covered by thermokarst wetlands (Gibson et al., 2020), with 70% of permafrost projected to completely disappear by 2100 (Gibson et al., 2021). Cyclical permafrost aggradation and degradation of permafrost peatlands have been common throughout the Holocene period, but the rate of permafrost thaw has rapidly increased in recent decades (Chasmer and Hopkinson, 2017; Turetsky et al., 2020; Zoltai, 1993).

Table 1. Characteristics of permafrost landforms found in the study region in order from most common to least common.

Permafrost Landform	Stratigraphy & Size	Active layer thickness	Permafrost thickness & temperature	Ice content (% by volume)	Segregated ice	Occurrence in study region
Peat Plateau (PP): 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 [13].	1.5–8.0 m of peat overlying fine-grained sediment [1-4] 10s to 100s of meters wide [1].	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: A peaty permafrost mound with a core of alternating layers of segregated ice and peat or mineral soil [13].	3.5–6.5 m of peat overlying fine-grained sediment [1] 10–30 m wide, <5 m tall [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 mineral soil [1]	Less common [7,8]
Polygonal Peat Plateau: A peat plateau with ice-wedge polygons [13].	0.9–3.6 m of peat overlying fine-grained sediment [1] Polygonal patterns ~15 m in diameter [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, only in coldest parts of the study region [7-9]
Lithalsa [5]: A permafrost mound or ridge forming in mineral-rich soils in warm discontinuous permafrost. Often beside water bodies.	10–15 m of silt and clay [5] 10–120 m wide, 0.5–8.0 m tall [5]	0.9–1.3 m [5]	5–10 m, ~ –0.8℃ [5]	50% [5]	Horizontal lenses up to 10 cm thick [5]	Only in Taiga Shield, most common in Great Slave Lowlands [5]

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), [13] Harris et al. (1988).

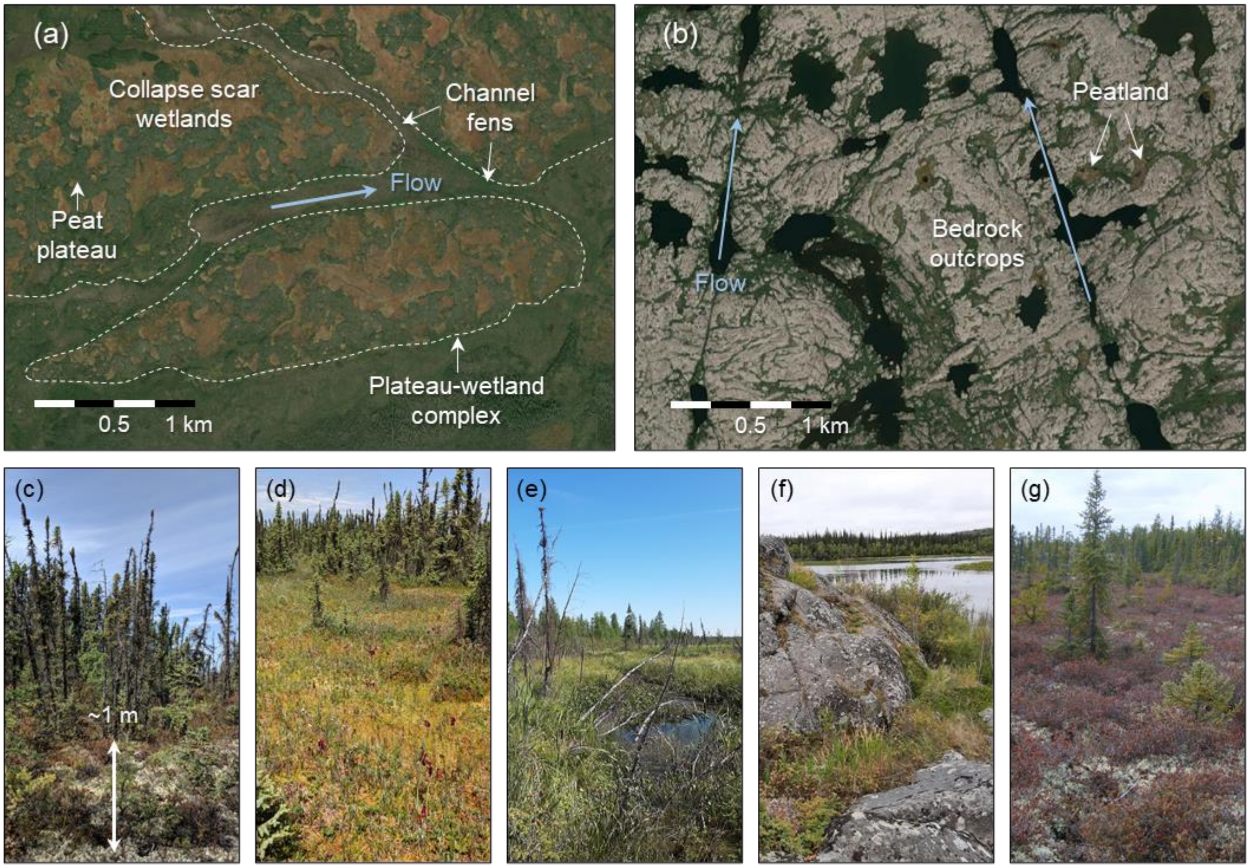

Figure 2. (a) Plateau-wetland complexes in the Taiga Plains. Green areas are intact permafrost-underlain peat plateaus, dark grey areas are permafrost-free runoff-conveying channel fens, and orange/brown areas are permafrost-free collapse scar (thermokarst) bogs and poor fens. (b) Bedrock uplands and lakes in the Taiga Shield. Grey areas are permafrost-free bedrock outcrops, and green/brown areas are permafrost-underlain soil-filled valleys and peatlands. (c) A treed peat plateau, (d) thermokarst bog, and (e) channel fen in the Taiga Plains. (f) A permafrost-free bedrock outcrop adjacent to a lake and (g) permafrost peatland in the Taiga Shield. Satellite imagery from Esri Canada and photos by L. Thompson, S. Wright, and C. Spence.

2.2 Taiga Shield

Surficial geology of the Taiga Shield includes lacustrine deposits and glacial till from post-glacial lakes and bedrock plains and hills from eroded Precambrian mountains and volcanoes (Ecosystem Classification Group, 2008). Bedrock types include granite, migmatite, gneiss, metasedimentary and metavolcanic rock (Spence and Woo, 2002). The landscape consists of bedrock uplands (Figure 2b,f) and soil-filled valleys that contain wetlands and lakes (Figure 2b,f,g; Spence, 2000; Spence & Woo, 2002a, 2002b, 2003). Lakes cover nearly one-quarter of the total area, and peatlands cover less than 5% (Ecosystem Classification Group, 2008). The southern Taiga Shield has a continental climate with short, cool summers and cold winters. MAAT and average annual precipitation (1981–2010) generally decreases with increasing latitude ranging from -2.9℃ to -4.3℃ and 288 mm/yr to 509 mm/yr (ECCC, 2021).

Permafrost and hydrological process information for the Taiga Shield mainly stem from the North Slave region (Figure 3b), where approximately 52% of the area is underlain by permafrost (Zhang et al., 2014). Shield hydrology has been described as a "fill-and-spill" process (Spence and Woo, 2003; Woo and Marsh, 2005) where runoff from bedrock uplands fills in valley bottoms until the valley storage threshold is exceeded and excess water drains (or spills) into the next valley or lake (Woo et al., 2008). Permafrost is associated with forests (mainly black spruce) and peatlands underlain by fine-grained silts and clays and consistently absent below bedrock outcrops (Brown, 1973; Morse et al., 2016). Black spruce peatlands may, or may not, be peat plateaus. In the North Slave region, reported values for permafrost thickness, active layer thickness (ALT), and MAGT at a depth of zero annual amplitude range from a few meters to 60 m, 0.3 m to 0.7 m, and -1.43℃ to -0.02℃, respectively (Brown, 1973; Karunaratne et al., 2008; Morse et al., 2016). Ice content is negligible (0–2%) in bedrock (O'Neill et al., 2019), but segregated ice as horizontal lenses (0.1 to 8 cm thick) can be found in frozen lacustrine soils (Johnston et al., 1963). Lithalsas (Table 1) 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).

Areal permafrost extent in the North Slave region has degraded by approximately 28% between 1950 and 2009 (Zhang et al., 2014). Morse et al. (2016) suggest permafrost in the fine-grained sediment beneath forests is presently being protected by considerable latent heat effects and the insulative properties of the organic ground cover, which combine to slow permafrost thaw. However, these landscapes are still increasingly vulnerable to climate change, and a considerable reduction in permafrost extent can be expected in a warmer climate. Zhang et al. (2014) estimated that minimal permafrost will remain in the North Slave region by 2090.

3 Mechanisms and Drivers of Permafrost Thaw

The study area is undergoing warming at 0.46°C per decade (1948–2012; Vincent et al., 2015). Higher air temperatures result in higher energy availability, which increases downward heat conduction from the surface and changes the active layer (Koven et al., 2013; Pastick et al., 2015; Slater and Lawrence, 2013). Surface water bodies and permafrost-free wetlands adjacent to permafrost drive lateral thaw through conduction as well as advection if surface water flows year-round (Devoie et al., 2021; Kurylyk et al., 2016). Groundwater flow, particularly when hydrologically connected to warmer surface water, can contribute to heat advection above, below, or adjacent to permafrost bodies (Devoie et al., 2021, 2019; Kurylyk et al., 2016; Sjöberg et al., 2016). Thaw at the base of the permafrost can also be driven by conduction from geothermal heat from the Earth's core (reported at 0.08 W/m^2 at 50 m depth; McClymont et al., 2013). If the ground cannot lose enough energy in winter to balance heat gains from summer, then the net result is progressive permafrost thaw. In permafrost peatlands of the Taiga Plains, Devoie et al. (2021) found that thaw rates from heat advection (115 cm/yr) were an order of magnitude higher than both downward thaw from the ground surface and thaw from below due to geothermal gradients (both 10 cm/yr, assuming isothermal permafrost conditions).

Permafrost temperatures are at or near 0°C in many locations within the study area, indicating that permafrost is currently thawing and/or is highly susceptible to thaw (Morse and Spence, 2017; Quinton et al., 2019). Processes that can initiate or accelerate permafrost thaw include wildfire, windthrow, surface flooding, resource exploration, human land development, and other ecosystem stressors that perturb or remove insulative vegetation (e.g., game trails, foot paths, all-terrain vehicle tracks, etc.) alter snow distribution, increase surface albedo, or increase soil moisture (Gibson et al., 2018; Holloway et al., 2020; Vitt et al., 1994; Williams et al., 2013). Snow cover is an excellent insulator, limiting heat loss from the ground (Woo, 2012). By affecting snow interception and redistribution processes, vegetation cover also affects the spatial distributions of snow (Connon et al., 2021) and, therefore, ground temperatures.

Changes in rainfall intensity, duration, and frequency also affect the rate of permafrost thaw (Douglas et al., 2020; van Huissteden, 2020) due to heat advection from warm summer rain (Douglas et al., 2020) and, more importantly, increases to the soil moisture and bulk thermal conductivity of soil. For example, end-of-summer frost table depths for peat plateaus and palsas are deepest in years with greater precipitation (Seppälä, 2011; Wright et al., 2009), as the higher thermal conductivity of saturated peat increases heat transfer to the frost table (van Huissteden, 2020; Walvoord and Kurylyk, 2016). However, when evaluating an active layer monitoring network in Alaska, Clayton et al. (2021) found that increased latent heat effect of wetter soils can also decrease active layer thickness, suggesting that soil heterogeneity can play a large role in how permafrost responds to changes in precipitation. Douglas et al. (2020) suggest a multi-year memory effect from anomalously wet summers that slow winter freeze-back, limiting ground cooling and supporting warmer subsurface conditions in subsequent summers. Yet, the relatively high thermal conductivity of frozen-saturated peat is highly effective at cooling the ground in winter (Woo, 2012). These opposing effects suggest a poorly understood threshold for the timing and degree of saturation that either: (1) result in effective heat loss in winter that protects permafrost; or (2) stores excess heat that subsequently thaws permafrost. Further work is needed to understand the thresholds and competing effects of soil moisture and changing precipitation patterns on permafrost thaw.

Wildfires have been observed to accelerate permafrost thaw throughout the study region (e.g., Smith et al., 2015; Spence et al., 2020; Zhang et al., 2015), particularly in the peatlands of the Taiga Plains, where ~40% of peat plateaus have burned in the last 60 years (Gibson et al., 2018). Since wildfire can remove insulative/shading vegetation and alter snow cover distribution and albedo, the supra-permafrost layer (Connon et al., 2018) and talik (perennially unfrozen soil) coverage typically increase following wildfire (Gibson et al., 2018; Holloway et al., 2020). In some cases, permafrost thaw in the study region from old wildfires (>30 years old) has recovered to pre-fire conditions, but thaw resulting from more recent fire disturbance may be irreversible under current climate warming trends (Gibson et al., 2018; Holloway and Lewkowicz, 2020; Zhang et al., 2015). Regions of the Taiga Shield with little forest cover and more exposed bedrock and lakes are "hydrologically resilient" to forest fires, meaning wildfires result in little hydrologic change since pre-fire conditions have little vegetation and permafrost to begin with (Figure 4b; Spence et al., 2020).

It is well documented that human-induced land cover change through the construction of roads, pipelines, communities, mines/gravel pits, oil and gas infrastructure, and seismic lines thaw underlying permafrost (Cao et al., 2016; de Grandpré et al., 2012; Huntington et al., 2007; Smith et al., 2008; Smith and Riseborough, 2010; Williams et al., 2013; Wolfe, 2015). Solar sheltering from the canopy is removed upon land clearing, increasing the ground heat flux. Soil compaction from construction can promote higher soil moisture contents, increasing heat transfer rates from the surface to the subsurface. (Sub)surface drainage is driven toward the depression, increasing soil moisture content and consequent permafrost thaw. Surface runoff can also enhance heat transport to the margins of linear disturbances that are compacted or paved (i.e., roads, cut lines, or pipeline corridors; Chen et al., 2020). In areas with warm and thin permafrost (MAGT >-2°C; < 20m thick), the combined effect of a pipeline corridor and climate warming is predicted to completely degrade underlying permafrost between 2030 and 2050, with effects possibly extending beyond the clearing and into the larger landscape (Smith and Riseborough, 2010). Some of the highest densities (>2.0 km/km^2) of seismic lines and linear infrastructure in the study region occur in the peatland-rich nexus of the British Columbia, Alberta, NWT borders (Strack et al., 2019), but the cumulative impacts on permafrost thaw, hydrology, and water quality remain poorly understood.

4 Observed impacts of permafrost thaw

Significant thaw-induced landcover, hydrologic, and water quality changes have been observed in the study region over the last half-century (Table 2). Many of these observations come from studies conducted since 1999 at the Scotty Creek Research Station (61.3°N, 121.3°W), approximately 50 km south of Fort Simpson, NWT (Figure 3a; Quinton et al., 2019), and sites located along transportation corridors such as the

Mackenzie Highway and the Mackenzie Valley pipeline from Norman Wells, NWT to Zama, Alberta. In the Taiga Shield, studies are generally limited to the North Slave region (Figure 3b), including the Baker Creek Research Basin located 7 km north of Yellowknife, NWT (62.5°N, 114.4°W). The drivers and processes that explain the observed changes are discussed in the proceeding sections.

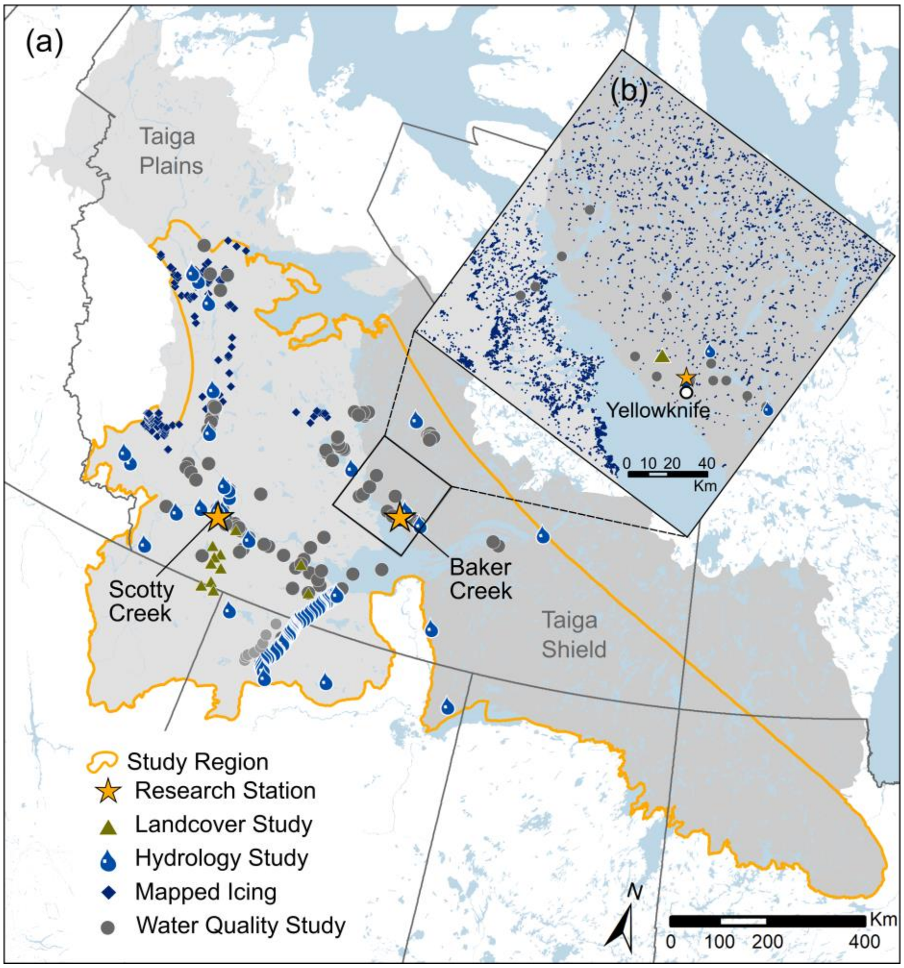

Figure 3. (a) Locations of data collection sites and field studies in the study region related to thaw-induced impacts to landcover, hydrology, and water quality. The location of icing studies and mapped icings have been given a unique symbol but still fall under the hydrology category. Note that larger remote sensing studies are not shown. (b) The North Slave region with mapped icings (blue) from 1985–2014 from Morse and Wolfe (2015). See supplementary material for study citations and coordinates.

Table 2. Observed changes in landcover, hydrology, and water quality in the study area directly tied to permafrost thaw. Note that this is not an exhaustive list but includes representative changes and trajectories.

