# FROM SCIENCE TO POLICY IN THE YUKON AND NORTHWEST TERRITORIES

An Integrated Regional Impact Study (IRIS) of Climate and Societal Change

# DE LA SCIENCE AUX POLITIQUES PUBLIQUES DANS LE YUKON ET LES TERRITOIRES-DU-NORD-OUEST

Une étude intégrée d’impact régional (EIIR) des changements climatiques et sociétaux


**CHIEF EDITOR**
Martin Tremblay

**EDITORS**
Kimberly Fairman, Pertice Moffitt, Philip Sedore, Benoit Turcotte, Stephanie Wright, and Avery Zammit



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## An Integrated Regional Impact Study (IRIS) of Climate and Societal Change

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# Foreword

Canada's North is experiencing some of the greatest impacts of environmental and societal changes on the planet. For nearly 20 years, ArcticNet has helped develop knowledge and expertise required to document and evaluate northern change to make evidence-based decisions and enable efficient and socially acceptable adaptation strategies. Until recently, ArcticNet's activities and three previous Integrated Regional Impact Studies (IRIS) focused on Inuit Nunangat, which includes Nunatsiavut, Nunavik, Nunavut and the Inuvialuit Settlement Region. The Hudson Bay region was also the subject of a fourth IRIS, with participation from Inuit and First Nations. The development of these IRISs initiated connections between Northerners, Inuit and Indigenous experts, provincial, territorial and federal managers and academic researchers in natural, social and health sciences in the Arctic.

ArcticNet, initially a Network of Centres of Excellence of Canada starting in 2003, is now funded by the Strategic Science Fund since 2024. This program aims to mobilize the expertise and resources of independent third-party science and research organizations to improve excellence in science, technology and innovation in Canada. ArcticNet has developed, together with Inuit Tapiriit Kanatami and Polar Knowledge Canada, a new vision to connect and leverage national knowledge assets to better understand and prepare for a changing Arctic with research results ultimately supporting a healthy, self-determined and dynamic Arctic; a strengthened Canadian leadership position in the global Arctic; and a diverse pool of specialists trained in the Arctic.

This latest IRIS for the Yukon and the Northwest Territories provides key elements of knowledge for better decision-making and more effective adaptation. With this IRIS, the entire Canadian North is now covered through a series of five integrated regional impact studies.

Christine Barnard, Ph.D.
Executive Director

Philippe Archambault, Ph.D.
Scientific Director

# Preface

ArcticNet is funded by the Strategic Science Fund of Innovation, Science and Economic Development Canada (2024-2029) and was previously funded as a Network of Centres of Excellence Canada (2003-2025). ArcticNet brings together scientists and managers from natural, health, and social sciences with their partners from Inuit, First Nations and Métis organizations;northern communities; federal, territorial, and provincial governments; as well as the private sector to study the impacts of climate change and development in the Canadian Arctic. ArcticNet's research program covers Canada's entire subarctic and arctic regions, from the Yukon to Nunatsiavut. It focuses on five main priorities: well-being, infrastructure, energy, ecosystems, and the economy.

Over time, ArcticNet research projects have contributed to the publication of five IntegratedRegional Impacts Studies (IRIS), each corresponding to one of the five major political, physiographic and oceanographic regions of the Canadian Arctic: 1) Western and Central Arctic region (including the Inuvialuit Settlement Region, the Yukon North Slope and Herschel Island, and the Kitikmeot region of Nunavut; 2) the Eastern Arctic region (including the Qikiqtaaluk and  Kivalliq regions of Nunavut); 3) the Hudson Bay region; 4) the Eastern Subarctic region (including Nunavik and Nunatsiavut) (see the figure on the right) and 5) the Yukon and Northwest Territories region. Each IRIS  is structured to highlight current knowledge regarding the impacts of climate and societal changes and to help policy and decision-makers in formulating strategies that will mitigate the impacts of, and support adaptation to, these changes.

The authors would like to thank the editors of this manuscript, supporters and observers, as well as the researchers, students, scientists, reviewers and partners of the Network for their contributions to this IRIS for the Yukon and the Northwest Territories region.

# Introduction

Canada's North is significantly affected by a range of climate change impacts, including altered weather, changing sea levels, melting ice, and thawing permafrost, all of which affect human, physical, and built environments. Indigenous people in the North have demonstrated great resilience for centuries through adaptation. For generations, populations in Canada's subarctic and Arctic regions have lived on and from the land, constantly adapting their activities to maintain their way of life and well-being. Climate change poses an unprecedented and irreversible threat that will only exacerbate other stressors (e.g. social inequalities and environmental issues) northerners face.

The Integrated Regional Impact Study (IRIS) for the Yukon and the Northwest Territories is a compilation of key knowledge (e.g. human, physical and built environments) that addresses some of the regional interests and needs (figure 1). The aim of the IRIS is to facilitate better accessibility of knowledge and to provide relevant, practical and comprehensible information for sound decision-making at a regional scale.

This IRIS consists of two parts: a Synthesis and Recommendations article that summarizes the key findings and associated recommendations from the larger knowledge report and a knowledge report. The knowledge report is divided into seven topic-defined chapters: 1) Addictions and Mental Health, 2) Caribou Management and Food Security, 3) Mine Remediation, 4) Permafrost and Water Quality, 5) Permafrost and Water Hydrology, 6) Permafrost-related Geohazard on Yukon Highways, and 7) Impact of Climate Change on Hydrological Hazards. Within most of these chapters, scientists and other experts have linked environmental change and regional priorities.

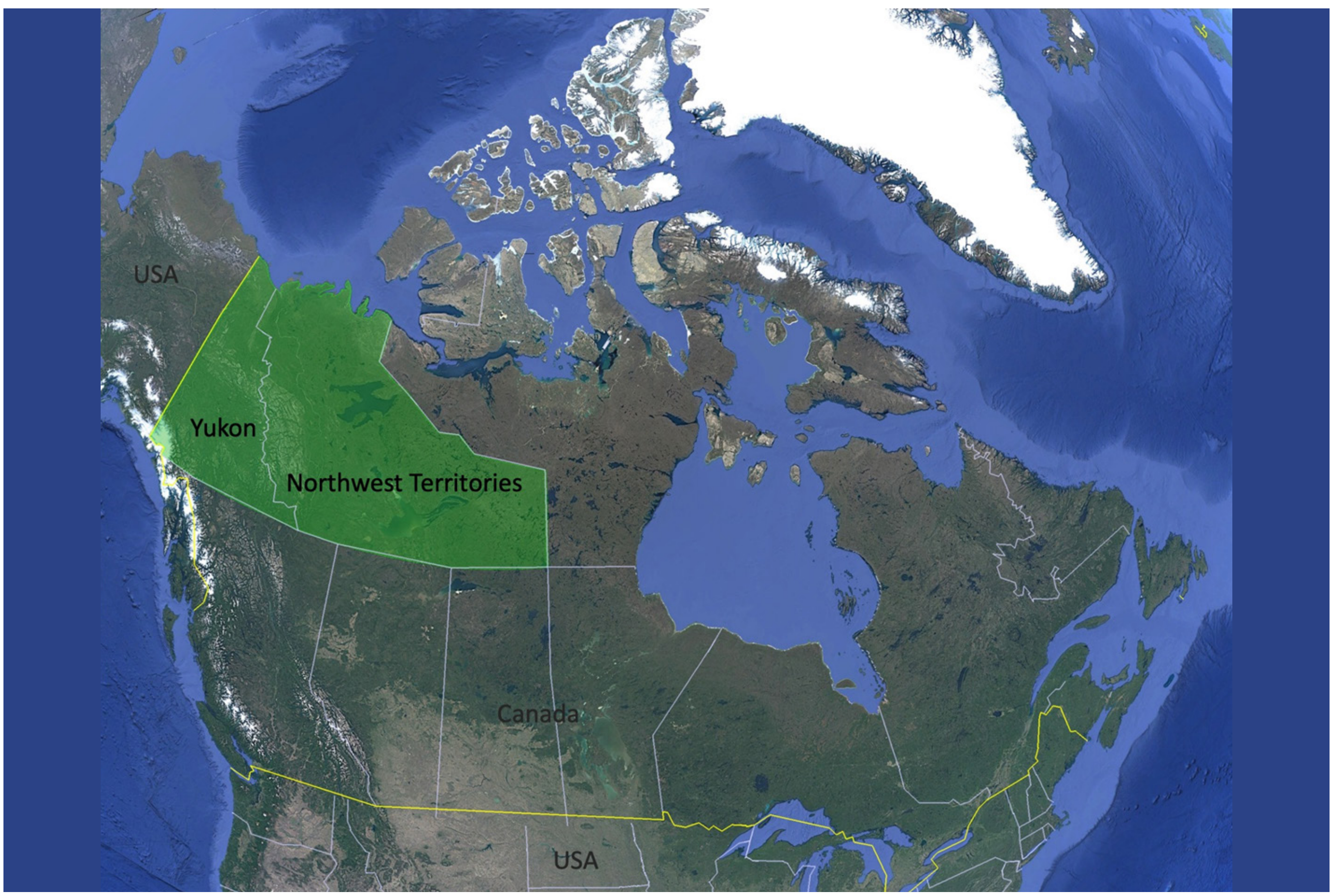


Figure 1. Area covered by the IRIS in Yukon and Northwest Territories (Source: Google Map)

# Synthesis and Recommendations

## Human Environment

### Key Findings

The Northwest Territories (NWT) has diverse, distinct, and resilient peoples. For generations in the NWT, the Tłı̨chǫ and Sahtu people, two Dene First Nation peoples, have been stewards the land. Knowledge keepers in this territory have formed a way of being, living, and doing, that forged community, languages, traditions, and systems. Their lives were built around the landscape and its many inhabitants, including the wildlife. The Tłı̨chǫ and Sahtu people adapted to the many transitions they experienced with the modernization of their territories. However, hardships and suffering at the hands of colonizers have left lasting impacts on the mental health and well being of Tłı̨chǫ and Sahtu citizens.

This section on the human environment includes two chapters about human well-being in the Arctic. The first chapter is a policy brief about the effects of the regional caribou hunting ban on food security and community well-being in the Tlicho region (Kim et al., 2024). The second chapter is a discussion paper about overcoming struggles of addictions and poor mental health in two regions of the NWT and, through the words of Elders, a path to well-being (Moffitt et al., 2024)

The Tlicho and Sahtu people experienced a traumatic disruption of their language and way of life from the historical legacy of residential schools, inequities, and systemic racism. This has created discord and has led, in some cases, to grave outcomes of addictions, homelessness, and domestic violence.

The resilience and strength from strong cultural, spiritual, and linguistic stabilities enabled the people to survive and grow. Their innovations are shared through the words and actions of Elders that guide the Tlicho and Sahtu territory to restoration and resurgence. A model of Indigenous Health Promotion is suggested to address interventions to overcome these grave outcomes of colonization.

### Recommendations

Public policy needs to include the Indigenous worldview to support health.Empower communities to take action for the health and wellness of their citizens and create supportive environments for health that include language, cultural activities and a strong sense of direction in Indigenous citizens' lives.

Apply a community based approach to health and wellness services to achieve health goals. For example, Elders, through traditional knowledge, practices, and ceremonies, create positive spaces for health promotion. Additionally, communities should encourage personal skill development to provide a sense of proficiency that is imperative for health and wellness.

Education about historical colonialism and oppression must be taught and understood to promote healing.

Indigenous methodologies and cultural education enable effective cultural change. Use cultural camps and land experiences led by local Indigenous people to promote a sense of belonging and cultural continuity to help foster resilience and hope.

## Natural Environment

### Key Findings

Permafrost, ground that is frozen for more than two consecutive years, is found sporadically in subarctic regions, but it dominates arctic environments. In the wetland-dominated Taiga Plains of the NWT, permafrost is mainly associated with black spruce peatlands (i.e., peat plateaus). When permafrost thaws, the ground subsides, the overlying trees drown, and the land cover is replaced by permafrost-free wetlands (bogs and fens). The land cover changes driven by permafrost thaw allow water to move more easily over land and through the ground, which increases basin-scale drainage and ultimately increases wintertime and annual streamflow. With sustained drainage of wetlands, the landscape can become dry enough to allow new permafrost-free forests to form.

Permafrost in the bedrock-dominated Taiga Shield, NWT is associated with peatlands and fine-grained soil-filled bedrock valleys and is absent beneath exposed bedrock. The impacts of permafrost thaw on surface and groundwater in this environment are poorly understood, but similar land cover changes are possible in peatlands and ice-rich sediment (i.e., peat plateaus and lithalsas).

The continued thaw of permafrost peatlands is expected to significantly alter the quality of headwater streams, rivers, and lakes. For instance, the enhanced waterlogged conditions due to permafrost thaw create hotspots for producing methylmercury, a highly toxic compound that biomagnifies in food webs. The increased hydrologic connectivity between organic-rich peatlands and stream networks may result in increased downstream delivery of dissolved organic matter, including carbon, nutrients, and bound metals (e.g., methylmercury, iron, selenium, and lead). However, it is unknown how much these hotspots will contribute to the overall basin delivery of methylmercury and to what degree it will biomagnify in downstream food webs.

Yukon landscapes are shaped by their glacial histories, where the presence or absence of glacial activity has left lasting legacies on soil and ground characteristics, impacting the temperature, thickness, and ground ice content of permafrost. In areas that were glaciated during the most recent glaciation, permafrost tends to be relatively thin (< 20 m) and warm (> -2°C), with the possibility of ice-rich ground near the surface. Unglaciated terrains host older, thicker, and colder permafrost, with massive ice of various origins spreading from near the surface to tens of meters in depth. The thickest permafrost in the Yukon has been established in these ice-free areas where the ground surface was subjected to the coldest climate for the longest periods of time. Areas that are between glacial limits are considered transition zones, where the potential for buried massive ice remains.

### Recommendations

Establish a groundwater monitoring network in the NWT and expand the Yukon Observation Well Network to a set of regionally representative landscapes. In both Territories, baseline groundwater information (quantity and quality) must be established and assessed relative to long-term surface water trends. Groundwater monitoring and targeted groundwater studies in the Yukon are also necessary for water resource management and prediction of slope failures.

Examine linkages between permafrost thaw and contaminants of concern, particularly those that accumulate in food chains (i.e., biomagnify) like methylmercury and persistent organic pollutants. Methylmercury should be a regularly sampled parameter in water quality monitoring programs, particularly in wetland-dominated regions.

Investigate the impacts of permafrost thaw on hydrology and water quality throughout the subarctic, but particularly in the Taiga Shield where little research has been done to understand the impacts of permafrost thaw on ground and surface water systems. Such studies are needed to assess baseline conditions relevant to water management and northern development projects.

Situate permafrost thaw related geohazards within the broader geological and glacial context of the region to account for the glacial history and possibility of buried glacial ice. These studies should also include groundwater as an important component of permafrost thaw processes, and use groundwater monitoring practices to fully understand its effect.

## Built Environment

### Key Findings

The hydrological regime of watersheds is tied to traditional ways of living, healthy ecosystems, energy production, transportation of goods, the mining industry, and recreational activities. Climate change will continue to profoundly impact the hydrological regime of subarctic and Arctic watersheds by altering several components of the water cycle. Interestingly, few statistical trends exist to confirm the net impact of higher air temperatures and changing precipitation patterns on low, average, and high streamflow conditions in Yukon's rivers. This uncertainty results from the complex interaction between dominant and less dominant hydrological factors (with impacts that may cancel one another), but also from the occurrence of extreme events in recent hydrological records.

In a context where water balance and hydrological models still produce inaccurate short-term forecasts for various reasons (including the lack of input data), and because these models are rarely calibrated for hydrological extremes, it remains difficult to rely on similar tools to generate representative future design hydrological conditions. Since life in the North is tied to water availability, and considering that the resilience of cold region infrastructure and communities depends on informed design or adaptation hydrological criteria, there is an immediate need to (at least qualitatively) evaluate the impact of climate change on flows and water levels in small and large watercourses and water bodies.

Throughout the Yukon, the presence of a road may be sufficient to induce the gradual thaw of permafrost. However, climate change will likely accelerate these effects, increasing the instances and scale of permafrost-related geohazards such as sinkholes, landslides, and surface water icings. These geohazards are often directly linked to the melting of ground ice within permafrost and threaten infrastructure and residents of northern regions. Groundwater flow likely also plays an important but poorly understood role in initiating permafrost thaw-related geohazards that bear further examination and monitoring.

With many permafrost-induced geohazards being preceded by pre-conditioning processes such as localized heat flow, groundwater flow, thaw settlement, and deformation, it is possible to anticipate the failure at vulnerable sites via a warning system. The nature and configuration of such an array must be based on proper site characterization where permafrost conditions are analyzed, the potential hazard identified, and related preconditions and processes considered.

Indigenous communities in the Taiga Plains and Taiga Shield regions have expressed concerns about degraded water quality and contamination from various sources such as landfills, oil and gas facilities, and mine tailings. These issues are also related to permafrost thaw, which can interact with the storage and transport of contaminants and potentially impact water quality. Previously operational mines in NWT have left behind contaminants that interact with permafrost, and ongoing permafrost thaw may worsen the situation by increasing the range of contaminant flow.

With quartz mining comes the possibility of high-risk accidental failure in mining processes, as demonstrated by Mount Polly, BC, in 2014 and Eagle Gold, YT, in 2024. These examples illustrate how contaminants can enter the environment through a failure in mining infrastructure. Climate change may make traditional mine infrastructure vulnerable through thawing permafrost and increased precipitation. More than ever, functional passive treatment systems must be developed and instrumentalized to clean up northern mining contaminants.

One such contaminant is Nitrate. Nitrate contamination in groundwater is often associated with mining activities, which can be treated using passive and semi-passive treatment systems. In cold conditions, bioreactors are also effective in treating Selenium and Antimony. Saturated covers are preferable in a Northern context over water, and soil covers for waste rocks in mining operations as they do not require a dam and reduce the amount of soil required while still preventing acid rock drainage.

### Recommendations

Considering that extreme hydrological events associated with climate change will generate the most significant impacts on ecosystems and infrastructure of the North, develop alternate methods to predict future subarctic and Arctic river conditions. This can be done by investigating the causes and consequences of extreme hydrological events at a regional scale and by developing and adapting empirical or conceptual (0-D) hydrological models.

In a context where hydrology-related geohazards will increasingly affect northern communities and infrastructure, investigate the impact of climate change on the stability (i.e., evolving alignment and geometry) of stream and river channels, on the hydrological regime of small creeks, on the hydrology of placer and quartz mining sites, as well as on the occurrence of extreme weather patterns such as heat domes and atmospheric.

Conduct site-specific permafrost studies to better understand local environmental conditions and determine the possibility of segregated ice or buried glacial ice. Additionally, create early warning systems for at-risk infrastructure to increase road user safety.

Examine and monitor groundwater flow to determine its connection to the initiation of permafrost thaw-related geohazards. New and/or expanded groundwater monitoring networks are needed to inform baseline conditions prior to new development projects. Further studies on contaminant mobilization driven by permafrost thaw are needed to quantify the risk of pre-existing contaminated sites.

Continue to develop Passive treatment systems (PTS) as they are a sustainable and low-maintenance alternative to conventional active mine remediation. They make use of natural materials and processes and require minimal maintenance. However, further research is needed to determine their effectiveness in colder climates. Additionally, mine remediation and restoration can serve as a tool for reconciliation.

Implement and continue to research tangible water management and infrastructure design adaptation measures for industrial sites such as active and decommissioned mines. Additionally, it is crucial to accurately document extreme hydrological events, especially those informing land use and infrastructure design.

# PART 1

## The Impacts of a Regional Caribou Hunting Ban on Food Security and Community Wellbeing in the Tłı̨chǫ Region: A Policy Brief

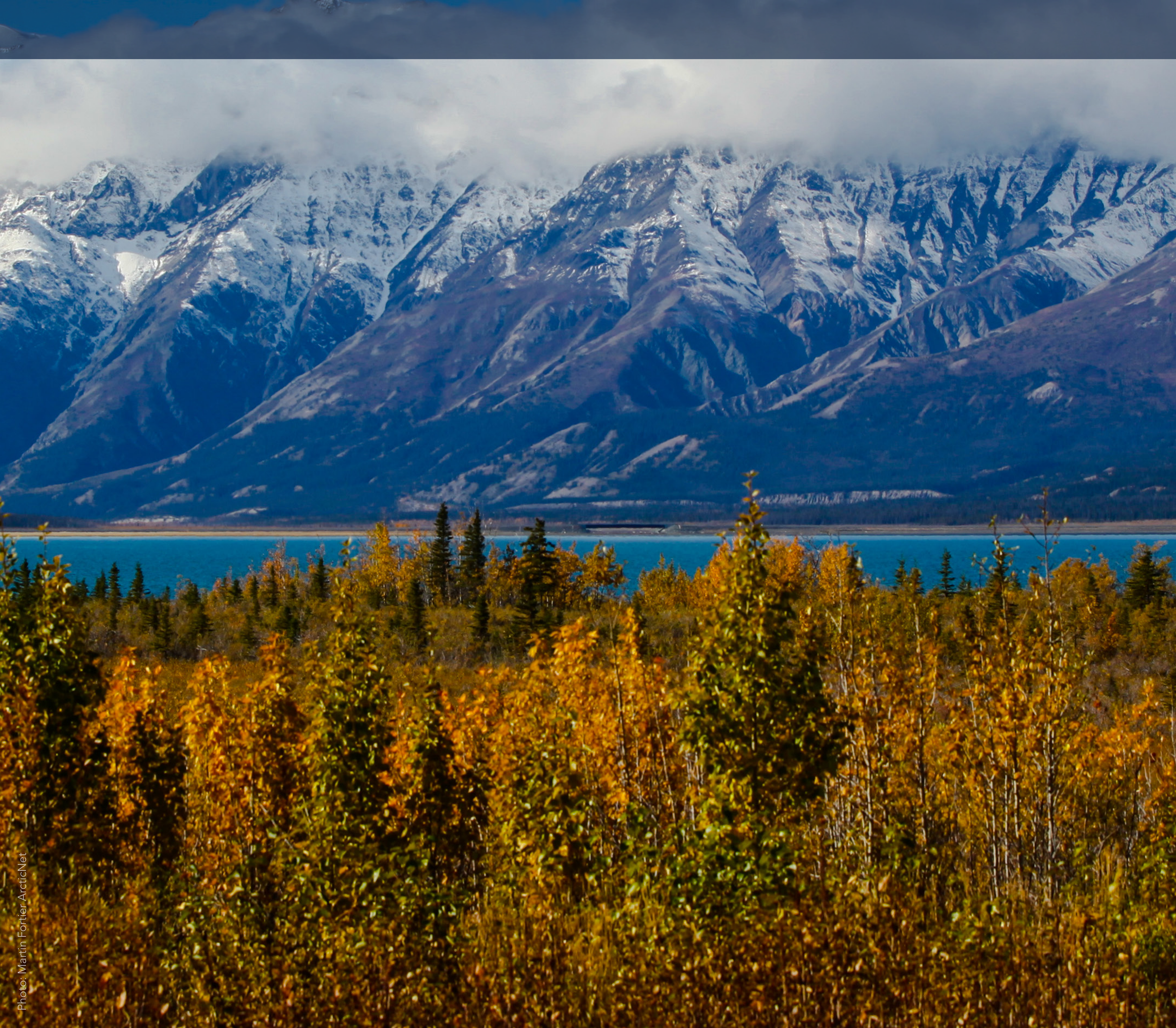

Photo: Martin Fortier ArcticNet

**Esther Kim[1,2], Sophie Isabelle Grace Roher[1,2], Kimberly Fairman[2], John B. Zoe[2]**

1. Dalla Lana School of Public Health, University of Toronto
2. Institute for Circumpolar Health Research


# Abstract

The Tłı̨chǫ region have lived alongside the Bathurst caribou herd since time immemorial, and depend on them for much more than simply a source of food and sustenance (Tłichǫ Government 2016). The caribou serve as the cornerstone of many cultural practices important for individual and community wellbeing. However, within the past 40 years, the herd has declined by almost 99%, causing many to worry that the herd may disappear forever (GNWT n.d.a). In response to this decline, the Tłı̨chǫ Government (TG) and the Government of the Northwest Territories (GNWT) have imposed a strict hunting ban for the Bathurst herd since 2015. Although this ban was put in place with the best interest of the Bathurst caribou in mind, there have been many direct and indirect consequences of this hunting ban experienced by the Tłı̨chǫ people. Namely, the ban has led to: 1) the loss of opportunities for sharing traditional knowledge and language across generations, 2) greater food insecurity, and 3) the forced adoption of a western, reductionist perspective through which the caribou are understood, which is directly in contrast to the Tłı̨chǫ perspective that is grounded in reciprocity and mutual respect. In conclusion, this policy brief proposes three recommendations for policy- and decision-makers to consider:

# Policy Recommendations

- Deeper investigations into the lived experiences of the impacts of the hunting ban, led by communities, for the communities.
- Supporting and strengthening existing initiatives, such as Ekwǫ Nàxoède K'è ("Boots on the Ground"), which help address the issue of the declining herd in a way that is aligned with Tłı̨chǫ perspectives and worldviews.
- Inviting an advisory council comprised of local community leaders and rightsholders to the decision-making table at the Wek'èezhìi Renewable Resources Board.

# 1. Background

## 1.1. Who are the Caribou?

The Bathurst caribou herd refers to one of the nine main barren-ground caribou herds that spend most of their time in the Northwest Territories (NWT) and the Bathurst Inlet in Nunavut (GNWT n.d.b). Barren-ground caribou are distinct from other types of caribou in the NWT, such as the Boreal and Northern Mountain caribou, because of the long migratory journeys between their summer and winter grounds. In the summers, the Bathurst caribou travel as far north as the Bathurst Inlet where they have their calving grounds, while in the winters they may come as far south as northern Saskatchewan (Figure 1) (GNWT n.d.c). This reliable migratory journey repeated over many generations is what made it possible for the Bathurst herd to play a significant role in shaping the cultural and social landscape for the Tłı̨chǫ - a landscape that extends beyond colonial borders established by the Government of Canada, as can be seen in Figure 2 below (Tłı̨chǫ Government 2016). For example, the community of Wekweètì was intentionally established at the north shore of lake Wekweètì in 1970, which is an important transportation corridor for the Bathurst herd's bi-annual migration (Tłı̨chǫ Government 2016). In this way, the caribou have served as "the lifeline of northern people" and are an important cultural and social cornerstone for the Tłı̨chǫ people (Galloway 20215: 00:05:17).

Unfortunately, there has been a sharp decline in the number of caribou and a shift in caribou migratory patterns in recent years. Where once thousands of Bathurst caribou used to travel past Wekweètì, now community members must travel much further to see even a few hundred. For a herd population that was estimated to be close to half a million (427,000) in the late 1980s, a count in June 2021 estimated a total of 6,243 caribou – a 99% decline across a span of 40 years (GNWT n.d.a). Rather than one direct cause for this decline, it is thought to be a combination of several factors, including industry development, human activity, climate change, and the emigration of Bathurst caribou to neighbouring herds (Chen et al. 2017; GNWT 2022; Kendrick et al. 2005; Parlee et al. 2018; Tłı̨chǫ Government 2013; Tłı̨chǫ Government and GNWT 2022; Williams 2018).

## 1.2. Who is involved?

In response to this decline, a hunting ban was introduced in 2010 by the GNWT, which prevents anyone, including both Indigenous and non-Indigenous people, from intentionally killing caribou from the Bathurst herd. Though this hunting ban was originally introduced by the GNWT, it is now managed by the Wek'èezhìi Renewable Resources Board (WRRB).


Figure 1. Map of Bathurst herd migratory range (Chen et al. 2014)

The WRRB is a board composed of eight individuals, plus an additional Chairperson, for a total of nine members. Two members are appointed by the GNWT, two members are appointed by the Government of Canada, and four are appointed by the TG (GNWT and Wek'eezhii Renewable Resources Board n.d.). The Chairperson is nominated by these eight members of the board. The board was established in 2005, when the Tłįchǫ Agreement was negotiated and signed by the Dogrib Treaty 11 Council, the GNWT, and the Government of Canada (15). This combined land claim and self-government agreement, considered the first of its kind, created the mandates for the TG to have certain powers and jurisdictions over the lands, wildlife, and resources surrounding the four Tłįchǫ communities: Gamètì, Wekweètì, Whatì, and Behchokǫ̀ (Figure 2). Nonetheless, it is important to keep in mind that the traditional territories of the Tłįchǫ extend beyond the border that is defined by the Tłįchǫ Agreement, and lie within the boundaries known as "Mǫwhì Gogha Dè Nįįtłèè" which were first described by Chief Mǫhwhìì during the negotiations for Treaty 11 in 1921 (Tłįchǫ Government 2005).

Although the TG gained certain jurisdictions over their traditional territories through the ratification of the Tłįchǫ Agreement, wildlife harvesting management fell under the purview of the WRRB, who is responsible for overseeing the wildlife and land resources within the Wek'èezhìi (also known as the "management area") boundary of the traditional Tłįchǫ territory (Figure 2) (Tłįchǫ Government n.d). The board exists to act in the public interest, which means that it is neither part of the TG nor the federal or territorial government, but serves as an institution to facilitate co-management over the wildlife and lands within the Wek'èezhìi boundary (Tłįchǫ Government et al. 2005). Moreover, all decisions and actions related to wildlife management within the Wek'èezhìi boundary must be presented before the WRRB, whether they are being proposed by the TG, GNWT or other institutions.

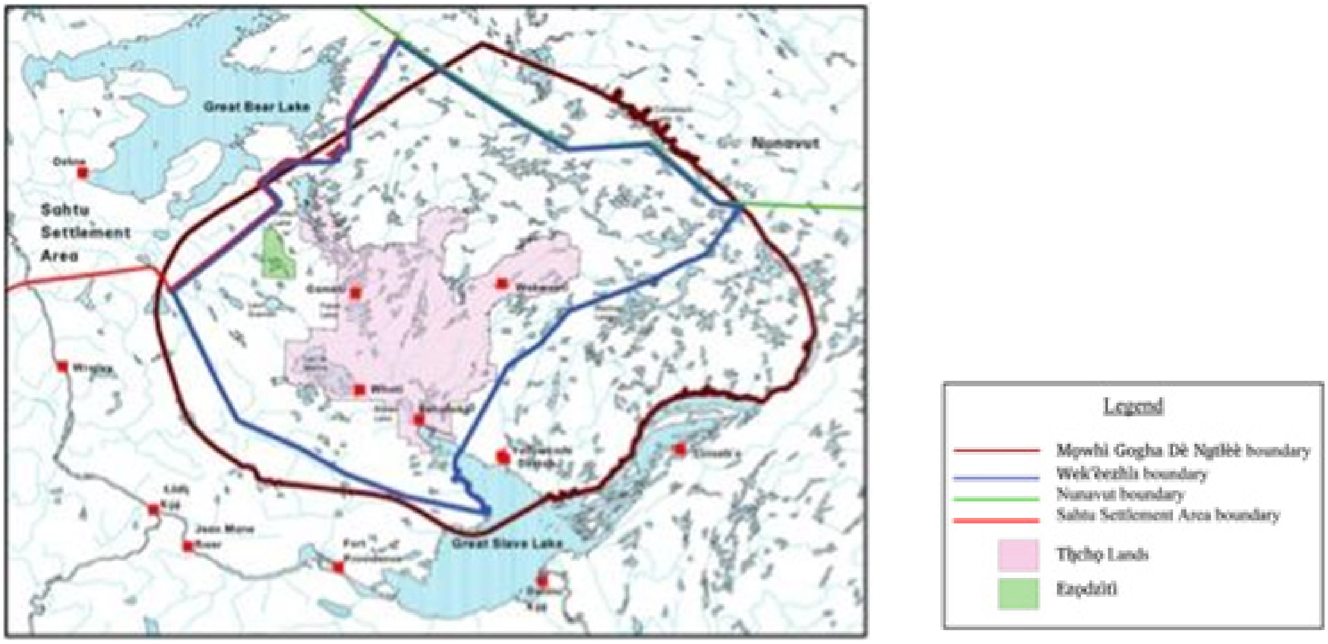


Figure 2. Boundary map of Tłı̨chǫ region (Source: Tłı̨chǫ Government et al. 2005)

## 1.3. How did the hunting ban come into place?

In response to the sharp population decline and risk of disappearance of the herd from the NWT, due to reasons described in the previous section (please see 'Who Are the Caribou'), the GNWT announced in December 2009 that a strict hunting ban would take place starting January 1, 2010. This initial ban was signed without allowing sufficient time for meaningful consultation with the TG or community members that would be impacted by such a dramatic ban (CBC News 2009 and 2010). The Environment and Natural Resources (ENR) Minister at the time, Michael Miltenberger, asserted that the GNWT had the authority to impose such bans, although many others, most notably members of the TG, argued that this was simply not the case, and did not adhere to the terms of the Tłı̨chǫ Agreement (CBC News 2010; Tłı̨chǫ Government 2005). However, the introduction of this hunting ban initiated further conversations between the GNWT and the TG, who eventually agreed to submit a joint management proposal to the WRRB in March 2010, as a way to adapt the hunting ban to better fit the people living in the region (CBC News 2009 and 2010). The proposal was for the development of a three-year recovery plan, and it was accepted in 2011, leading to the official implementation of a reassessed hunting ban on the Bathurst caribou. At the time, the reassessed hunting ban included a harvest target of 300 caribou allocated for both the Tłı̨chǫ communities and the Yellowknives Dene First Nation. All other harvesting by outfitters or individuals from other regions was not allowed. Other measures were also put in place at the time, including harvest targets for neighbouring herds, a harvest ratio goal of 85:15 for bulls to cow, and other herd monitoring activities (Wek'èezhìi Renewable Resources Board 2010).

Since 2010, the joint management proposal has gone through several renewals and re-iterations. For a complete timeline of the hunting ban policy, see Appendix A. Since 2015, there has been a complete ban on harvesting the Bathurst herd, including by the Tłı̨chǫ people. A mobile 'no hunting' zone was also created, based on the location of several collared caribou of the Bathurst herd, and since 2020, a wolf culling pilot project has been underway as well (Haggert 2020).

Although the hunting ban may have been put in place for the best interest of the Bathurst herd, it has also had serious ramifications on the wellbeing of the Tłı̨chǫ. As will be discussed below, the Tłı̨chǫ have a multidimensional relationship with the caribou. While the ban has significantly undermined their access to an important source of food, the consequences of a hunting ban is to be felt across multiple domains of life.

# 2. Impacts

To explore the impacts of the Bathurst hunting ban on food security and community wellbeing, the following section is informed by a combination of literature and informal conversations between the first author (Esther Kim) and individuals from the Tłı̨chǫ region. The connections between culture, identity, language, and land that are highlighted in this policy brief are foundational aspects of Traditional Knowledge. Given the sacredness of Traditional Knowledge, and valid concerns among Indigenous Elders of appropriation and misuse, it is often excluded from research (Hill 2003). In response to these concerns, the information presented in this brief has been reviewed and approved by John B. Zoe, who is an advisory resource person to the TG and has contributed to many projects that uphold the Tłı̨chǫ language and way of life. He is also included in this brief as a co-author (John B. Zoe).

## 2.1. Loss of Opportunities to Learn Traditional Knowledge and Language

Within the context of Tłı̨chǫ culture, caribou hunting is not practiced simply for the sake of obtaining a caribou. Rather, every step of the journey, from preparing to go out, to taking care of the caribou bones, are accompanied by opportunities to observe and learn hands-on skills and knowledge about the surrounding land (Panza-Beltrandi 2019; Tłı̨chǫ Government 2022a).

Rooted in a culture of experiential and oral learning, these practical experiences on the land are the primary ways that knowledge is often shared and taught from Elders and older adults to younger children. The rising cost of equipment and increased distance to travel to see the herds – both of which are also mediated by climate change – already make it difficult for communities to bring their children out on the land with them. The imposition of a hunting ban has only exacerbated these challenges (McMillan 2012). In some cases, communities have been able to fund trips for small groups of hunters to hunt caribou from neighbouring herds; however, these are costly endeavors that cannot be expected to replace regular traditional hunting practices.

Beyond the transfer of practical skills, being physically out on the land is also a fundamental component for learning Indigenous languages. Indigenous languages are derived from the landscape, and they have the capacity to hold knowledge about a person's history, culture and worldview (Biddle and Swee 2012; Chiblow and Meighan 2022). For example, traditional place names serve as mnemonics for a variety of narratives and teachings, and culturally relevant information can only be transmitted and preserved across generations when Elders and youth pass through the sites together (Andrews and Zoe 1997). Learning and actively engaging in one's traditional language is also linked to well-being, as languages serve as extensions and expressions of cultural identity, which in turn is an important factor for an overall sense of wellbeing (Brown et al. 2012; McIvor et al. 2009). Therefore, decreased opportunities to be on the land and engage in traditional caribou hunting practices directly links to decreased opportunities for learning traditional knowledges and language, which are in turn critical for maintaining individual and community well-being.

## 2.2. Impacts on Food Security

Food security is achieved when "all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (World Food Summit 1996). Using this definition, the hunting ban threatens food security for the Tłı̨chǫ in three ways.

First, for communities to have access to the foods that they define as necessary for healthy and active lives, Tłı̨chǫ people need to have access to the lands and water, traditional knowledge, and the ability to exercise this knowledge. This concept is embodied in the values of Indigenous food sovereignty, which "inherently asserts Indigenous peoples' self-determination of their own culturally sustainable food systems" (Settee and Shukla 2020). In other words, communities need to have the autonomy, power, and space to define their own healthy food systems. These rights are also upheld by legal documents such as the United Nations Declaration of Rights for Indigenous Peoples, and the Truth and Reconciliation Commission (TRCC 2012; United Nations 2007). For many traditional and cultural practices, including language, being physically out on the land is an essential foundation in the learning process, as was mentioned in the previous section above. The hunting ban thus becomes a direct ban from both the land and the ability to exercise traditional hunting practices, as it limits the capacity of individuals to engage in activities related to hunting caribou that could not otherwise be replicated indoors or in a different context. Presently, the hunting ban exists as the result of a joint proposal between the TG and the GNWT, which on paper makes it appear to be a decision that included Tłı̨chǫ involvement; however, the legacy of the hunting ban is such that it began with a strict imposition led solely by the GNWT. Additionally, much of the evidence being used to support the decision is based on western principles of resource management, which are distinct from Indigenous principles, as will be described in following sections (see 'Barrier to Relationship with Caribou').

The second way the hunting ban impacts food security is that it directly alters the dietary habits of the Tłı̨chǫ. A decrease in access to caribou for daily nourishment has led to diets being supplemented by a greater proportion of market foods, which are considered store-bought foods shipped from the south. This shift from traditional to market foods is experienced by many Indigenous communities across the continent, and is coined the term 'nutrition transition' (Halseth 2015). Compared to traditional foods, market foods are not as nutrient-dense per amount of food consumed and may lead to more negative physical health outcomes (Receveur et al. 1997). Meanwhile, caribou alone can provide an excellent source of protein, iron, vitamin A, and vitamin B, as well as a fair source of magnesium, potassium, and calcium (GNWT n.d.c). In this way, market foods may be a comparably poorer source of physical nutrition, ultimately leading to a decrease in overall health.

Finally, the hunting ban directly impacts food security for the Tłı̨chǫ by disrupting the way that communities define what a healthy and active life looks like, and the role that food plays to support that life. From a biomedical perspective, food is narrowly defined in terms of its nutritional benefits to physical health. On the other hand, for the Tłı̨chǫ, food serves a broader role that is more in line with a holistic perspective of health. From an Indigenous perspective, health is characterized by physical, mental, emotional, and spiritual dimensions that are all interconnected, and can each be influenced by the food that one consumes. To feel well, all four of these dimensions need to be in balance, and when even one area is out of balance, it can affect the other aspects as well. In this way, the knowledge about which foods are considered important, and how food is prepared and shared, all communicate deeper messages about identity and culture. In Tłı̨chǫ food systems, caribou serves as the primary source of "food, clothing, shelter, and material culture" (Walsh 2021). In this way, the caribou not only provide physical nourishment, but also help sustain the emotional, mental, and spiritual aspects of well-being by way of providing opportunities to embody and practice Tłı̨chǫ culture. Therefore, the implementation of a hunting ban weakens Tłı̨chǫ food security by removing a source of food that is crucial for the physical, as well as emotional, mental, and spiritual aspects of health.

## 2.3. Barrier to Relationship with Caribou

From the Tłı̨chǫ perspective, the caribou are actors with their own agency who cannot be managed by people (Walsh 2021). In one traditional story, shared in a report by the Tłı̨chǫ Research and Training Institute, Caribou and Fish are said to have offered themselves to be the primary foods for the Tłı̨chǫ people during a discussion with other first creatures in the North (Tłı̨chǫ Government 2013 and 2016). Knowing this, rather than engaging with the caribou solely based on herd size, which reduces the character of the herd to that of an impersonal number, the Tłı̨chǫ have developed hunting and management systems positioned on aspects of mutual respect for the caribou's autonomy and agency. These practices are embedded in a lifestyle that actively maintains a balanced and reciprocal relationship between the people and caribou, which involve regularly being physically out on the land and seeing with their own eyes, over several generations, the health and state of the Bathurst herd. These practices stand in stark contrast to the ways that herd sizes are often estimated by Western systems, which include aerial photo surveys and satellite data, all collected from a distance and conducted once or twice a year (GWNT n.d.d). In some cases, Tłı̨chǫ Elders have said that "if [the people] are not out there on the land, the caribou will go away", highlighting the importance of maintaining that relationship through concrete actions of being on the land (Galloway 2021: 00:18:08). Moreover, it is this philosophy that has helped sustain healthy caribou and Tłı̨chǫ populations for thousands of years prior to the imposition of settler colonialism to the North. Thus, the last major impact of the hunting ban is that it effectively severs this reciprocal relationship, and forces individuals to abide by a western, reductionist approach to caribou management strategies instead.

Resource management strategies broadly encompass "the sum of the social and cultural processes" that guide the use of the resource in question (Atlas et al. 2021). Throughout the last century, government-led caribou management strategies have not had much success in maintaining healthy caribou populations, and in some cases have even led to "greater socioeconomic implications than ecological" (Parlee et al. 2018). The top-down, centralized approaches practiced by western institutions stand in direct contrast to Indigenous methodologies, which account for a spiritual reciprocity between humans and wildlife alongside a physical one, based on the reality of the wildlife's agency. There has historically been a largely one-sided application of western perspectives when it comes to the way resources have been managed, despite this fundamental difference between Indigenous and Western approaches. The forced uptake of western principles of management, presently exemplified in the hunting ban, has ultimately led to a severed relationship between the Tłı̨chǫ and the caribou. It is this broken relationship that is then manifested as a decline in health for both populations; as the people depend on the caribou, the caribou also depend on the people, and the outcomes of their wellbeing are inextricably linked.

Solutions to mend this severed relationship cannot come from Western, top-down models of resource management, but must stem from the deeper Traditional Knowledge held by Tłı̨chǫ communities. One potential ongoing solution is currently being led by the Department of Culture and Lands Protection of the TG, by investing in learning opportunities for individual hunters who may not have had prior access to traditional hunting teachings, such as treating the caribou bones with respect and knowing what tools are respectful to use on the caribou (Tłı̨chǫ Government 2022a). The TG also drives the Ekwǫ̀ Nàxoède K'è ("Boots on the Ground") project, in partnership with the WRRB and the GNWT ENR, which is a caribou monitoring program that began in 2016. The project provides opportunities for people to "do what they have always done and let those methods [become] research methods" (Galloway 2021: 00:14:13). The project applies a Tłı̨chǫ methodology of "we watch everything" as the theoretical framework to underpin the project, and operationalizes a "do as hunters do" method to guide data collection (Tłı̨chǫ Government 2022b). The strength of both of these projects comes from the fact that they directly arise from Tłı̨chǫ knowledge systems. These projects also demonstrate the ways that the Tłı̨chǫ continue to cultivate a relationship with the caribou, despite the hunting ban, which contributes to sever it.

# 3. Final recommendations

The impacts of the Bathurst hunting ban can be characterized into three broad categories: 1) a loss of opportunities to share traditional knowledge, 2) weakened food security for impacted communities, and 3) barriers to maintaining a relationship with the caribou. The culmination of these impacts will directly and indirectly influence the health and wellbeing of individuals and communities in the Tłı̨chǫ region. Recommendations for future steps include:

- Deeper investigations into the lived experiences of these impacts, led by communities, for the communities.
- Supporting and strengthening existing initiatives, such as Ekwǫ Nàxoède K'è ("Boots on the Ground").
- Inviting an advisory council comprised of local Dene leaders and rightsholders to the decision-making table at the Wek'èezhìi Renewable Resources Board.

While the Bathurst herd has been the topic of many discussions in the past decade, they are just one of the several barren-land caribou herds across the North that have shown alarming declines. The way that the current hunting ban impacts Tłı̨chǫ communities will be important for neighboring herds and communities that may have to make similar decisions in terms of addressing the declines they observe in their own herds, such as for herds across the Yukon and Nunavut (Brown 2020; Lamberink 2022a).

The decline of the Bathurst herd cannot be attributed to a single factor but is rather the overall outcome of multiple interacting causes which include the effects of mining, human activity, and climate change (Chen et al. 2017; GNWT 2022; Kendrick et al. 2005; Parlee et al. 2018; Tłı̨chǫ Government 2013; Tłı̨chǫ Government and GNWT 2022; Williams 2018). Nonetheless, the implementation and continued emphasis of a hunting ban, while simultaneously not addressing these other causes with proportional emphasis, places a disproportionate burden on individuals and members of community who depend on caribou for sustenance and well-being (Parlee et al. 2018). For example, despite the known negative impacts of mining activity on caribou herds and their health, similar degrees of limitations for development projects have not been put in place (Lamberink 2022b; Parlee et al. 2005). Indeed, in March 2022, the Ekati Arctic Canadian Diamond Company (Ekati Diamond Company) received approval to continue a project at Point Lake, which is directly within a main migratory route for the Bathurst herd. The accompanying management plans for the approved project include building ramps for the caribou to use when crossing access roads (Blake 2021). However, according to a recent report by Aurora Wildlife Research and the Independent Environmental Monitoring Agency, it is shown that the management plans proposed by mining companies (such as the Ekati Diamond Company) are unsuccessful, and that the impacts of mining continue to harm the health and wellbeing of caribou herds in the area (Poole et al. 2021). Therefore, while it is unquestionable that something needs to be done in order to protect the Bathurst herd, it is important to weigh the outcomes with the direct and indirect negative impacts of the hunting ban in the Tłı̨chǫ region.

This current brief has summarized some potential impacts that the hunting ban of the Bathurst herd has on the food security and well-being of the Tłı̨chǫ. As one Elder shared, there is a reciprocal relationship between the people and the land, such that "when we see sick land, we feel sick, [and when we] see healthy land, we feel healthy" (Blake 2021).