Observed Change	Location in Study Area	Trajectory	Stressors/Drivers	Selected References
Landcover				
Forest area	N-S transect from northern BC to Scotty Creek [1]; Scotty Creek, NWT [2-4]; Taiga Plains [5]	Loss and gain, 1970-2010 [1]; 2012–2018 [3]; 1947–2018 [4] Loss, 1977–2010 [2]; 2000 – 2014 [5]	Climate warming, forest inundation with permafrost thaw leading to forest loss [1-5]; Wetland drainage leading to afforestation [3,4]	[1] Carpino et al., 2018; [2] Baltzer et al., 2014; [3] Dearborn and Baltzer, 2021; [4] Carpino et al., 2021; [5] Helbig et al., 2016
Wetland area	Scotty Creek, NWT [1,2]	Increase, 1970–2008 [1]; 1955–2015 [2]	Warming climate, land disturbance	[1] Quinton et al., 2011; [2] Gibson et al., 2018
Lake and pond area	Southern Shield [1]; Northern Shield [2,6]; Upper Mackenzie [3]; Northern Alberta [4]; Kakisa Basin, NWT [5]	Decrease, 2000–2009 [1,5]; Increase, 2000–2009; [2,3,4]; Stable, 1947–2012 [5]; increase in ponds, 1945–2005 [6]	Changing precipitation, increased temperature, permafrost thaw.	[1–4] Carroll et al., 2011; [5] Coleman et al., 2015; [6] Morse et al., 2017
Hydrology				
End-of-season thaw depth (supra-permafrost layer thickness)	Hay River, AB-NWT [1]; Petitot River, NWT [2]; Scotty Creek, NWT [3,4]; Mackenzie River Valley [5]	Stable/Increase, 1963–2017 [1]; Stable, 1988–2000 [2]; Increase, 1998–2018, 1955–2015, 1990s–2010s [3,4,5]	Organic layer thickness supports stable conditions [1,2]. Warming climate, wildfire, changing precipitation, land disturbance [1,3,4,5].	[1] Holloway & Lewkowicz, 2020; [2] Nixon et al., 2003; [3] Quinton et al., 2011; [4] Gibson et al., 2018; [5] CALM, 2020
Spatial distribution of taliks	Scotty Creek, NWT [1,2]	Increase, 2011–2015, 1955–2015 [1,2]	Climate warming, human disturbance [1], wildfire [2]	[1] Connon et al., 2018; [2] Gibson et al., 2018
Surface-subsurface connectivity	Scotty Creek, NWT	Increase at local scale, 1996–2012	Climate warming, landcover change	Connon et al., 2014
Icings (Aufeis)	North Slave Region, NWT [1]; Central Mackenzie Valley near Normal Wells, NWT [2]	Variable, 1985–2014 [1]; Stable, 2004–2016 [2]	Changing autumn rainfall, and mid-winter melts [1]	[1] Morse and Wolfe, 2015; [2] Glass et al., 2021
Wetland Storage	Scotty Creek, NWT	Decrease, 2003–2017	Climate warming, increasing hydrologic connectivity	Haynes et al., 2018
Lake Runoff	Caribou Mountains, AB	Increase, 2015	Changing precipitation and increasing temperature	Gibson et al., 2015
Winter baseflow (only significant trends presented)	Taiga Plains; Taiga Shield north of Yellowknife [1]; Lower Liard River Valley, NWT [2]; Liard River Basin, NWT [3]	Increases, 1939-2007; 1996–2012; 1972–2012 [1-3];	Warming climate, wildfire, changing precipitation [1-3]; Thin overburden, low ice content [4]	[1] St. Jacques & Sauchyn, 2009; [2] Connon et al., 2014; [3] Shrestha et al., 2019

Annual Streamflow (only significant trends presented)	Taiga Plains Rivers: Birch [1,2], Blackstone [2], Scotty [2], Jean-Marie [1, 2] Trout, Martin, La Martre; Taiga Shield River: Camsell [1]	Increase 1970s–2007 [1]; 1996–2012 [2];	Warming climate, groundwater activation [1]; Landcover change, groundwater activation [2]	[1,3] St. Jacques & Sauchyn, 2009; [2] Connon et al., 2014
Water Quality				
DOC concentrations	Hay River, Buffalo River and other rivers from Fort Providence to Slave Lake, AB.	Highest in non-permafrost basins, 2011	Presence of permafrost dampened DOC while peatlands increased DOC	Olefeldt et al., 2014
Nitrogen concentrations	Scotty Creek [1], Boundary Creek [2]	Increasing, 2016 [1]; 2015–2017 [2]	Permafrost thaw, wildfire	[1] Ackley et al., 2021; [2] Spence et al., 2020
Phosphorus flux	Liard River	Increasing, seasonal, 1970s–2010s	Winter trend follows streamflow trends	Shrestha et al., 2019
Phosphorus concentrations	Notawhoka Creek [1], Scotty Creek, NWT [1, 2]	Increasing, 2016	Permafrost thaw, wildfire	[1] Burd et al., 2018; [2] Ackley et al., 2021
Methylmercury concentrations	Scotty Creek, NWT [1], Hay River basin [2], Taiga Plains and Mackenzie Valley [3]	Increasing in wetlands, 2013 [1]; 2019 [2]; Stable at catchment scale, 2019 [3]	Permafrost thaw, groundwater connectivity	[1] Gordon et al., 2016; [2] L. Thompson (unpublished data); [3] Thompson et al., in review
Mercury concentrations	Taiga Plains and Mackenzie Valley	Stable at catchment scale, 2019 [3]	Permafrost thaw, hydrological connectivity	Thompson et al., in review

5 Impacts of Permafrost Thaw on Landcover

Permafrost can support certain ecosystems by controlling soil temperature, soil moisture, root zones, and subsurface hydrology (Woo, 2012). Thaw of ice-rich permafrost can lead to ground surface subsidence and inundation (thermokarst), and the wholesale replacement of one plant community with another (Sannel and Kuhry, 2011; Vallée and Payette, 2007; Vitt et al., 1994), as seen in the Taiga Plains (Table 2). The resulting landcover changes have direct impacts for Indigenous land users such as changing traditional access routes, wildlife habitat and populations, traditional medicines, and country foods. In the Taiga Shield, the impacts of permafrost thaw on landcovers are less well understood. However, it is reasonable to assume that since the region is dominated by ice-poor, consolidated bedrock, permafrost thaw is not coupled with ground surface subsidence and would therefore be less disruptive to landcovers. Although permafrost thaw would not result in considerable surface subsidence, thaw may alter the hydrological connectivity of Shield basins, thereby impacting lake levels and altering shoreline landcover.

Methods of delineating permafrost terrain from optical imagery have advanced significantly in recent years (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 review; however, many of the thaw-induced landcover changes observed in the study area were initially identified and measured from remote sensing. These included documented shrinkage of peat plateaus (Quinton et al., 2011; Robinson and Moore, 2000), forest cover changes throughout the southern margin of discontinuous permafrost (Carpino et al., 2018), delineation of lake expansion (Korosi et al., 2017) and contraction (Carroll et al., 2011), and thermokarst features (Gibson et al., 2021; Morse et al., 2017).

5.1 Peatlands

Climate warming has accelerated permafrost thaw in the Taiga Plains and transformed forest- and permafrost-dominated landscapes to those that are increasingly wetland-dominated and permafrost-free (Table 2; Gibson et al., 2020; Quinton et al., 2011). Natural or anthropogenic land disturbances accelerate this landscape transformation (Figure 4a-i), including forest fires (Gibson et al., 2018), land clearing for seismic line surveys (Braverman and Quinton, 2016; Williams et al., 2013), and community infrastructure (Haynes et al., 2019). Since peat plateaus also occur in the Taiga Shield, it is suspected similar changes occur (Figure 4b-iii), but the relatively small proportion of peatlands in this ecoregion likely prevents this process from having an impact at regional scales. However, further investigation is needed to confirm this.

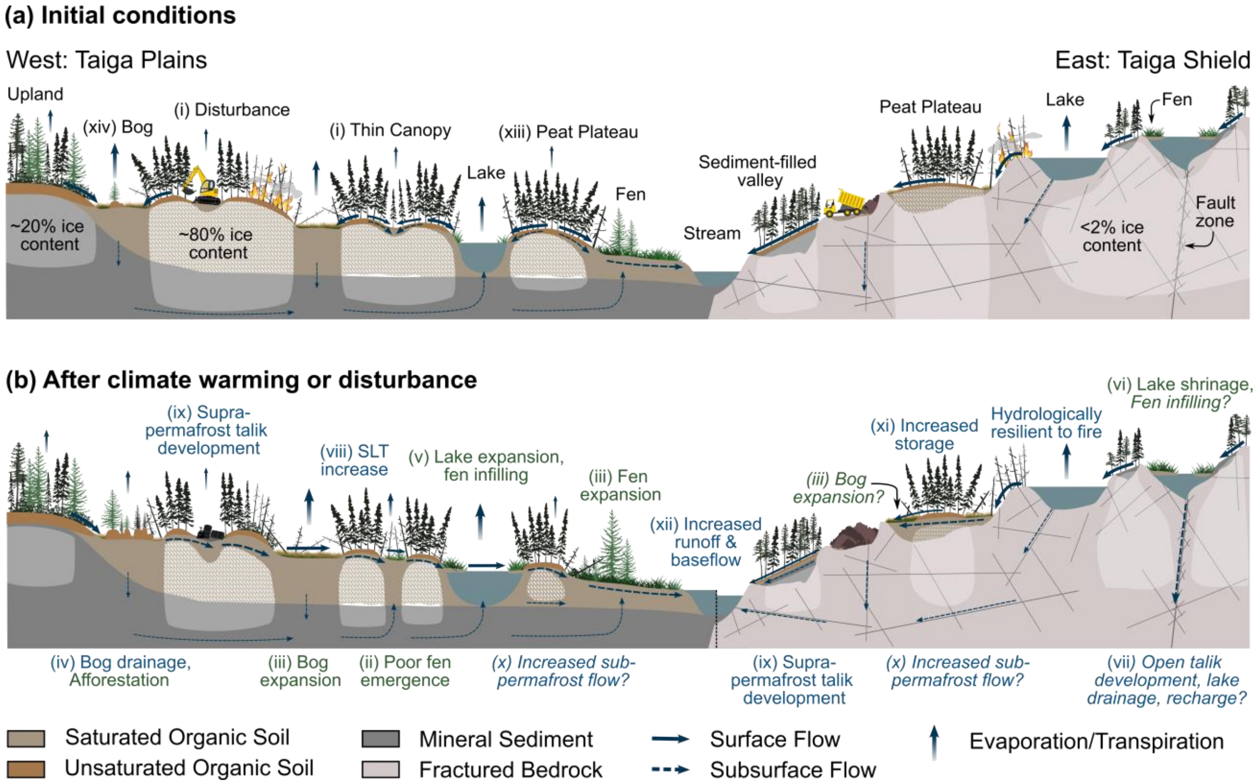

Figure 4. (a) Initial discontinuous permafrost conditions for a conceptual cross-section from the peatland-dominated Taiga Plains in the west to the bedrock/lake-dominated Taiga Shield in the east. The thickness of blue arrows indicates the relative magnitude of hydrologic fluxes. (b) Permafrost conditions and resulting changes to landcover (green text) and hydrology (blue text) following progressive climate warming and/or disturbance. Italicized text with a question mark indicates a high degree of uncertainty and requires further investigation. SLT = Supra-permafrost layer thickness. All labels are described and referenced in text.

Permafrost thaw following a disturbance, and surface warming first presents as a depression in the permafrost table, which leads to a small supra-permafrost talik within a peat plateau, a layer directly above permafrost that remains unfrozen year-round (Figure 4a-i; Carpino et al., 2021; Connon et al., 2018). Surface and subsurface water is driven toward these depressions, increasing heat transfer and deepening the depressions. The impacted permafrost continues to degrade vertically until the eventual loss of the forested plateau, and a thermokarst wetland (bog or poor fen) is formed in its place (Figure 4b-ii; Gordon et al., 2016; Chasmer et al., 2011b; Quinton et al., 2011). Permafrost can also be degraded laterally by heat transfer from neighbouring surface water, which similarly expands bogs, lakes, and fens at the expense of plateaus (Figure 4b-iii). Plateaus continue to degrade and collapse until isolated bogs coalesce and form an interconnected network of bogs with interspersed and fragmented peat plateaus (Chasmer & Hopkinson, 2017; Connon et al., 2015; Hayashi et al., 2011). Permafrost thaw, therefore, allows wetlands to develop hydrological connections with the basin drainage network (Connon et al., 2014) and partially drain (Haynes et al., 2018). Progressive drainage of wetlands supports the development of hummocks (Haynes et al., 2020) that are sufficiently dry to support the growth of black spruce trees (Disher et al., 2021) and eventual forest regeneration (Figure 4b-iv; Carpino et al., 2021). Despite black spruce forests experiencing a net decline throughout the Taiga Plains from permafrost thaw (Carpino et al. 2018), forest productivity is still increasing due, in part, to the new growth of non-dominant species like tamarack trees (*Larix laricina*) (Dearborn and Baltzer, 2021) and the continued growth of larger black spruce in the middle of plateaus (Chasmer et al., 2011).

The cycle of peat plateau and palsa collapse followed by forest regeneration has 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 for tree growth. However, rising surface temperatures in the Taiga Plains 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) suggested a conceptual model where the re-emergence of a forest cover (due to thaw-enhanced wetland drainage) occurs without the re-development of permafrost. Since the timeframe of forest recovery does not depend on the 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). However, the transition to a permanent permafrost-free environment is highly uncertain in terms of the intermediate stages, timing, and the resulting landcover.

5.2 Lake and Pond Area

As permafrost thaws, the opening of hydrologic pathways can result in either: (1) an influx of water leading to lake expansion; or (2) newly activated pathways that promote lake drainage and shrinkage (Walvoord and Kurylyk, 2016). Additionally, gradual lateral permafrost thaw of terrestrial features can lead to lake expansion (Figure 4b-v). At the national scale, Carroll et al. (2011) found surface water gains in the Hay-Zama lakes area, Alberta, and a small reduction in the Kakisa basin, NWT (Taiga Plains) between 2000–2009. In contrast, no lake expansion (1950s–2012) was observed from remote sensing and paleo-reconstruction of two lakes in the Kakisa basin, although fen cover had significantly increased (Coleman et al., 2015). As Kokelj and Jorgenson (2013) noted, fen infilling can be a significant factor in lake shrinkage and complicate directional detection (Figure 4b-v), which may be a factor 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 lake area on the nearby Boreal Plains is strongly influenced by inter-annual wet and dry periods (Pugh, 2021), which likely dominates over thaw-driven effects. In the Mackenzie Wood Bison Sanctuary, NWT, remote sensing coupled with paleo-reconstruction showed that lake expansion since the 1980s represented a positive net change in the water balance (Korosi et al., 2017). The primary factors leading to lake expansion were increased temperature and precipitation, while increased groundwater inputs from permafrost thaw were not predominant (Korosi et al., 2017).

Recent studies of lithalsa permafrost features in the North Slave suggest that lithalsa thaw will expand the surface area of thermokarst ponds (Table 2; Morse et al., 2017). An inventory of thermokarst ponds indicated 3138 ponds expanded or developed between 1945–2005, but the relative increase in aerial extent remained relatively low (Morse et al., 2017). Ponding was most commonly observed in the low elevation glaciolacustrine deposits within the North Slave Lowland (Morse et al., 2017). At the national scale, remote sensing analysis by Carroll et al. (2011) showed net losses in lake area in the Taiga Shield between 2000–2009. The observed lake declines are not well known and may relate to potential changes in permafrost coverage, decadal atmospheric circulation, and precipitation patterns (Bonsal and Shabbar, 2011) or fen infilling (Figure 4b-vi). The development of open taliks beneath lakes, which typically form along structural zones of weakness like fault zones (Woo, 2012), could also enable the drainage of lakes in upland areas (Figure 4b-vii). However, the long-term trajectory and drivers of thaw-induced lake extent changes in the Taiga Shield require further investigation.

6 Impacts of Permafrost Thaw on 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. Inadequate baseline and historical data remain a challenge in the study region and globally. There is a general lack of understanding of large-scale and longer-term impacts of permafrost thaw, particularly in peatlands outside the Liard River basin in western NWT (Mack et al., 2021) and throughout most of the Taiga Shield.

6.1 Snowmelt and Evapotranspiration

Vegetation can influence snow cover dynamics, where forested areas, particularly along margins, can maintain thicker snow cover than open areas exposed to wind and solar radiation (Woo, 2012). Thus, when landcover is altered due to permafrost thaw, it has implications for snow cover, associated snow water equivalents (SWE), and snowmelt dynamics. For example, Connon et al. (2021) recently found statistically different end-of-winter SWE between wetlands and plateau forests in the lower Liard River valley. However, these differences were not large enough to measurably impact basin-scale averages in SWE. As such, it is unlikely that shifting snow distributions due to thaw-induced landcover change will considerably alter basin-scale runoff dynamics. However, the resulting increase in hydrologic connectivity will likely alter the timing and magnitude of snowmelt runoff, commonly the largest annual runoff event in the study region.

Transforming landcovers have direct influences on evapotranspiration rates. With black spruce dominating the landcover of permafrost peatlands (Figure 4a), 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). As bogs expand with thaw (Figure 4b-iii), the extent of low-transpiration black spruce decreases, and the extent of saturated wetland vegetation increases (including *Sphagnum* mosses) resulting in increased evapotranspiration (ET) rates (Carpino et al., 2021; Warren et al., 2018). Even though mosses are non-vascular and non-transpiring, the expansion of wetland areas covered by these mosses results in evaporation through capillary rise, becoming a dominant component of the ET budget (Waddington et al., 2015). However, under progressive permafrost thaw and sustained wetland drainage (Haynes et al., 2018), both lower water tables (Waddington et al., 2015) and increased coverage of permafrost-free treed bogs (Strilesky and Humphreys, 2012; Warren et al., 2018) would likely decrease ET rates (Figure 4b-iv). The afforestation following wetland drainage would return the landcover to a low-transpiration forest cover (Carpino et al., 2021), but this has not been as well studied as collapse bogs or permafrost plateaus (Disher et al., 2021; Haynes et al., 2020). Changes in lake extent would also influence the ET component of the water balance.

6.2 Groundwater

Deepening of the active layer from climate warming has been reported in the literature (Walvoord and Kurylyk, 2016), but caution is needed when interpreting ALT data, given the wide interpretation of how the active layer is defined. The long-standing definition (used herein) refers to the layer of ground above permafrost that thaws and re-freezes each year (Muller, 1943). However, ALT is sometimes used synonymously with "end-of-season thaw depth," even if a perennially thawed layer (talik) exists (Harris et al., 1988). To avoid confusion, the term supra-permafrost layer thickness (SLT) is used to define the thickness of the layer between the ground surface and the permafrost table. In the Taiga Plains, SLTs near the Ochre River, Willowlake River, and Fort Simpson have all significantly increased since the 1990s (Figure 5; CALM, 2020). In contrast to these findings, Holloway and Lewkowicz (2020) found that SLTs in the uplands along the Mackenzie Highway (Taiga Plains) exhibited little change between 1962 and

2017/2018 due to insulation from thick organic layers (>50 cm). In the Taiga Shield, there is a lack of knowledge regarding the trends in SLT. It is possible that where the ground is thermally buffered by thick organic cover and fine-grained substrate (Morse et al., 2016), SLT has remained relatively stable over the past several decades, as observed by Holloway and Lewkowicz (2020). However, further investigation is required to assess multi-decadal changes in ALT/SLT in the Taiga Shield region.