# Appendix A

Timeline of hunting ban (Level 1015; Tłı̨chǫ Government and GNWT 2015, 2019 and 2022; Walsh 2021; Wek'èezhìi Renewable Resources Board 2010 and 2016)

| YEAR | EVENTS |
|---|---|
| 2009 | • ENR notifies WRRB of concerns on the decline of the Bathurst herd<br>• ENR, TG, and WRRB begin holding discussions on conservation of the Bathurst herd, which slightly stall by November 2009<br>• (December) GNWT announces a strict hunting ban on Bathurst herd, which is expected to begin January 1, 2010 |
| 2010 | • (January) ENR imposes an emergency interim no-hunting zone for all people until a management plan is created. The interim measures include:<br>  ◦ Zero hunting of the Bathurst herd<br>  ◦ Bison hunting regulations in two nearby management zones were adapted to allow for more bison tags to be distributed to provide higher access to bison for food and sustenance.<br>• (March) TG and ENR submit a joint proposal on management of caribou in Wek'eezhii to WRRB<br>• A series of public hearings are held to obtain community input on the hunting ban<br>• The WRRB responds to the joint proposal with a list of recommendations, to be implemented January 1, 2011. The emergency interim measures will stay in place until then. |

| YEAR | EVENTS |
| --- | --- |
| 2011 | • The Joint management Proposal is passed, and an Aboriginal harvest target of 300 Bathurst caribou per year is implemented, from 2011-2013.<br>  ◦ This harvest target is split evenly between the TG and the Yellowknives Dene<br>  ◦ Harvest limits are also in place for the neighboring Bluenose-East herd of 2800 per year, to be allocated between the Sahtu, Dehcho, and Tlicho.<br>  ◦ All commercial, outfitter, and resident harvesting is banned |
| 2012 | • A Bathurst herd calving ground survey does not show any indication of the herd's numbers improving |
| 2013 | • (spring) WRRB recommends that the limited harvest restrictions from the 2010 Joint Management Proposal extend into the 2013/2014 season. (source) |
| 2014 | • (December) The TG and ENR submit a second Joint Proposal on Caribou Management actions for the Bathurst herd, for the years 2016-2019 |
| 2015 | • (January) ENR proposes a mobile no-hunting zone (based on collared caribou), which the WRRB accepts on an interim basis until June 2015<br>• The Mobile Core Bathurst Caribou Conservation Area (MCBCCA) and subsequent mobile no-hunting zone is established<br>• (June) ENR conducts an updated population survey on the Bathurst herd, concluding that the population is still declining |
| 2016 | • A series of public hearings take place to discuss the 2016-2019 Joint Management Proposal<br>• (May) The proposal is accepted, and the total allowable harvest is now set to zero, until the 2019 hunting ban.<br>• An exception is made for an allowance of 15 bulls for "ceremonial hunts", which can only be allowed based on written request from an Indigenous government to the GNWT ENR |
| 2017 | • The *Bathurst Caribou Advisory Committee* is established. The committee includes members from across the NWT, Nunavut, and Saskatchewan. |
| 2018 | • (June) A survey of the calving grounds indicate that the herd has still declined since the last survey in June 2015. During this survey, researchers also begin to observe members of the Bathurst herd emigrating to neighboring herds. |
| 2019 | • TG and ENR submit another Joint Proposal for the management of the Bathurst herd. This time, the proposal is for two years (2019-2021), to reflect a two-year surveying period (shortened from the previous periods of three years).<br>• The proposal is accepted, which extends the zero total allowable harvest policy and confirms the continued use of the MCBCCA |
| 2021 | • The Bathurst Caribou Advisory Committee submits the Bathurst Caribou Management Plan. This plan includes recommendations for annual review of the Bathurst caribou, and serves as the primary guidance on Bathurst management.<br>• Another survey is done, which indicates that the herd is still declining but at a slower rate. |
| 2022 | • (January) TG and ENR submit another Joint Proposal for 2022-2024<br>• (May) This most recent proposal is accepted, with additional recommendations surrounding the monitoring of the herd, and a greater emphasis on research concerning herd emigration. |

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# PART 2

## Overcoming Struggles with Addictions and Poor Mental Health in the Northwest Territories: A Path to Wellbeing

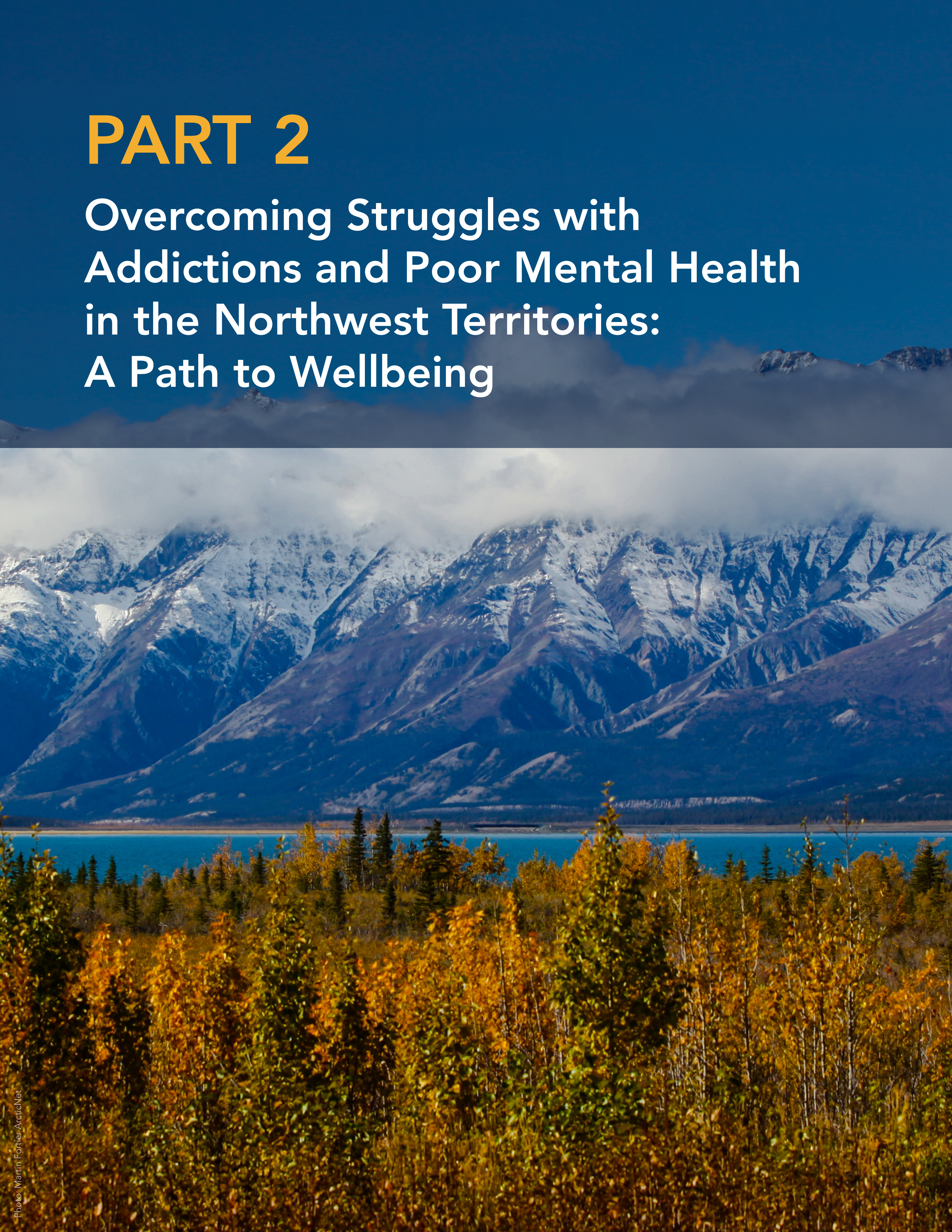

Photo: Martin Fortier ArcticNet

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# Abstract

Struggles with addictions and poor mental health are of grave concern to all peoples in the Northwest Territories. Many people have suffered from trauma related to the historical context of residential schooling, inequities, and systemic racism. This trauma has led to poor outcomes that co-exist with substance use and poor mental health, such as domestic violence, homelessness and stigmatizing processes that cause exclusion. These struggles are chronic and problematic and yet communities are tackling these issues with thoughtful initiatives and hopeful goals for a better future. This chapter will explore addictions and mental health from spaces and places of resilience. Health promotion efforts positioned with land-based programs, Elders' teachings, and strong cultural identities are forging the way towards well-being.

# Key Recommendations

- Community Elders provide wisdom and guidance for community health and change
- Elders, through traditional knowledge, practices, and ceremonies, create positive spaces for health promotion
- Indigenous methodologies and cultural education enable effective cultural change
- Research and interventions must consider multiple factors within innovative approaches
- Community based research with local people and community contexts provides positive outcomes
- Education about historical colonialism and oppression must be taught and understood to promote healing
- Cultural camps and land experiences led by local Indigenous people foster resilience
- Resilience and hope are ignited through belonging and cultural continuity

# 1. Overcoming Struggles with Addictions and Poor Mental Health in the Northwest Territories: A Path to Wellbeing

Too often addictions and mental health are presented from a place of deficit, perhaps because of an overwhelming inability to decrease the occurrence of the issues, conceptualize why it may be occurring, or to improve recovery and influence change. In this chapter, we will begin by articulating these challenges and end by approaching addictions and mental health from a strength-based place.

Across Canada, 78% of Canadians reported consuming alcohol in the last year with 21% acknowledging at least one alcohol-related harm (Statistics Canada 2020). These harms include being unable to stop drinking or unable to do what you would normally be doing as a result of alcohol, needing to drink alcohol first thing in the morning, not being able to remember what occurred because of the alcohol consumed, or feeling guilty about drinking. The Northwest Territories (NT) has a higher rate of heavy drinkers (32%) than the national rate (17%) [CIHI 2017]; this rate is also higher when comparing Indigenous peoples (32%) with non-Indigenous (26%) (GNWT 2019).

In Canada, it is estimated that alcohol-related annual costs are 6.2 billion dollars, accounting for lost productivity, amounts spent within the health care and criminal justice systems as well as other direct costs such as research and prevention efforts (CSUCH Scientific Working Group 2020). Health care costs alone related to alcohol total an estimated 5.4 billion dollars annually. Costs in the territories are highest as a result of the increased rates of alcohol use as well as higher health care costs for service delivery. The NT has more than double the number of hospitalizations entirely caused by alcohol when compared to all other provinces and territories in Canada (Canadian Centre on Substance Use and Addiction 2019). The GNWT (2019) noted that the main reason for hospitalizations for mental health are for substance use, primarily alcohol, and the rate of these admissions (2021/100,000) are four times that of the national rate (510/100,000). It was also noted that during the pandemic, the number of alcohol-related hospital admissions increased. In addition, the NT Chief Public Health Officer in a CBC news article identified that 15 people died from drug overdoses between

2016 and 2021 (CBC News 2022). It is clear that we have a substance abuse issue in the territory and it is an expensive one.

There is no doubt that substance abuse is both a symptom and indicator of poor mental health, but it does not stand alone. Domestic violence, including intimate partner violence, suicide, femicide, and homicide, all detract from the well-being of northerners (Fikowski and Moffitt 2018; Moffitt et al. 2013; Moffitt and Fikowski 2018). These serious and sometimes fatal outcomes destroy family and community life through grief and trauma and contribute to feelings of overwhelming despair leading to a cycle of substance use. It is well known that there is a disparity of accessible and available mental health resources and services in remote communities. Remote communities are highly populated with Indigenous people who are gravely affected by these inequities and other structural barriers, such as incongruent cultural care, lack of adequate mental health funding, and an absence of mental health strategies (Gone and Trimble 2012; Montesanti et al. 2022).

The struggles with addictions and poor mental health in the north can be traced historically to processes of colonialism, systemic racism, and oppression (Burnette, Renner and Figley 2019; Gameon and Skewes 2021). These health and social inequities are often overlooked creating a focus on mental health and addictions rather than the originating causes. Despite these structural barriers and oppressive experiences, the strength of the peoples of the NT has endured. Having now described some of these health disparities, we now elucidate the resilience of the people in the face of such disparities and explore further strategies to wellbeing both from the published literature and knowledge holders in the NT. An Indigenous health promotion theoretical framework will guide and format the discussion.

# 2. Indigenous Health Promotion

Indigenous health promotion has been described as utilizing traditional knowledge systems, Indigenous ways of knowing and living, and fostering ancestral spirituality, relationality, land-based activities and cultural continuity as distinct components (Sanchez-Pimienta et al., 2020). This study describes a process of digital storytelling with youth to learn more about Indigenous health promotion. They found that "connection" embodies and enables equality, relationship and leadership for youth. This element of connection through relationships is what distinguishes Indigenous from Western health promotion.

Previously, health promotion efforts in Indigenous communities have been described by some researchers as "a moral project of control through intervention" (McPhail-Bell et al. 2015). Although the intent is to empower and support people within their own self-determined good health, there is an ethical tension because of paternalistic acts and stigma that marginalizes and produces inequities, and where control is used to attempt to enforce good health practices. In contrast, Greenwood and Lindsey (2019) recommend restoring our Settler/Indigenous relationality (rather than furthering paternalism) to restore a more positive health promotion experience through addressing and working at the intersections of land, health, and knowledge.

In Canada, the National Collaborating Centre for Aboriginal Health prefaces Indigenous knowledge and relational thinking as the basis of knowledge translation and health promotion. It is recommended that we recognize and respect utilization of Indigenous knowledge as a way to overcome inequities and promote culture, language, ceremony, and traditions to improve health.

As well, Mundel and Chapman (2010) suggest a decolonizing approach to Indigenous health promotion that includes Indigenous healing, sharing the legacy of colonization and creating a context of cultural celebration through, in this study, a community garden. The research they conducted created a space to work together and share stories. This can be done in many other ways. For example, land-based healing in the NT is promoted at the Arctic Indigenous Wellness Camp in Yellowknife led by Indigenous Elders and counsellors. Wellness camps are being created around the territory as positive steps to cultural continuity in conjunction with healing and good health.

Another example is provided by Biderman et al. (2021) in research with stakeholders in Atlantic Canada where they identified pathways for sexual health promotion among Indigenous boys and men. This area of research is just beginning to grow, but is much needed since Indigenous communities share a high burden of sexual health illness outcomes including the human immune-deficiency virus (HIV), sexually transmitted infections (STIs) and blood-borne infections along with decreased condom use and increased sexualized violence (Biderman et al. 2021). Historical loss, a type of intergenerational trauma caused by colonialism, is associated with sexual-risk taking behaviours. As well, the loss of community traditional teachings and rites of passage about sexual health and well-being are attributed to colonial processes: in particular, residential schooling. Biderman et al. (2021) describe the following pathways to promote sexual health for Indigenous boys and men: developing healthy relationships and highlighting role models, providing access to comprehensive sexual health information, and fostering open communication.

Varcoe et al. (2017 and 2021) developed and implemented a health promotion intervention for Indigenous women survivors of intimate partner violence (IPV). The intervention builds on a former theory called Health Enhancement after Leaving (iHEAL) and is called Reclaiming our Spirit (ROS). Their iHEAL theory recognized that the health promotion strategy required was to strengthen capacity to limit intrusion (experiences of ongoing abuse, unwanted life changes, negative health consequences, personal and financial costs) and thus develop well-being. Intrusion was seen as all things that get in the way of a woman's abilities to manage their health and take personal control (Varcoe et al. 2017). The registered nurse-led intervention took place with 12 to 14 visits over six months with women at a predetermined safe location. Safeguarding, managing basics, managing symptoms, renewing self, regenerating family, and cautiously connecting were identified to address intrusion.

From these beginnings, ROS now involves intervention through collaboration among Indigenous women, Elders and nurses through a Circle process (Varcoe et al. 2021). A decolonizing approach was ensured by having a steering committee of Indigenous women, utilizing an Indigenous lens/worldview, and interviewing Indigenous elders. ROS significantly improved women's quality of life and trauma symptoms, but not chronic pain disability. Some women were recruited into the study but were unable to participate due to "extreme poverty, structural violence, high levels of trauma and substance use" (Varcoe et al., 2021). Despite this, ROS is a promising Indigenous health promotion intervention for survivors of IPV.

# 3. Social Determinants, Inequities and Systemic Racism

Greenwood et al. (2022) describe the National Coordinating Centre for Indigenous Health's conceptual change model through three interconnected layers: structural change, systemic change, and service delivery change. This strength-based model is an important application within the NT to transform inequities and systemic racism.

## 3.1. Structural Change

At the structural level, enablers include the Truth and Reconciliation (TRC) Calls to Action, the National Inquiry into Indigenous Missing and Murdered Women and Girls (MMIWG) Calls for Justice and the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP).

A mandate of the GNWT (2019 to 2023) is to implement UNDRIP through changes in the legislation and policies of the NT by collaborating with Indigenous governments and the federal government. Many rights are declared including cultural, spiritual, economic, political, and constitutional rights that foster ethnic identity and possession of lands, the transmission of histories, languages, beliefs, traditions, and equitable relationships within societies. Strategies for implementing UNDRIP include capacity building, research using indigenous methodologies, cultural education for health professionals, increased funding and resources for Indigenous health, and a reduction of inequities. HotiiTs'eeda, the NT Strategy for Patient-Oriented Research (SPOR) program support unit, is an example of capacity building for and by Indigenous people.

Throughout the world, nations are taking action to implement UNDRIP and disrupt colonialism and inequities that Indigenous peoples endure. Mason Durie (2004) described an Indigenous model for health promotion that consists of the following elements: cultural identity and access to the Māori world, environmental protection, healthy lifestyles, participation in society, leadership, and autonomy. These same elements in the NT would disrupt the current structural barriers and enhance the well-being of all northerners.

## 3.2. Systemic Change

At the systems or operational level, change is needed in the NT to reduce inequities that contribute to high crime rates, addictions, and poor mental health, include limited access to health services, housing, and employment. Indigenous-owned or community-based strategies that are developed contextually (i.e. in rural and remote locations) provide opportunities towards well-being. One researcher suggests reducing crime through "holistic healing circles, Indigenous sentencing courts, community justice groups, night patrols and safe houses" as well as "improving employment opportunities, providing better housing, improving health care, creating better future prospects for youth and offering an education informed by traditional Indigenous pedagogies" (DeKeseredy 2022)

## 3.3. Service Delivery Change

Greenwood et al. (2022) used the example of the pandemic to address knowledge mobilization that was implemented to combat misinformation during COVID 19, access to services for individuals and vaccine hesitancy. Within the knowledge translation that occurred during the pandemic, webinars were held to address mental health, social isolation and loneliness and to consider healing and connecting with tradition. As well, Moffitt et al. (2021) described the exacerbation of intimate partner violence during the pandemic and recommended changes that were needed to support victims. These researchers suggested enhanced risk assessment (evaluating the harm a victim may be facing through structured interviews with professionals, utilizing online tools to help a victim to identify personal risk factors), ris

k management (working with perpetrators with helpful strategies to reduce risk – like close monitoring) and safety planning (protection strategies like planning an escape route, saving and storing money, and having an emergency bag ready).

# 4. Substance use and Mental Health

## 4.1. Substance Use and Addictions

Risk factors that contribute to alcohol and other drug use in Indigenous populations internationally include economic marginalization, cultural dispossession, discrimination, cultural assimilation, family conflict and violence and a family history of alcohol abuse, as well as recurrent trauma, loss and disempowerment, high rates of unemployment, and social disconnection (Stewart et al. 2018). In this systematic review, these authors examined studies that measure the effectiveness of community-based interventions such as strong leadership, strong community engagement, program development by a paid position, and infrastructure for long term stability. They highlight the need for? culturally appropriate interventions and Indigenous participants as part of the review? team.

The Auditor General of Canada (2022) conducted an audit on Addictions Prevention and Recovery Services in the NT and found an inadequate response to preventing addiction and in the follow-up of residents with addictions. Because addictions are a major issue in the territory, the Department of Health and Social Services agreed to improve in the following areas: providing services that are equitable, coordinated and culturally safe, creating after-care services, and evaluating trends and services.

Logie et al. (2018) conducted a cross-sectional survey with 199 participants from the NT (154 were Indigenous) with the aim to explore mental health risk factors and STI vulnerability. In their research, they report an association between mental health (including depression and substance use) and increased multiple partners affecting their sexual health. In another publication, Logie et al. (2019) looked at food insecurity and IPV and found that both contribute to lower Safer Sex Efficacy. This evidence speaks to the need for synthesized approaches in both research and interventions for these multiple health challenges; treating them in silos does not address the complexity of what is happening within their social contexts.

## 4.2. Intimate Partner Violence

A major driver of mental health in the NT is the presence too often ending in suicides (Redvers et al., 2015), homicides and femicides [the murder of women and girls] (Fikowski and Moffitt 2018; Moffitt et al. 2013; Moffitt and Fikowski 2018). During the pandemic, the number of homicides in the NT increased from two in 2019 to five in 2020 and the number of emergency protection orders also increased (Moffitt et al. 2020). IPV is gendered with most of the victims are women. Women with disabilities are noted to have increased vulnerability.

Tutty et al. (2020) identifies that women with disabilities who are abused by intimate partners have more severe mental health disorders and are often overlooked in research. It is important that both counsellors and service workers are educated about disabilities and assessment so that they are provided with needed resources and services (Moffitt and Fikowski 2017; Tutty et al. 2020).

Dawson (2021) documents the necessity for accurate data collection and reporting as a preventative measure for the occurrence of femicide in Canada. Often times, the data is being collected by men and the variables and measures do not accurately reflect the context and nuances of these deaths (Dawson 2021). Recording and understanding the unique contexts surrounding femicide are essential to shape effective preventative and protective strategies to combat future occurrences. Issues such as the relationship of the perpetrator to the victim (women are often killed by men they know), a history of family or IPV, whether a protection order was in place, or whether this was a domestic related death are necessary data to inform prevention strategies. As well, the NT could consider a death review committee that would help to investigate details of femicides.

## Community Responses to IPV

Florence Barnaby and Rosa Mantla, two co-authors of this chapter, engaged as cultural leaders of sharing circles[1] in their communities. In this section, they share their wisdom as advocates of peaceful and healthy communities.

### 4.2.1. Rádeyįlįkóe (Fort Good Hope)

Florence brought together youth and Elders in the community of Fort Good Hope. As is the tradition in the communities, she asked an Elder to begin with a prayer. The Elder began the session with the following words:

> "Lord God, we need your help. We welcome you to sit here with us…help us to go through what needs to be done in our community with the Elders and the youth and everyone because sometimes we face a lot of issues…so, I am asking you to help us with granting wisdom, understanding, and knowledge…" (Elder, September 17, 2019).

Spirituality and tradition combine in this way to create a space that is respectful and honours the relationship between youth and Elders to forge a future with decreased violence and improved well-being. A youth in the room spoke up about 1) the importance of understanding the root cause of violence and 2) educating the community about intergenerational trauma. She shared what she was told and what she researched:

> "…it felt like a diagnosis for me to come to the reality that intergenerational trauma stems from what happened to Indigenous people throughout their lifetime. I tried to make a timeline in my head of the trauma we came across and I guess one of the first traumas was giving us gray blankets to give us diseases like smallpox and tuberculosis. That was a trauma that Katchodene people suffered and then I thought what else after that. I heard a story where police would take fur away from fur harvesters, steal it…there was trauma being abused and taking something away and throughout more history alcohol. Harvesters introduced alcohol, wanted our people drunk so that they could make these horrible deals and scam them. And I thought, what else?

1 The quotes and stories in this section were taken from research that was conducted by the first author and her colleagues (Moffitt et al. 2019) utilizing a sharing circle method. Seven sharing circles were conducted across the NWT and two communities are being highlighted here. Utilizing a sharing circle approach, we learned about how communities conceptualized violence and what strategies could be used to prevent family violence. This was part of a large study that began with a scoping review looking for best practices to prevent violence. It addresses the research question: What do Indigenous people and newcomers to Canada living in the NWT say about family violence and ways to end family violence in their communities? The findings from the study can be found in a report entitled "Community wisdom: creating a comprehensive approach to end family violence in the Northwest Territories". This project was funded by the GNWT.

> There is more. And residential school. One of the main and biggest traumas on our people that were taken away as four or five or six year-olds, maybe even younger, and brainwashed to stop speaking your language, to not knowing anything about who you are as an Indigenous person, and then you get removed from residential schools and go back home. So, it all accumulates, and I ask myself, was there any resources after that to provide us recovery for the psychological damage that was put onto us? And I thought, gee there are so many people who cannot speak about residential school right now. At our last SSI [define this acronym] meeting where a lot of people [gathered], mend didn't want to go there, and so I thought that just proves that they are not getting the help that they need. So, to this day, family violence comes from the trauma that we Indigenous people suffered during an extensive timeline that I think that we should really be educated on." (Youth, September 17, 2019).

This prompted stories from the group of their residential school experiences and some of the actions and supports that have helped them. An Elder shared her story of violence that began with a residential school experience at age four and carried on through the disconnection and loss of immediate family to violent relationships in her evolving life.

> "…I stayed there for seven years [sent to Aklavik] but I don't recall the first two years. I kind of forgot my language. In the summertime, maybe I was down there one or two years and then the mission took us home…I couldn't remember my mom. My sister brought me there. She said this woman is my mom but I had never seen her before. She is going to look after you and then I will come back and pick you up…I really started crying. My mom and my brother were trying to make me cheer up…but for a long time I remembered the Sisters and I wanted to cry. And later on there was violence in the school…the older girls that were looking after you were really mean…how many times I was pushed out the door, outside, I wouldn't know. Standing outside shivering…one day. This Sister grabbed me by the arm…she said that this girl reported that you stole her money. Where am I going to put that money? I have no pockets. I think the Sister just wanted o put her hands on me. She spanked me so hard that I bleed my nose and I do not know myself anymore and when I woke up I was on a little short table…Oh it was ever mean…Later on, I went home and found that my mom was getting married…they were up at the fish camps and later on I was sent back to school again. I think I was sent back to school maybe four times…and then I caught tuberculosis. I was put in the hospital and I was there for about two years before I got better and I was sent home. And then my mom remarried… my mom was scared…the third step-dad was so violent…I met my husband who was even more violent. I thought he would kill me before he left me…"(Elder, September 17, 2019)

One elder talked about attending church and the importance of forgiveness to let go of the pain from her experience. She said:

> "…I started going to the [name of Church]. I went through lots of violent readings and I do my own violence readings and the Pastor told us that whatever happens you have to forgive. Oh, I was tough hearted. I went to those meetings and I forgave him everything he had done to me. It was his doing not mine…" (Elder, September 17, 2019).

Some people talked about using substances to control the pain: "to cover up the pain when you use substance, their pain from someone that is close to them. I think that is it" (Youth, September 17, 2019). This prompted an Elder to share this powerful story:

> "Today, the only thing that saved me. I took a gun and I put it [points to her body]. There was no shell in it. I was trying it out. Where are the shells? I could not find it just then. I was going to shoot myself…I thought I have got to get help. I went to the drop-in centre. I went across there and I asked will you help me? And another time, a long time ago, it bothered me and then they told me we got a treatment centre – go to [place]. I said ok, I will do that…I went to the nurse and they gave me a medical and I was ready to be accepted…I started packing to get ready and there in there in the top drawer the shells were right there whereas I could not find it two days before that. So that is how things happen in our life. There must have been someone watching over me and then I went and got sobered up and got involved with healthy people. There was this woman. She was working with me. A woman she helped me a lot- how to talk with people, how to address things, how to respect people, and then when

> something else happened to me. My dad died in 1975, in 1993, his Bible came to me…from the Bible it said, if you don't forgive, God said I will not forgive you… [I visited a woman] she was there and she got nervous. She thought I was going to say something mean to her. I asked her, can I have some tea and she said sure I will make you some tea. She couldn't understand. She saw me as a different person. And we sat down and I said you know I am sorry for everything bad I called you. Things about you are not so bad. I'm not judging you because I am not perfect myself. I forgive you…I floated out of there because that was the best thing that happened to me. We became friends…" (Elder, September 17,2019).

This story was framed with personal experience and the way that respect and the forgiveness of people has led to compassion and renewed love of life. Another Elder went on to talk about cultural identity and how it can be restored by community events. She said:

> "...like a spiritual gathering for elders and youth…we can have workshops and an open fire and drum dancing…handgames…go and get wood like a good workout on the land…and you come back after working really hard out on the land all refreshed. We would have fresh tea, coffee, Bannock and Dene cooking…"

These experiences contribute to cultural identity and continuity through learning about one's ancestors and personal history. One participant said "getting to know yourself to try to help others". An elder said:

> "There is no more powerful tools than traditional tools actually. Nothing is more powerful than that - finding your way through stories, praise and offerings, cleaning ourselves with water. We should do those things, going to the water and letting the water run and cleaning while our sisters are outside drumming and waiting for us. Those are the real healing moments. The youth are celebrating those tools."

Another elder spoke about the importance of language as it is intertwined with one's cultural identity with these words:

> "I don't believe our language is dying, It's sleeping. How could we revive it? I always tell everybody the kids always talking it [is the way]… Say something to them in Dene. Everyday just see them and just say something to them [in Dene]… Go home and speak it. So we are really pushing that now."

And furthermore, it was suggested:

> "We need an evening class for Elders, adults, who ever would like to learn their culture and their language. They could probably have a teacher like Miss Betty. The elders to come and teach us like Slavey words and everything. I think that is really important and really push for an on-the-land program, Culture and Land Centre."

## 4.3. Behchokǫ̀

Rosa began the meeting with a prayer in her Tłı̨chǫ language that set the tone and prepared people for the purpose of the meeting:

> "We thank the Creator for the good days that he gives us everyday. Either its warm, sunny, rainy, windy, but we survive through these challenges of weather because it is nature. Nature that we can't do anything about. We don't control it, but we have to learn to live with it and work with it. The purpose of this gathering is what we learn from each other [about violence], how we share, and how we are going to support our people through these issues of violence that we have in our communities, in our lives, in our homes, in our workplace-even for young people, how they reflect on themselves…a lot of young people go through a lot of health issues, some can be in their genes, like eczema or other sickness and they blame their own families and that's how they get angry, or they get violent…so we think about healthy relationships for the future of our young people. Especially their children and their children. We need to be prepared to have something for them in the future." (Elder Rosa, July 15, 2019).

In this opening prayer, Rosa shared her wisdom about violence and the support that is needed in the community for future generations. She thanked people for coming and sharing their knowledge.

An Elder who lives with his adult child shared about the anger that they both deal with and the ways anger exists between them, directly linking it to alcohol use. Sometimes his son says he will go for treatment and sometimes they talk together about each others' problems. The Elder encourages his adult son to "be strong" and "pray". He describes his way of coping like this:

> "I like to walk around, around the people. I'm happy with it. I don't want to stay home alone, you know. I like to walk around and talk to people, talk to friends. Sometimes they say something funny and we laugh, you know. Yesterday, I was home, [name] phoned me, told me to come over. I said "ok I'll be there". I like to do this. They know my problems. I've been in residential school. Everything builds inside of me. That's why sometimes I get angry about it. I talk to my son. I always worry about my son. Sometimes, if you walk out that door, I tell him "if you walk out that door, make it fast, come back". I don't want to stay alone. Sometime, go out, come back right away. I tell him if it's a bad story, don't bring it back. Just leave it there, you know? If it's a funny story, bring it back and we will laugh." (Elder, July 15, 2019).

Community support and fellowship is a valued asset for this Elder. It is a way to cope with his trauma.

Another participant described leaving the community and going to a women's shelter. She stated "I don't want my kids to grow up the way I was grown up…It wasn't easy. It was a tough life.". She points to another participant and says "I was with her. Me and her were at the shelter…we got to know each other. Until this day, we talk. How are you doing? You know". She goes on to describe the importance of breaking the cycle of abuse for the children, while at the same time supporting other women in the community.

> "That's the reason I left their dad, because there was too much alcohol involved…I just wanted peace and quiet for my kids. Right now, my kids are grown up. I just don't want that. It is just not healthy. Some days it's hard. Some days we have good days, we have bad days, you know. It's hard especially being a single parent…a lot of the young women my age. They come to me. Sometime I talk to them. They come to me for advice. I just do the best I can. As a mother, I just tell them to do the best for their kids. If you know your kids are not safe and its not a good relationship, just leave. Just keep moving on, what's back is back [there] eh? It was hard but I am thankful for this day. I'm here with the people that are really there. You know, listening and participating. Some days were hard but I just kept going on. I'm really thankful for all of the love and support that was there. And I know who to turn to and who to talk to. It wasn't easy to build ourselves back up from where we were…Because some of us we have no mom, we have no dad, some of them lost their siblings. That was the hardest part to let go. Some of us are recovering from the grief. And that one, is the hardest part, to talk about it. It is good to share these stories to pass them on to our kids, for the future." (Tlicho participant, July 15, 2019).

Today, and as President of the Tlicho Elders' Society, Rosa is an activist against all forms of violence. Through her work with the Elders' Society, she brings Elders together to address their concerns. She describes the initiative this way:

> "We held seven Elders' meetings on how to find solutions to Elder abuse. We also had one meeting on how to deal with the effects of Indian Residential Schooling. Many of our people suffered in Residential Schools. In these meetings, the Elders decided to create a formal society that will give them a strong voice to focus on the issues that our Elders are still facing everyday. One of the agreed upon purposes is to plan programs for Elders, including development of skills in counselling and advocacy, so Elders can become better influencers and educators in all areas of social services. The society wants to see a better response to all Elders' abuse issues…the mission and vision is to find effective strategies to help our Elders shed the residual effects of residential schooling and the other attributes of the oppressive colonization that is still with us today… for Elders rights in their home communities, especially for the right to live without fear and abuse in their own homes. The vision is to have all Tlicho Elders living with a support network that helps in all areas of daily living, and that each Elder can live feeling safe and secure in their own homes, in their own communities."

# 5. Resilience and Hope in the NT

Resilience is defined as a pattern of positive adaptations following exposures to stress, adversity, or risk (Masten 2014). While some authors contend that the two dimensions of resilience are adaptation and adversity, resilience is much more complex. Another way of considering resilience is a process to access resources to sustain personal well-being. This western view of resilience is missing the collective view of resilience that comes from an Indigenous worldview (Liebenberg et al. 2008). Understanding the barriers and structural influences on well-being along with protective strategies in Indigenous populations must be thoroughly understood to develop workable health promotion interventions. In Alaska, Barnett et al. (2020) evaluated the effectiveness of culture camps as a health promotion intervention with youth, specifically addressing prevention of youth suicide and to promote mental health and wellness. In the week-long culture camps, they found that the camps provided youth with a more positive mood, increased sense of belonging and greater capacity to handle life's stressors.

The concepts of resilience and hope are appearing in the published literature particularly with projects with Indigenous youth (Hatala et al. 2017). In a grounded theory with youth exploring time and the future, findings are described through major themes of distressing times and then resilience and time for the future (Hatala et al. 2017). Resilience is supported and their futures considered through three subthemes: nurturing a sense of belonging, developing self-mastery, meaning-making processes, and cultural continuity. Within the findings of this work, there are implications and strategies that premise themselves within a context of resilience and hope to consider for the NT. Hatala et al. (2017) suggests that resilience can be fostered by looking ahead with a future time orientation.

# 6. Conclusion and Implications

Strategies and implications for policy, practice, and community-led development are identified to support recovery and influence change regarding substance use in the NWT. These are premised within a context of resilience and hope, realized through an understanding of oppression and social justice, and guided by the wisdom of Elders whose land we are situated on. Community Elders, like Florence Barnaby and Rosa Mantla, can lead us through cultural innovations to assist with strength-based community approaches and healing. Uppermost in their approaches is community Elders working with youth to strengthen and enhance cultural knowledge and ways of being which in turn provides cultural continuity and strong Indigenous identities.

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# PART 3

## Mine Remediation Research in the Yukon

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# Abstract

In the context of climate change, it is recognized the there will be an increased need for minerals that can support an energy transition, which open a debate on the role that mining should play in the Canadian economy, especially in the Canadian North. To this point, mining activities in the North have primarily focused on gold, silver, zinc, lead, and diamonds. However, there is an opportunity to focus on resources that hold greater strategic weight, such as copper, cobalt, graphite, lithium, and nickel; all essential ingredients in making batteries for electric vehicles.

However, it must also be remembered that historical practices from the past have led to a controversial mining legacy and social and environmental best practices must be developed to support sustainable mining. These practices must include the meaningful inclusion of First Nations peoples, whose traditional lands house these precious minerals.

The Natural Sciences and Engineering Research Council (NSERC) Industrial Research Chair (IRC) in Northern Mine Remediation (NMR) at Yukon University, led by Dr. Guillaume Nielsen is a research program partnering with the seven Yukon active mines, also known as the Yukon Mining Research Consortium (YMRC) and intends to bring scientific evidence and answers to challenges the mining industry is facing in the North.

Nielsen's work focuses on three main research trends: (i) Water Treatment by Passive or Semi-Passive Technologies; (ii) Solid Waste Management and (iii) Mine Revegetation. Collaboration with Yukon First Nations communities allows the NMR team to bring First Nation world views and traditional knowledge in research projects undertaken under the Chair program.

This chapter intends to present why research is needed in mine reclamation and remediation, especially in Northern environments, as well as examples of specific research projects built under the IRC in NMR. The social impact of research in the North will also be discussed with northerners involved as researchers, students or research assistants and First Nation community work that has been developed using research, remediation and restoration as tools that can be used toward reconciliation.

This chapter has been written in collaboration between Dr. Nielsen, research assistants, YukonU students, a First Nation community citizen, and a First Nation school teacher.

# Key Recommendations

- Continue to develop Passive treatment systems (PTS) as they are a sustainable and low-maintenance alternative to conventional active mine remediation.
- Use natural materials and processes and require minimal maintenance.
- Encourage further research to determine PTS effectiveness in colder climates.
- Additionally, mine remediation and restoration can serve as a tool for reconciliation.
- Implement and continue to research tangible water management and infrastructure design adaptation measures for industrial sites such as active and decommissioned mines.

# 1. Introduction to the Industrial Research Chair in Northern Mine Remediation

Helaina Moses, co-writer of this report is a citizen of the First Nation of Na-Cho Nyak Dun. Therefore, her story has been taken as an example of Yukon's historical relationship with the mining industry.

Mining activities have impacted First Nation traditional territories in the Yukon for decades. It started with the Klondike Gold Rush era of the Yukon in the 19$^{th}$ century. Of course, every Yukon First Nation experienced the gold rush era a little bit differently, but generally, this can be seen as a shared experience with colonial consequences. An archetype example of this is the relationship that the First Nation of Na-Cho Nyak Dun (FNNND) had with mining during the Klondike Gold Rush era.

When the settlers came up, the Stewart River in the Traditional Territory of the First Nation of Na-Cho Nyak Dun (Meaning flowing from our ancestral waters or also known as Big River People in the Northern Tutchone language) to start their journey to find gold, it brought more discovery of the Silver Deposit in Keno Hill which turned Mayo into a port for steamboats for ore transportation. This is when the trading posts were born in Yukon, and First Nations used fur for currency to buy things they never used before like flour, tea, and sugar.

Currency and money were not part of the First Nation lifestyle. Their ancestors valued their lands and resources. Back in the Gold Rush era, First Nation people were introduced to a lifestyle that they did not understand. They were nomadic people and did not tend to stay in one place. They depended on the land for resources and water for survival. This colonial introduction has impacted their traditional lifestyle and culture. Years later, the Klondike Highway was built, which led to more traffic. Roads made it more accessible to First Nation's traditional territories and remote wilderness, which led to the further exploitation of natural resources.

Since the Gold Rush, the need for metals and minerals has increased and led to the development of many new mines, including in Northern Canada. These mines often produce water, tailings and waste rocks that are contaminated and require specific management and treatment during the construction, operation, and closure of a mine to protect the North's sensitive environment.

In 1915, Reverend Julius Kendi arrived at Fraser Falls, where people of the First Nation of Na-Cho Nyak Dun usually dried fish. Reverend Kendi asked the First Nation of Na-Cho Nyak Dun to decide on a location where he could place a village. Two miles south of the Village of Mayo on the banks of the Stewart River, the location of the village is now known as "the Old Village". Albert Tom was the traditional chief at the old Village on the Stewart River for 55 years.

Members of the First Nation of Na-Cho Nyak Dun were instrumental in guiding the Council of Yukon First Nations and its First Nations members during the 1984 negotiations collapse and rejection of the proposed agreements on self-determination. The two crucial issues for the Council of Yukon First Nations and their member communities were the lack of self-government and the extinguishment of Indigenous rights. These two critical elements were eventually included in the successful 1993 agreements, known as the Umbrella Final agreement. The Umbrella Final Agreement, signed May 29, 1993, by the Government of Yukon, the Government of Canada and the Council of Yukon First Nations, was the legal framework in which self-governance could be individually negotiated with the individual First Nations (The Government of Yukon 1993). Additionally, this agreement covered land, water management and surface/sub-surface rights among other important aspects (The Government of Yukon 1993).

The First Nation of Na-Cho Nyak Dun today has a membership of 650+. As a self-governing First Nation, the First Nation of Na-Cho Nyak Dun can make laws on behalf of their citizens and their lands. Under the land claims agreement, the First Nation now owns 4,739.68 square kilometres of settlement lands and has received in compensation $14,554,654 for which a trust has been established. The First Nation has been actively involved in affairs of the Mayo community, attempting to promote a better, healthier lifestyle for its future generations and a strong economy based on its abundant natural resources. This includes searching for better and more efficient ways to ensure mining activities in their community are being cleaned up and that the land is usable for future generations.

Proper remediation activities, proactively implemented at the beginning of a mining endeavor, reduce overall costs, and lessen the potential for environmental damage, thus allowing mine closure impacts to be minimized, the mine footprint to be rehabilitated to a pre-mining state, and mine operators to reduce costs (Fox and Cundill 2018; Monosky and Keeling 2021; Kemp et al. 2023). Importantly, while many remediation approaches have been proven effective in southern latitudes, their efficacy and optimization in cold northern climates have not been investigated (Tumeo and Guinn 1997). Mining companies are being asked to demonstrate the effectiveness of these approaches in their licensing and regulatory processes but lack scientific evidence to prove they work in cold climates (Tumeo and Guinn 1997).

Recognizing the need for careful planning to respond to remediation needs at all stages of a northern mine's life, leaders in Yukon's mining industry have identified the need for applied research to ensure the best practices in northern environments are created. To build this research capacity, Yukon University hosts the Natural Sciences and Engineering Research Council (NSERC) Industrial Research Chair for Colleges (IRCC) in Northern Mine Remediation (NMR).

The IRCC in NMR has deep knowledge of the mining industry and has built partnerships with the seven mining companies currently operating in the Yukon territory (Newmont Corp., BMC Minerals (No. 1) Ltd., Victoria Gold Corp., Casino Mining Corp., Selwyn Chihong Mining Ltd. and Alexco Resource Corp. and Minto Metals Corp. – known collectively as the Yukon Mining Research Consortium (YMRC). The YMRC has identified research needs in several areas specific to the Yukon mining sector that this IRCC must address. Specifically, these are: **(i) Water Treatment by Passive or Semi-Passive Technologies:** The mining industry is currently investing in and using active water treatment technologies. A transition to cost-competitive passive treatment technologies will benefit the mining industry, but scientific evidence of efficacy in cold climates is required to support this transition; **(ii) Mine Waste Management:** Tailings management represents one of the biggest challenges the mining industry is facing. Climate change and its impacts (including increased warmer temperatures, increased precipitation, and permafrost thaw) bring a pressing need for new tailings management methods that can be implemented in the North, in this rapidly changing environment. **(iii) Mine Revegetation:** Revegetation after mining in Yukon is limited by a lack of commercially available, locally sourced seeds of northern plants and minimal knowledge of successful revegetation techniques in cold climates. The IRCC in Northern Mine Remediation will test a revegetation technique at a partner's mine site that could feasibly be completed with locally-sourced seeds.

Community engagement with Yukon First Nations is always part of the research process. Traditional knowledge and First Nations world views are included in each research project built into the IRCC in NMR.

Most importantly, this IRCC holds collaboration on research activities and knowledge sharing with industry and First Nations as a critical component of a successful IRCC research program. The IRCC in Northern Mine Remediation also creates student research positions, is involved in college teaching courses, and increases research collaboration with Yukon University's existing faculty members.

# 2. Research Needs under NMR

## 2.1. Need for Semi-passive biological water treatment technologies in cold climate.

Currently, the Northern mining industry uses active technologies to treat mine-impacted water. Active treatments rely on expensive chemicals, labor, and long-term infrastructure and are not the most favourable to the environment and sustainability of the industry.

Passive treatment systems (PTS) offer a promising alternative to conventional active treatments. PTS are based on chemical and biological reactions that naturally occur in the environment and offer a potentially sustainable option for long-term mine drainage treatment during and after mine closure. PTS are defined as technologies that use natural materials to promote natural chemical and biological processes and require less maintenance once installed than conventional processes (Johnson and Hallberg 2005; Younger et al. 2002). More specifically, PTS allow the removal

### Box 1.

*I have traveled all over from Beaver River to Red Mountain, monitoring permafrost melt and collecting baseline data. Working with Keno Hill for the reclamation closure planning. I helped in research projects at different mines with the Yukon Research Centre. (Putting two worlds together for a positive future) I was involved in Bioreactor projects for passive water treatment options.*

*Helaina Moses*

Throughout Helaina's career, she has been involved in projects with Yukon University and with different mining companies and learned different techniques and research from different viewpoints. This has helped her a lot during her experience as a scientist and working with the First Nations to do internal research. She has worked with the Yukon University Research Centre in the past to complete water sampling of the Silver King bioreactor, where she taught the youth of Mayo, Yukon. They learned how the semi-passive bioreactor technology works, and the data it provides.

of contaminants from water using biological or geochemical processes. The process requires limited or no power or chemicals after construction and can last for decades with minimal human maintenance (Gusek and Wildeman 2002). Semi-passive treatment systems are similar but require some human intervention to ensure their success. However, compared to the status quo the effort required using semi-passive methods is marginal.

Metals move through the water, and when they are dissolved, they are more mobile. Plants can take them up through their roots. Depending on the species of the plant and animals, they can be absorbed through ingestion. This way, metals can transfer from a mine site to the wider environment. The community of Mayo is concerned about the metal intake from harvesting the land. That is why it is so important for the First Nation of Na-cho Nyak Dun to research the effects of long-term mining around our traditional territory.

From a First Nation perspective, the First Nation of Na-cho Nyak Dun has contributed to conduct its own surveys and is putting together a contaminant monitoring program for local hunters to submit samples of wild harvests. The Yukon Government and the First Nation are interested in metal levels in local moose and using samples from local hunters to test for metal contents. They, as a nation, want to restore and protect this area for future generations. This is a starting point for capacity building within the First Nation based on traditional knowledge, and the connection with the land. They want their great-grandchildren to harvest from this area without the effects of bioaccumulation and bioavailability in local wildlife that are creating concerns for human health. It is very important to protect their Traditional Territory, **and applied research can help the remediation of heavy metals in Yukon's communities.**

This project has brought the community knowledge of what's happening with the old mining adits, and what passive water treatment can provide to their community, to help heal the lands they live on and protect the environment from harmful heavy metals leaching into water and food resources.

## 2.2. Semi-passive bioreactors to treat Nitrogen.

Nitrate is one of the most widespread groundwater contaminants and is often associated with mining, both from nitrate-based explosives used in the extraction process and nitrate chemicals used in mineral processing (e.g. cyanide leaching in gold processing) (Dash et al. 2009; Bailey et al. 2013). Passive and semi-passive treatment systems have been identified as a cost-efficient way to treat mine-impacted water. Passive systems require minimal attention after installment whereas semi-passive technologies rely on periodic maintenance and additions of materials such as carbon sources (Trumm 2009; Ness et al. 2014). Biological treatment of nitrate contamination relies on naturally occurring microbial populations that transform nitrogen species. These biological processes are sensitive to changes in various parameters such as flow rate, pH and temperature. Therefore, conditions in cold climates, such as Canada's subarctic zone, present various challenges to implementing successful biological technologies to treat nitrates. This is an emerging field of research that has been catalyzed by the need for passive or semi-passive treatment options for the closure plans of developing mines as dictated by modern legislation and regulatory bodies.

To address this Northern challenge associated with Nitrogen, the NMR team built a Master's degree project in partnership with the Institut National de la Recherche Scientifique (INRS) in Quebec and Minto Metals as industrial partner.

This project aims to inform closure treatment plans for Minto Mine, a copper gold mine in central Yukon Territory, 240 km northwest of Whitehorse. Minto Mine has identified a need for semi-passive treatment of nitrite and nitrate that can successfully operate in cold subarctic conditions. Therefore, this applied research project will tailor treatment technologies to on-site conditions, first in the lab, then at the mine at a pilot scale. **A semi-passive biological treatment system will be designed using cold-adapted nitrifying and denitrifying bacteria native to the Minto Mine site.**

### 2.2.1. Inoculum collection

Bacterial samples were taken from 20 locations at Minto mine. A total of 16 sediment samples targeting denitrifying bacteria were collected and 4 nitrifying samples were collected. For each location, the GPS coordinates,

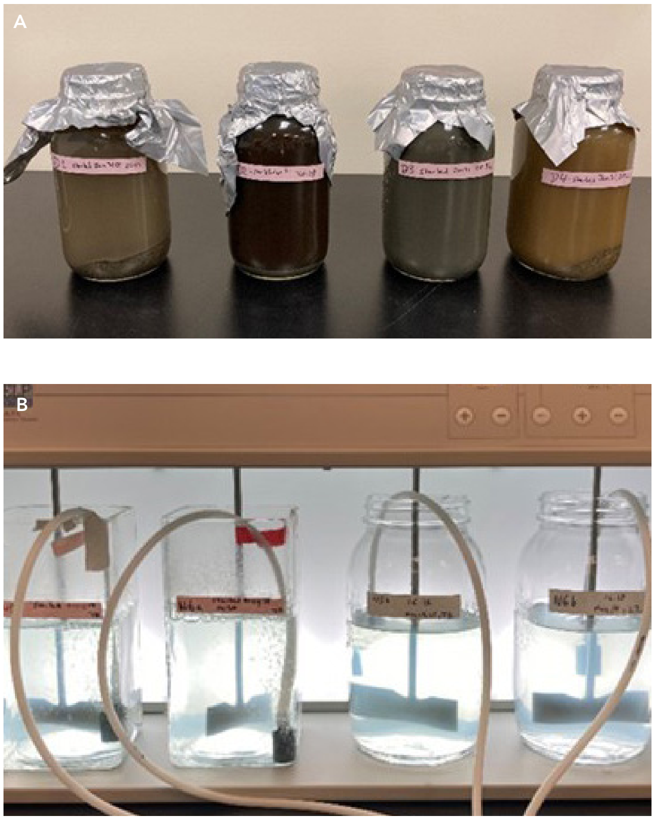


Figure 1. Anoxic denitrifying bioreactors(a). Aerobic nitrifying bioreactors (b).

Figure 2. The pilot-scale treatment system will be installed on the mine site in an insulated, mobile laboratory.

depth of sample, visual and odour observations were recorded. Water samples were collected from the surface of the water.

### 2.2.2. Biomass development and optimization

To develop the targeted denitrifying bacteria from each sediment sample, sixteen 1 L bioreactors (Figure 1a) were inoculated with sediment from each sample site. Bacterial growth was supported by a growth medium well-represented in the literature (Widdel and Pfennig 1981; Nokhal and Schlegel 1983; Widdel and Bak 1992; Strohm et al. 2007; Hahnke et al. 2014), comprised of various nutrients, trace elements, chelating agent, and nitrates. Bioreactors were sealed to maintain anoxic conditions, which are optimal for microbial denitrification. Bioreactors were sampled weekly for three weeks, for ammonium, nitrite and nitrate concentrations, as well as changes in pH, dissolved oxygen, conductivity and oxidation-reduction potential. After the first batch of 16 bioreactors, all but one inoculum sources were combined into another bioreactor test that was conducted in duplicate, to optimize the biomass.

To develop the targeted nitrifying bacterial populations, four 1 L bioreactors Figure 1b) were inoculated with the water samples collected from the mine. Bacterial growth was supported by a growth medium well-represented in the literature, comprised of various nutrients, trace elements, chelating agent, and ammonium. Bioreactors were stirred and aerated with air pumps to maintain aerobic conditions, which are optimal for microbial nitrification. Bioreactors were sampled weekly over three weeks, for ammonium, nitrite and nitrate concentrations, as well as changes in pH, dissolved oxygen, conductivity and oxidation-reduction potential.

### 2.2.3. Preliminary results, Conclusion and Next Steps

All 16 denitrifying bioreactors were successful in decreasing nitrate concentrations after three weeks. With an initial nitrate concentration of 250mg/L, all bioreactors were successful and removed 98 to 100% (below detection limits). The optimized denitrifying biomass were also successful in decreasing (100%, below detection limit) nitrate concentrations. The nitrifying bioreactors

Figure 3: BR1 and 1b(a); BR2 and 2b(b) and YRC Shed(c).

were not successful in decreasing the ammonium concentrations and the development of a nitrifying biomass is ongoing.