Sustained increases in SLTs lead to the development of supra-permafrost taliks (Figure 4b-ix). Such taliks have been well characterized in the permafrost peatlands of the Taiga Plains (e.g., Connon et al., 2018; Devoie et al., 2019; Gibson et al., 2018) and are suspected of having developed in soil-filled valleys following wildfire in the Taiga Shield (Spence et al., 2020). As taliks expand at the expense of permafrost, they become hydrologically connected with adjacent permafrost-free wetlands and/or surface water bodies, promoting heat advection and accelerating thaw (Connon et al., 2018; Devoie et al., 2021; Kurylyk et al., 2016; Sjöberg et al., 2016). 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 streams and rivers (Connon et al., 2014). Connon et al. (2018) also found that as supra-permafrost taliks increase on peat plateaus, the ALT decreases due to the increased heat capacity introduced by a saturated talik layer and rising winter temperatures that reduce the depth of re-freeze.

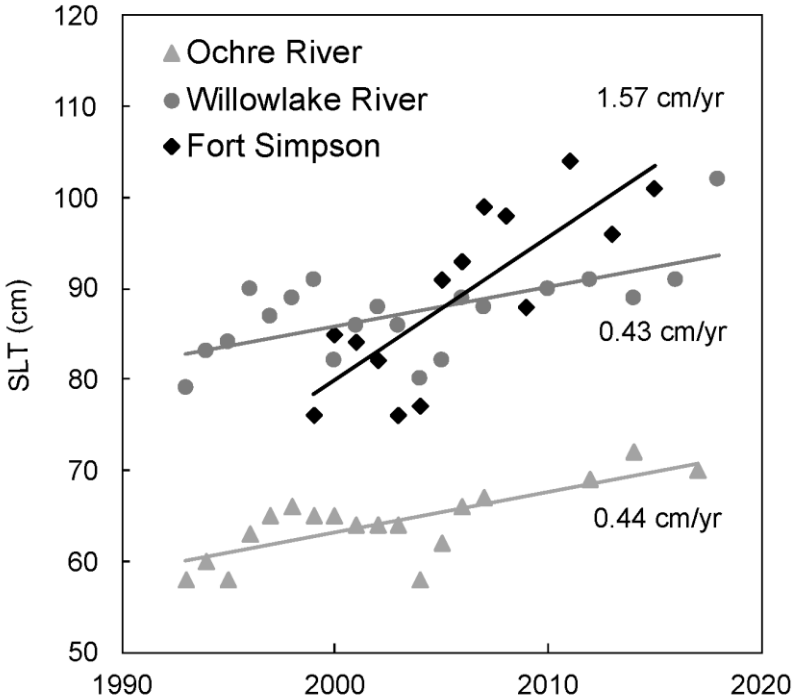

Figure 5. Monitoring of average SLT between 1993–2017 for the Ochre River (63.466, -123.693), 1993–2018 for Willowlake River (62.697, -123.065), and 1999–2015 for Fort Simpson (61.888, -121.602). Data sourced from CALM (2020). All trends are significant ($p \leq 0.01$) as determined from a Mann-Kendall trend test.

At regional scales in the Taiga Plains (i.e., the Mackenzie Valley), permafrost impacts the location of groundwater recharge but does not appear to influence groundwater discharge (Michel, 1986). Depending on the location of permafrost thaw relative to local and regional groundwater flow systems, either groundwater recharge or discharge zones can emerge following a complete loss of permafrost (Figure 4b-ii; Gordon et al., 2016). However, predicting how these systems will continue to evolve and integrate with surface water systems is not well known. Sub-permafrost groundwater flow (i.e., groundwater flow below permafrost) also occurs in peatlands in the Taiga Plains (Figure 4a). Here, the thin (typically <10 m) and discontinuous nature of permafrost results in numerous open taliks beneath water bodies and thermokarst wetlands that allow for the exchange of supra- and sub-permafrost groundwater. Since much of the southern Taiga Plains are underlain by low permeability silts and clays with low vertical hydraulic gradients, sub-permafrost groundwater contributions in these areas are anticipated to be relatively low (Hayashi et al., 2004). However, relatively higher sub-permafrost groundwater flows are possible within higher permeability peat, mineral sediment, and fractured bedrock. These groundwater flows may continue to increase as permafrost thaws, and new pathways are activated (Figure 4b-x) or may already be well developed, particularly in zones of sporadic permafrost. Additionally, thaw-induced landcover changes that alter evapotranspiration rates and snow cover dynamics have implications for groundwater recharge and extraction. For example, recharge can increase beneath newly permafrost-free forested areas due to greater snow capture relative to open areas (Young et al., 2020). Further research is needed to understand the influences of thaw-induced landcover change on groundwater recharge/discharge dynamics and the basin-scale implications.

The thaw-induced impacts to groundwater systems in the Taiga Shield are not well understood. The relatively shallow permafrost (<50 m) and abundance of permafrost-free lakes and bedrock outcrops likely result in a highly connected subsurface system. Localized groundwater flow systems can occur through fractured rock networks (Spence and Woo, 2002; Thorne et al., 1998; Woo, 2012) and highly conductive fault zones that commonly underlie lakes (Woo, 2012). As permafrost thaws in the soil-filled bedrock valleys, groundwater recharge and storage are likely to increase (Figure 4b-xi; Morse and Spence, 2017). Thawing of bedrock may lead to increased sub-permafrost groundwater flow through the reactivation of fracture networks and fault zones (Figure 4b-x) and the development or expansion of supra- and inter-permafrost (i.e., between permafrost) taliks (Morse & Spence, 2017; Rouse, 2000). However, evidence for this is lacking, and the resulting changes to larger-scale basin behaviour are unknown. Morse & Spence (2017) suggest flow can also occur through taliks below lakes, but the configuration of these taliks is not well documented. The development of open taliks beneath lakes may also increase groundwater recharge to sub-permafrost aquifers (Figure 4b-vii) and influence discharge rates to downstream streams and rivers (Figure 4b-xii).

6.3 Icings (Aufeis)

Groundwater discharging through taliks along river and stream banks in winter can result in riverine icings (sheet-like masses of layered ice), which affect the seasonal water balance (Reedyk et al., 2011). Since river baseflow is the primary water source 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), so as winter air temperatures increase and permafrost thaw continues, the primary zones of icing occurrences may migrate northward. Additionally, riverine icings are unlikely to develop if baseflows increase to the point that an open water channel is maintained over the winter. There is generally a lower occurrence of icings in the extensive discontinuous permafrost zone of the Taiga Plains than continuous permafrost zones (Crites et al., 2020). Icing investigations in the Taiga Plains have been sparse and limited to north of Fort Simpson, NWT (Figure 3; Crites et al., 2020; Glass et al., 2021; Reedyk et al., 2011). Therefore, the influence of changing baseflows on riverine icing development remains a knowledge gap for most of the Taiga Plains study 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 study region, but this could be counteracted by rising air temperatures and continued decreases in mid-winter warming events (≥5°C) (Morse and Wolfe, 2017). At present, the highest icing density is associated with highly fractured bedrock in the Shield that is likely permafrost free (Figure 3b; Morse and Wolfe, 2015), suggesting icing occurrence could increase as permafrost thaws in the future and basins become more hydrologically connected (Spence et al., 2020; Spence et al., 2014). Longer-term changes of icings in the Taiga Shield remain highly uncertain (Morse and Wolfe, 2017, 2015).

6.4 Peatlands

Thaw-induced landcover changes observed in peatlands of the Taiga Plains impact both local- and basin-scale hydrology. Surface and subsurface runoff from peat plateaus is directed along sloped margins into adjacent collapsed bogs and poor fens, which store or route water to the stream network (Figure 4a-xiii). 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). As the landscape undergoes thaw-induced land cover change, the relative proportion of storage features (thermokarst wetlands) and routing features (fens) changes, which impacts how much water can reach the stream network (discussed in detail in Section 6.6).

In the initial stages of permafrost thaw, collapsed bogs are generally disconnected from the hydrologic network (Carpino et al., 2021; Connon et al., 2014). Runoff and precipitation added to isolated bogs and depressions within the plateau are primarily removed through evaporation and/or possibly groundwater recharge since surrounding permafrost plateaus act as hydrologic dams (Figure 4a-xiv; Quinton et al., 2009). Thus, groundwater storage temporarily increases under isolated bog expansion (Carpino et al., 2021). During periods of high water availability, isolated bogs can become ephemerally connected and follow a fill-and-spill process, similar to Shield hydrology, to activate hydrologic connectivity to adjacent collapsed bogs and channel fens (Connon et al., 2015). The expansion and deepening of supra-permafrost taliks on permafrost plateaus enables year-round hydrologic connectivity between landcovers (Figure 4b-ix; Connon et al., 2014). The thawing and shrinking of permafrost plateaus that previously acted as a subsurface hydrogeological barrier enable drainage of isolated bogs (Connon et al., 2014) and a decline in basin storage as the landscape is converted to higher runoff-producing wetlands (Haynes et al., 2018).

Similarly, when water availability and frost tables are high during the snowmelt period, linear disturbances (e.g., seismic lines and winter roads) become filled with water and behave like isolated bogs on peat plateaus with a fill-and-spill drainage pattern (Braverman and Quinton, 2016; Williams et al., 2013). Williams et al. (2013) hypothesized that linear disturbances might begin to function more like channel fens and increase basin drainage with progressive permafrost thaw, but further research is needed to confirm this. Similarly, 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).

6.5 Lake Environments

Lateral lake expansion can contribute to the toppling of trees and other vegetation, soil erosion on shorelines, and changes to lake water quality. Lateral subsurface thaw beneath the shoreline can also accelerate shoreline collapse and permafrost thaw (Figure 4b-v; Kokelj et al., 2009). Thermokarst lake contraction or expansion impacts water storage, routing, and landscape connectivity. 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, reflect enhanced groundwater recharge (Walvoord and Kurylyk, 2016), and increase evaporation rates (Song et al., 2020). In boreal Alberta, more runoff was generated from permafrost thaw-influenced lakes in the Caribou Mountains relative to lower elevation sites with lesser peatland/permafrost influence (Gibson et al., 2015). However, this response may wane as permafrost becomes extensively thawed.

The Taiga Shield has the highest proportion of lakes in the study area, which can attenuate surface runoff, such that streamflow responses from spring freshet or storm events are delayed (Morse & Spence, 2017). For example, the Taltson River typically experiences peak flows in early July (Kokelj, 2003), which is notable from the snowmelt peaks in early May in the Taiga Plains (Hayashi et al., 2004). Due to the fill-and-spill process that controls basin runoff, thaw-induced increases in the storage capacity of soil-filled bedrock valleys (Figure 4b-xi) during dry periods could mean less water contributes to basin runoff and, therefore, reduced 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. As open taliks develop beneath lakes, particularly at higher latitudes, lake levels may decline by connecting surface water to deeper flow systems and increasing sub-permafrost groundwater recharge (Figure 4b-vii). Thaw-enhanced groundwater 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.

6.6 Streamflow

Streamflow has been increasing throughout the study region (Table 2) and 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). Three explanations for increasing streamflow in discontinuous permafrost terrain in a warmer climate have been proposed in the literature and will be further discussed below: (i) water released from thawing permafrost; (ii) reactivation of subsurface flow paths; and (iii) thaw-induced landcover changes.

(i) An early explanation for rising streamflow was that permafrost thaw supplied additional water inputs to streams from ice converting to liquid water (St. Jacques and Sauchyn, 2009; Walvoord and Striegl, 2007). However, recent 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), including studies in 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).

(ii) 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). Increases in 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 2; Connon et al., 2014; Shrestha et al., 2019; St. Jacques & Sauchyn, 2009). Thaw-induced talik development is likely to enable wintertime groundwater discharge (Figure 4b-xii). 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 on peat plateaus 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).

(iii) 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 peat plateaus and subsurface reactivation could not fully explain increases in annual runoff (Connon et al., 2014). Precipitation also did not increase during periods of increased runoff. Instead, permafrost thaw resulted in a landscape shift to a higher runoff producing landcover (Connon et al., 2014). This shift likely needs to happen in tandem with either reduced evapotranspiration (somewhat permanent), or reduced water storage (transient), where the latter is documented in Haynes 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 and/or competing effects of landcover change and groundwater reactivation on streamflow and how this varies across landscapes require additional investigation to predict hydrologic change across the region.

Evidence for landcover change driving increases in streamflow is supported by runoff ratios in the Liard River valley increasing between 1996–2012 (Connon et al., 2014). Figure 6 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, significant 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 and low storage crystalline bedrock.

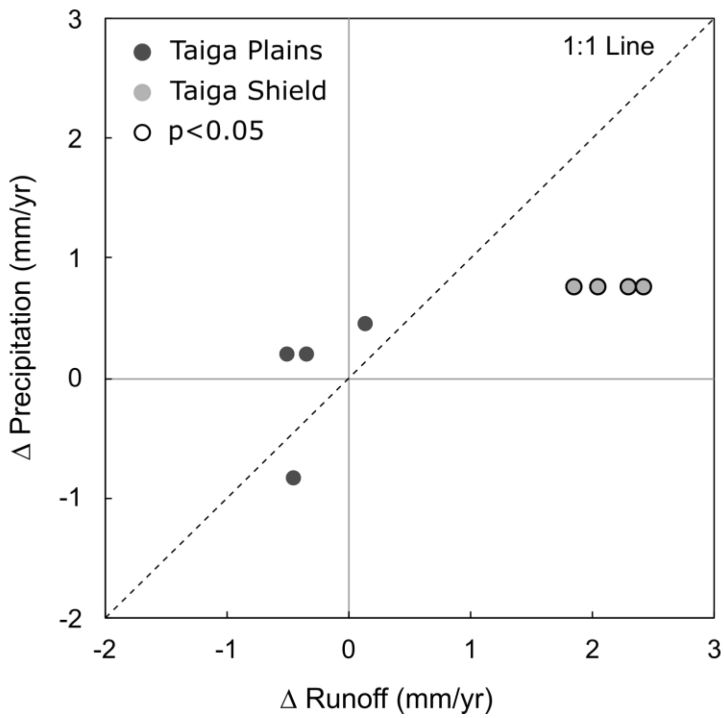

Figure 6. Changes in annual precipitation versus changes in runoff between 1978 and 2017 for basins in the Taiga Plains and Taiga Shield with similar proportions of permafrost coverage. The 1:1 line indicates where a unit change in precipitation will result in an equal unit change in runoff. Plotting off the line, like the basins shown in the Taiga Plains, suggest other factors like thaw-induced landcover change are altering runoff patterns. Significance (circled marker) and magnitude of change were determined from a Mann Kendall test. Runoff data were 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.

As noted in Section 6.5, thaw-induced increases in bedrock valley storage in the Taiga Shield (Figure 4b-xi; Morse & Spence, 2017) may reduce the hydrologic connectivity of the fill-and-spill drainage network and lead to more intermittent and delayed streamflow responses to nival freshet or summer rainfall events.

Streamflow 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, evidenced by considerable icing at the stream outlet. Since icings form from groundwater discharge, these results suggested that forest fire promoted talik development and increased hydrologic connectivity (Figure 4b-ix).

7 Impacts of Permafrost Thaw on Water Quality and Biogeochemistry

Permafrost thaw and the resulting alterations to landcover and hydrology can impact downstream water quality. Stores of organic matter, nutrients, metals, and point-source anthropogenic contaminants previously locked in permafrost may become mobilized due to thaw (AMAP, 2015; Frey and McClelland, 2009; Miner et al., 2021b; Vonk et al., 2015), with implications ranging from ecosystem health to drinking water quality and the toxicity of country foods. Here, site-specific studies are summarized regarding the potential impacts of permafrost thaw and wildfire on water quality within the Taiga Plains, and to a lesser extent, in the Taiga Shield. The studies utilized space-for-time approaches (e.g., Olefeldt et al., 2014) and paired catchment comparisons (e.g., Tank et al., 2018). Where aspects of water quality and biogeochemistry have not been investigated in the study region, studies from representative external regions are drawn upon, such as the peatland-rich Western Siberian Lowlands or Fennoscandia.

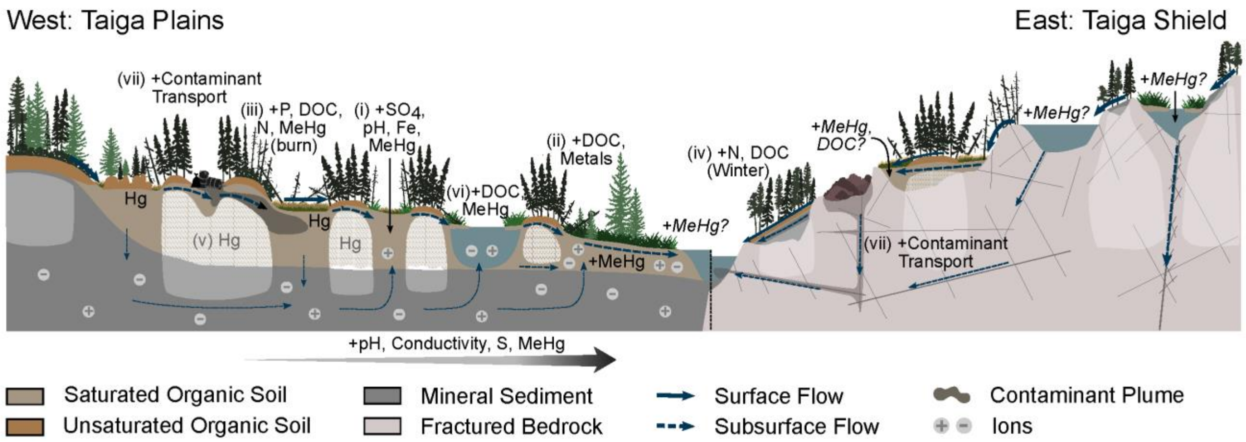

Figure 7. Conceptual cross-section of the impacts to water quality in the Taiga Plains and Taiga Shield following progressive permafrost thaw from climate warming and/or land disturbance. Refer to Figure 4a for initial permafrost conditions and landcover descriptions. The '+' before text indicates an increase in concentration and/or mobilization of the specified water quality parameter. Italicized text with a question mark indicates a high degree of uncertainty and requires further investigation. P: phosphorus, N: nitrogen, S: sulfur, Fe: iron, Hg: mercury, DOC: dissolved organic carbon, MeHg: methylmercury.