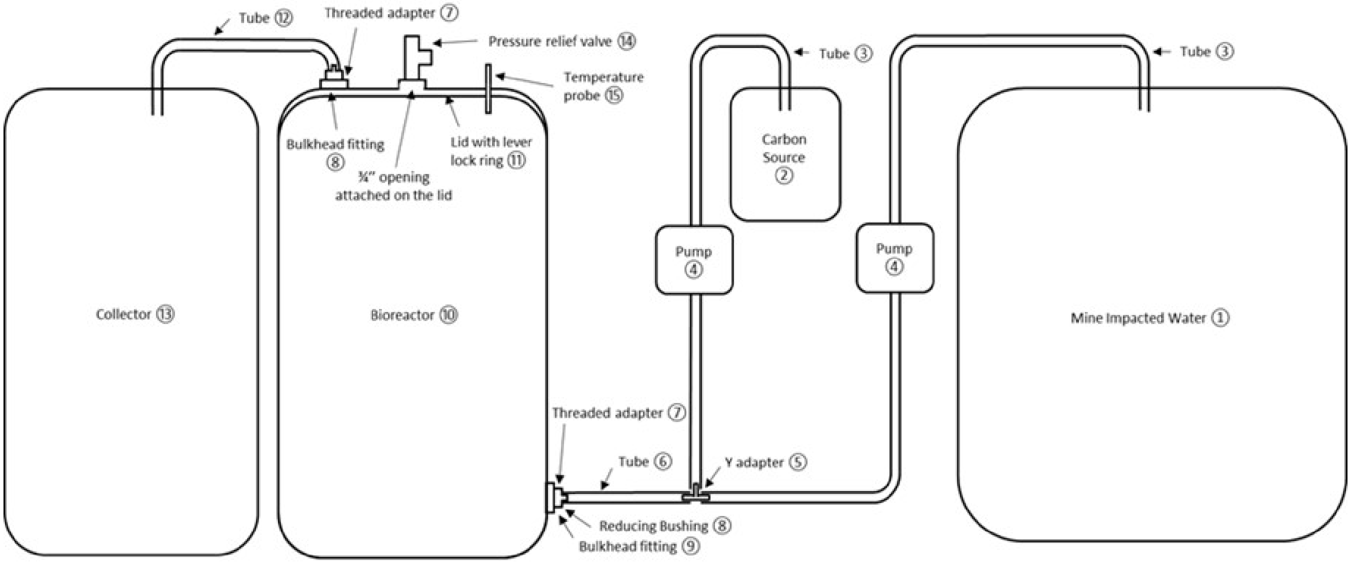
Initial results confirm that the targeted bacterial populations have been successfully found on the mine site and have been optimized in the lab. Next steps include testing the various carbon sources and growth mediums in their potential to support the optimized inoculum in denitrification. Bacterial populations, carbon sources and growth substrates will be tested in lab-scale column studies to design an optimal water treatment system. In order to generate applicable knowledge for industrial partners, laboratory tests will be focused on simulating real-life conditions at the mine. Especially, the pilot scale experiment will consider real hydraulic retention time, on site temperature and freeze and thaw cycles. Following the design and testing of an optimized treatment system, the system will be scaled up to a pilot system that will be installed on the mine site to treat real mine-impacted water (Figure 2). The pilot scale system would test the effectiveness of the design when exposed to real MIW (Mine-Impacted Water) and changing conditions such as temperature, seasonal freeze, and thaw, changing water quality and varying water quantity.

## 2.3. Semi passive bioreactors to treat Heavy Metal

Traditional heavy metal removal from mine impacted water (MIW) is usually done with using active treatment technologies and requires extensive infrastructure, expertise, and on-going maintenance. As a result, this project explored the use sulfate reducing bioreactors containing endemic bacterial inoculum as a semi-passive treatment option and attempted to determine their capacity for heavy metal removal throughout the seasonal temperature fluctuations and freezing cycles experienced in northern environments. This project determined the effects of real mine conditions (including freeze-thaw cycles and extreme cold temperatures) on bacterial capacity to remove heavy metals from mine impacted water. With a greater understanding of the impacts of temperature on bacterial performance, bioreactors of this kind could provide a viable and economic passive water treatment option capable of operating effectively within Arctic and Sub-Arctic regions.

This pilot-scale project took place at Eagle Gold mine operated by Victoria Gold, which is the largest gold mine in the Yukon Territory, located in central Yukon approximately 375 km north of Whitehorse. The purpose of this project was to study local bacterial populations' adaptation to seasonal freeze and thaw cycles and their capacity to remove heavy metals (Sb, Se, and As) from mine impacted water. The project established four bioreactors (BRs) containing bacterial inoculum collected from the site to explore passive water treatment options suitable for mining projects at northern latitudes.

Four bioreactors were assembled at Eagle Gold mine on Aug 7th and 8th, 2019. Two BRs were inside of a heated shed maintained to stay above 5°C minimum, and two were outside of the shed exposed to seasonal freezing cycles (Figure 3).




| Number | Name | Number | Name | Number | Name |
|---|---|---|---|---|---|
| 1 | Intermediate Bulk Container | 6 | Masterflex L/S 16 Tubing | 11 | Polyethylene Lid with Steel Lever Lock Ring |
| 2 | 10 L Glass with Magnetic Stirrer | 7 | 1/8" NPT – 1/8" ID Nylon Threaded Adapter | 12 | Masterflex L/S 16 Tubing |
| 3 | Masterflex L/S 16 Tubing | 8 | ¾" NPT – 1/8" ID Nylon Reducing Bushing | 13 | 55 Gallon Open Head Polyethylene Drum |
| 4 | Masterflex Peristaltic Pump | 9 | 2" NPT – ¾" NPT Nylon Bulkhead Fitting | 14 | 30-psi Pressure Relief Valve |
| 5 | 1/8" ID Y Adapter | 10 | 55 Gallon Open Head Polyethylene Drum | 15 | Digi-Sense Replacement Temperature Probe |

Figure 4: Experiment design for this study.

Two collector drums inside of the shed remained open, while the other two collector drums outside of the shed were covered with lids and steel lever locks to prevent leaves and dust from entering the collectors. Temperature probes were installed on the lid of each BR (Figure 4).

Each BR was filled with 20% v/v wood chips (local Yukon white spruce) and 20% v/v inoculum. The wood chips and inoculum were mixed thoroughly in the BRs, and the remaining 170L was filled with MIW. Data collection was completed on a weekly basis and spanned from Aug 2019 to June 2022. The samples from effluent drums were collected after stirring the contents. Parameters recorded included pH, conductivity, temperature, sulphates, total organic carbon, and a range of heavy metals with particular attention to arsenic, antimony, and selenium. Bacterial sampling and analysis, including DNA characterization, is being completed by a researcher from UBC where results are currently under investigation.

### 2.3.1. Preliminary results & Conclusion

Bacterial capacity to remove Selenium (Se) and Antimony (Sb) (contaminants of concern highlighted by Victoria Gold) from the MIW were investigated. Se and Sb removal by the BRs system was promising, with a relatively high removal rate for both elements. Initial Se concentration in mine impacted water was 1.03 µg/L and the highest removal percentage was 94.3%. Initial Sb concentration mine impacted water was up to 3.5 µg/L and highest removal percentage was 96.4%.

The bacterial population contrast measured in the BRs located outside the shed versus within the shed suggested the physiological adaptation of the bacterial community to cold temperatures on site.

Throughout this project, bioreactors demonstrated their ability to remove contaminants from mine impacted water. Bacterial activity responsible for removal was detected through sulfate reduction. The rate of removal resulting from greater bacterial activity appeared to correlate BR temperatures, and thus higher removal was witnessed during summer with lower removal during winter. Importantly, the seasonal freezing of the bioreactors located outside did not appear to affect their ability to remove the targeted elements.

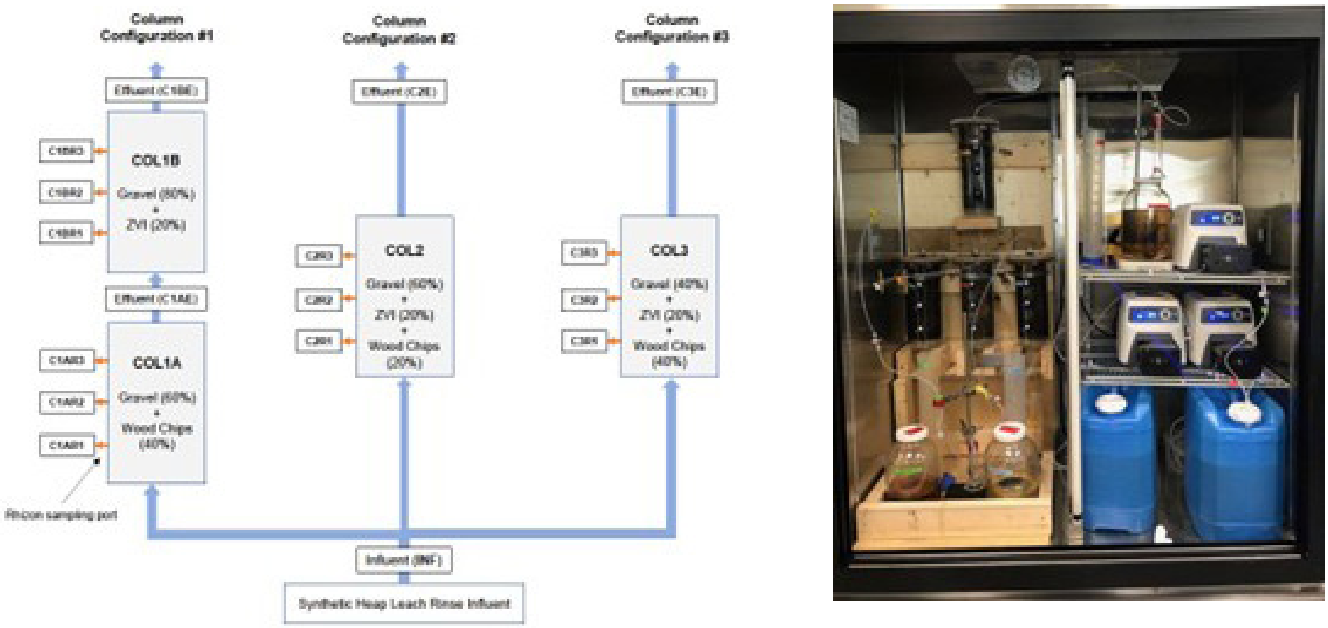



Figure 5. Column configurations and substrate proportions prepared by Lorax Environmental Services Ltd.

## 2.4. Semi-passive treatment column technology to treat mine impacted water under cold conditions

### 2.4.1. Introduction

This lab scale project evaluated the use of semi-passive treatment at closure to treat drain down seepage water from the decommissioned heap leach facility (HLF) under cold conditions. Arsenic (As), nitrate (NO3) and Uranium (U) are identified parameters of potential concern. Concerning levels of NO3 that impact groundwater can cause methemoglobinemia in newborn children and adults deficient in glucose-phosphate dehydrogenase, can negatively impact wildlife/ecosystems, especially fish and marine animals (Murphy, 1991; Camargo et al., 2005). Additionally, there is debate around the potential of cancer-causing potential of nitrate (Murphy 1991; Powlson et al. 2008). U has no essential biologic function, and is known for its radioactivity, toxicity, and carcinogenic properties (Bjørklund et al. 2020). As, is also known for being carcinogenic, but also can cause cutaneous manifestations associated with arsenic poisoning (Brown and Ross 2002). All three of these chemicals are extremely problematic for local populations, animals and ecosystems. Finding proven methods to bioremediate these chemicals in a northern context is a priority. As and U represent leached components from the ore while nitrate represents a residual product of cyanide degradation. This study used various proportions of locally available woodchips and gravel, zero-valent iron (ZVI) based on permeable reactive barrier (PRB) technology and denitrifying bacteria through biological reactor to treat synthetic MIW.

### 2.4.2. Methodology

#### Column Materials, Construction and Operation

Three configurations of semi-passive treatment were investigated in this experiment (Figure 5). First column (C1) was comprised of two reaction cells, with the first (C1A) designed to promote denitrification in the absence of ZVI and second (C1B) attached in series to remove U and As using ZVI. The second (C2) and third (C3) columns were designed as single reaction cells containing all reactive materials in varied proportions except ZVI, which was packed with constant 20% proportion in all the columns containing it as indicated in Figure 5. To mimic the cold conditions of a real mine site, columns were kept refrigerated at 5° C for the duration of the 9-month experiment. Influent was refrigerated for a minimum of 3 days before being added to maintain a consistent temperature within the columns to avoid disturbance to microbial populations. The flow rate, controlled by peristaltic pump, was adjusted accordingly to reach target hydraulic retention time (HRT) of 4 days.

### 2.4.3. Results & Discussion

The PRBs successfully removed As and U at rates exceeding 99%.

The As removal was minimal in C1A. In all other columns, the As removal rates exceeded 99%. The fastest removal was observed in C2. The fact that C1A was the only column lacking ZVI in the substrate mixture and had the minimal As removal, indicates that ZVI played an important role in removing As from MIW. Indeed, in all other columns showed higher removal rates and presence of ZVI in their substrate mixtures. The removal of As within columns 2 and 3 does not appear to have been affected by the sodium acetate added to the influent in weeks 20 to 32.

Uranium removal does not occur as early in the columns as As. Uranium and As are known to compete for reactive sites on iron, so As may be using more reactive sites at the beginning of the column, with U being removed later in the columns where more ZVI surfaces are available. C3 had the highest removal of U followed by C2 and C1B. Uranium concentration was negatively affected by addition of sodium acetate. This may have been related to the changes in the general chemistry (alkalinity, pH, DO) in the columns associated with the sodium acetate amendment, used as a supplement carbon source to support bacterial activity.

Before sodium acetate addition, the nitrate removal was largely due to ZVI, as the highest rate of removal occurred in the column that did not contain woodchips (C1B). After the addition, nitrate removal increased in C1A up to 98.76%. The addition of sodium acetate coincided with clogging and high HRT, in C1. The increase in carbon may have led to a rapid increase of microbes that could have potentially obstructed the hydraulic pathways within the column. The other 2 columns also experienced increased nitrate removal with the amendment, C2 to 47.05% and in C3 to 45.58% in week 32. Nitrate removal decreased once the sodium acetate was no longer added as of week 33.

The leach test revealed that gravels raised the pH of the Deionized Water (DIW) from an initial neutral pH to between 8 to 9 pH even after 24 hours of agitation. Cyanide was identified as a potentially problematic by-product generated by the system. The agitated shake flask tests revealed that ZVI did not leach cyanide in either case (with DIW or MIW) even after 14 days. The lack of MIW limited further investigation.

### 2.4.4. Conclusion

The semi-passive technique using ZVI, gravel and wood chips as PRBs showed promising results at 5°C in subarctic weather for 9 months. All the columns successfully removed As at rates exceeding 99%, both before and during the sodium acetate amendment. While the columns were able to remove all contaminants of concern, they were not removed simultaneously. Both As and U were contained by Zero Valent Iron, gravel, and woodchips. The mechanism of their removal was studied by Synchrotron analysis at Canadian Light Source Inc. It was found that both precipitation and absorption played a role in the removal of As and U. C1 performed better in removing 99% of both As and $NO_3$ after addition of sodium acetate but compromised U removal. C2 performed better during the acetate amendment by removing 99% As and almost 50% of both U and $NO_3$, simultaneously. C3 performed better in the absence of sodium acetate by removing 99% of As, U and nearly 50% of $NO_3$. Thus, depending on the nature of contaminant, each column plays an individual role. Hydraulic retention time potentially influenced the rate of removal of As and nitrate and therefore must be considered when designing an *in-situ* bioreactor for mine remediation. The flow rate issues seen in C1 in weeks 25 to 32 suggest that the system may be clogged over time.

More research is required to determine the longevity of the system as configured. In addition, cyanide is a potentially problematic by-product generated in the system and requires further investigation.

## 2.5. Need for new Solid Mine waste management technologies

### 2.5.1. Oxygen diffusion in Saturated Covers following Freeze and Thaw cycles.

This study was developed using laboratory scale replicates of saturated covers and make inferences regarding oxygen diffusion solely based on the data observed. Theoretically, saturated covers could be preferred in a Northern context, as water covers are subject to major freeze and thaw cycles and require hard infrastructure, like a dam. As water covers freeze and thaw, they expand and contract and can be problematic for hard infrastructure. Additionally, soil covers are not the most practical in cold climates as soil is a limited resource. Saturated covers remove the need for a dam or other hard infrastructure and reduce the required amount of soil necessary for a proper cover to keep the waste rocks anoxic and prevent acid rock drainage. Additionally, saturated covers have been shown to be effective in warmer climates (Yanful 1993; Romano et al. 2003; Pabst et al. 2018) but have yet to be fully tested in arctic and sub-arctic climates. This laboratory-scale test was an attempt to prove their efficacy.

The material used as saturated cover in this study was synthetic silica flour (70 μm). This inert material is a good proxy for non-acid generating tailings, a material which is widely investigated by the mining industry as material for saturated cover. The silica flour material mimicked the physical properties of real tailings without any additional variables introduced by unpredictable tailing material.

A clear, instrumented column was created for this experiment (Figure 6). The column had three 5TM temperature and unfrozen volumetric water content probes fixed to three evenly spaced places along the length of the column, using custom made 3D parts. Sourcing an oxygen probe was difficult, because most dissolved oxygen probes are not made to be able to withstand negative temperatures. After much research, the Oakton DO 450 Waterproof Portable Meter was attached to the base of the column. According to the manufacturer, the probe was able to work at temperatures down to -10oC. However, it had not been evaluated at negative temperatures for prolonged periods.

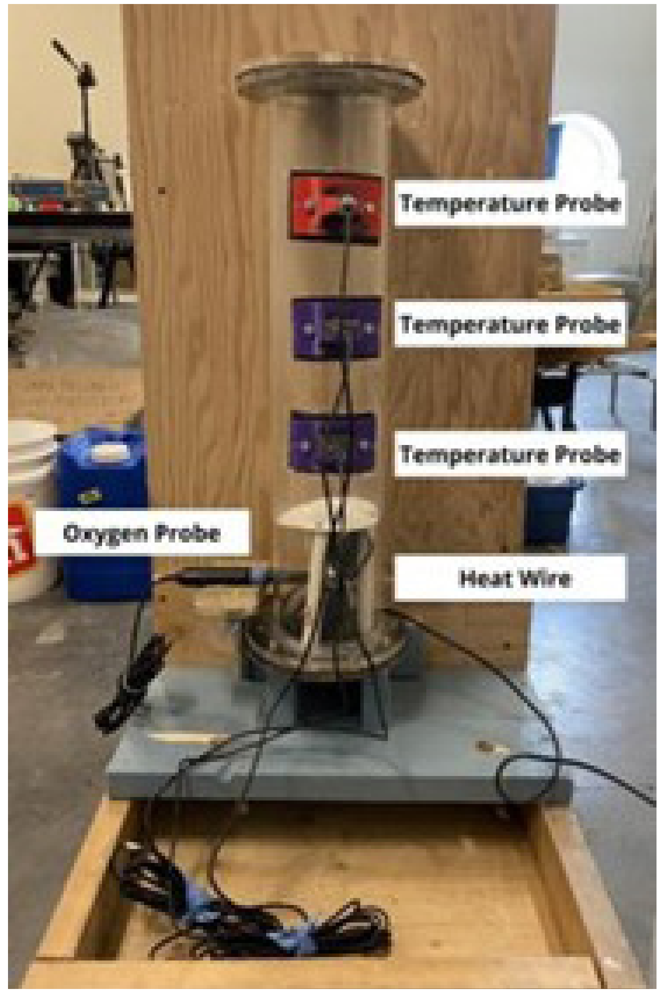



Figure 6: Instrumented column.

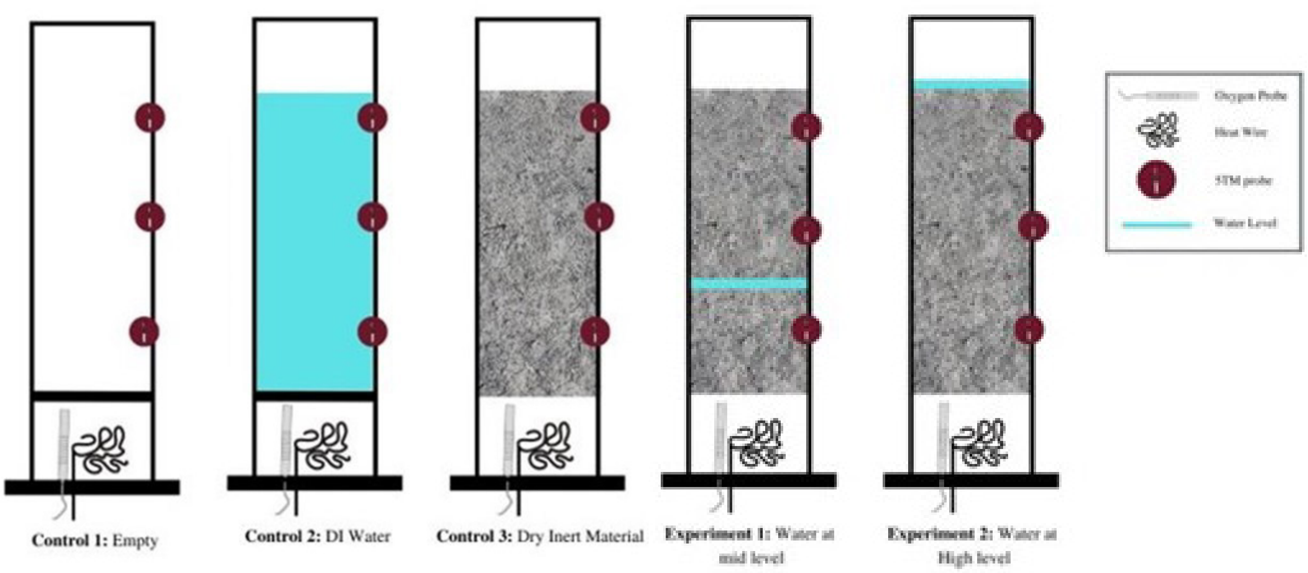



Figure 7: Column set up.

So, to ensure freeze and thaw could be carried out, an additional heat source, in the form of a gutter de-icing wire, was applied at the base of the column to ensure the area around the probe stayed above 0oC.

Two different levels of cover material saturation (fully saturated and mid-level saturation), as well as three controls subject to different temperature tests to evaluate oxygen saturation (Figure 7). The three controls were: a water filled column, an empty column and a dry cover material filled column. The temperature tests were ambient temperature, cold temperature (the column was frozen the entire time), and thaw conditions (column material going from frozen back to room temperature). These temperature tests allowed for the observation of oxygen diffusion in each of the different phases of a freeze and thaw cycle. The duration of the tests was 121 hours, because that was the point at which complete oxygen saturation (100% or above) was observed within the controls.

To ensure that oxygen diffusion within the cover material was observed with as few variables as possible, a constant flow of oxygen was attached to the top of the column (using 95% pure oxygen injected at a flow rate of 5L per minute) after the column was purged to 0% oxygen using nitrogen gas (attached to the base of the column). This allowed for the top of the column to be a 100% oxygen environment.

### 2.5.2. Results and conclusion

Preliminary findings, completed with oxygen injections instead of a constant flow of oxygen in a freeze and thaw scenario indicated that both mid-level saturation and high-level saturation of the inert material may have functioned as a good oxygen barrier during the freezing process and let some oxygen pass during the thawing process. The partial saturation of the inert material (mid-level water) decreased the oxygen saturation by 96% following a freeze and thaw cycle. The full saturation of inert material (high-level water) decreased the oxygen saturation by 95% following a freeze and thaw cycle. Overall, there was not a significant difference in oxygen saturation between the mid-level water and high-level water, but a significant difference in oxygen saturation in the controls versus the saturated columns, with a strong ability of the saturated columns to limit oxygen diffusion.

This project is still currently underway, with ongoing testing of cover material saturation in ambient temperatures to ensure findings from the previous experiment was due specifically to the conditions introduced by a freeze and thaw cycle, and not by time influencing diffusion percent. Thus far, there has been evidence in the water filled column, empty column and fully saturated column ambient temperature duplicates suggesting that a saturated cover is both a good barrier to oxygen diffusion, but also that a freeze and thaw cycle has significant variation in the percent oxygen saturation.