7.1 Physical Parameters

Permafrost thaw and increased connectivity to groundwater may influence the electrical conductivity (EC) and pH of surface water bodies. EC is influenced by water movement through mineral sediment, and where landcover shifts from peat plateau to minerotrophic wetlands with high groundwater connectivity (e.g., channel fens), EC increases (Figure 7-i). Thermokarst bogs are defined by lower groundwater connectivity and therefore have lower EC than fens (Hayashi et al., 2004b; Olefeldt and Roulet, 2012). While peatlands are often acidic environments, nutrient-poor peatlands (e.g., bogs and peat plateaus) have a substantially lower pH than nutrient-rich fens (Vitt and Chee, 1990). Groundwater connection and the buffering capacity of carbonate bedrock can thus lead to a higher pH in peat-rich catchments, as observed in Western Siberian Lowlands catchments with a latitudinal decrease of pH (Frey et al., 2007; Pokrovsky et al., 2015). The predicted increase of pH and EC with permafrost thaw (Frey and McClelland, 2009) will likely be most pronounced in the continuous and extensive discontinuous permafrost regions of the Taiga Plain as new groundwater pathways develop (Figure 8a; Mertens, 2018; Thompson and Olefeldt, 2020).

It is unlikely that permafrost thaw in the permafrost fringe of the Taiga Plains and Shield will increase suspended sediment loads. Large-scale disturbances and mass movements that increase downstream suspended sediment loads by several orders of magnitude (e.g., retrogressive thaw slumps and active layer detachments; Kokelj et al., 2013) are uncommon in the region, especially on lower Strahler-order streams and rivers (Kokelj et al., 2017; Olefeldt et al., 2016). While increased suspended sediment loads downstream from permafrost peatlands are not expected, increased runoff and intensity of peak flows (Section 6.6) could potentially increase sediment transfer and turbidity, such as from bank abrasion and resuspension of channel sediment stores (Krickov et al., 2020).

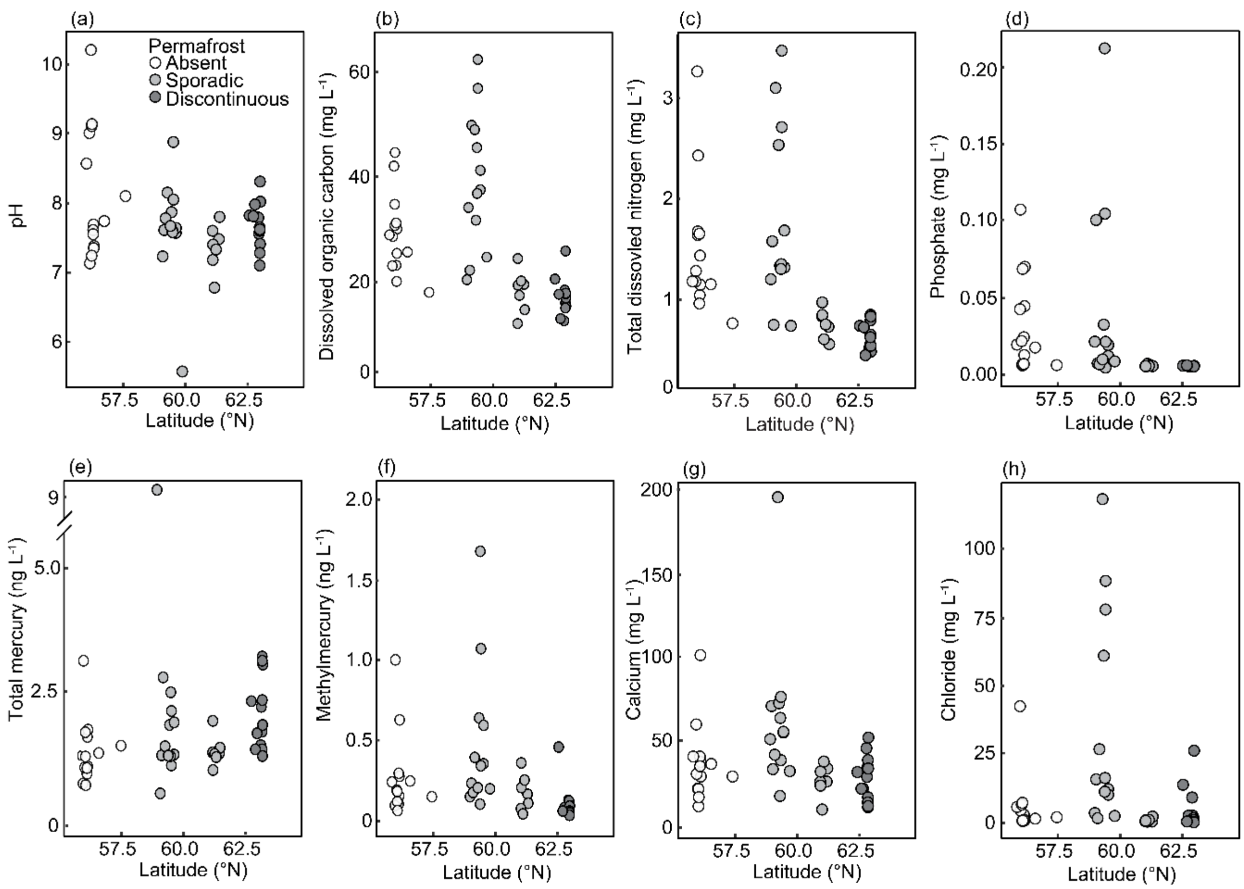

Figure 8. Water chemistry variables as a function of latitude for streams and small lakes within the Boreal Plains and Taiga Plains of Alberta and the Northwest Territories, including (a) pH, (b) dissolved organic carbon, (c) total dissolved nitrogen, (d) phosphate, (e) total mercury, (f) methylmercury, (g) calcium, and (h) chloride (data from Thompson & Olefeldt, 2020).

7.2 Organic Matter

Peatlands are major sources of dissolved organic carbon (DOC) to boreal streams (Moore, 2013), and the magnitude of annual DOC export to the Mackenzie River is amongst the highest in the world (Li et al., 2017). DOC is a substrate for microbial activity and plays an important role in water quality. Dissolved organic matter (DOM) controls light penetration in water bodies, with implications for phototransformations of neurotoxic methylmercury (Klapstein and O'Driscoll, 2018; Thompson et al., In Review) 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 a strong interest in understanding how DOC concentrations in northern streams may be affected by permafrost thaw.

Permafrost presence and peatland cover are important controls on DOC concentrations in waterbodies (Figure 7-ii). A survey of rivers in northern Alberta and southern NWT found DOC concentrations increased with basin peatland cover but were consistently lower north of the permafrost boundary (Olefeldt et al., 2014). Patterns of DOC concentrations within peatland lakes across the Taiga Plains were also higher in the sporadic and permafrost-free zones than further north (Figure 8B; Thompson & Olefeldt, 2020). Similar patterns have been observed in the Western Siberian Lowlands, where permafrost-influenced rivers had low DOC concentrations, and permafrost-free basins had significantly higher DOC concentrations that increased with peatland cover (Frey and Smith, 2005). These studies suggest that ongoing permafrost thaw may increase DOC concentrations in permafrost peatland basins. Furthermore, both solute concentrations and the hydrologic regimes of rivers control DOC export. Therefore, the increasing runoff regimes due to thaw-induced landcover change (Section 6.6) could further contribute to higher DOC export in the Taiga Plains, but further research is needed.

Wildfire may also influence DOC concentrations, but the Taiga Plains and Shield evidence suggest that the influence is muted through the continuum of soil porewater to catchment outlet (Tank et al., 2018). While higher DOC concentrations have been observed in the porewater of burned peatlands in the Taiga Plains (Ackley et al., 2021; Burd et al., 2018; Figure 7-iii), catchment export was only modestly higher in a burned site compared to a paired unburned catchment (Burd et al., 2018). At a paired burned/unburned catchment study in the Taiga Shield, concentrations of DOC in ice-free seasons were similar but were elevated during winter in the burned catchment (Spence et al., 2020; Figure 7-iv). In a survey of 50 sites across the Taiga Plains and Taiga Shield, there was no significant difference in DOC concentrations between burned and unburned sites (Tank et al., 2018).

In non-peatland environments, enhanced groundwater flow paths from thaw have resulted in decreases of DOC from 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). In northern Sweden, groundwater influence (inferred from EC) was related to lower DOC concentrations and aromatic quality relative to peatland sources, with increased groundwater contributions in wetter years (Olefeldt & Roulet, 2012). While DOC export has decreased in the Yukon River (1978-1980 compared to 2001-2003), attributed to increasing groundwater connections that adsorb DOC (Striegl et al., 2005; Walvoord and Striegl, 2007), longer-term carbon (C) export has increased in the peatland-influenced Mackenzie River (Tank et al., 2016). This increase may be due to limited groundwater contributions from the underlying low-permeability glacial till despite groundwater activation with permafrost thaw. Instead, the surface water and wetland-dominated systems become increasingly effective at delivering peatland DOC to the main river system, with minimal dilution from deepened groundwater flow paths through thick peat deposits (Figure 7).

To identify permafrost thaw and the mobilization of organic matter, radiocarbon dating of DOC determines whether the source of C is from the decomposition of relatively young plant or peat matter (modern C) or the decomposition of plant or peat matter previously frozen in permafrost (aged C). Currently, DOC in Taiga Plains streams is predominately modern, with only a minor contribution from millennial-aged peatland soil C (Burd et al., 2018; Tanentzap et al., 2021). However, an abrupt DOC aging event in 2018 was detected in the Mackenzie River north of Tsiigehtchic, NWT (Schwab et al., 2020). This was also detected in two large tributaries to the Mackenzie River (Peace and Liard rivers), which was attributed to petrogenic organic C stores and mobilization from permafrost peat (Campeau et al., 2020). 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 DOC-adsorbent sediment (Campeau et al., 2020). However, as noted in a recent synthesis of radiocarbon DOC and POC across the pan-Arctic, it is difficult to conclude whether aged organic matter released from deep soils is generated because of terrestrial disturbance or regular permafrost C cycling (Estop-Aragonés et al., 2020).

7.3 Nutrients

Terrestrial disturbances due to permafrost thaw, wildfire, and increasing human influence (i.e., agriculture and wastewater, Section 7.6) may enhance nutrient fluxes in the Taiga Plains and Shield ecoregions. Peatlands are nutrient-limited systems, dominated by organic forms rather than more bioavailable inorganic forms (Moore et al., 2019). The changes in organic nutrient forms resulting from permafrost thaw are likely to mirror DOC (Section 7.2). Lakes and rivers in the Taiga Plains showed the highest total nitrogen (N) concentrations (dominated by organic N forms) and phosphate (PO_4^{3-}) concentrations in permafrost-free and sporadic permafrost zones relative to discontinuous and continuous permafrost (Figure 8c-d; Thompson & Olefeldt, 2020). Similarly, particulate N 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). Chemical extractions from peatland soils in the sporadic permafrost region of northern Sweden showed that thawing peatlands mobilized high quantities of inorganic N, which was suggested to be taken up by plants rather than delivered to downstream environments (Keuper et al., 2012). However, downstream delivery of inorganic phosphorus (P) was observed in lakes of the southern Taiga Plains, resulting in enhanced algal productivity (i.e., chlorophyll-α concentrations) (Kuhn et al., 2021); inorganic N may be likewise “leaky” in the Taiga Plains.

Wildfire disturbances may also enhance the mobilization of nutrients from peatlands. For example, a comparison of burned and unburned catchments near Jean Marie River, NWT, found higher P yields from the burned catchment, with limited effects on N forms (Burd et al., 2018; Figure 7-iii). Both N and P increased in porewater of a burned peat plateau in Scotty Creek relative to unburned soils, which was attributed to release during peat combustion along with increased water residence time and decreased nutrient uptake by plants due to vegetation loss (Ackley et al., 2021; Figure 7-iii). At a paired burned/unburned catchment in the Taiga Shield, wintertime dissolved N concentrations were elevated during winter at the burned catchment (Spence et al., 2020; Figure 7-iv). 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, with no effect for larger rivers (Tank et al., 2018). Thus, the spatial scale at which permafrost thaw impacts nutrient mobilization is important to consider, with effects appearing to be muted at greater catchment scales.

7.4 Mercury

Atmospheric mercury (Hg) deposition from distant sources becomes bound to organic matter and accumulates in soils, especially organic-rich peatland soils (Grigal, 2003; Figure 7-v). Permafrost inhibits any further cycling of Hg, but its 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). Hg-related fish consumption advisories have been enacted for NWT lakes (GNWT, Health and Social Services, 2020). Numerous advisories in the peatland-rich Dehcho region are related to high Hg burdens, particularly in predatory species (e.g., northern pike and walleye) (Evans et al., 2013, 2005; Laird et al., 2018). Evidence suggests that Hg concentrations in biota are associated with the terrestrial delivery of DOC and Hg to lakes from lowlands (Figure 7-vi; (Evans et al., 2005; Moslemi-Aqdam et al., 2022), implying that thaw-mobilized DOC (Section 7.2) and Hg may influence Hg burdens in fish. In contrast, studies of fish in Yukon and Nunavut have not observed increasing Hg bioaccumulation (Chételat et al., 2015), potentially relating to the lesser influence of permafrost peatlands in those regions.

The transition of relatively dry peat plateaus into saturated fens and bogs enhances the microbial transformation of mercury's most toxic form, methylmercury (MeHg) (Fahnestock et al., 2019; Gordon et al., 2016; Poulin et al., 2019). MeHg 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 in the study region do not include MeHg as a regularly sampled parameter.

Permafrost thaw and the development of thermokarst wetlands have been shown to create hotspots of MeHg production (Figure 7-i). However, whether these hotspots can influence concentrations and fluxes at the basin level is unclear. Peatland MeHg dynamics have not been investigated in the Taiga Shield. The production of MeHg (methylation) is tied to the microbial community structure, DOM quantity and quality, Hg bioavailability, and the abundance of electron receptors (Bravo and Cosio, 2020). The nutrient-rich environment of thermokarst fens is more productive for methylation than nutrient-poor thermokarst bogs within the study area (Gordon et al., 2016) and other peatland-rich regions in Europe and North America (Fahnestock et al., 2019; Poulin et al., 2019; Figure 9). MeHg concentrations at a burned peat plateau were also elevated relative to a nearby unburned site, attributed to elevated DOC concentrations and favourable sulfate concentrations (Ackley et al., 2021; Figure 7-iii). However, MeHg and total Hg concentrations were not significantly elevated in rivers and lakes in the sporadic and discontinuous permafrost regions relative to the continuous permafrost zone of the Taiga Plains (Figure 8e-f; Thompson et al., In review). Still, peatland cover and DOC concentrations were key drivers for MeHg concentrations (Thompson et al., In review). Thermokarst peatland lakes show increasing Hg inputs (Klaminder et al., 2008; Korosi et al., 2015), and northern lakes in other regions have been methylation hotspots (Lehnherr et al., 2012; MacMillan et al., 2015; St. Louis et al., 2005; Varty et al., 2021). However, in the Taiga Plains, MeHg bound to DOM is likely delivered from surrounding wetlands rather than produced in situ (Branfireun et al., 2020; Bravo et al., 2017; Thompson et al., In Review). Downstream aquatic environments will likely receive increased inputs of Hg forms as permafrost thaw advances and landscapes transition to thermokarst wetlands.

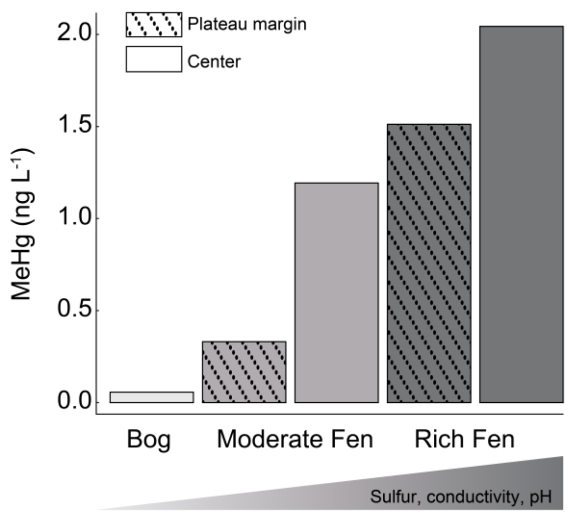

Figure 9. Barplot of methylmercury (MeHg) concentrations in permafrost-free wetlands draining to the Hay River, AB/NWT, where concentrations increased with wetland trophic status (L. Thompson, unpublished data).

7.5 Other Metals

Some evidence from external regions indicates that permafrost thaw in peatlands can lead to increased mobilization and downstream transport of metals complexed to DOM, such as lead (Pb), iron (Fe), and selenium (Se) that can impact aquatic biota (Klaminder et al., 2010; Patzner et al., 2020; Pokrovsky et al., 2018; Figure 7-ii). In northern Sweden, peatland thermokarst development led to an increased flux of Pb into the sediment of adjacent lakes (Klaminder et al., 2010). A study of Fe release through permafrost thaw in Sweden found that large quantities of organic matter are bound to reactive Fe; with waterlogging and oxygen limitation after permafrost thaw, Fe-reducing bacteria begin mobilizing both Fe and C (Patzner et al., 2020). In thaw lakes and rivers of the Western Siberian Lowlands, Se 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 Se, including DOC and Fe, were shown to be linearly correlated with Se concentrations (Pokrovsky et al., 2018). Since the primary driver of increased mobilization of these metals is the shift to anoxic conditions associated with thermokarst wetland development, similar trends may occur within the Taiga Plains. Thawing wetlands may likewise mobilize metals accumulated in peat within the Taiga Shield, although downstream effects may be less pronounced due to lower peatland coverage.

7.6 Point-Source Contaminants

Indigenous communities in the permafrost-fringe of the Taiga Plains and Taiga Shield have reported degraded water quality and expressed concern of water contamination from landfills, oil and gas facilities, and mine tailings (Christensen, 2015; Guyot et al., 2006; Mackenzie River Basin Board, 2021; Parlee and Maloney, 2017). Permafrost thaw can interact with the storage and transport of contaminants and potentially impact water quality (Grebenets et al., 2021; Miner et al., 2021; Figure 7-vii). For example, solid waste facilities in the NWT do not have engineered liners to contain leachate, so thaw-induced changes to hydrology may alter leachate transport to surface water receptors (Ripley, 2009). Additionally, solutes alter the freezing point of water (Woo, 2012), which could in turn, delay freeze back and enhance permafrost thaw. Recent modelling of a community sewage lagoon in the study region (undisclosed location) indicated that permafrost thaw increased hydrologic connectivity and transport of conservative/non-reactive solutes (e.g., chloride) to the nearby river (Mohammed et al., 2021). However, the authors also found that thaw-enhanced deep groundwater flow paths increased the residence times of reactive solutes, causing them to naturally degrade before reaching the river. Additional field investigations of point source contaminants like waste sites and lagoons are needed to support model development and assess risk to drinking water supplies from waste facilities.

Current and historic mining operations in the region include diamond, gold, lead, zinc, and silver mines in the Taiga Shield (Silke, 2009). A well-known case study of permafrost thaw interacting with mining activity is the Giant Mine in Yellowknife, NWT, which has posed significant health risks to nearby communities. During operation (1948-2004), arsenic trioxide (As_2O_3) dust (a by-product of gold ore roasting) was blown underground with the assumption that permafrost would contain the carcinogen (Jamieson, 2014; O'Reilly, 2015). However, permafrost is now largely absent from the site due to mine workings, so a thermosyphon system is needed to maintain frozen ground conditions (Jamieson, 2014). Still, seepages from the underground chambers are ongoing sources of arsenic to groundwater (Jamieson et al., 2013). Other point-source contaminants from mine sites that may be impacted from permafrost thaw include various hydrocarbons from fuel spills (Figure 7-vii) like at the abandoned Colomac mine in the Taiga Shield (Iwakun et al., 2008).

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 (AMAP, 2015). Freshwater cycling of PoPs is a current knowledge gap, and mobilization of PoPs with permafrost thaw is a concern for food web health (AMAP, 2015; 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). Similarly, recent work has highlighted projected increases in the thaw-induced emission of polycyclic aromatic compounds (PACs) (Muir and Galarneau, 2021), which are environmental pollutants generated from combustion, such as fossil fuels or wildfires (Abdel-Shafy and Mansour, 2016). PACs have been detected in the Hay River and Liard River, but levels were below water quality guidelines, and sources of the PACs were attributed to natural seeping from oil deposits in the environment and contributions from forest fires (Golder Associates, 2017; Stantec, 2016).

7.7 Groundwater Geochemistry

Re-activation of shallow and deep groundwater systems as permafrost thaws imposes uncertainty 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 thaw-activated subsurface pathways often drive surface processes (IPCC, 2019; McKenzie et al., 2021). Groundwater knowledge in the southern permafrost-fringe of the Taiga Plains and Shield is largely deficient (Golder Associates, 2017; VanGluck, 2016); many groundwater quality studies are concentrated in the western Canadian Arctic and Alaska and are lacking in peatland-dominated basins (Cochand et al., 2019). Few studies in the region directly measure groundwater geochemistry and instead make inferences based on surface water. For example, high ion concentrations in lakes and rivers of the Taiga Plains (Figure 8g-h; Mertens, 2018; Thompson and Olefeldt, 2020) indicate that connectivity of contemporary surface waters with ion-rich groundwater sources is common in the sporadic and discontinuous permafrost regions.

Thaw-induced increases in groundwater discharge and connectivity with surface waters (Section 6.2) may increase dissolved solids, EC, and ion concentrations in streams and lakes (Frey and McClelland, 2009). In addition, as the delivery of electron receptors such as sulfate increases with groundwater connectivity in wetlands, a consequence may be enhanced MeHg production (e.g., through sulfate-reducing bacteria) (Gordon et al., 2016; Figure 7-i). With thaw-enhanced hydrologic connectivity between wetlands, lakes, and streams, MeHg may be more easily transported to downstream waters. However, the impacts will likely be greatest in regions with widespread permafrost, such as the northern Taiga Plains, where thermokarst wetlands are not yet well connected to the basin drainage network. In general, more research is needed to understand the groundwater geochemistry changes in the southern reaches of the study area which may inform future changes in the north.

8 Summary and Knowledge Gaps

Rapid warming across the study region has resulted in permafrost thaw-driven landcover changes with direct impacts on the hydrology and water quality within and downstream of disturbed landscapes (Table 2). These changes are particularly pronounced for the peatland-dominated terrain of the Canadian Taiga Plains, where permafrost thaw is transforming black spruce forests underlain by permafrost to permafrost-free thermokarst wetlands. Here, in the initial stages of permafrost thaw, thermokarst bogs are hydrologically disconnected from other wetlands. Their formation temporarily increases groundwater storage, but their continued expansion results in an interconnected drainage network that forms a higher runoff-producing landcover. This landcover shift, along with increased supra-permafrost taliks, are considered the primary factors contributing to the observed increases in annual and winter streamflows in wetland-dominated basins. However, predicting the evolution and longer-term trajectory of increasingly integrated groundwater-surface water systems and the basin-scale implications remains a challenge. Sustained drainage of thermokarst wetlands can result in dry enough conditions to support the re-growth of permafrost-free black spruce forests, but this is a relatively recent advancement in landscape trajectory. As such, there are growing research opportunities for investigating the hydro(geo)logic and biogeochemical implications of afforested areas following permafrost thaw. Although considerable progress has been made in understanding the thaw-induced landcover impacts to discontinuous permafrost peatlands of the Taiga Plains, process-based studies largely stem from the Scotty Creek Research Station (Figure 3). Existing knowledge gaps should continue to be addressed here and at new locations in the study region to determine the transferability of these processes and fill spatial and temporal data gaps.

In the Taiga Shield, similar thaw-induced landcover changes as the Taiga Plains may occur in the peatlands that cover approximately 5% of the region, but this has not been well studied. Additional landcover changes stem from thermokarst pond development due to thawing lithalsas and changes in the areal extent of lakes that dominate the region. In contrast to the Taiga Plains, lake levels and streamflow in the Taiga Shield appear to be dominated by changes in precipitation instead of thaw-induced landcover change. However, permafrost thaw in soil-filled bedrock valleys may increase basin storage and alter the timing and magnitude of runoff events. Increased supra-permafrost taliks are also linked to icings which are most common in the Taiga Shield but remain relatively unstudied in the southern Taiga Plains. The development of open taliks beneath lakes may be a driver for observed declines in lake levels in the Taiga Shield, where lake drainage is facilitated through the thaw of highly conductive fracture zones resulting in sub-permafrost groundwater recharge. In both the Taiga Plains and Shield, thaw-induced activation of sub-permafrost flow systems may also increase with implications for stream baseflow, particularly where higher permeability substrate exists. However, direct evidence of this is lacking, limiting our understanding of flow and transport in these environments. Studies in the Taiga Shield primarily stem from the North Slave region, with limited groundwater investigation due to the logistical challenges and cost-prohibitive nature of such research in remote bedrock environments. Advancements in remote sensing will continue to provide invaluable information for remote areas, but new tools are needed to investigate remote and challenging subsurface environments.

As permafrost thaws in peatlands, the release of DOC, Fe, and contaminants may increase, while wildfire may enhance the aquatic release of nutrients. Waterlogged bogs and fens are environments that are more suited for the microbial production of MeHg than dry peat plateaus; thus, lakes and rivers may see increased concentrations of MeHg. As such, continued and expanded monitoring of MeHg in the region is needed. Additionally, studies that examine the potential release of PoPs and PACs with permafrost thaw in the region are lacking, although preliminary work has shown low concentrations of PACs in the Taiga Plains. Groundwater quality is a key knowledge gap in the thawing-permafrost fringe of the Taiga Plains and Shield, and further studies are needed to determine baseline groundwater quality in addition to impacts to downstream systems at much larger basin scales. The thaw-induced increase in hydrologic connectivity between landscapes means the potential for enhanced mobilization of contaminants, particularly non-reactive solutes. Additionally, fracture networks in the Taiga Shield pose a risk for rapid contaminant transport to receptors, but further research is needed on thaw-activated groundwater flow systems to understand the coupled transport in this environment. However, increased groundwater flow paths can increase residence times for solute reactions to take place and naturally attenuate contaminants, thereby limiting their impact on aquatic ecosystems and water supplies. Additional field investigations of point-source contaminants, such as community waste facilities and lagoons, are needed to improve our understanding of thaw-impacted contaminant transport in the study region.

Indigenous people who have lived in the study region for millennia are experiencing direct impacts of permafrost thaw-influenced landcover change and subsequent impacts on hydrology and water quality. Communities and Nations of the region are monitoring the land, sharing local and traditional knowledge, and producing data that document climate-driven changes. Such stewardship of the land through current/proposed Indigenous Protected and Conserved Areas (e.g., Edéhzhíe and Thaidene Nëné in NWT, Bistcho Lake in Alberta) are contributing to sustaining and monitoring waters in the study region. To fill knowledge gaps in our current understanding of landcover, hydrology, and water quality trajectories and re-orient from harmful research practices, western scientific institutions must prioritize engaging and collaborating with Indigenous-led and directed programs in a non-extractive way. In doing so, monitoring and research efforts will have the maximum benefit to those who live and rely on the land and those who study it.

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9 References

Abdel-Shafy, H.I., Mansour, M.S.M., 2016. A review on polycyclic aromatic hydrocarbons: Source, environmental impact, effect on human health and remediation. Egyptian Journal of Petroleum 25, 107–123. https://doi.org/10.1016/j.ejpe.2015.03.011

Ackley, C., Tank, S.E., Haynes, K.M., Rezanezhad, F., McCarter, C., Quinton, W.L., 2021. Coupled hydrological and geochemical impacts of wildfire in peatland-dominated regions of discontinuous permafrost. Science of The Total Environment 782, 146841. https://doi.org/10.1016/j.scitotenv.2021.146841

AMAP, 2015. AMAP Assessment 2015: Temporal Trends in Persistent Organic Pollutants in the Arctic., Arctic Monioring and Assessment Program.

Aylsworth, J.M., Kettles, I.M., 2000. Distribution of fen and bog in the Mackenzie Valley, 60°N-68°N.

Baltzer, J.L., Veness, T., Chasmer, L.E., Sniderhan, A.E., Quinton, W.L., 2014. Forests on thawing permafrost: fragmentation, edge effects, and net forest loss. Global Change Biology 20, 824–834. https://doi.org/10.1111/gcb.12349

Beilman, D.W., Robinson, S.D., 2003. Peatland permafrost thaw and landform type along a climatic gradient. Proceedings of the Eighth International Conference on Permafrost 1, 6.

Blanchfield, P.J., Rudd, J.W.M., Hrenchuk, L.E., Amyot, M., Babiarz, C.L., Beaty, K.G., Bodaly, R.A.D., Branfireun, B.A., Gilmour, C.C., Graydon, J.A., Hall, B.D., Harris, R.C., Heyes, A., Hintelmann, H., Hurley, J.P., Kelly, C.A., Krabbenhoft, D.P., Lindberg, S.E., Mason, R.P., Paterson, M.J., Podemski, C.L., Sandilands, K.A., Southworth, G.R., St Louis, V.L., Tate, L.S., Tate, M.T., 2021. Experimental evidence for recovery of mercury-contaminated fish populations. Nature. https://doi.org/10.1038/s41586-021-04222-7

Bonsal, B., Shabbar, A., 2011. Large-scale climate oscillations influencing Canada, 1900-2008., Canadian Biodiversity: Ecosystem Status and Trends 2010, Technical Thematic Report No. 4. Canadian Councils of Resource Ministers., Ottawa, ON.

Box, J.E., Colgan, W.T., Christensen, T.R., Schmidt, N.M., Lund, M., Parmentier, F.-J.W., Brown, R., Bhatt, U.S., Euskirchen, E.S., Romanovsky, V.E., Walsh, J.E., Overland, J.E., Wang, M., Corell, R.W., Meier, W.N., Wouters, B., Mernild, S., M\aard, J., Pawlak, J., Olsen, M.S., 2019. Key indicators of Arctic climate change: 1971–2017. Environ. Res. Lett. 14, 045010. https://doi.org/10.1088/1748-9326/aafc1b

Branfireun, B.A., Cosio, C., Poulain, A.J., Riise, G., Bravo, A.G., 2020. Mercury cycling in freshwater systems - An updated conceptual model. Science of The Total Environment 745, 140906. https://doi.org/10.1016/j.scitotenv.2020.140906

Braverman, M., Quinton, W.L., 2016. Hydrological impacts of seismic lines in the wetland-dominated zone of thawing, discontinuous permafrost, Northwest Territories, Canada: Hydrology of Seismic Lines in Discontinuous Permafrost. Hydrol. Process. 30, 2617–2627. https://doi.org/10.1002/hyp.10695

Bravo, A.G., Bouchet, S., Tolu, J., Björn, E., Mateos-Rivera, A., Bertilsson, S., 2017. Molecular composition of organic matter controls methylmercury formation in boreal lakes. Nat Commun 8, 14255. https://doi.org/10.1038/ncomms14255

Bravo, A.G., Cosio, C., 2020. Biotic formation of methylmercury: A bio–physico–chemical conundrum. Limnol Oceanogr 65, 1010–1027. https://doi.org/10.1002/lno.11366

Bring, A., Fedorova, I., Dibike, Y., Hinzman, L., Mård, J., Mernild, S.H., Prowse, T., Semenova, O., Stuefer, S.L., Woo, M.-K., 2016. Arctic terrestrial hydrology: A synthesis of processes, regional effects, and research challenges. Journal of Geophysical Research: Biogeosciences 121, 621–649. https://doi.org/10.1002/2015JG003131

Brown, J., Jr, O.J.F., Heginbottom, J.A., Melnikov, E.S., 1997. Circum-Arctic map of permafrost and ground-ice conditions. Circum-Pacific Map. https://doi.org/10.3133/cp45

Brown, R.J.E., 1973. Influence of climatic and terrain factors on ground temperatures at three locations in the permafrost region of Canada, in: North American Contribution to the 2nd International Conference on Permafrost. Presented at the 2nd International Conference on Permafrost, National Academy of Sciences, Washington, D.C., United States, pp. 27–34.

Brown, R.J.E., 1964. Permafrost investigations on the MacKenzie Highway in Alberta and MacKenzie District (Technical Paper No. 175). National Research Council of Canada. Division of Building Research. https://doi.org/10.4224/20358861

Burd, K., Tank, S.E., Dion, N., Quinton, W.L., Spence, C., Tanentzap, A.J., Olefeldt, D., 2018. Seasonal shifts in export of DOC and nutrients from burned and unburned peatland-rich catchments, Northwest Territories, Canada. Hydrol. Earth Syst. Sci. 22, 4455–4472. https://doi.org/10.5194/hess-22-4455-2018

Burgess, M.M., Smith, S.L., 2000. Shallow Ground Temperatures, The Physical Environment of the Mackenzie Valley, Northwest Territories: a Base Line for the Assessment of Environmental Change. Geological Survey of Canada.

Cabrerizo, A., Muir, D.C.G., De Silva, A.O., Wang, X., Lamoureux, S.F., Lafrenière, M.J., 2018. Legacy and Emerging Persistent Organic Pollutants (POPs) in Terrestrial Compartments in the High Arctic: Sorption and Secondary Sources. Environ. Sci. Technol. 52, 14187–14197. https://doi.org/10.1021/acs.est.8b05011

CALM, 2020. CALM North Summary Data Table [WWW Document]. Circumpolar Active Layer Monitoring. URL https://www2.gwu.edu/~calm/data/north.htm

Camill, P., 1999. Peat accumulation and succession following permafrost thaw in the boreal peatlands of Manitoba, Canada. Écoscience 6, 592–602. https://doi.org/10.1080/11956860.1999.11682561

Campeau, A., Soerensen, A.L., Martma, T., Åkerblom, S., Zdanowicz, C., 2020. Controls on the 14 C Content of Dissolved and Particulate Organic Carbon Mobilized Across the Mackenzie River Basin, Canada. Global Biogeochem. Cycles 34. https://doi.org/10.1029/2020GB006671

Cao, W., Sheng, Y., Wu, J., Li, Jing, Li, Jinping, Chou, Y., 2016. Simulation analysis of the impact of excavation backfill on permafrost recovery in an opencast coal-mining pit. Environ Earth Sci 75, 837. https://doi.org/10.1007/s12665-016-5659-5

Carpino, O., Haynes, K., Connon, R., Craig, J., Devoie, É., Quinton, W., 2021. Long-term climate-influenced land cover change in discontinuous permafrost peatland complexes. Hydrology and Earth System Sciences 25, 3301–3317. https://doi.org/10.5194/hess-25-3301-2021

Carpino, O.A., Berg, A.A., Quinton, W.L., Adams, J.R., 2018. Climate change and permafrost thaw-induced boreal forest loss in northwestern Canada. Environ. Res. Lett. 13, 084018. https://doi.org/10.1088/1748-9326/aad74e

Carroll, M.L., Townshend, J.R.G., DiMiceli, C.M., Loboda, T., Sohlberg, R.A., 2011. Shrinking lakes of the Arctic: Spatial relationships and trajectory of change: SHRINKING LAKES OF THE ARCTIC. Geophys. Res. Lett. 38, n/a-n/a. https://doi.org/10.1029/2011GL049427

Chasmer, L., Hopkinson, C., 2017. Threshold loss of discontinuous permafrost and landscape evolution. Global Change Biology 23, 2672–2686. https://doi.org/10.1111/gcb.13537

Chasmer, L., Quinton, W., Hopkinson, C., Petrone, R., Whittington, P., 2011. Vegetation Canopy and Radiation Controls on Permafrost Plateau Evolution within the Discontinuous Permafrost Zone, Northwest Territories, Canada. Permafrost and Periglacial Processes 22, 199–213. https://doi.org/10.1002/ppp.724

Chen, L., Fortier, D., McKenzie, J.M., Sliger, M., 2020. Impact of heat advection on the thermal regime of roads built on permafrost. Hydrological Processes 34, 1647–1664. https://doi.org/10.1002/hyp.13688

Chételat, J., Amyot, M., Arp, P., Blais, J.M., Depew, D., Emmerton, C.A., Evans, M., Gamberg, M., Gantner, N., Girard, C., Graydon, J., Kirk, J., Lean, D., Lehnherr, I., Muir, D., Nasr, M., J. Poulain, A., Power, M., Roach, P., Stern, G., Swanson, H., van der Velden, S., 2015. Mercury in freshwater ecosystems of the Canadian Arctic: Recent advances on its cycling and fate. Science of The Total Environment 509–510, 41–66. https://doi.org/10.1016/j.scitotenv.2014.05.151

Christensen, L., 2015. The Accessibility, Quality, and Safety of the Liard First Nation's Drinking Water Supply. Yukon Research Centre, Yukon College.

Clayton, L.K., Schaefer, K., Battaglia, M.J., Bourgeau-Chavez, L., Chen, J., Chen, R.H., Chen, A., Bakian-Dogaheh, K., Grelik, S., Jafarov, E., Liu, L., Michaelides, R.J., Moghaddam, M., Parsekian, A.D., Rocha, A.V., Schaefer, S.R., Sullivan, T., Tabatabaeenejad, A., Wang, K., Wilson, C.J., Zebker, H.A., Zhang, T., Zhao, Y., 2021. Active layer thickness as a function of soil water content. Environ. Res. Lett. 16, 055028. https://doi.org/10.1088/1748-9326/abfa4c

Cochand, M., Molson, J., Lemieux, J., 2019. Groundwater hydrogeochemistry in permafrost regions. Permafrost Periglacial Processes 30, 90–103.

Coleman, K.A., Palmer, M.J., Korosi, J.B., Kokelj, S.V., Jackson, K., Hargan, K.E., Courtney Mustaphi, C.J., Thienpont, J.R., Kimpe, L.E., Blais, J.M., Pisaric, M.F.J., Smol, J.P., 2015. Tracking the impacts of recent warming and thaw of permafrost peatlands on aquatic ecosystems: a multi-proxy approach using remote sensing and lake sediments. Boreal Environment Research 20, 363–377.