## 2.6. Need for Mine Revegetation in the North

Mining activities may leave disturbed sites with top organic soil removed and reclamation and restoration work must be done. Revegetation is a key process in reclamation as it ultimately determines future land uses by people and wildlife (Guittony 2020). The majority of boreal reclamation research focuses on oil sands mining in the Boreal Plains Ecoregion of Alberta with a strong emphasis on soil amendments of peat and forest floor materials, as well as extensive tree planting (Dhar et al. 2018). Forest floor salvage and peat amendments can reintroduce plant propagules and improve soil characteristics; tree planting reduces the time to canopy closure and can limit establishment of weedy species (Macdonald et al. 2015). In the Yukon, most mines are in remote locations without significant peat or topsoil resources. Access to locally sourced tree seedlings is also limited. Best practice in revegetation is to optimize

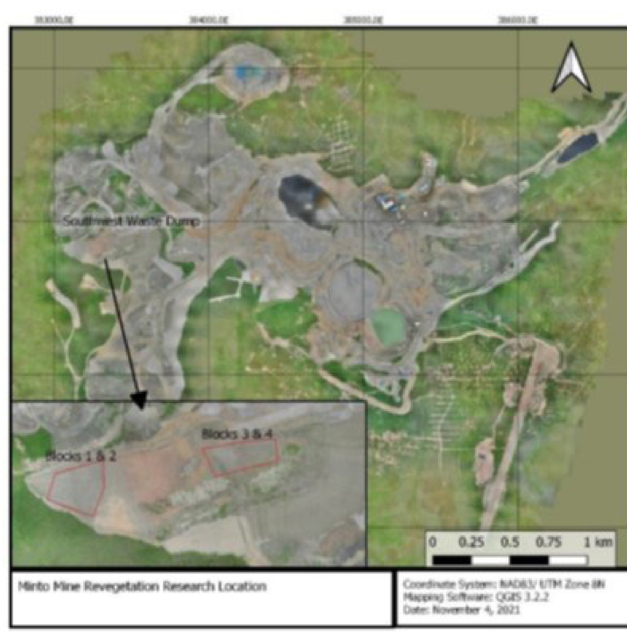



Figure 8. Minto Mine revegetation research location on the Southwest Waste Dump.

the use of local resources (Guittony 2020) and thus exploring alternative techniques for northern regions is warranted.

Utilization ofwoody shrubs in restoration projects has been documented in dry, arid climates, but not tested in northern systems (Gómez et al 2004; Castro et al. 2004; Gómez-Aparacio et al. 2005). Research studying shrub encroachment in arctic and alpine tundra provides evidence that tall shrubs have a strong, year-round influence on northern non-forested community dynamics (review by Myers-Smith et al. 2011). Plants can facilitate the survival and growth of their neighbors by providing more favorable environmental conditions such as reduced soil and air temperature extremes, nitrogen fixation, attracting pollinators and providing physical protection from herbivory (Castro et al. 2004 Baraza et al. 2006; Padilla and Pugnaire 2006; Dona and Galen 2007; Brooker et al. 2008). In cold climates, vertical structure such as a shrub canopy can increase the capture of snow which dramatically alters both summer and winter soil conditions (Kreyling 2019). Vertical structure can also reduce the loss of soil and seeds to wind erosion (Peterson 2001).

To test this revegetation technique, a site visit to Minto Mine was completed May 27th, 2021, to identify a location for the research. Site criteria were a 1.5 ha area with minimal slope, final soil cover in place, minimal existing vegetation, and significant wind exposure. The site would need to remain undisturbed for a minimum of four years. A suitable site was identified on the Southwest Waste Dump (Figure 8.).

Green alder and smooth-leaf mountain avens were selected for tall and short biotic structures. Primary succession processes in northern systems indicate shrubs, especially nitrogen fixers, have a prominent role. Nitrogen fixation by shrubs in early seral stages is a primary determinant of total nitrogen within the climax system though legumes can also contribute (Jacobson and Birks 1980; Chapin et al. 2006; Buma et al. 2017). Green alder is well known nitrogen fixer; the evidence is inconclusive for smooth-leaf mountain avens though yellow mountain avens (D. drummondii) are capable (Kohls et al. 1994; Rhoades et al. 2008; Callender et al. 2016). Mat-forming shrubs, especially Dryas spp., and erect shrubs also capture wind-blown soil fines which stimulates soil development on glacial moraines and outwash (Viereck 1966; Birks 1980; Buma et al. 2017). These species are native to the Yukon and tolerate poorly developed soils and harsh conditions associated with mine sites.


Figure 9. Planting rows of alder along a stringline in Block 2 in 2021 (a). Green alder in 2022 (b)

### 2.6.1. Revegetation: a social need

The challenge of defining meaningful goals and objectives of revegetation projects is not a new one. There is extensive coverage within the ecological restoration literature of which indicators should be used to measure "success" (e.g. review by Prach et al. 2019).

Objectives and indicators are almost exclusively ecological despite increasing acknowledgement that socio-economic outcomes are also important (Aronson et al. 2010; Hallett et al. 2013; Wortley et al. 2013; Prach

### Box 2. The Northern Mine Remediation course/workshop for First Nations communities.

Over the last 3.5 years, the *Northern Mine remediation* team was involved in more than 7 course programs as guest speaker or designed laboratory modules. Approximately 25 students were hired and trained as research assistants. Workshops for First Nation communities were given between 5 and 12 times per summer (in 2019, 2020 and 2021) and an NMR 9 modules course was designed for First Nation communities. This course was given in Pelly Crossing with Selkirk First Nation students in 2020 and 2021.

The Northern Mine Remediation workshops for communities was offered to remote First Nation communities for several years and was well received. As a result, the need to create content that would go deeper in all aspects of the workshop arose.

The NMR course offered a class experiment where the students grew bacteria in laboratory scale columns to treat mine impacted water and offered 9 modules (1-3 hours/modules) to discuss with guest speakers about different topics related to mining. At the end of the course, a poster is produced by the students.

The modules are presented in the list below:

**Modules summary:**

1. Laboratory scale sulfate reducing bioreactor implementation.
2. Environmental monitoring program at Yukon University
3. Environmental monitoring at Minto Mine
4. Mine Revegetation in the North: Meeting Yukon community expectations of reclamation success
5. Why involving First Nation communities in research projects important?
6. YukonU Research lab visit
7. Mine processing: metallurgy and geology department
8. Minto's constructed wetland treatment system (CWTS) presentation
9. Bioreactors conclusion

In 2020 and 2021, Dr. Nielsen gave the Northern Mine Remediation course in Pelly Crossing, on Selkirk First Nation self-governed land. The *Northen Mine Remediation* team collaborated with Mr. Colin Prentice: high school science teacher at Eliza Van Bibber School. Mr. Prentice had worked at Minto Mine, a local mine on Selkirk First Nations land, and managed mine water remediation before becoming a teacher. He wrote a testimonial letter about the course. He said:

*"As Dr. Nielsen and his guest experts taught, I was stunned by the way my students became engaged learners who acquired and improved practical scientific field skills. The senior students became proficient in using appropriate protective equipment, and were familiar with standard sterile techniques for water and biological sampling. The junior students, seeing the seniors perform complex scientific procedures, were able to begin learning those same skills with student mentorship.... I was pleased with the engagement I saw in my students because I knew it would improve their learning outcomes, but I was happier still that the skills they were developing translate directly to summer student employment in environmental science fields.... This [course] helped my students relate to new material and connect it to broader learning. This effect was made stronger by the fact that the technology we were studying was being piloted and implemented by Minto Mine, a local copper mine that is located on Selkirk First Nation land." "One of the reasons the experiential mine remediation course was so effective in engaging students was the inclusion of local professionals and subject matter experts. Among the guest speakers were former Eliza Van Bibber School graduates, local community members, and even a parent of one of the students. It was immediately evident that students connected with these speakers. One speaker, who is a member of Selkirk First Nation, spoke about Dän Ki, or traditional ways of knowing and being. He discussed his experience, and how he was using environmental science in tandem with traditional ways to protect the land and preserve his traditions.... As a final wrap-up to the course, Dr. Nielsen invited the class to tour Yukon University campus, and perform chemical analysis on water samples in a university research lab. Students were taught how to use leading edge analytical equipment, then prepped and ran analysis on samples they took from the experiment in the classroom. We also then toured campus, showing students the dormitories, classrooms, and recreational facilities.... Improving post-secondary success rates from community high school graduates is challenging at the best of times, and this program helped students imagine themselves at university in tangible and immediate ways. I cannot state firmly enough how powerful this contribution is to student success after high school."*

et al. 2019). Integrating local perspectives and participation into revegetation project decision-making and delivery has been demonstrated to produce improved both social and ecological outcomes (Davenport et al. 2010; Lauer et al. 2017; Fox and Cundhill 2018; Jellinek et al. 2018; Reyes-García et al. 2019).

Social studies are currently being designed to explore how Yukon communities envision revegetation success. Based on initial discussions with potential community partners, definitions of revegetation success are much more complex than an ecological outcome.

The need of mixing traditional knowledge with western science is an important first step in working with First Nation communities. Traditional Knowledge represents a powerful link to a community's past. It offers information about a people's history, the land they have lived on, how they procured and processed resources. Indigenous people know the land better than anyone else, their ancestors have travelled in the Yukon for generations. All their ancestor's knowledge has been passed down for generations. Working together to restore the land and water is a common interest we all share and benefits both research and First Nation communities.

To engage with First Nation communities, the Northern Mine Remediation research program designed workshops and course (See Box 2.).

# 3. Conclusion

As demonstrated in this chapter, there is still a significant need to continue mining remediation research in the North. This chapter has demonstrated particular areas of need and shown the work that has been done on these areas thus far. First, this chapter looked at the work being done so far regarding the creation of semi-passive treatments for mine impacted water in cold climates. Following this, the treatment of nitrogen species and heavy metals using bioreactors, battling sub-arctic and arctic temperatures. Next, the report focused on mining waste management, with our experimentation on the development of saturated covers, focusing on the impact of freeze and thaw cycles to mitigate oxygen diffusion. This would improve tailings management and challenge the industrial standard of using soil or water covers to stabilize tailings in

Northern Climates, where they have never been used. Penultimately, the focus shifted towards mine revegetation, and what success in mine revegetation looks like from a community perspective. Making an active mine green, is not the ultimate goal based on our preliminary discussions with community partners, and as such, as social science study is required to determine what success would look like. Finally, this report discussed further community engagement, in the form of the Northern Mine Remediation Course/Workshop. Not only does this program aim to give students valuable scientific skills and teach them about the process of remediating an active mine, but it also destigmatizes students to the idea of post-secondary education, which is common in Yukon's communities.

Looking to the future, there needs to be a continued research and development of *applied* mining remediation techniques and technologies that function and can be counted on in harsh northern climate. To continue this work, however, there is a barrier that must be considered and overcome. Technological capacity is something that must be overcome. In our past research projects, we have used some of the world's most cutting-edge tools such as the synchrotron at Canadian light source, and genomic characterization at UBC.

On a closing note, working in the Yukon as an ethical researcher, we must always consider its impact on our First Nations. Very often researchers overlook their own impact on furthering reconciliation and unintentionally further the colonial status quo in Canada. It is for this reason that we include and discuss with our indigenous partners about mine remediation and will continue to do so. Mine remediation and restoration can and should be used as a tool to further reconciliation.

### Bio Guillaume Nielsen

Dr. Guillaume Nielsen, Natural Sciences and Engineering Research Council (NSERC) Industrial Research Chair for Colleges (IRCC) in Northern Mine Remediation (NMR) at Yukon University, is leading the way in applied research projects that support mining companies as they develop environmental best practices. Nielsen works in partnership with six major Yukon mining companies – Newmont Corp., BMC Minerals (No. 1) Ltd., Victoria Gold Corp., Casino Mining Corp., Selwyn Chihong Mining Ltd. And Alexco Resource Corp. and Minto Metals Corp. – known collectively as the Yukon Mining Research Consortium (YMRC).

### Bio Helaina Moses

Helaina Moses describes herself as a land healer. She first started her career in the Environmental field in the mining industry, worked in the industry for 9 years, and then worked for multiple mining industries in the Yukon, including Alexco, Minto Mine & Victoria Gold Corp.

She grew up with her grandfather's teachings. He always took her out to hunt, trap, and fish. He would always remind her that the First Nation of Na-Cho Nyak Dun didn't have grocery stores to get food in his younger days, they had to learn to live off the land and use what was around them. That's where it all started for Helaina's career. Her grand father taught her how important it is to take care of the land and the land will take care of you. He said one day sickness will come and then what are you going to do when no food truck comes to our community.

Helaina enjoys working outside and making a difference in her community. She enjoys seeing the land earthy with clean water and health animals to harvest. This means a lot to her and her family at home, as it is their tradition to keep the water clean and the land healthy for future generations. Their traditional Territory has many scars on the land from historic mining eras.

### Bio Avery Zammit

Avery James Zammit M.A. is the Project Officer for the Industrial Research Chair for Colleges (IRCC) in Northern Mine Remediation (NMR) and Climate Change Research (CCR) at the YukonU Research Centre in Whitehorse, YT. Avery holds an Honours Bachelor of Arts in Political Science from York University and a Master of Arts in Political Science, Sociology and History from the University of Siegen, in Germany. These programs included semesters at the University of Helsinki, Finland and the University of Bologna, Italy. As a Project Officer, Avery supports research projects by managing the operations and activities of research teams, organizing field logistics, coordinating meetings, and writing and editing reports for funders, research partners and collaborators.

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# PART 4

## Permafrost Thaw-induced Impacts on Landcover and Hydrology in the Taiga Plains and Taiga Shield - Part I

Photo Credit : S. Wright

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# Abstract

The Taiga Plains and Taiga Shield ecozones of northwestern Canada have experienced rapid and widespread permafrost thaw over recent decades, particularly in regions of discontinuous permafrost. This article reviews the thaw-induced impacts on landcover and hydrology for this region and provides recommendations to address identified knowledge gaps. A companion article (Part II) expands on the thaw-induced impacts on water quality.

In the Taiga Plains, permafrost is linked to peatlands where its thaw converts the land from forests underlain by permafrost to permafrost-free collapsed (thermokarst) wetlands. When the active layer deepens to the point it can no longer re-freeze in winter, a talik (perennially unfrozen ground) develops above the permafrost that further accelerates permafrost thaw. The spatial distribution of such taliks has been increasing in the Taiga Plains, particularly beneath areas burned by wildfire and human disturbance. Continued thaw leads to increased surface and subsurface hydrologic connectivity between landcover types and the basin drainage network, thereby increasing basin runoff and groundwater discharge to streams. Thaw-induced landcover change is considered the primary driver of the observed increases in annual streamflow in the southern Taiga Plains, with thaw-activated groundwater flow being a secondary driver. Streamflow increases are likely temporary in


Discontinuous permafrost peatland in southern NWT. S.

the absence of precipitation changes since sustained permafrost thaw enables bogs to drain, resulting in dry enough conditions for forests to regenerate.

The impacts of permafrost thaw in the Taiga Shield are not well known, but it is unlikely to result in considerable landcover changes due to high spatial coverage of permafrost-free bedrock and lakes and low occurrence of peatlands (<5%). However, permafrost thaw may impact landcover through changes in the spatial extent of lakes driven by the reactivation of groundwater flow paths and increasing basin storage capacity that reduces basin runoff and lake inflow. Talik extent in the Taiga Shield, especially beneath lakes, is not well known. It is possible that permafrost thaw beneath soil-filled valleys and lakes may increase groundwater recharge and reactivate deep groundwater flow systems in fractured and faulted bedrock, but further research is needed.

Groundwater monitoring throughout the region is greatly lacking, leaving considerable knowledge gaps for the impacts of permafrost thaw on groundwater systems. Increases in shallow talik development from thaw can increase winter baseflow and the development of riverine icings. Icings are more common in the Taiga Shield and can comprise a significant portion of annual water budgets. Icings are not well documented in the Taiga Plains, and their trajectories in the Taiga Shield are highly uncertain.

# Recommendations

- Conduct permafrost mapping at local and regional scales relevant to community planning.
- Establish a groundwater monitoring network within a set of regionally representative landscapes.
- Investigate groundwater-surface water interactions that span diverse landscapes.
- Assess multi-decadal changes in lake extent in the Taiga Shield to infer subsurface changes.
- Map spatial and temporal changes in riverine icings in the Taiga Plains.

# 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 it is relatively thin and warm and can be heated from all sides (Devoie et al., 2021). Even slight increases in air temperature or land disturbance from human or natural causes can lead to permafrost thaw (Quinton et al. 2009). As such, the southern fringe of the discontinuous permafrost zone is rapidly losing permafrost with a ~10–50% reduction in areal coverage over the last 50–60 years (Beilman and Robinson 2003; Chasmer and Hopkinson 2017; Zhang et al. 2014). Wildfires are also increasing in frequency, severity, and quantity in the North (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).

The discontinuous permafrost zone of the Taiga Plains and Taiga Shield ecozones are experiencing pronounced thaw-driven impacts on the land and water. 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 resulting from climate change, wildfire, or land disturbance 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. Changes in landcover directly impact the hydrologic functioning of an area, leading to changes in the routing, storage, and connectivity of surface and subsurface waters (Quinton et al. 2011b).

# 2. The Taiga Plains and Taiga Shield

This report focuses on the discontinuous permafrost zone of the Taiga Plains and Taiga Shield ecozones of western Canada (Figure 1). 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). Permafrost is relatively thin (1.5 m to 17 m) and warm (-2°C to -0.2°C) and is strongly linked to peatlands due to the thermal buffering provided by peat (Figure 2a). 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). Tree-covered peat plateaus (commonly black spruce) are the predominant permafrost landform in the Taiga Plains (Figure 2c; Zoltai and Tarnocai 1974). Permafrost 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 of permafrost occurrence, followed by fine-grained substrate (Burgess and Smith 2000). Common permafrost thaw features 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).

The landscape of the Taiga Shield consists of bedrock uplands (Figure 2b,f) and soil-filled valleys that contain wetlands and lakes (Figure 2b,f,g; Spence 2000; Spence and Woo 2002, 2003). Lakes cover nearly one-quarter of the total area, and peatlands cover less than 5% (Ecosystem Classification Group, 2008). Permafrost and hydrological process information for the Taiga Shield mainly stem from the North Slave region near Yellowknife, where approximately 52% of the area is underlain by permafrost (Zhang et al. 2014). Permafrost is associated with forests (mainly black spruce), and peatlands underlain by fine-grained silts and clays and consistently absent below bedrock

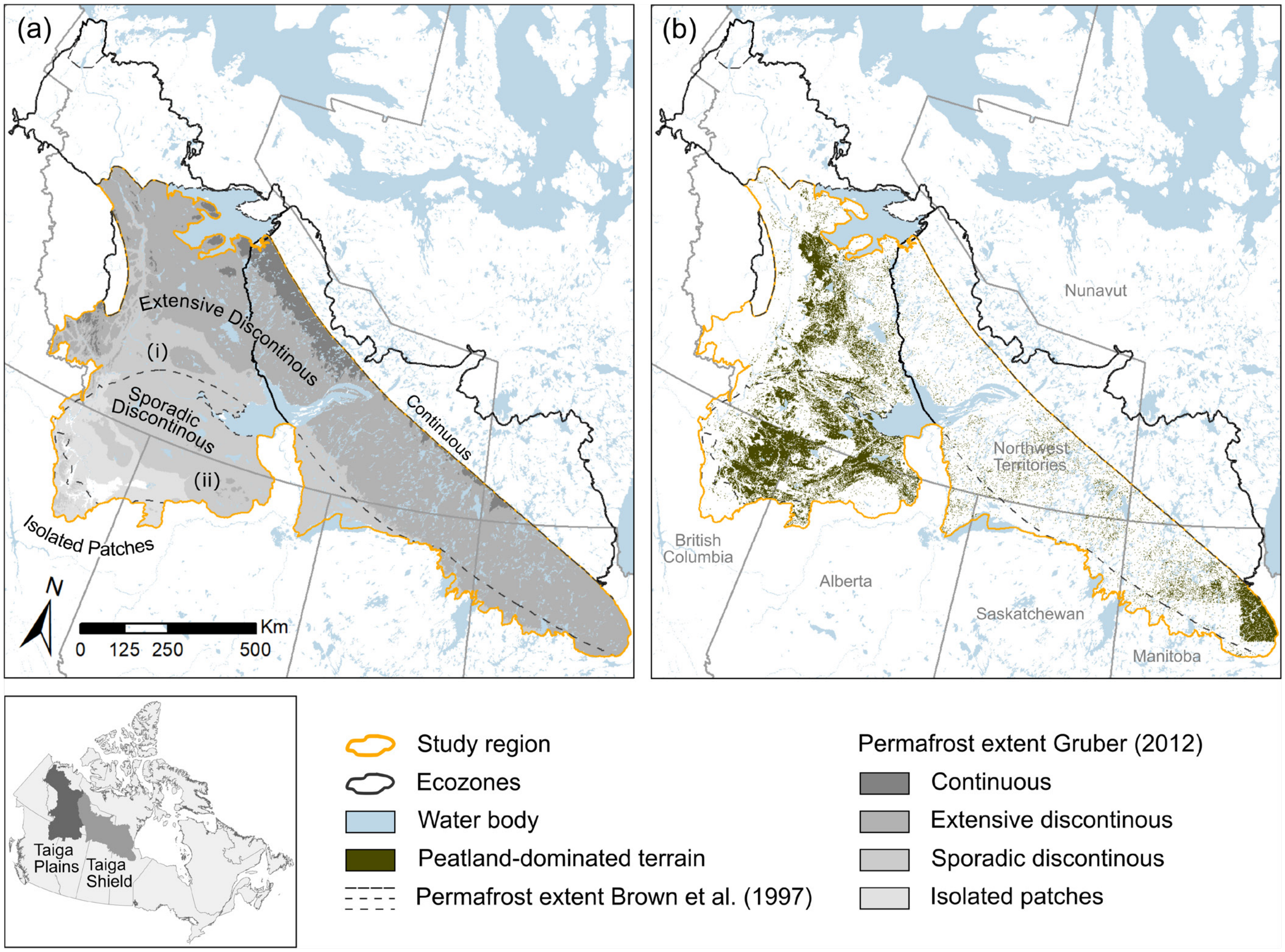


Figure 1. (a) Permafrost extent within the Taiga Plains and Taiga Shield ecozones. The continuous permafrost zone is excluded but includes sporadic (<10% areal coverage), isolated (10-50% areal coverage), and extensive discontinuous permafrost (50-90% areal coverage). Areas of higher elevation typically have higher permafrost extent such as (i) the Horn Plateau and (ii) the Caribou Mountains. (b) Predicted distribution of peatland-dominated terrain in the Taiga Plains and Taiga Shield. Ecozone boundaries are based on the National Ecological Framework for Canada (Ecological Stratification Working Group, 1995). Figure from Wright et al. (2022).

outcrops (Brown 1973; Morse et al. 2016). Reported permafrost thickness ranges from a few meters to 60 m with temperatures between -1.43°C and -0.02°C (Brown 1973; Karunaratne et al. 2008; Morse et al. 2016). Ice content is negligible (0–2%) in bedrock (O'Neill et al. 2019), but horizontal ice lenses (0.1 to 8 cm thick) can be found in frozen fine-grained soils (Johnston et al. 1963). Lithalsas (large permafrost mounds) 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).

## 2.1. Thaw-Induced Landcover Change

### 2.1.1. Peatlands

In the Taiga Plains, permafrost degradation results in a transition from a landscape dominated by forested peat plateaus to one dominated by permafrost-free bogs and fens (Figure 2d,e; Gibson et al. 2020; Quinton et al. 2011a). Early stages of permafrost thaw (Figure 3) form small taliks above the permafrost (Carpino et al. 2021; Connon et al. 2018). Thinning of tree cover or land disturbance over permafrost allows more of the sun's energy to reach the ground, which causes a depression

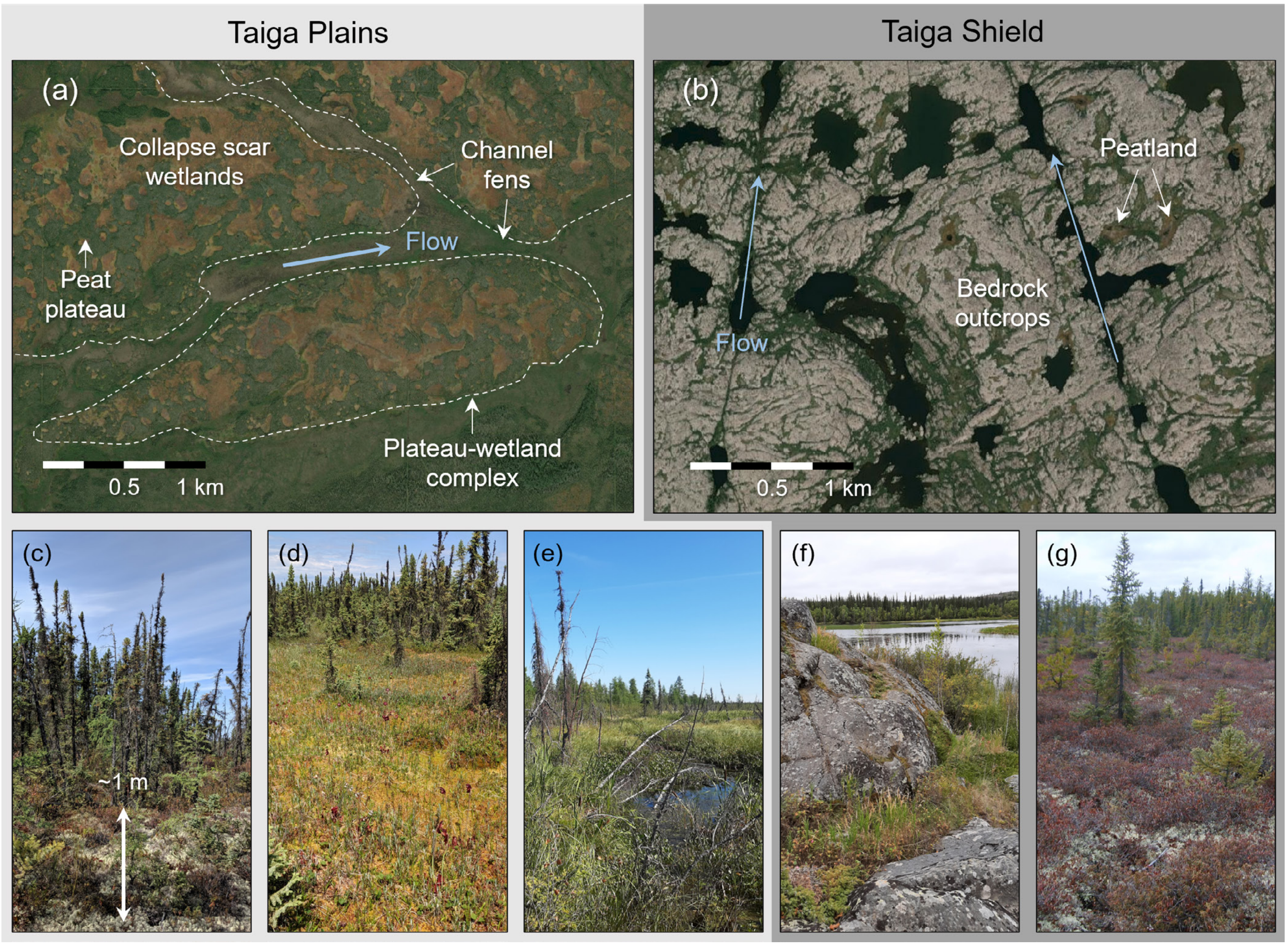


Figure 2. (a) Plateau-wetland complexes in the Taiga Plains. Green areas are intact permafrost-underlain peat plateaus, dark grey areas are permafrost-free runoff-conveying channel fens, and orange/brown areas are permafrost-free collapse scar (thermokarst) bogs. (b) Bedrock uplands and lakes in the 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. Figure modified from Wright et al. (2022).

on the top of the permafrost (Figure 3 II ). Groundwater pools in the depression and the wetter soils lead to further thaw and depression expansion. As this feedback continues, the ground subsides, water pools on land, and trees become waterlogged and die. The result is a complete loss of permafrost and the formation of a collapsed bog (Figure 3 III; Chasmer et al. 2011b; Quinton et al. 2011).