Connon, R., Devoie, É., Hayashi, M., Veness, T., Quinton, W., 2018. The Influence of Shallow Taliks on Permafrost Thaw and Active Layer Dynamics in Subarctic Canada. Journal of Geophysical Research: Earth Surface 123, 281–297. https://doi.org/10.1002/2017JF004469

Connon, R.F., Chasmer, L., Haughton, E., Helbig, M., Hopkinson, C., Sonnentag, O., Quinton, W.L., 2021. The implications of permafrost thaw and land cover change on snow water equivalent accumulation, melt and runoff in discontinuous permafrost peatlands. Hydrological Processes 35, e14363. https://doi.org/10.1002/hyp.14363

Connon, R.F., Quinton, W.L., Craig, J.R., Hanisch, J., Sonnentag, O., 2015. The hydrology of interconnected bog complexes in discontinuous permafrost terrains. Hydrological Processes 29, 3831–3847. https://doi.org/10.1002/hyp.10604

Connon, R.F., Quinton, W.L., Craig, J.R., Hayashi, M., 2014. Changing hydrologic connectivity due to permafrost thaw in the lower Liard River valley, NWT, Canada. Hydrological Processes 28, 4163–4178. https://doi.org/10.1002/hyp.10206

Crites, H., Kokelj, S.V., Lacelle, D., 2020. Icings and groundwater conditions in permafrost catchments of northwestern Canada. Scientific Reports 10, 3283. https://doi.org/10.1038/s41598-020-60322-w de Grandpré, I., Fortier, D., Stephani, E., 2012. Degradation of permafrost beneath a road embankment enhanced by heat advected in groundwater. Can. J. Earth Sci. 49, 953–962. https://doi.org/10.1139/e2012-018

Dearborn, K.D., Baltzer, J.L., 2021. Unexpected greening in a boreal permafrost peatland undergoing forest loss is partially attributable to tree species turnover. Global Change Biology n/a. https://doi.org/10.1111/gcb.15608

Dene Tha' First Nation, 2021. Bistcho Lake. URL https://bistcholake.ca/bistcho-lake/ (accessed 1.10.22).

Devoie, É.G., Craig, J.R., Connon, R.F., Quinton, W.L., 2019. Taliks: A Tipping Point in Discontinuous Permafrost Degradation in Peatlands. Water Resources Research 55, 9838–9857. https://doi.org/10.1029/2018WR024488

Devoie, É.G., Craig, J.R., Dominico, M., Carpino, O., Connon, R.F., Rudy, A.C.A., Quinton, W.L., 2021. Mechanisms of Discontinuous Permafrost Thaw in Peatlands. Journal of Geophysical Research: Earth Surface 126, e2021JF006204. https://doi.org/10.1029/2021JF006204

Di Capua, G., Bohle, M., Hildebrandt, D., Marone, E., Peppoloni, S., Schneider, S., 2022. Push for ethical practices in geoscience fieldwork. Nature 601, 26.

Disher, B.S., Connon, R.F., Haynes, K.M., Hopkinson, C., Quinton, W.L., 2021. The hydrology of treed wetlands in thawing discontinuous permafrost regions. Ecohydrology 14, e2296. https://doi.org/10.1002/eco.2296

Douglas, T.A., Blum, J.D., Guo, L., Keller, K., Gleason, J.D., 2013. Hydrogeochemistry of seasonal flow regimes in the Chena River, a subarctic watershed draining discontinuous permafrost in interior Alaska (USA). Chemical Geology 335, 48–62. https://doi.org/10.1016/j.chemgeo.2012.10.045

Douglas, T.A., Turetsky, M.R., Koven, C.D., 2020. Increased rainfall stimulates permafrost thaw across a variety of Interior Alaskan boreal ecosystems. npj Climate and Atmospheric Science 3, 1–7. https://doi.org/10.1038/s41612-020-0130-4

ECCC, 2021. Canadian Climate Normals 1981-2010 Station Data [WWW Document]. URL https://climate.weather.gc.ca/climate_normals/results_1981_2010_e.html?stnID=4268&autofwd=1 (accessed 2.2.22).

Ecological Stratification Working Group, 1995. A national ecological framework for Canada.

Ecosystem Classification Group, 2009. Ecological Regions of the Northwest Territories – Taiga Plains. Department of Environment and Natural Resources, Government of the Northwest Territories, Yellowknife, NT, Canada.

Ecosystem Classification Group, 2008. Ecological Regions of the Northwest Territories – Taiga Shield. Department of Environment and Natural Resources, Government of the Northwest Territories, Yellowknife, NT, Canada.

Ensom, T., Makarieva, O., Morse, P., Kane, D., Alekseev, V., Marsh, P., 2020. The distribution and dynamics of aufeis in permafrost regions. Permafrost and Periglacial Processes 31, 383–395. https://doi.org/10.1002/ppp.2051

Estop-Aragonés, C., Olefeldt, D., Abbott, B.W., Chanton, J.P., Czimczik, C.I., Dean, J.F., Egan, J.E., Gandois, L., Garnett, M.H., Hartley, I.P., Hoyt, A., Lupascu, M., Natali, S.M., O'Donnell, J.A., Raymond, P.A., Tanentzap, A.J., Tank, S.E., Schuur, E.A.G., Turetsky, M., Anthony, K.W., 2020. Assessing the Potential for Mobilization of Old Soil Carbon After Permafrost Thaw: A Synthesis of 14 C Measurements From the Northern Permafrost Region. Global Biogeochem. Cycles 34. https://doi.org/10.1029/2020GB006672

Evans, M., Lockhart, W.L., Doetzel, L., Low, G., Muir, D., Kidd, K., Stephens, G., Delaronde, J., 2005. Elevated mercury concentrations in fish in lakes in the Mackenzie River Basin: The role of physical, chemical, and biological factors. Science of The Total Environment 351–352, 479–500. https://doi.org/10.1016/j.scitotenv.2004.12.086

Evans, M., Muir, D., Brua, R.B., Keating, J., Wang, X., 2013. Mercury Trends in Predatory Fish in Great Slave Lake: The Influence of Temperature and Other Climate Drivers. Environ. Sci. Technol. 47, 12793–12801. https://doi.org/10.1021/es402645x

Fahnestock, M.F., Bryce, J.G., McCalley, C.K., Montesdeoca, M., Bai, S., Li, Y., Driscoll, C.T., Crill, P.M., Rich, V.I., Varner, R.K., 2019. Mercury reallocation in thawing subarctic peatlands. Geochem. Persp. Let. 33–38. https://doi.org/10.7185/geochemlet.1922

Frey, K.E., McClelland, J.W., 2009. Impacts of permafrost degradation on arctic river biogeochemistry. Hydrological Processes: An International Journal 23, 169–182.

Frey, K.E., Siegel, D.I., Smith, L.C., 2007. Geochemistry of west Siberian streams and their potential response to permafrost degradation: GEOCHEMISTRY OF WEST SIBERIAN STREAMS. Water Resour. Res. 43. https://doi.org/10.1029/2006WR004902

Frey, K.E., Smith, L.C., 2005. Amplified carbon release from vast West Siberian peatlands by 2100. Geophys. Res. Lett. 32, L09401. https://doi.org/10.1029/2004GL022025

Gibson, C., Chasmer, L.E., Thompson, D.K., Quinton, W.L., Flannigan, M.D., Olefeldt, D., 2018. Wildfire as a major driver of recent permafrost thaw in boreal peatlands. Nature Communications 9, 3041. https://doi.org/10.1038/s41467-018-05457-1

Gibson, C., Cottenie, K., Gingras-Hill, T., Kokelj, S.V., Baltzer, J., Chasmer, L., Turetsky, M., 2021. Mapping and understanding the vulnerability of northern peatlands to permafrost thaw at scales relevant to community adaptation planning. Environ. Res. Lett. https://doi.org/10.1088/1748-9326/abe74b

Gibson, C., Morse, P.D., Kelly, J.M., Turetsky, M.R., Baltzer, J.L., Gingras-Hill, T., Kokelj, S.V., 2020. Thermokarst Mapping Collective: Protocol for organic permafrost terrain and preliminary inventory from the Taiga Plains test area, Northwest Territories (No. Open Report 2020-010). Northwest Territories Geological Survey.

Gibson, J.J., Birks, S.J., Yi, Y., Vitt, D.H., 2015. Runoff to boreal lakes linked to land cover, watershed morphology and permafrost thaw: a 9-year isotope mass balance assessment: Boreal Lakes Isotope Mass Balance Assessment. Hydrol. Process. 29, 3848–3861. https://doi.org/10.1002/hyp.10502

Glass, B.K., Rudolph, D.L., Duguay, C., Wicke, A., 2021. Identifying groundwater discharge zones in the Central Mackenzie Valley using remotely sensed optical and thermal imagery. Can. J. Earth Sci. 58, 105–121. https://doi.org/10.1139/cjes-2019-0169

Golder Associates, 2017. Liard and Petitot River Basins State of Knowledge Report (No. 1547195).

Gordon, J., Quinton, W., Branfireun, B.A., Olefeldt, D., 2016. Mercury and methylmercury biogeochemistry in a thawing permafrost wetland complex, Northwest Territories, Canada: Northwest Territories, Canada. Hydrol. Process. 30, 3627–3638. https://doi.org/10.1002/hyp.10911

Government of the Northwest Territories, 2020. Water Management and Monitoring: Community-based Monitoring. Environment and Natural Resources. URL https://www.enr.gov.nt.ca/en/services/water-management-and-monitoring/community-based-monitoring (accessed 2.10.22).

Government of the Northwest Territories, Health and Social Services, 2020. Site Specific Fish Consumption Advice [WWW Document]. Fish Consumption Guidance. URL https://www.hss.gov.nt.ca/en/services/fish-consumption-guidance/site-specific-fish-consumption-advice (accessed 12.16.21).

Grebenets, V.I., Tolmanov, V.A., Iurov, F.D., Groisman, P.Y., 2021. The problem of storage of solid waste in permafrost. Environ. Res. Lett. 16, 105007. https://doi.org/10.1088/1748-9326/ac2375

Grigal, D.F., 2003. Mercury Sequestration in Forests and Peatlands: A Review. J. Environ. Qual. 32, 393–405. https://doi.org/10.2134/jeq2003.3930

Gruber, S., 2012. Derivation and analysis of a high-resolution estimate of global permafrost zonation. The Cryosphere 6, 221–233. https://doi.org/10.5194/tc-6-221-2012

GTN-P, 2016. Global Terrestrial Network for Permafrost Database: Permafrost Temperature Data (TSP - Thermal State of Permafrost).

Guyot, M., Dickson, C., Paci, C., Furgal, C., Chan, H.M., 2006. Local observations of climate change and impacts on traditional food security in two northern Aboriginal communities. International Journal of Circumpolar Health 65, 403–415. https://doi.org/10.3402/ijch.v65i5.18135

Hanes, C.C., Wang, X., Jain, P., Parisien, M.-A., Little, J.M., Flannigan, M.D., 2019. Fire-regime changes in Canada over the last half century. Can. J. For. Res. 49, 256–269. https://doi.org/10.1139/cjfr-2018-0293

Harris, S.A., French, H.M., Heginbottom, J.A., Johnston, G.H., Ladanyi, B., Sego, D.C., Everdingen, R.O. van, 1988. Glossary of Permafrost and Related Ground-Ice Terms.

Hayashi, M., McClymont, A.F., Christensen, B.S., Bentley, L.R., Quinton, W.L., 2011. Thawing of permafrost peatlands: Effects of water-energy feedback on landscape evolution, in: Refereed Proceedings of the Joint Meeting of the International Association of Hydrogeologists, Canadian National Chapter and the Canadian Quaternery Association. Quebec City.

Hayashi, M., Quinton, W.L., Pietroniro, A., Gibson, J.J., 2004. Hydrologic functions of wetlands in a discontinuous permafrost basin indicated by isotopic and chemical signatures. Journal of Hydrology 296, 81–97. https://doi.org/10.1016/j.jhydrol.2004.03.020

Haynes, K.M., Connon, R.F., Quinton, W.L., 2019. Hydrometeorological measurements in peatland-dominated, discontinuous permafrost at Scotty Creek, Northwest Territories, Canada. Geoscience Data Journal 6, 85–96. https://doi.org/10.1002/gdj3.69

Haynes, K.M., Connon, R.F., Quinton, W.L., 2018. Permafrost thaw induced drying of wetlands at Scotty Creek, NWT, Canada. Environ. Res. Lett. 13, 114001. https://doi.org/10.1088/1748-9326/aae46c

Haynes, K.M., Smart, J., Disher, B., Carpino, O., Quinton, W.L., 2020. The role of hummocks in re-establishing black spruce forest following permafrost thaw. Ecohydrology. https://doi.org/10.1002/eco.2273

Heffernan, L., Estop-Aragonés, C., Knorr, K.-H., Talbot, J., Olefeldt, D., 2020. Long-term Impacts of Permafrost Thaw on Carbon Storage in Peatlands: Deep Losses Offset by Surficial Accumulation. Journal of Geophysical Research: Biogeosciences 125, e2019JG005501. https://doi.org/10.1029/2019JG005501

Helbig, M., Pappas, C., Sonnentag, O., 2016. Permafrost thaw and wildfire: Equally important drivers of boreal tree cover changes in the Taiga Plains, Canada. Geophysical Research Letters 43, 1598–1606. https://doi.org/10.1002/2015GL067193

Holloway, J.E., Lewkowicz, A.G., 2020. Half a century of discontinuous permafrost persistence and degradation in western Canada. Permafrost and Periglacial Processes 31, 85–96. https://doi.org/10.1002/ppp.2017

Holloway, J.E., Lewkowicz, A.G., Douglas, T.A., Li, X., Turetsky, M.R., Baltzer, J.L., Jin, H., 2020. Impact of wildfire on permafrost landscapes: A review of recent advances and future prospects. Permafrost and Periglacial Processes 31, 371–382. https://doi.org/10.1002/ppp.2048

Hugelius, G., Loisel, J., Chadburn, S., Jackson, R.B., Jones, M., MacDonald, G., Marushchak, M., Olefeldt, D., Packalen, M., Siewert, M.B., Treat, C., Turetsky, M., Voigt, C., Yu, Z., 2020. Large stocks of peatland carbon and nitrogen are vulnerable to permafrost thaw. Proc Natl Acad Sci USA 117, 20438–20446. https://doi.org/10.1073/pnas.1916387117

Huntington, H.P., Boyle, M., Flowers, G.E., Weatherly, J.W., Hamilton, L.C., Hinzman, L., Gerlach, C., Zulueta, R., Nicolson, C., Overpeck, J., 2007. The influence of human activity in the Arctic on climate and climate impacts. Climatic Change 82, 77. https://doi.org/10.1007/s10584-006-9162-y

Indigenous Leadership Initiative, 2021. Indigenous Protected and Conserved Areas. URL https://www.ilinationhood.ca/indigenous-protected-and-conserved-areas (accessed 1.10.22).

IPCC, 2019. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, edited by: Pörtner, H.-O.,Roberts, D. C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai M., Okem, A., Petzold, J., Rama, B., and Weyer, N. M.

Iwakun, O., Biggar, K., Van Stempvoort, D., Bickerton, G., Voralek, J., 2008. Fuel contamination characterization in permafrost fractured bedrock at the Colomac mine site. Cold Regions Science and Technology, Fifth International Conference on Contaminants in Freezing Ground 53, 56–74. https://doi.org/10.1016/j.coldregions.2007.10.001

Jafarov, E.E., Romanovsky, V.E., Genet, H., McGuire, A.D., Marchenko, S.S., 2013. The effects of fire on the thermal stability of permafrost in lowland and upland black spruce forests of interior Alaska in a changing climate. Environ. Res. Lett. 8, 035030. https://doi.org/10.1088/1748-9326/8/3/035030

Jamieson, H.E., 2014. The Legacy of Arsenic Contamination from Mining and Processing Refractory Gold Ore at Giant Mine, Yellowknife, Northwest Territories, Canada. Reviews in Mineralogy and Geochemistry 79, 533–551. https://doi.org/10.2138/rmg.2014.79.12

Jamieson, H.E., Bromstad, M.L., Nordstrom, D.K., 2013. Extremely arsenic-rich, pH-neutral waters from the Giant Mine, Canada. Proceedings of the First International Conference on Mine Water Solutions in Extreme Environments. Mine Water Solutions 82–84.

Jin, X.-Y., Jin, H.-J., Iwahana, G., Marchenko, S.S., Luo, D.-L., Li, X.-Y., Liang, S.-H., 2020. Impacts of climate-induced permafrost degradation on vegetation: A review. Advances in Climate Change Research. https://doi.org/10.1016/j.accre.2020.07.002

Johnston, G.H., Brown, R.J.E., Pickersgill, D.N., 1963. Permafrost investigations at Thompson, Manitoba: terrain studies, Technical Paper (National Research Council of Canada. Division of Building Research); no. DBR-TP-158. National Research Council of Canada. https://doi.org/10.4224/20375716

Karlsson, J.M., Lyon, S.W., Destouni, G., 2012. Thermokarst lake, hydrological flow and water balance indicators of permafrost change in Western Siberia. Journal of Hydrology 464–465, 459–466. https://doi.org/10.1016/j.jhydrol.2012.07.037

Karunaratne, K.C., Kokelj, S., Burn, C., 2008. Near-surface permafrost conditions near Yellowknife, Northwest Territories, Canada. Presented at the Proceedings Ninth International Conference on Permafrost.

Keuper, F., Bodegom, P.M., Dorrepaal, E., Weedon, J.T., Hal, J., Logtestijn, R.S.P., Aerts, R., 2012. A frozen feast: thawing permafrost increases plant-available nitrogen in subarctic peatlands. Glob Change Biol 18, 1998–2007. https://doi.org/10.1111/j.1365-2486.2012.02663.x

Klaminder, J., Hammarlund, D., Kokfelt, U., Vonk, J.E., Bigler, C., 2010. Lead Contamination of Subarctic Lakes and Its Response to Reduced Atmospheric Fallout: Can the Recovery Process Be Counteracted by the Ongoing Climate Change? Environ. Sci. Technol. 44, 2335–2340. https://doi.org/10.1021/es903025z

Klaminder, J., Yoo, K., Rydberg, J., Giesler, R., 2008. An explorative study of mercury export from a thawing palsa mire. Journal of Geophysical Research: Biogeosciences 113. https://doi.org/10.1029/2008JG000776

Kokelj, S.A., 2003. Hydrologic Overview of the North and South Slave Regions. Water Resources Division - Indian and Northern Affairs Canada, Yellowknife, Northwest Territorie.

Kokelj, S.V., Jorgenson, M.T., 2013. Advances in Thermokarst Research: Recent Advances in Research Investigating Thermokarst Processes. Permafrost and Periglac. Process. 24, 108–119. https://doi.org/10.1002/ppp.1779

Kokelj, S.V., Lacelle, D., Lantz, T.C., Tunnicliffe, J., Malone, L., Clark, I.D., Chin, K.S., 2013. Thawing of massive ground ice in mega slumps drives increases in stream sediment and solute flux across a range of watershed scales. J. Geophys. Res. Earth Surf. 118, 681–692. https://doi.org/10.1002/jgrf.20063

Kokelj, S.V., Lantz, T.C., Kanigan, J., Smith, S.L., Coutts, R., 2009. Origin and polycyclic behaviour of tundra thaw slumps, Mackenzie Delta region, Northwest Territories, Canada. Permafrost Periglac. Process. 20, 173–184. https://doi.org/10.1002/ppp.642

Kokelj, S.V., Lantz, T.C., Tunnicliffe, J., Segal, R., Lacelle, D., 2017. Climate-driven thaw of permafrost preserved glacial landscapes, northwestern Canada. Geology 45, 371–374. https://doi.org/10.1130/G38626.1

Korosi, J.B., McDonald, J., Coleman, K.A., Palmer, M.J., Smol, J.P., Simpson, M.J., Blais, J.M., 2015. Long-term changes in organic matter and mercury transport to lakes in the sporadic discontinuous permafrost zone related to peat subsidence. Limnol.Oceanogr. 60, 1550–1561.