Water held in the wetlands beside the permafrost also enhances permafrost thaw along the edge of plateaus causing wetlands to expand and forested plateaus to shrink. Continued thaw results in further collapse of plateau edges until isolated collapsed bogs coalesce, forming an interconnected network of bogs with peat plateau "islands" (Figure 3 IV; Chasmer & Hopkinson 2017; Connon et al. 2015). 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 (Figure 3 V) that are sufficiently dry to support the growth of black spruce trees (Figure 3 VI) and eventual forest regeneration (Figure 3 VII). Since the timeframe of forest recovery does not depend on the relatively slow process of permafrost aggradation, the trajectory of forest regeneration following permafrost thaw may be on the scale of decades rather than centuries (Carpino et al. 2021).

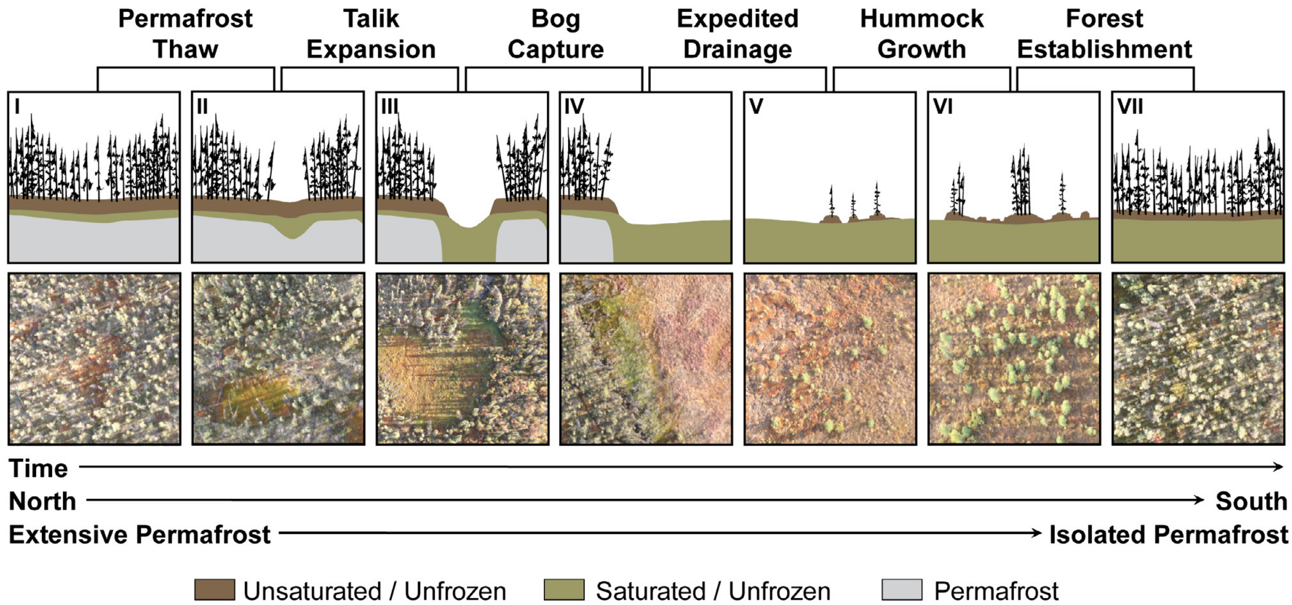


Figure 3. Conceptual framework by Carpino et al. (2021) of landscape trajectory. Satellite images at different locations in the Scotty Creek basin, NT, are used as a proxy for changes in time.

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

### 2.1.2. 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). One of the most dramatic impacts of permafrost thaw on lake extent is catastrophic drainage where entire lakes can drain over 24-hour periods, as seen in northern Yukon (Lantz and Turner 2015) and northern Alaska (Jones and Arp 2015). In contrast, gradual permafrost thaw along shorelines can also lead to lake expansion over decadal timeframes. On a national scale, surface water gains have been observed in the Hay-Zama lakes area, Alberta, and a small reduction in the Kakisa basin, NWT (Taiga Plains) between 2000–2009 (Carroll et al. 2011). No evidence of lake expansion (1950s–2012) was observed in remote sensing and paleo-reconstruction of two lakes in the Kakisa basin, although fen cover had significantly increased (Coleman et al. 2015). This long-term stability contrasts with lake area declines in the Kakisa basin observed by Caroll et al. (2011). As Kokelj and Jorgenson (2013) noted, fen infilling can be a major factor in lake shrinkage and complicate directional detection, which may be a driver for the lakes in the Kakisa basin.

Recent studies of lithalsa permafrost features in the Taiga Shield suggest that lithalsa thaw will expand the surface area of thermokarst ponds (Morse et al., 2019). An inventory of thermokarst ponds in the North Slave Upland and Lowland found that between 1945–2005, 3138 ponds expanded or developed (Morse et al. 2017). However, the surface water area increased in only 3.75 km$^2$ of the 4348 km$^2$ study area due to the thermokarst pond's small size. Ponding was most common in the low elevation glaciolacustrine deposits within the North Slave Lowland (Morse et al. 2017). Remote sensing analysis of net changes in surface water area across Canada between 2000–2009 shows net losses in the Taiga Shield (Carroll et al. 2011), but the drivers of these changes are poorly understood. The relatively short timeframe of assessment leaves uncertainties for longer term changes. A knowledge gap is thus present for the landscape trajectory of the Taiga Shield.

## 2.2. Thaw-Induced Changes to Hydrology

The thaw-induced landcover changes discussed have implications on the routing, storage, and connectivity of surface and subsurface water. Each landcover serves a particular hydrologic function, so when there is a shift away from one cover to another, there is a concurrent change in the hydrologic behavior of a basin. Permafrost thaw can result in changes to the depth of seasonal thaw (active layer), soil moisture, surface water-groundwater connectivity, streamflow discharge, and surface and subsurface water storage. Many thaw-induced hydrologic changes have been observed over recent decades in the Taiga Plains and Shield. However, inadequate baseline and historical data continue to be a challenge in the study region and across the globe. There is a general lack of understanding of large-scale and long-term impacts, particularly in peatlands outside of the Liard River basin in western NT.

### 2.2.1. Evapotranspiration

In the early stages of thaw in permafrost peatlands, black spruce dominate the landcover, so evapotranspiration rates are relatively low due to its low transpiration rates (Warren et al. 2018). At this stage, understory vegetation is the primary contributor to evapotranspiration (Chasmer et al. 2011b). As a result of bog expansion, the basin is covered by a greater proportion of saturated wetland vegetation (including *Sphagnum* mosses). Although mosses are non-vascular their surfaces can experience evaporative losses. This along with growth of vascular plants prior to the establishment of trees may increase evapotranspiration rates (Figure 3 IV, V; Carpino et al. 2021). The hydrologic changes resulting from a full transition to permafrost-free, treed-wetlands remain uncertain and require further investigation. However, under dryer surface conditions and increases in black spruce growth, evapotranspiration rates are likely to decline.

### 2.2.2. Active Layer

Under climate change, increasing surface temperatures drive more heat into the ground, and permafrost thaws from the top down. This thaw can increase the active layer, which is the uppermost layer of ground that freezes and thaws each year. Annual end-of-season thaw depths have significantly increased in the Taiga Plains near Fort Simpson (CALM 2020), at Scotty Creek Research Station (Quinton et al. 2019), and along the banks of Manners Creek (Nixon 2000; Nixon et al. 2003) over the last two decades. In contrast, active layer thickness (ALT) along the Mackenzie Highway in the Hay River basin exhibited little change from 1962 to 2017/2018 except at some locations that had experienced fire (Holloway and Lewkowicz 2020). Here, organic matter layers greater than 50 cm had maintained consistent ALTs at most revisited sites. There is a lack of knowledge regarding the trends in ALT for the Taiga Shield, especially where permafrost exists in bedrock at higher latitudes. It is possible that where thick organic cover coincides with a fine-grained substrate, ALT has remained relatively stable over the past several decades, as observed in the Hay River basin (Holloway and Lewkowicz 2020). Further investigation is required to assess changes in ALT in the Taiga Shield region.

### 2.2.3. Groundwater

Sustained warming can increase the active layer to the point where not all the soil can re-freeze in the winter. This forms a perennially unfrozen layer on top of the permafrost called a supra-permafrost talik. On peat plateaus, permafrost underlying a talik has been found to degrade five times faster than permafrost without a talik, as it limits permafrost cooling in the winter and increases connections to warmer surface water (Connon et al., 2018). Wildfire or land disturbance generally enhances supra-permafrost talik development and permafrost degradation, both in the Taiga Plains (Gibson et al. 2018) and Taiga Shield (Spence et al. 2020). Groundwater can also flow beneath permafrost (sub-permafrost groundwater). The discontinuous nature of permafrost in the study area means an interconnected groundwater system of supra- and sub-permafrost groundwater. In the permafrost peatlands of the Taiga Plains, groundwater flow is predominantly in the thick organic soils as opposed to the underlying low permeability silty clay (Hayashi et al. 2004). In the Precambrian Shield, localized groundwater flow systems can occur through fracture networks and highly conductive fault zones that commonly underlie lakes (Woo 2012).

Permafrost thaw and changing landcover type can reduce shallow sub-surface runoff and increase groundwater recharge and storage (Lamontagne-Hallé et al. 2018; Walvoord and Kurylyk 2016). However, the impacts of permafrost thaw and landcover changes on larger-scale groundwater systems throughout the study region are not well understood. Thaw-induced changes to vegetation influence snow distribution, which impacts snowmelt recharge (Young et al. 2020). Groundwater levels can also be impacted by changes to evapotranspiration rates due to thaw-induced landcover change. For example, as temperatures increase and growing seasons become longer, it is expected that evapotranspiration rates will also increase for both the Taiga Plains and Shield (Bring et al. 2016), which could lower groundwater levels.

The presence of permafrost and associated interaction with groundwater is a considerable knowledge gap for most of the Taiga Plains. In the Mackenzie Valley north of Fort Simpson, permafrost considerably impacts groundwater recharge but does not appear to influence where groundwater discharge occurs (Michel, 1986). In the Liard and Petitot River basins, groundwater monitoring is limited, and no longer-term records are available (Golder Associates 2017). The role of permafrost on the hydrology and hydrogeology of the southern Taiga Shield is largely unknown due to the absence of both permafrost and groundwater monitoring in this region. Morse and Spence (2017) hypothesize that permafrost in the soil-filled bedrock valleys likely reduces groundwater storage capacity and promotes runoff. As permafrost thaws in valleys under warming conditions, groundwater recharge and storage will likely increase. Flow may also occur through taliks below lakes, but the configuration of these taliks is not well documented. Thawing would lead to groundwater flow reactivation through deep fracture networks and fault zones (Morse and Spence 2017; Rouse 2000). However, evidence for this is lacking, and the resulting changes to larger-scale basin behaviour are unknown.

### 2.2.4. Icings

Groundwater discharging through taliks along river and stream banks in winter can result in riverine icings (Woo 2012), which are sheet-like masses of layered ice. Ground icings along roadways can damage roadways and block culverts, leading to flooding during melt events. The formation of icings alters the seasonal water balance of a basin by storing streamflow as ice and slowly releasing it in later seasons (Reedyk et al. 2011). Since river baseflow (groundwater discharge) is the primary source of water for riverine icings (Crites et al. 2020), expansion of taliks may increase riverine icing occurrence. However, icing occurrence is closely related to low winter air temperatures and the presence of frozen ground (Crites et al. 2020; Ensom et al. 2020). Thus, as winter air temperatures continue to increase and permafrost further degrades, icing occurrence may also decline. Icing investigations in the Taiga Plains have been limited to higher latitudes of the study region with a limited assessment of icing trends (Crites et al. 2020; Glass et al. 2021; Reedyk et al. 2011). The influence of changing baseflows on riverine icing development remains a knowledge gap for the Taiga Plains study region.

In the subarctic Taiga 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 (Morse and Wolfe 2017). At present, the highest icing density is associated with highly fractured bedrock in the Shield that is likely permafrost-free (Morse and Wolfe 2015), suggesting icing occurrence could increase as permafrost thaws, and basins become more hydrologically connected (Spence et al. 2020; Spence et al. 2014). Long-term changes in icings in the Taiga Shield are highly uncertain (Morse and Wolfe 2017, 2015). Both in the Taiga Plains and Shield, the occurrence of ground icings may increase as northern development expands and roadway culverts, cut slopes, and built structures impede the natural flow of water (Woo 2012). Additionally, sustained permafrost thaw may open new pathways for sub-permafrost to discharge to surface and expand ground icing occurrence.

### 2.2.5. Lakes

Thaw-driven lake decline or lake expansion impacts water storage, routing, and landscape connectivity. Lake expansion can contribute to the toppling of trees, vegetation, and soil erosion on shorelines, impacting water quality, and lateral subsurface thaw beneath the shoreline can accelerate shoreline collapse and permafrost degradation (Kokelj et al. 2009). Lake drainage has been associated with decreased surface water storage, where subsurface flow paths are enhanced at the expense of surface waters (Karlsson et al. 2012). In contrast, lake expansion may increase surface water storage and reflect enhanced groundwater recharge (Walvoord and Kurylyk 2016). Permafrost thaw in boreal Alberta was shown to influence lake runoff (Gibson et al. 2015). Higher runoff was generated from permafrost thaw-influenced lakes in the Caribou Mountains relative to lower elevation sites with lesser peatland/permafrost influence. However, this response may wane in the late stages of permafrost thaw.

The high population of lakes in the Taiga Shield can attenuate surface runoff such that streamflow responses from spring freshet or storm events are delayed (Morse and Spence 2017). Due to the fill-spill process that controls basin runoff, increases in the storage capacity of soil-filled bedrock valleys could mean less water contributes to basin runoff and, therefore, lake inflow (Morse and Spence 2017). The volume of water from melting ice in permafrost is unlikely to dramatically affect lake levels due to the relatively low ice content in the Taiga Shield (Spence et al. 2014). However, water routing and storage changes resulting from permafrost thaw may affect the network of lakes in the Taiga Shield. As open taliks develop beneath lakes, lake levels may decline, connecting surface water to deeper flow systems (Walvoord and Kurylyk 2016). Thaw-enhanced subsurface water flow beneath lakes in the Taiga Shield could explain the declines in lake levels observed by Carroll et al. (2011), but the configuration of taliks in this area is unknown.

### 2.2.6. Streamflow and Winter Baseflow

Increases in streamflow have been observed throughout the study region. For example, the Trout, Birch, Martin, and Jean-Marie Rivers have all significantly increased between 1978 and 2017 (Figure 4). The drivers of increased streamflow vary by region and landcover but have been correlated to increasing air temperatures (Peterson et al. 2002). Three explanations for increasing streamflow in discontinuous permafrost terrain under climate warming have been proposed in the literature as follows:

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

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

iii. **Thaw-induced land cover changes:** For the permafrost peatlands of the lower Liard River Valley, liquid water inputs from thawing permafrost and subsurface reactivation could not fully explain the increases in runoff (Connon et al. 2014), and precipitation did not significantly increase. Instead, the explanation for rising streamflow is that thaw-induced landcover changes are altering the basin runoff dynamics. In the early stages of peat plateau permafrost thaw (Figure 3 I, II), the majority of collapse bogs are disconnected from the hydrologic network by relatively impermeable permafrost (Carpino et al. 2021; Connon et al. 2014). As permafrost continues to thaw, landcovers become increasingly connected to the drainage network, allowing water from precipitation and snowmelt to reach the basin outlet and increase streamflow. The low permeability of the underlying silty clay may be why thaw-activated groundwater flow was not a dominating factor in streamflow rise in this setting compared to others (Kurylyk and Walvoord 2021). However, the cumulative effects of landcover change and subsurface reactivation on streamflow and how this varies across landscapes require additional investigation to predict hydrologic change across the region.

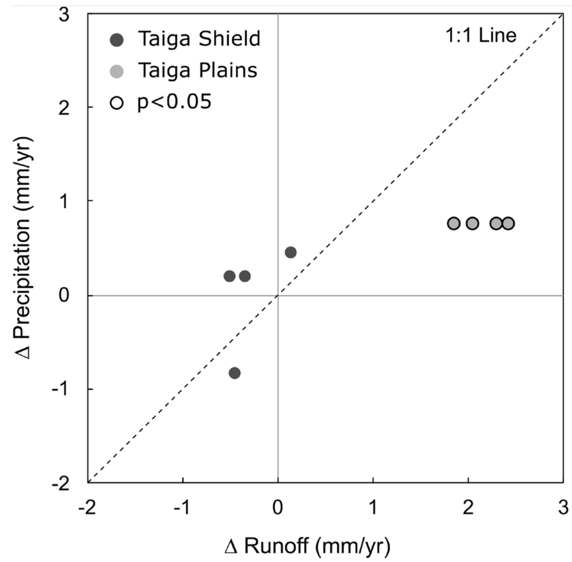


Figure 4. Changes in annual precipitation versus changes in runoff between 1978 and 2017 for basins in the Taiga Plains and Taiga Shield with similar proportions of permafrost coverage. The 1:1 line indicates where a unit change in precipitation will result in an equal unit change in runoff. Plotting off the line, like the basins shown in the Taiga Plains, suggest other factors like thaw-induced landcover change are altering runoff patterns. No change in precipitation was statistically significant. Figure from Wright et al. (2022).

Evidence for landcover change driving rises in streamflow is supported by runoff ratios in the Liard River valley. Figure 4 illustrates that, despite non-significant changes in annual precipitation between 1978 and 2017, annual runoff significantly increased for basins in the Taiga Plains underlain by permafrost. However, changes in annual runoff were not observed for basins in the Taiga Shield with similar proportions of permafrost, likely due to limited thaw-induced landcover changes associated with the bedrock-dominated terrain. Future thaw-induced impacts to streamflow in the Taiga Shield are possible and may be tied to declines in permafrost extent in soil-filled bedrock valleys that could increase subsurface storage (Morse and Spence 2017). Due to the fill-and-spill drainage pattern of the Shield environment (Spence and Woo 2003), higher storage capacity would need to be met before downstream flow and connectivity could occur (Morse and Spence 2017). Increased subsurface storage may lead to more intermittent flows and delayed streamflow responses to spring freshet or large summer rainfall events.

# 3. Summary

In the Taiga Plains, the predominant permafrost landform is forested peat plateaus, under which ice-rich permafrost is present (Figure 5a, left). Forested uplands with insulating mosses may also be underlain with permafrost. Permafrost maps at local and regional scales are needed for improved community decision making and planning. Wildfire, human development, and increasing air temperatures are triggers for permafrost thaw (Figure 5a-i). As ice-rich permafrost thaws, the land surface subsides, and the dry plateaus are replaced with waterlogged collapse bogs and fens (Figure 5b-iii). This process may be accelerated by the development of supra-permafrost taliks, which are enhanced beneath human or natural disturbances like wildfire (Figure 5b-ix). While the collapse bogs may initially be disconnected from other wetlands and temporarily increase groundwater storage, continued development of collapse wetlands and the expansion of channel fens that act as conduits for flow results in a higher runoff-producing landcover (Figure 5b-xii). Subsurface connectivity and groundwater flow will likely increase and may contribute to increased annual and winter flows in rivers. Over time, collapse bogs may develop elevated hummocks with dry enough conditions to support the re-growth of black spruce (Figure 5b-iv), but this afforestation will most likely not support the regeneration of permafrost.

In the Taiga Shield, the ice-poor permafrost in the fractured Precambrian bedrock is most commonly in valleys filled with fine-grained soils (silts and clays) or peatland (Figure 5a, right). Limited permafrost mapping has been conducted throughout the Taiga Shield and should be conducted at scales relevant to community planning. As permafrost thaws, landcover changes may be limited to the peat plateaus that cover 5–10% of the region (Figure 5b-iii), pond development from thawing lithalsas, or altered lake extent (Figure 5b-vi). Permafrost thaw beneath lakes may initiate lake drainage along high permeability fracture networks or faults, leading to lake shrinkage and increased sub-permafrost groundwater recharge (Figure 5b-vii). Alternatively, increased inflow from thaw upslope may result in lake expansion. Wildfire, land disturbance, or temperature increases can expand supra-permafrost taliks (Figure 5b-ix) and increase winter baseflows and icing development (Figure 5b-xii). Reduced permafrost in soil-filled valleys can also increase basin storage (Figure 5b-xi) and may lead to changes in runoff patterns.

The impacts of permafrost thaw on groundwater systems remain highly uncertain across the Taiga Plains and Shield and should be a focus of future research. In particular, permafrost and groundwater interactions have received limited attention in the Taiga Shield. Thaw-induced changes to sub-permafrost groundwater systems and the integration of groundwater into surface water are also poorly understood. Additional uncertainties include the impacts of thawing permafrost peatlands on surrounding groundwater systems in various landscapes. It is recommended that a groundwater monitoring network be established in diverse landscapes across the Taiga Plains and Shield to better understand how groundwater systems are changing under climate change and due to permafrost thaw.

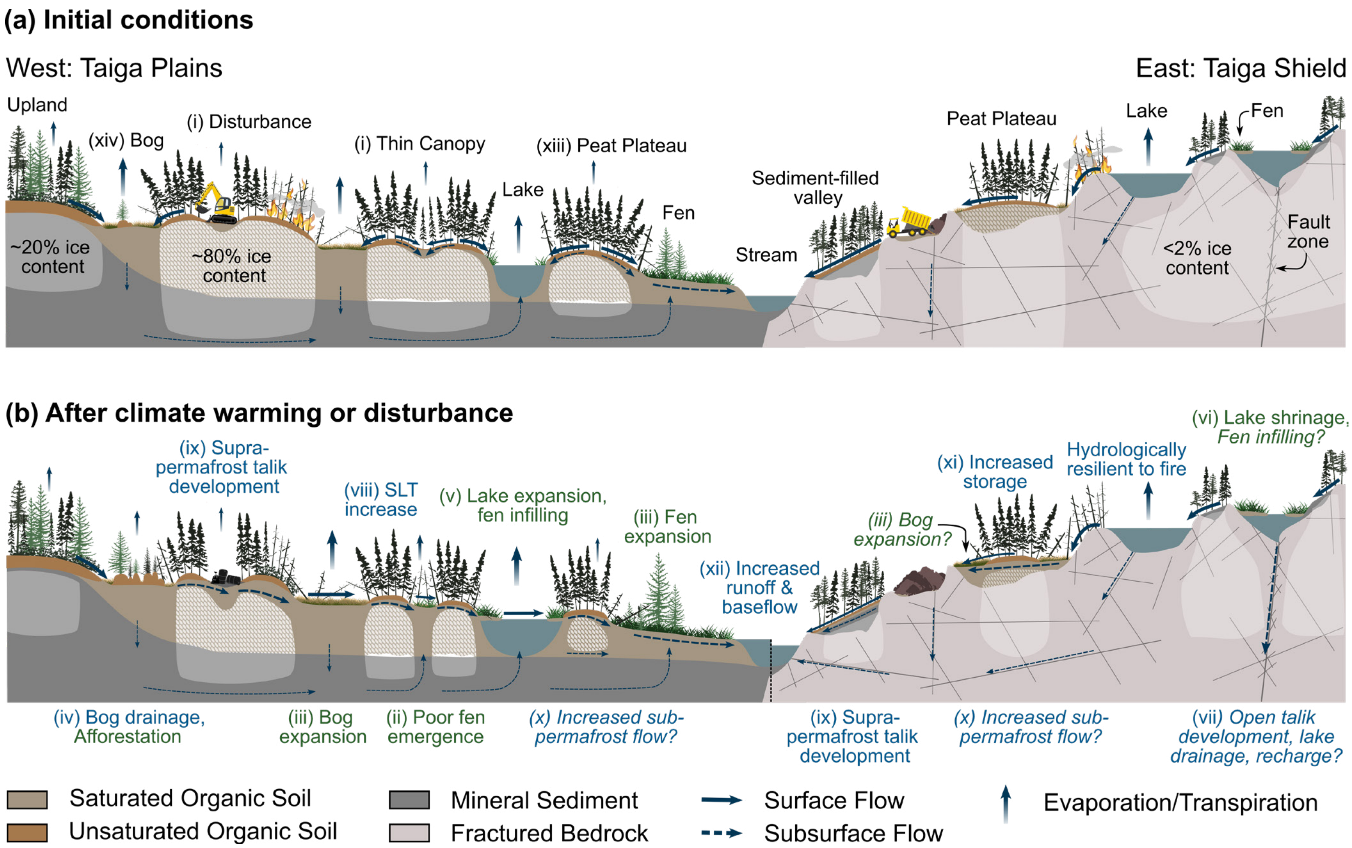


Figure 5. (a) Initial conditions for a conceptual cross-section from the peatland-dominated Taiga Plains in the west to the bedrock/lake-dominated Taiga Shield in the east. The thickness of blue arrows indicates the relative magnitude of hydrologic fluxes. (b) Permafrost conditions and resulting changes 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. Figure from Wright et al. (2022).