Korosi, J.B., Thienpont, J.R., Pisaric, M.F.J., deMontigny, P., Perreault, J.T., McDonald, J., Simpson, M.J., Armstrong, T., Kokelj, S.V., Smol, J.P., Blais, J.M., 2017. Broad-scale lake expansion and flooding inundates essential wood bison habitat. Nature Communications 8, 14510. https://doi.org/10.1038/ncomms14510

Koven, C.D., Riley, W.J., Stern, A., 2013. Analysis of Permafrost Thermal Dynamics and Response to Climate Change in the CMIP5 Earth System Models. J. Clim. 26, 1877–1900. https://doi.org/10.1175/JCLI-D-12-00228.1

Krickov, I.V., Lim, A.G., Manasypov, R.M., Loiko, S.V., Shirokova, L.S., Kirpotin, S.N., Karlsson, J., Pokrovsky, O.S., 2018. Riverine particulate C and N generated at the permafrost thaw front: case study of western Siberian rivers across a 1700 km latitudinal transect. Biogeosciences 15, 6867–6884. https://doi.org/10.5194/bg-15-6867-2018

Krickov, I.V., Lim, A.G., Manasypov, R.M., Loiko, S.V., Vorobyev, S.N., Shevchenko, V.P., Dara, O.M., Gordeev, V.V., Pokrovsky, O.S., 2020. Major and trace elements in suspended matter of western Siberian rivers: First assessment across permafrost zones and landscape parameters of watersheds. Geochim.Cosmochim.Acta 269, 429–450.

Kuhn, M.A., Thompson, L.M., Winder, J.C., Braga, L.P.P., Tanentzap, A.J., Bastviken, D., Olefeldt, D., 2021. Opposing Effects of Climate and Permafrost Thaw on CH 4 and CO 2 Emissions From Northern Lakes. AGU Advances 2. https://doi.org/10.1029/2021AV000515

Kurylyk, B.L., Hayashi, M., Quinton, W.L., McKenzie, J.M., Voss, C.I., 2016. Influence of vertical and lateral heat transfer on permafrost thaw, peatland landscape transition, and groundwater flow. Water Resources Research 52, 1286–1305. https://doi.org/10.1002/2015WR018057

Kurylyk, B.L., Walvoord, M.A., 2021. Permafrost Hydrogeology, in: Yang, D., Kane, D.L. (Eds.), Arctic Hydrology, Permafrost and Ecosystems. Springer International Publishing, Cham, pp. 493–523. https://doi.org/10.1007/978-3-030-50930-9_17

Kwong, Y.T.J., Gan, T.Y., 1994. Northward migration of permafrost along the Mackenzie highway and climatic warming. Climatic Change 26, 399–419. https://doi.org/10.1007/BF01094404

Laird, M.J., Henao, J.J.A., Reyes, E.S., Stark, K.D., Low, G., Swanson, H.K., Laird, B.D., 2018. Mercury and omega-3 fatty acid profiles in freshwater fish of the Dehcho Region, Northwest Territories: Informing risk benefit assessments. Science of The Total Environment 637–638, 1508–1517. https://doi.org/10.1016/j.scitotenv.2018.04.381

Latulippe, N., Klenk, N., 2020. Making room and moving over: knowledge co-production, Indigenous knowledge sovereignty and the politics of global environmental change decision-making. Current Opinion in Environmental Sustainability 42, 7–14. https://doi.org/10.1016/j.cosust.2019.10.010

Lehnherr, I., St. Louis, V.L., Kirk, J.L., 2012. Methylmercury Cycling in High Arctic Wetland Ponds: Controls on Sedimentary Production. Environ. Sci. Technol. 46, 10523–10531. https://doi.org/10.1021/es300577e

Lemmen, D.S., Duk-Rodkin, A., Bednarski, J.M., 1994. Late glacial drainage systems along the northwestern margin of the Laurentide Ice Sheet. Quaternary Science Reviews 13, 805–828. https://doi.org/10.1016/0277-3791(94)90003-5

Li, M., Peng, C., Wang, M., Xue, W., Zhang, K., Wang, K., Shi, G., Zhu, Q., 2017. The carbon flux of global rivers: A re-evaluation of amount and spatial patterns. Ecological Indicators 80, 40–51. https://doi.org/10.1016/j.ecolind.2017.04.049

Lim, A.G., Sonke, J.E., Krickov, I.V., Manasypov, R.M., Loiko, S.V., Pokrovsky, O.S., 2019. Enhanced particulate Hg export at the permafrost boundary, western Siberia. Environmental Pollution 254, 113083. https://doi.org/10.1016/j.envpol.2019.113083

Ma, J., Hung, H., Macdonald, R.W., 2016. The influence of global climate change on the environmental fate of persistent organic pollutants: A review with emphasis on the Northern Hemisphere and the Arctic as a receptor. Global and Planetary Change 146, 89–108. https://doi.org/10.1016/j.gloplacha.2016.09.011

Mack, M., Connon, R., Makarieva, O., McLaughlin, J., Nesterova, N., Quinton, W., 2021. Heterogenous runoff trends in peatland-dominated basins throughout the circumpolar North. Environ. Res. Commun. 3, 075006. https://doi.org/10.1088/2515-7620/ac11ed

Mackenzie River Basin Board, 2021. Mackenzie River Basin State of the Aquatic Ecosystem Report.

MacMillan, G.A., Girard, C., Chételat, J., Laurion, I., Amyot, M., 2015. High Methylmercury in Arctic and Subarctic Ponds is Related to Nutrient Levels in the Warming Eastern Canadian Arctic. Environ. Sci. Technol. 49, 7743–7753. https://doi.org/10.1021/acs.est.5b00763

McClelland, J.W., Holmes, R.M., Peterson, B.J., Stieglitz, M., 2004. Increasing river discharge in the Eurasian Arctic: Consideration of dams, permafrost thaw, and fires as potential agents of change. Journal of Geophysical Research: Atmospheres 109. https://doi.org/10.1029/2004JD004583

McClymont, A.F., Hayashi, M., Bentley, L.R., Christensen, B.S., 2013. Geophysical imaging and thermal modeling of subsurface morphology and thaw evolution of discontinuous permafrost. Journal of Geophysical Research: Earth Surface 118, 1826–1837. https://doi.org/10.1002/jgrf.20114

Mcintyre, J., Beauchamp, D., 2007. Age and trophic position dominate bioaccumulation of mercury and organochlorines in the food web of Lake Washington. Science of The Total Environment 372, 571–584. https://doi.org/10.1016/j.scitotenv.2006.10.035

McKenzie, J.M., Kurylyk, B.L., Walvoord, M.A., Bense, V.F., Fortier, D., Spence, C., Grenier, C., 2021. Invited perspective: What lies beneath a changing Arctic? The Cryosphere 15, 479–484. https://doi.org/10.5194/tc-15-479-2021

Mergler, D., Anderson, H.A., Chan, L.H.M., Mahaffey, K.R., Murray, M., Sakamoto, M., Stern, A.H., 2007. Methylmercury Exposure and Health Effects in Humans: A Worldwide Concern. AMBIO: A Journal of the Human Environment 36, 3–11. https://doi.org/10.1579/0044-7447(2007)36[3:MEAHEI]2.0.CO;2

Mertens, A., 2018. Spatial variability and controls on surface water chemistry and quality in a heterogeneous landscape: the Western Boreal Forest (Master of Science). University of Alberta, Edmonton, AB.

Michel, F.A., 1986. Hydrogeology of the central Mackenzie Valley. Journal of Hydrology 85, 379–405. https://doi.org/10.1016/0022-1694(86)90068-5

Miner, K.R., D’Andrilli, J., Mackelprang, R., Edwards, A., Malaska, M.J., Waldrop, M.P., Miller, C.E., 2021a. Emergent biogeochemical risks from Arctic permafrost degradation. Nat. Clim. Chang. 11, 809–819. https://doi.org/10.1038/s41558-021-01162-y

Miner, K.R., D’Andrilli, J., Mackelprang, R., Edwards, A., Malaska, M.J., Waldrop, M.P., Miller, C.E., 2021b. Emergent biogeochemical risks from Arctic permafrost degradation. Nat. Clim. Chang. 11, 809–819. https://doi.org/10.1038/s41558-021-01162-y

Mohammed, A.A., Bense, V.F., Kurylyk, B.L., Jamieson, R.C., Johnston, L.H., Jackson, A.J., 2021. Modeling Reactive Solute Transport in Permafrost-Affected Groundwater Systems. Water Resources Research 57, e2020WR028771. https://doi.org/10.1029/2020WR028771

Moore, T.R., 2013. Dissolved Organic Carbon Production and Transport in Canadian Peatlands, in: Baird, A.J., Belyea, L.R., Comas, X., Reeve, A.S., Slater, L.D. (Eds.), Geophysical Monograph Series. American Geophysical Union, Washington, D. C., pp. 229–236. https://doi.org/10.1029/2008GM000816

Moore, T.R., Knorr, K.-H., Thompson, L., Roy, C., Bubier, J.L., 2019. The effect of long-term fertilization on peat in an ombrotrophic bog. Geoderma 343, 176–186. https://doi.org/10.1016/j.geoderma.2019.02.034

Morse, P.D., McWade, T.L., Wolfe, S.A., 2017. Thermokarst ponding, North Slave region, Northwest Territories (No. 8205). https://doi.org/10.4095/300531

Morse, P.D., Spence, C., 2017. Permafrost and hydrogeology interactions: subarctic Canadian Shield, in: Natural Resources Canada, Contribution Series 20170091. Presented at the GeoOttawa 2017, Canadian Geotechnical Society (CGS) in collaboration with the Canadian National Chapter of the International Association of Hydrogeologists (IAH-CNC), Ottawa, Ontario.

Morse, P.D., Wolfe, S.A., 2017. Long-Term River Icing Dynamics in Discontinuous Permafrost, Subarctic Canadian Shield. Permafrost and Periglacial Processes 28, 580–586. https://doi.org/10.1002/ppp.1907

Morse, P.D., Wolfe, S.A., 2015. Geological and meteorological controls on icing (aufeis) dynamics (1985 to 2014) in subarctic Canada. Journal of Geophysical Research: Earth Surface 120, 1670–1686. https://doi.org/10.1002/2015JF003534

Morse, P.D., Wolfe, S.A., Kokelj, S.V., Gaanderse, A.J.R., 2016. The Occurrence and Thermal Disequilibrium State of Permafrost in Forest Ecotopes of the Great Slave Region, Northwest Territories, Canada. Permafrost and Periglacial Processes 27, 145–162. https://doi.org/10.1002/ppp.1858

Moslemi-Aqdam, M., Baker, L.F., Baltzer, J.L., Branfireun, B.A., Evans, M.S., Laird, B.D., Low, G., Low, M., Swanson, H.K., 2022. Understanding among-lake variability of mercury concentrations in Northern Pike (Esox lucius): A whole-ecosystem study in subarctic lakes. Science of The Total Environment 153430. https://doi.org/10.1016/j.scitotenv.2022.153430

Muir, D.C.G., Galarneau, E., 2021. Polycyclic aromatic compounds (PACs) in the Canadian environment: Links to global change. Environmental Pollution 273, 116425. https://doi.org/10.1016/j.envpol.2021.116425

Muller, S.W., 1943. Permafrost or permanently frozen ground and related engineering problems (Strategic Engineering Study No. Special Report No. 62). U.S. Engineers Office, Ann Arbor, Michigan.

Natural Resources Canada, 2017. Wooded Areas, Saturated Soils and Landscape in Canada - CanVec Series - Land Features [WWW Document]. URL https://open.canada.ca/data/en/dataset/80aa8ec6-4947-48de-bc9c-7d09d48b4cad (accessed 7.10.19).

Nguyen, T.-N., Burn, C.R., King, D.J., Smith, S.L., 2009. Estimating the extent of near-surface permafrost using remote sensing, Mackenzie Delta, Northwest Territories. Permafrost and Periglacial Processes 20, 141–153. https://doi.org/10.1002/ppp.637

Nitze, I., Grosse, G., Jones, B.M., Romanovsky, V.E., Boike, J., 2018. Remote sensing quantifies widespread abundance of permafrost region disturbances across the Arctic and Subarctic. Nature Communications 9, 5423. https://doi.org/10.1038/s41467-018-07663-3

Olefeldt, D., Goswami, S., Grosse, G., Hayes, D., Hugelius, G., Kuhry, P., McGuire, A.D., Romanovsky, V.E., Sannel, A.B.K., Schuur, E. a. G., Turetsky, M.R., 2016. Circumpolar distribution and carbon storage of thermokarst landscapes. Nature Communications 7, 13043. https://doi.org/10.1038/ncomms13043

Olefeldt, D., Persson, A., Turetsky, M.R., 2014. Influence of the permafrost boundary on dissolved organic matter characteristics in rivers within the Boreal and Taiga plains of western Canada. Environ. Res. Lett. 9, 035005. https://doi.org/10.1088/1748-9326/9/3/035005

Olefeldt, D., Roulet, N.T., 2012. Effects of permafrost and hydrology on the composition and transport of dissolved organic carbon in a subarctic peatland complex: DOC IN A SUBARCTIC PEATLAND COMPLEX. J. Geophys. Res. 117. https://doi.org/10.1029/2011JG001819

O'Neill, H.B., Wolfe, S.A., Duchesne, C., 2019. New ground ice maps for Canada using a paleogeographic modelling approach. The Cryosphere 13, 753–773. https://doi.org/10.5194/tc-13-753-2019

O'Reilly, K., 2015. Liability, legacy, and perpetual care: government ownership and management of the Giant Mine, 1999–2015. Mining and Communities in Northern Canada 341.

Panda, S.K., Prakash, A., Solie, D.N., Romanovsky, V.E., Jorgenson, M.T., 2010. Remote sensing and field-based mapping of permafrost distribution along the Alaska Highway corridor, interior Alaska. Permafrost and Periglacial Processes 21, 271–281. https://doi.org/10.1002/ppp.686

Parlee, B., Maloney, E., 2017. Local and Traditional Knowledge in Watershed Governance: Report of the 2016 Community-Based Research Projects in the Mackenzie River Basin. 93.

Pastick, N.J., Jorgenson, M.T., Wylie, B.K., Nield, S.J., Johnson, K.D., Finley, A.O., 2015. Distribution of near-surface permafrost in Alaska: Estimates of present and future conditions. Remote Sens. Environ. 168, 301–315. https://doi.org/10.1016/j.rse.2015.07.019

Patzner, M.S., Mueller, C.W., Malusova, M., Baur, M., Nikeleit, V., Scholten, T., Hoeschen, C., Byrne, J.M., Borch, T., Kappler, A., Bryce, C., 2020. Iron mineral dissolution releases iron and associated organic carbon during permafrost thaw. Nat Commun 11, 6329. https://doi.org/10.1038/s41467-020-20102-6

Pawley, S.M., Utting, D.J., 2018. Permafrost classification model for Northern Alberta (gridded data, GeoTIFF format).

Pelletier, N., Talbot, J., Olefeldt, D., Turetsky, M., Blodau, C., Sonnentag, O., Quinton, W.L., 2017. Influence of Holocene permafrost aggradation and thaw on the paleoecology and carbon storage of a peatland complex in northwestern Canada. The Holocene 27, 1391–1405. https://doi.org/10.1177/0959683617693899

Peterson, B.J., Holmes, R.M., McClelland, J.W., Vörösmarty, C.J., Lammers, R.B., Shiklomanov, A.I., Shiklomanov, I.A., Rahmstorf, S., 2002. Increasing River Discharge to the Arctic Ocean. Science 298, 2171–2173. https://doi.org/10.1126/science.1077445

Petrone, K.C., Jones, J.B., Hinzman, L.D., Boone, R.D., 2006. Seasonal export of carbon, nitrogen, and major solutes from Alaskan catchments with discontinuous permafrost: ALASKAN CATCHMENT EXPORT. J. Geophys. Res. 111, n/a-n/a. https://doi.org/10.1029/2005JG000055

Pokrovsky, O.S., Bueno, M., Manasypov, R.M., Shirokova, L.S., Karlsson, J., Amouroux, D., 2018. Dissolved Organic Matter Controls Seasonal and Spatial Selenium Concentration Variability in Thaw Lakes across a Permafrost Gradient. Environ. Sci. Technol. 52, 10254–10262. https://doi.org/10.1021/acs.est.8b00918

Pokrovsky, O.S., Manasypov, R.M., Loiko, S., Shirokova, L.S., Krickov, I.A., Pokrovsky, B.G., Kolesnichenko, L.G., Kopysov, S.G., Zemtzov, V.A., Kulizhsky, S.P., Vorobyev, S.N., Kirpotin, S.N., 2015. Permafrost coverage, watershed area and season control of dissolved carbon and major elements in western Siberian rivers. Biogeosciences 12, 6301–6320. https://doi.org/10.5194/bg-12-6301-2015

Poulin, B.A., Ryan, J.N., Tate, M.T., Krabbenhoft, D.P., Hines, M.E., Barkay, T., Schaefer, J., Aiken, G.R., 2019. Geochemical Factors Controlling Dissolved Elemental Mercury and Methylmercury Formation in Alaskan Wetlands of Varying Trophic Status. Environ. Sci. Technol. 53, 6203–6213. https://doi.org/10.1021/acs.est.8b06041

Pugh, E.A., 2021. From Drought to Deluge: Implications of variable hydrologic connectivity on lake ecosystem functions in the Boreal Plains of Western Canada (PhD Thesis). University of Alberta, Edmonton.

Quinton, W., Berg, A., Braverman, M., Carpino, O., Chasmer, L., Connon, R., Craig, J., Devoie, É., Hayashi, M., Haynes, K., Olefeldt, D., Pietroniro, A., Rezanezhad, F., Schincariol, R., Sonnentag, O., 2019. A synthesis of three decades of hydrological research at Scotty Creek, NWT, Canada. Hydrology and Earth System Sciences 23, 2015–2039. https://doi.org/10.5194/hess-23-2015-2019

Quinton, W.L., Hayashi, M., Chasmer, L.E., 2011. Permafrost-thaw-induced land-cover change in the Canadian subarctic: implications for water resources. Hydrological Processes 25, 152–158. https://doi.org/10.1002/hyp.7894

Quinton, W.L., Hayashi, M., Chasmer, L.E., 2009. Peatland Hydrology of Discontinuous Permafrost in the Northwest Territories: Overview and Synthesis. Canadian Water Resources Journal / Revue canadienne des ressources hydriques 34, 311–328. https://doi.org/10.4296/cwrj3404311

Quinton, W.L., Hayashi, M., Pietroniro, A., 2003. Connectivity and storage functions of channel fens and flat bogs in northern basins. Hydrological Processes 17, 3665–3684. https://doi.org/10.1002/hyp.1369

Reedyk, S., Woo, M.-K., Prowse, T.D., 2011. Contribution of icing ablation to streamflow in a discontinuous permafrost area. Canadian Journal of Earth Sciences. https://doi.org/10.1139/e95-002

Ren, J., Wang, X., Gong, P., Wang, C., 2019. Characterization of Tibetan Soil As a Source or Sink of Atmospheric Persistent Organic Pollutants: Seasonal Shift and Impact of Global Warming. Environ. Sci. Technol. 53, 3589–3598. https://doi.org/10.1021/acs.est.9b00698

Ripley, S., 2009. Navigating the Waters of Change: Strengthening the Capacity of NWT Communities to Respond to the Impacts of Climate Change on Municipal Water and Wastewater Systems. Ecology North.

Robinson, S.D., Moore, T.R., 2000. The Influence of Permafrost and Fire upon Carbon Accumulation in High Boreal Peatlands, Northwest Territories, Canada. Arctic, Antarctic, and Alpine Research 32, 155–166. https://doi.org/10.2307/1552447

Rouse, W.R., 2000. Progress in hydrological research in the Mackenzie GEWEX study. Hydrological Processes 14, 1667–1685. https://doi.org/10.1002/1099-1085(20000630)14:9<1667::AID-HYP80>3.0.CO;2-K

Rydberg, J., Klaminder, J., Rosén, P., Bindler, R., 2010. Climate driven release of carbon and mercury from permafrost mires increases mercury loading to sub-arctic lakes. Science of The Total Environment 408, 4778–4783. https://doi.org/10.1016/j.scitotenv.2010.06.056

Sannel, A.B.K., Kuhry, P., 2011. Warming-induced destabilization of peat plateau/thermokarst lake complexes. Journal of Geophysical Research: Biogeosciences 116. https://doi.org/10.1029/2010JG001635

Schwab, M.S., Hilton, R.G., Raymond, P.A., Haghipour, N., Amos, E., Tank, S.E., Holmes, R.M., Tipper, E.T., Eglinton, T.I., 2020. An Abrupt Aging of Dissolved Organic Carbon in Large Arctic Rivers. Geophys. Res. Lett. 47. https://doi.org/10.1029/2020GL088823

Seppälä, M., 2011. Synthesis of studies of palsa formation underlining the importance of local environmental and physical characteristics. Quaternary Research 75, 366–370. https://doi.org/10.1016/j.yqres.2010.09.007

Shatilla, N.J., Carey, S.K., 2019. Assessing inter-annual and seasonal patterns of DOC and DOM quality across a complex alpine watershed underlain by discontinuous permafrost in Yukon, Canada. Hydrol. Earth Syst. Sci. 23, 3571–3591. https://doi.org/10.5194/hess-23-3571-2019

Shrestha, R.R., Prowse, T.D., Tso, L., 2019. Modelling historical variability of phosphorus and organic carbon fluxes to the Mackenzie River, Canada. Hydrology Research 50, 1424–1439. https://doi.org/10.2166/nh.2019.161

Silke, R., 2009. The Operational History of Mines in the Northwest Territories, Canada. NWT Geoscience Office, Yellowknife, NWT.

Sjöberg, Y., Coon, E., Sannel, A.B.K., Pannetier, R., Harp, D., Frampton, A., Painter, S.L., Lyon, S.W., 2016. Thermal effects of groundwater flow through subarctic fens: A case study based on field observations and numerical modeling. Water Resources Research 52, 1591–1606. https://doi.org/10.1002/2015WR017571

Sladen, W., 2017. Icings near the Tibbitt to Contwoyto Winter Road, Great Slave Uplands, Northwest Territories (Masters Thesis). Carleton University, Ottawa, Ontario.

Slater, A.G., Lawrence, D.M., 2013. Diagnosing Present and Future Permafrost from Climate Models. Journal of Climate 26, 5608–5623. https://doi.org/10.1175/JCLI-D-12-00341.1

Smith, L.C., Pavelsky, T.M., MacDonald, G.M., Shiklomanov, A.I., Lammers, R.B., 2007. Rising minimum daily flows in northern Eurasian rivers: A growing influence of groundwater in the high-latitude hydrologic cycle. Journal of Geophysical Research: Biogeosciences 112. https://doi.org/10.1029/2006JG000327

Smith, S., Nixon, M., Burgess, M., 2013. TSP Canada Geological Survey. Geological Survey of Canada, Ottawa.

Smith, S.L., Burgess, M.M., Riseborough, D.W., 2008. Ground temperature and thaw settlement in frozen peatlands along the Norman Wells pipeline corridor, NWT Canada: 22 years of monitoring, in: Ninth International Conference on Permafrost, Proceedings Volume 2. Fairbanks, Alaska.

Smith, S.L., Riseborough, D.W., 2010. Modelling the thermal response of permafrost terrain to right-of-way disturbance and climate warming. Cold Regions Science and Technology 60, 92–103. https://doi.org/10.1016/j.coldregions.2009.08.009

Smith, S.L., Riseborough, D.W., Bonnaventure, P.P., 2015. Eighteen Year Record of Forest Fire Effects on Ground Thermal Regimes and Permafrost in the Central Mackenzie Valley, NWT, Canada. Permafrost and Periglacial Processes 26, 289–303. https://doi.org/10.1002/ppp.1849

Smith, S.L., Romanovsky, V.E., Lewkowicz, A.G., Burn, C.R., Allard, M., Clow, G.D., Yoshikawa, K., Throop, J., 2010. Thermal state of permafrost in North America: a contribution to the international polar year. Permafrost and Periglacial Processes 21, 117–135. https://doi.org/10.1002/ppp.690

Solomon, C.T., Jones, S.E., Weidel, B.C., Buffam, I., Fork, M.L., Karlsson, J., Larsen, S., Lennon, J.T., Read, J.S., Sadro, S., Saros, J.E., 2015. Ecosystem Consequences of Changing Inputs of Terrestrial Dissolved Organic Matter to Lakes: Current Knowledge and Future Challenges. Ecosystems 18, 376–389. https://doi.org/10.1007/s10021-015-9848-y

Song, C., Sheng, Y., Zhan, S., Wang, J., Ke, L., Liu, K., 2020. Impact of amplified evaporation due to lake expansion on the water budget across the inner Tibetan Plateau. Int J Climatol 40, 2091–2105. https://doi.org/10.1002/joc.6320

Spence, C., 2000. The Effect of Storage on Runoff from a Headwater Subarctic Shield Basin. Arctic 53, 237–247.

Spence, C., Hedstrom, N., Tank, S.E., Quinton, W.L., Olefeldt, D., Goodman, S., Dion, N., 2020. Hydrological resilience to forest fire in the subarctic Canadian shield. Hydrological Processes 34, 4940–4958. https://doi.org/10.1002/hyp.13915

Spence, C., Kokelj, S.A., Kokelj, S.V., Hedstrom, N., 2014. The process of winter streamflow generation in a subarctic Precambrian Shield catchment. Hydrological Processes 28, 4179–4190. https://doi.org/10.1002/hyp.10119

Spence, C., Norris, M., Bickerton, G., Bonsal, B.R., Brua, R., Culp, J.M., Dibike, Y., Gruber, S., Morse, P.D., Peters, D.L., 2020. The Canadian Water Resource Vulnerability Index to Permafrost Thaw (CWRVIPT). Arctic Science 1–26.

Spence, C., Woo, M., 2003. Hydrology of subarctic Canadian shield: soil-filled valleys. Journal of Hydrology 279, 151–166. https://doi.org/10.1016/S0022-1694(03)00175-6

Spence, C., Woo, M., 2002. Hydrology of subarctic Canadian shield: bedrock upland. Journal of Hydrology 262, 111–127. https://doi.org/10.1016/S0022-1694(02)00010-0

St. Jacques, J.-M., Sauchyn, D.J., 2009. Increasing winter baseflow and mean annual streamflow from possible permafrost thawing in the Northwest Territories, Canada. Geophysical Research Letters 36. https://doi.org/10.1029/2008GL035822

St. Louis, V.L., Sharp, M.J., Steffen, A., May, A., Barker, J., Kirk, J.L., Kelly, D.J.A., Arnott, S.E., Keatley, B., Smol, J.P., 2005. Some Sources and Sinks of Monomethyl and Inorganic Mercury on Ellesmere Island in the Canadian High Arctic. Environ. Sci. Technol. 39, 2686–2701. https://doi.org/10.1021/es049326o

Stantec, 2016. State of Aquatic Knowledge for the Hay River Basin.

Strack, M., Hayne, S., Lovitt, J., McDermid, G.J., Rahman, M.M., Saraswati, S., Xu, B., 2019. Petroleum exploration increases methane emissions from northern peatlands. Nat Commun 10, 2804. https://doi.org/10.1038/s41467-019-10762-4

Strilesky, S.L., Humphreys, E.R., 2012. A comparison of the net ecosystem exchange of carbon dioxide and evapotranspiration for treed and open portions of a temperate peatland. Agricultural and Forest Meteorology, Land-Atmosphere Interactions: Advances in Measurement, Analysis, and Modeling – A Tribute to T. Andrew Black 153, 45–53. https://doi.org/10.1016/j.agrformet.2011.06.006

Tanentzap, A.J., Burd, K., Kuhn, M., Estop-Aragonés, C., Tank, S.E., Olefeldt, D., 2021. Aged soils contribute little to contemporary carbon cycling downstream of thawing permafrost peatlands. Glob Change Biol 27, 5368–5382. https://doi.org/10.1111/gcb.15756

Tank, S.E., Olefeldt, D., Quinton, W.L., Spence, C., Dion, N., Ackley, C., Burd, K., Hutchins, R., Mengistu, S., 2018. Fire in the Arctic: The effect of wildfire across diverse aquatic ecosystems of the Northwest Territories. Polar Knowledge: Aqhaliat 1, 31–38.

Tank, S.E., Striegl, R.G., McClelland, J.W., Kokelj, S.V., 2016. Multi-decadal increases in dissolved organic carbon and alkalinity flux from the Mackenzie drainage basin to the Arctic Ocean. Environ. Res. Lett. 11, 054015. https://doi.org/10.1088/1748-9326/11/5/054015

Tank, S.E., Vonk, J.E., Walvoord, M.A., McClelland, J.W., Laurion, I., Abbott, B.W., 2020. Landscape matters: Predicting the biogeochemical effects of permafrost thaw on aquatic networks with a state factor approach. Permafrost and Periglac Process 31, 358–370. https://doi.org/10.1002/ppp.2057

Tarnocai, C., Kettles, I.M., Lacelle, B., 2011. Peatlands of Canada.

Teixeira, M.R., Nunes, L.M., 2011. The impact of natural organic matter seasonal variations in drinking water quality. Desalination and Water Treatment 36, 344–353. https://doi.org/10.5004/dwt.2011.2524

Thompson, L.M., Kuhn, M.A., Winder, J.C., Braga, L.P.P., Hutchins, R.H.S., Tanentzap, A.J., St. Louis, V.L., and Olefeldt, D. Concentrations of methylmercury in peatland-rich catchments along a 1700 km permafrost gradient. (Under review, Environmental Science & Technology, ID es-2021-07044k).

Thompson, L., Olefeldt, D., 2020. CIMP 199: Water quality of peatland ponds and streams on a latitudinal transect (dataset). Datastream. https://doi.org/10.25976/rzkg-7n02

Thorne, G.A., Laporte, J., Clarke, D., 1998. The Effects of Frozen Soils on Groundwater Recharge and Discharge in Granitic Rock Terrane of the Canadian Shield. Nordic Hydrology 29, 371–384. https://doi.org/10.2166/nh.1998.0028

Turetsky, M.R., Abbott, B.W., Jones, M.C., Anthony, K.W., Olefeldt, D., Schuur, E.A.G., Grosse, G., Kuhry, P., Hugelius, G., Koven, C., Lawrence, D.M., Gibson, C., Sannel, A.B.K., McGuire, A.D.,

2020. Carbon release through abrupt permafrost thaw. Nat. Geosci. 13, 138–143. https://doi.org/10.1038/s41561-019-0526-0

Vallée, S., Payette, S., 2007. Collapse of permafrost mounds along a subarctic river over the last 100 years (northern Québec). Geomorphology 90, 162–170. https://doi.org/10.1016/j.geomorph.2007.01.019

van Huissteden, J., 2020. Thawing Permafrost, 1st ed. Springer International Publishing. https://doi.org/10.1007/978-3-030-31379-1

VanGluck, J., 2016. Preliminary State of Groundwater Knowledge in the Transboundary Region of the Mackenzie River Basin, Northwest Territories. ARKTIS Solutions Inc.

Viereck, L.A., Johnston, W.F., 1990. Picea mariana, in: Agriculture Handbook 654. U.S. Department of Agriculture, Forest Service, Washington, DC, pp. 227–237.

Vincent, L.A., Zhang, X., Brown, R.D., Feng, Y., Mekis, E., Milewska, E.J., Wan, H., Wang, X.L., 2015. Observed Trends in Canada's Climate and Influence of Low-Frequency Variability Modes. J. Climate 28, 4545–4560. https://doi.org/10.1175/JCLI-D-14-00697.1

Vitt, D.H., Chee, W.-L., 1990. The relationships of vegetation to surface water chemistry and peat chemistry in fens of Alberta, Canada. Vegetatio 89, 87–106. https://doi.org/10.1007/BF00032163

Vitt, D.H., Halsey, L.A., Zoltai, S.C., 1994. The Bog Landforms of Continental Western Canada in Relation to Climate and Permafrost Patterns. Arctic and Alpine Research 26, 1–13. https://doi.org/10.1080/00040851.1994.12003032

Vonk, J.E., Tank, S.E., Bowden, W.B., Laurion, I., Vincent, W.F., Alekseychik, P., Amyot, M., Billet, M.F., Canário, J., Cory, R.M., Deshpande, B.N., Helbig, M., Jammet, M., Karlsson, J., Larouche, J., MacMillan, G., Rautio, M., Walter Anthony, K.M., Wickland, K.P., 2015. Reviews and syntheses: Effects of permafrost thaw on Arctic aquatic ecosystems. Biogeosciences 12, 7129–7167. https://doi.org/10.5194/bg-12-7129-2015

Vonk, J.E., Tank, S.E., Walvoord, M.A., 2019. Integrating hydrology and biogeochemistry across frozen landscapes. Nat Commun 10, 5377. https://doi.org/10.1038/s41467-019-13361-5

Waddington, J.M., Morris, P.J., Kettridge, N., Granath, G., Thompson, D.K., Moore, P.A., 2015. Hydrological feedbacks in northern peatlands. Ecohydrology 8, 113–127. https://doi.org/10.1002/eco.1493

Walvoord, M.A., Kurylyk, B.L., 2016. Hydrologic Impacts of Thawing Permafrost—A Review. Vadose Zone Journal 15, vzj2016.01.0010. https://doi.org/10.2136/vzj2016.01.0010

Walvoord, M.A., Striegl, R.G., 2007. Increased groundwater to stream discharge from permafrost thawing in the Yukon River basin: Potential impacts on lateral export of carbon and nitrogen. Geophys. Res. Lett. 34, L12402. https://doi.org/10.1029/2007GL030216

Warren, R.K., Pappas, C., Helbig, M., Chasmer, L.E., Berg, A.A., Baltzer, J.L., Quinton, W.L., Sonnentag, O., 2018. Minor contribution of overstorey transpiration to landscape evapotranspiration in boreal permafrost peatlands. Ecohydrology 11, e1975. https://doi.org/10.1002/eco.1975

Williams, T.J., Quinton, W.L., Baltzer, J.L., 2013. Linear disturbances on discontinuous permafrost: implications for thaw-induced changes to land cover and drainage patterns. Environ. Res. Lett. 8, 025006. https://doi.org/10.1088/1748-9326/8/2/025006

Wolfe, S., 2015. Disequilibrium permafrost conditions on NWT Highway 3 [WWW Document].

Wolfe, S.A., O'Neill, H.B., Duchesne, C., 2021. A ground ice atlas of Canada.

Wolfe, S.A., Stevens, C.W., Gaanderse, A.J., Oldenborger, G.A., 2014. Lithalsa distribution, morphology and landscape associations in the Great Slave Lowland, Northwest Territories, Canada. Geomorphology 204, 302–313. https://doi.org/10.1016/j.geomorph.2013.08.014

Woo, M., 2012. Permafrost Hydrology. Springer-Verlag, Berlin Heidelberg. https://doi.org/10.1007/978-3-642-23462-0

Woo, M., Marsh, P., 2005. Snow, frozen soils and permafrost hydrology in Canada, 1999–2002. Hydrological Processes 19, 215–229. https://doi.org/10.1002/hyp.5772

Woo, M.-K., Kane, D.L., Carey, S.K., Yang, D., 2008. Progress in permafrost hydrology in the new millennium. Permafrost and Periglacial Processes 19, 237–254. https://doi.org/10.1002/ppp.613

Wotton, B.M., Flannigan, M.D., Marshall, G.A., 2017. Potential climate change impacts on fire intensity and key wildfire suppression thresholds in Canada. Environ. Res. Lett. 12, 095003. https://doi.org/10.1088/1748-9326/aa7e6e

Wright, N., Hayashi, M., Quinton, W.L., 2009. Spatial and temporal variations in active layer thawing and their implication on runoff generation in peat-covered permafrost terrain. Water Resources Research 45. https://doi.org/10.1029/2008WR006880

Yoshikawa, K., Hinzman, L.D., 2003. Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near council, Alaska. Permafrost and Periglacial Processes 14, 151–160. https://doi.org/10.1002/ppp.451

Young, N.L., Lemieux, J.-M., Delottier, H., Fortier, R., Fortier, P., 2020. A Conceptual Model for Anticipating the Impact of Landscape Evolution on Groundwater Recharge in Degrading Permafrost Environments. Geophysical Research Letters 47, e2020GL087695. https://doi.org/10.1029/2020GL087695

Zhang, Y., Olthof, I., Fraser, R., Wolfe, S.A., 2014. A new approach to mapping permafrost and change incorporating uncertainties in ground conditions and climate projections. The Cryosphere 8, 2177–2194. https://doi.org/10.5194/tc-8-2177-2014

Zhang, Y., Wolfe, S.A., Morse, P.D., Olthof, I., Fraser, R.H., 2015. Spatiotemporal impacts of wildfire and climate warming on permafrost across a subarctic region, Canada. Journal of Geophysical Research: Earth Surface 120, 2338–2356. https://doi.org/10.1002/2015JF003679

Zoltai, S.C., 1993. Cyclic Development of Permafrost in the Peatlands of Northwestern Alberta, Canada. Arctic and Alpine Research 25, 240–246. https://doi.org/10.2307/1551820

Zoltai, S.C., Tarnocai, C., 1974. Perennially Frozen Peatlands in the Western Arctic and Subarctic of Canada. Canadian Journal of Earth Sciences. https://doi.org/10.1139/e75-004