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# PART 5

## Permafrost Thaw-induced Impacts on Water Quality in the Taiga Plains and Taiga Shield - Part II

Photo: Phillip Meintzer & Dene Tha' First Nation

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# Abstract

Widespread landscape change initiated by permafrost thaw in the extensive peatlands of the Taiga Plains has cascading impacts on water quality as drier, intact peat plateaus collapse into waterlogged fens and bogs. The release of previously frozen materials (e.g., organic matter, nutrients, metals, and point-source anthropogenic contaminants) in combination with changes to environmental conditions and hydrological connectivity has led to emergent research fields examining aspects of ecosystem health, drinking water quality, and toxicity of country foods.

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

Anoxic conditions in thermokarst wetlands that develop post-thaw may be hotspots for the production of methylmercury. However, it is unknown how much these hotspots will contribute to the overall basin delivery of methylmercury and to what degree it can be expected to affect the biomagnification of mercury in downstream food webs. Downstream delivery of other metals

bound to organic compounds are also likely to increase from thawing peatlands (e.g., iron, selenium, and lead). Overall, the influence of permafrost thaw in peatlands on downstream water quality is still poorly understood, both with regards to the magnitude of change and to what degree these impacts might be attenuated within larger rivers and basins with longer water residence times.

While there is a continued need for long-term monitoring of large rivers, smaller sub-basins with large peatland extents should be considered for long-term monitoring, as well as site-level research into processes that may help predict future changes. A key knowledge gap is potential changes to groundwater quality as subsurface hydrological pathways expand due to permafrost thaw in peatlands. While many processes can be inferred from research in other regions, specific regional characteristics may modify the response, and thus, predictions should be based on research carried out within the region.

Relevant links: Thaw-induced impacts on land and water in discontinuous permafrost: A review of the Taiga Plains and Taiga Shield, northwestern Canada; The Dehcho Collaborative on Permafrost informational video

# Recommendations

- Expanded monitoring of groundwater quality in the Northwest Territories and northern Alberta
- Examination of linkages between permafrost thaw and persistent organic pollutants in the region
- Broad focus on water quality studies in the Taiga Shield region
- Addition of methylmercury as a regularly sampled parameter in water quality monitoring programs
- Continuous examination of long-term water quality trends of major rivers draining the Mackenzie Basin

# 1. Introduction

Permafrost thaw in northern Canada has cascading impacts on landcover, hydrology, and water quality that may alter drinking water quality and ecosystem health, including contaminants in country food such as freshwater fish and marine animals. Rapid warming, enhanced wildfire activity, and anthropogenic disturbance has resulted in widespread permafrost thaw in the southern fringe of the discontinuous permafrost, which is highly sensitive to disturbance or slight increases in temperature (Figure 1; Quinton et al. 2009). Peatlands, which are widespread in the southern Mackenzie River basin, are the most southern refuge of frozen ground due to the insulating quality of peat. Still, landscape collapse in peatlands due to permafrost thaw is extensive and results in the expansion of lakes, waterlogged bogs, and fens (Gibson et al. 2021; Zoltai 1993). In addition, hydrologic connectivity is enhanced on the surface of the landscape and in subsurface groundwater pathways (Connon et al. 2014), providing potential for increased downstream transport of organic matter, nutrients, metals, and point-source anthropogenic contaminants previously frozen in permafrost (Burd et al. 2018; Gordon et al. 2016; Miner et al. 2021; Olefeldt et al. 2014).

This chapter synthesizes studies of water quality in waters of the southern Mackenzie Basin, focusing on the Taiga Plains and Taiga Shield ecozones. The Taiga Plains are peatland-dominated, covering nearly half of the total area (Ecosystem Classification Group 2007), while the Taiga Shield is characterized by Precambrian bedrock uplands and valleys with lakes (25% of the area) or peatlands (less than 5% of the area) (Ecosystem Classification Group 2008). Further details on permafrost thaw processes and impacts on hydrology are highlighted in (link to Part I). Where data gaps exist, studies from external, peatland-rich regions such as the Western Siberian Lowlands or Fennoscandia are drawn on.


Figure 1: Permafrost peatlands, M'behcho (Bistcho Lake), Alberta.

# 2. Physical Parameters

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

The acidic or basic properties of water are measured through pH. Pure water has a neutral pH of 7, with lower values for acidic waters and higher for basic. pH influences the solubility and uptake by organisms (bioavailability) of chemical constituents such as nutrients and metals (Hassan Omer 2020). While peatlands are typically characterized as acidic environments, nutrient-poor peatlands (e.g., bogs and peat plateaus) have a substantially lower pH than nutrient-rich fens (bogs: 3.5 – 4.5, fens: 5.5 – 7.5; Urban et al. 1989); landscape transition from peat plateaus to richer wetlands such as fens corresponds to increasing pH trends. Indeed, an increasing pH pattern was observed in the Western Siberian Lowlands (Frey et al. 2007; Pokrovsky et al. 2015), where decreasing permafrost extent corresponded to less acidic surface waters, attributed to the buffering effect of carbonate bedrock and increased groundwater connection. A similar latitudinal pattern was observed in lakes and streams of the Taiga Plains (Figure 2a).

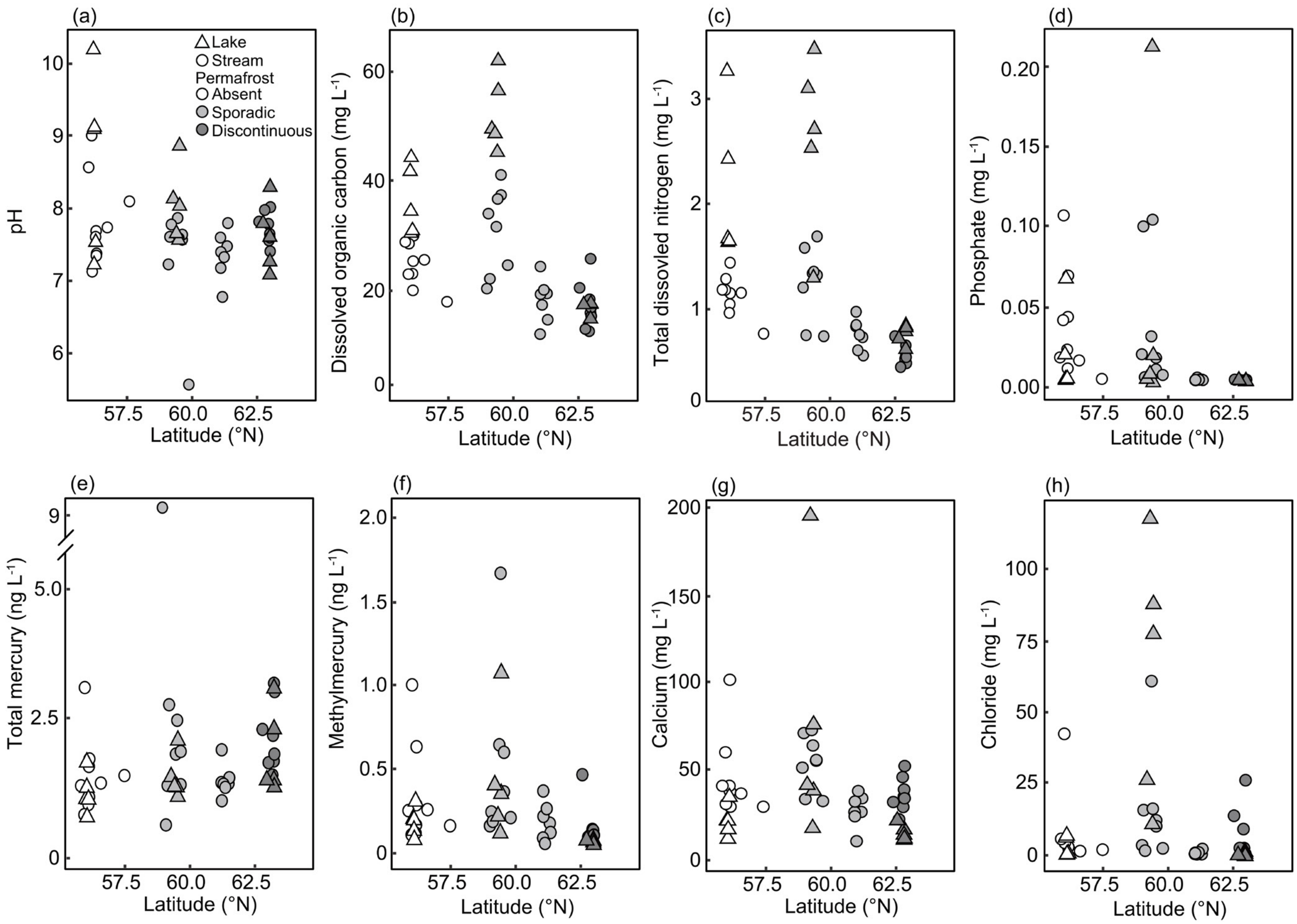


Figure 2: Water chemistry variables as a function of latitude for streams and small lakes within the Boreal Plains and Taiga Plains of Alberta and the Northwest Territories, including (a) pH, (b) dissolved organic carbon, (c) total dissolved nitrogen, (d) phosphate, (e) total mercury, (f) methylmercury, (g) calcium, and (h) chloride (data from Thompson & Olefeldt, 2020, figure from Wright et al. (2022).

Specific conductance measures the ability of electricity to be conducted through the water. As conductivity is influenced by connection with mineral sediment, groundwater connectivity can be indicated by conductance. Dissolved salts sourced primarily from weathering processes, including calcium, magnesium, sodium, and potassium, contribute to the specific conductivity. Lakes and rivers typically range from 50 to about 1500 µS cm$^{-1}$ (McNeely et al. 1979). Minerotrophic land covers which receive water inflow and nutrients from groundwater and those that convey water, like channel fens, have higher conductivity (Hayashi et al. 2004; Olefeldt and Roulet 2012). As basins become more hydrologically connected and groundwater contributions increase with permafrost thaw, conductivity is predicted to increase (Frey and McClelland 2009).

Total suspended solids (TSS) is a measurement of solid material per volume of water, an important parameter influenced by erosion, either natural or driven by human activities (CCME 1999). Phosphorus, metals, and organic matter can adsorb to suspended solids; thus, higher TSS concentrations may correspond to higher concentrations of those parameters. However, parameters adsorbed to particulates are typically less bioavailable. High quantities of suspended materials increase water treatment costs and can damage fish gills, decreasing disease resistance and reducing growth rates (Hassan Omer 2020). TSS generally increases with river size and river flow. Higher flows allow for greater river sediment suspension and erosion, but TSS concentrations further vary between basins based on landscape characteristics such as slope and landcover (Meybeck et al. 2003). In regions affected by permafrost thaw slumps (e.g., the Peel Plateau), the debris that flows from thawed hillslopes can increase downstream suspended sediment loads by several orders of magnitude (Kokelj et al. 2013). Hillslope thermokarst coverage is minimal in the Taiga Plains and Shield (Olefeldt et al. 2016), and permafrost thaw in peatlands has not been associated with increased particulate loads (Krickov et al. 2020), although increased runoff and intensity of peak flows (See Part 1) could potentially increase sediment transfer and turbidity, such as from bank abrasion and resuspension of channel sediment stores (Krickov et al. 2020).

# 3. Organic Matter

Dissolved organic matter (DOM) is a complex mixture of organic compounds produced both external to surface waters in soil organic layers, vegetation canopy, and litter (Moore 2013) and internally within rivers and lakes through primary productivity (Rautio et al. 2011). DOM contains carbon (dissolved organic carbon or DOC) but also dissolved organic nitrogen (DON) and phosphorus (DOP) (Moore 2013). High concentrations of DOM result in dark, tea-like brown waters (e.g., Figure 3).


Figure 3: High dissolved organic matter concentrations in Sambaa Deh (Trout River), Northwest Territories.

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

Permafrost presence and peatland cover are important controls on DOC concentrations. A survey of rivers in northern Alberta and southern Northwest Territories found DOC concentrations increased with basin peatland cover but were consistently lower north of the permafrost boundary (Olefeldt et al. 2014), with similar findings in the Western Siberian lowlands (Frey and Smith 2005). In addition, concentrations of DOC in peatland lakes and streams across the Taiga Plains were consistently higher in sporadic and permafrost-free regions compared to more northern sites with greater permafrost extent (Figure 2b). These findings suggest increased DOC concentrations and export may result from continued permafrost thaw in the region.

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), catchment export was only modestly higher in a burned site compared to a paired unburned catchment (Burd et al. 2018). In 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). 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, deepened groundwater flow paths from thaw have resulted in decreases of DOC in basins in Alaska (Douglas et al. 2013; Petrone et al. 2006) and Yukon (Shatilla and Carey 2019) as mineral soil can readily adsorb DOC (Kothawala et al. 2012). Groundwater influence (inferred from electrical conductivity) in northern Sweden was related to lower DOC concentrations and aromatic quality relative to peatland sources, where groundwater contributions increased in wetter years (Olefeldt and Roulet 2012). While long-term carbon export has increased in the peatland-influenced Mackenzie River (Tank et al. 2016), carbon export has decreased in the Yukon River, attributed to increasing groundwater connections that deliver less DOC (Walvoord and Striegl 2007).

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

# 4. Nutrients

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

Permafrost has been shown to influence nutrient concentrations. For example, lakes and rivers in Taiga Plains showed the highest dissolved nitrogen and phosphate in permafrost-free and sporadic permafrost zones relative to discontinuous and continuous permafrost (Figure 2c-d). Likewise, particulate nitrogen in the Western Siberian Lowlands rivers had the highest concentrations and fluxes in the sporadic and discontinuous permafrost, attributed to thawing, deeper peat soils (Krickov et al. 2018). Extractions from permafrost peatland soils in northern Sweden showed that thawing peatlands mobilized high quantities of nitrogen. The remobilized nitrogen was suggested to be preferentially taken up by plants rather than delivered to downstream environments (Keuper et al. 2012). However, downstream delivery of inorganic phosphorus 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 follow a similar pattern.

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 phosphorus yields from the burned catchment, with limited effects on nitrogen forms (Burd et al. 2018). Both nitrogen and phosphorus 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). 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). 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.

# 5. Mercury

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

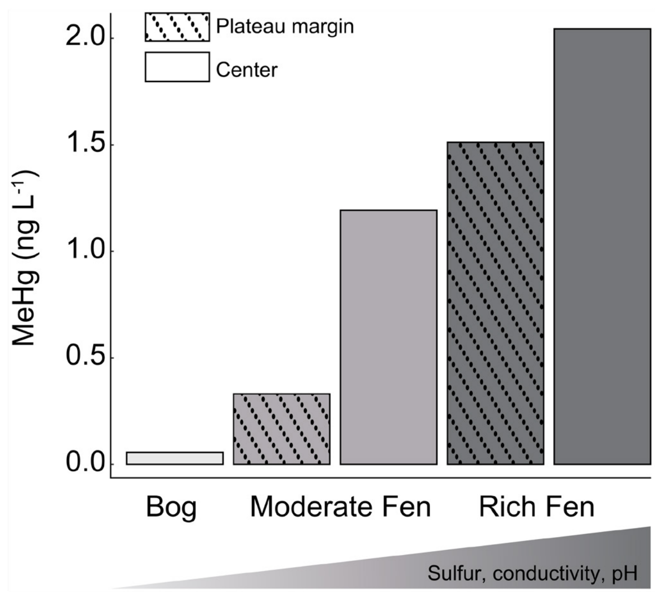


Figure 4. Barplot of methylmercury (MeHg) concentrations in permafrost-free wetlands draining to the Hay River, AB/NWT, where concentrations increased with wetland trophic status (L. Thompson, unpublished data, figure from Wright et al. (2022).

Methylmercury 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 and 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 southern Mackenzie Basin do not include methylmercury as a regularly sampled parameter.

Permafrost thaw and the development of thermokarst wetlands have been shown to create hotspots of methylmercury production. However, it is unclear whether these hotspots can influence concentrations and fluxes at the basin level. The production of methylmercury (methylation of inorganic mercury) is tied to the microbial community structure, dissolved organic matter quantity and quality, mercury bioavailability, and the abundance of electron receptors (Bravo and Cosio 2020). The nutrient-rich environment of thaw fens was more productive for methylation than nutrient-poor thaw bogs in Sweden (Fahnestock et al. 2019), Alaska (Poulin et al. 2019), Scotty Creek research site in the

Liard basin (Gordon et al. 2016), and peatlands draining to the Hay River (Figure 4). Methylmercury and total mercury concentrations were not elevated in the rapidly thawing sporadic and discontinuous permafrost regions in a survey of Taiga Plains rivers and lakes relative to continuous permafrost zones (Figure 2e-f). However, peatlands and DOC were key drivers for methylmercury concentrations (Thompson et al., 2023).

Thermokarst peatland lakes release mercury and carbon (Klaminder et al. 2008; Korosi et al. 2015), and organic-rich ponds have been recognized as sites with high sediment mercury methylation in High Arctic (Lehnherr et al. 2012; MacMillan et al.,2015; St. Louis et al. 2005). In the Northwest Territories, small lakes in peat-rich areas had high DOM and methylmercury concentrations (Evans et al. 2005), suggesting higher methylmercury production within the lake sediments. However, DOM may be a primary vector of methylmercury from external sources such as wetlands to lakes (Branfireun et al. 2020; Bravo et al. 2017). This model was observed in small peatland lakes across the Taiga Plains, where trends in water chemistry suggested that methylmercury was predominantly sourced from surrounding fens (Thompson et al. 2023). While peatland lakes may not be sites of high methylmercury production, they will likely receive increased inputs of mercury forms as permafrost thaw advances and landscapes shift to thermokarst wetlands.

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

## 5.1. Other Metals

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

## 5.2. Point Source Contaminants

In the Taiga Plains and Taiga Shield, Indigenous communities have reported degraded water quality and expressed concern about water contamination from landfills, oil and gas facilities, and mine tailings relating to permafrost thaw (Christensen, 2015; Guyot et al., 2006; Mackenzie River Basin Board, 2021; Parlee & 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). 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). Additional field investigations of point source contaminants like waste sites and lagoons are needed to support model development and assess the risk to drinking water supplies from waste facilities.

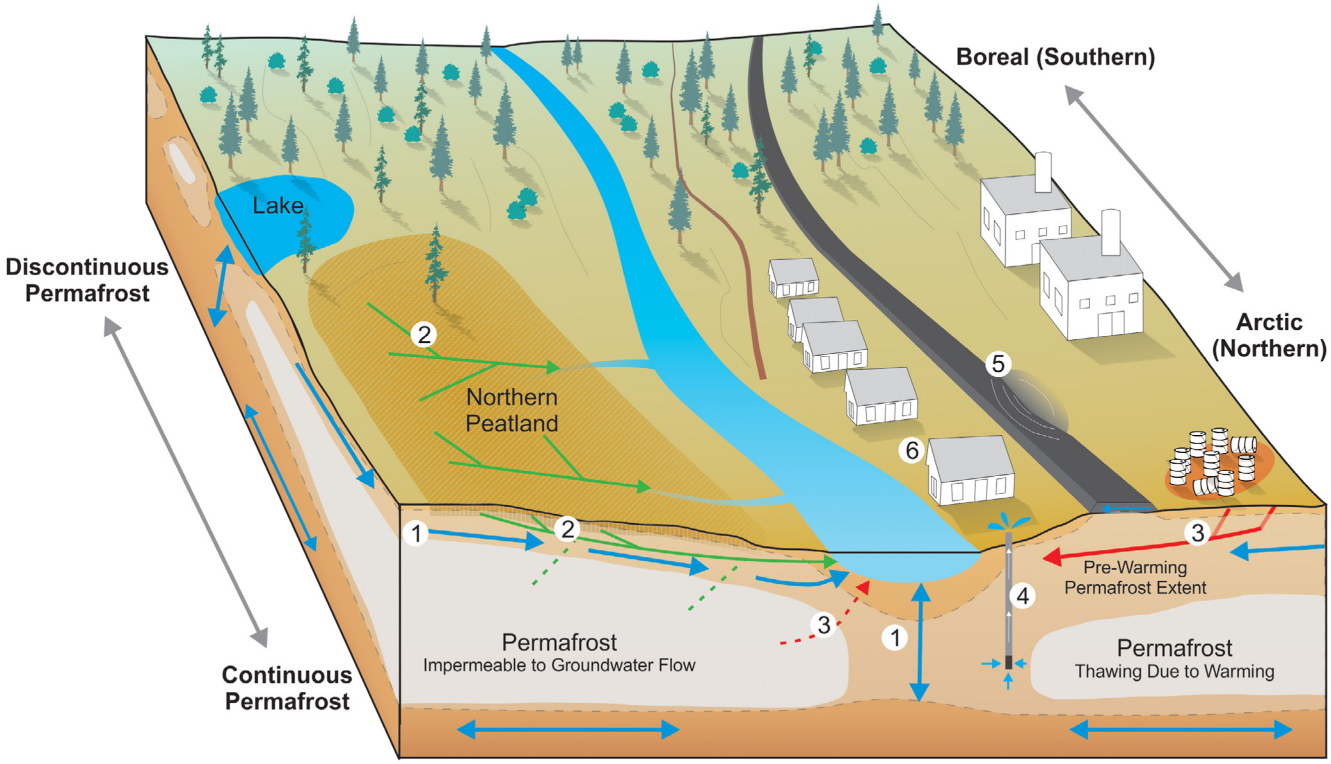


Figure 5. Pathways for groundwater to catalyse environmental change in the Arctic (McKenzie et al., 2021). (1) Arctic warming and permafrost thaw promote increased flux, circulation, and connectivity of groundwater above and below permafrost. (2) Groundwater transports carbon and nutrients from terrestrial to aquatic environments via progressively deeper subsurface flow paths with top-down permafrost thaw (green arrows). Permafrost carbon may be mobilized in the aqueous phase upon thaw and transported to inland waters (dashed green lines and arrows). (3) As permafrost thaws, there are opportunities for increased transport of contaminants (e.g. industrial waste, sewage) due to enhanced groundwater flow (red arrows). Sequestered contaminants, such as pathogens or mercury, are released as permafrost thaws and transported via groundwater flow (dashed red arrow). (4) Water resources will change as permafrost thaws, including increased potential for groundwater development. (5) Groundwater flow can enhance permafrost thaw rates, leading to land subsidence and destruction of surface infrastructure such as roads or buildings. (6) The incorporation of cryohydrogeology in planning for northern communities and future economic development would enhance resiliency in the face of environmental changes. Figure from McKenzie et al. (2021).

Mining operations in the region are extensive and include extraction of diamond, gold, lead, zinc, and silver (Silke 2009). Throughout NWT, previously operational mines have a legacy of contaminants that interact with ongoing permafrost thaw. Hydrocarbons have been detected in groundwater around the abandoned Colomac mine due to fuel spills; ongoing thaw may increase the range of contaminant flow (Iwakun et al. 2008). During the operation of the Giant Mine (1948-2004), in close proximity to Yellowknife, NWT, arsenic trioxide ($As_2O_3$) dust from gold ore roasting was collected underground under the assumption that permafrost would contain the carcinogen (Jamieson 2014; O'Reilly 2015). As permafrost has degraded from mine workings, a system to artificially maintain frozen ground conditions is required (Jamieson 2014) while the underground chambers remain a source of arsenic into groundwater (Jamieson et al. 2013).

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

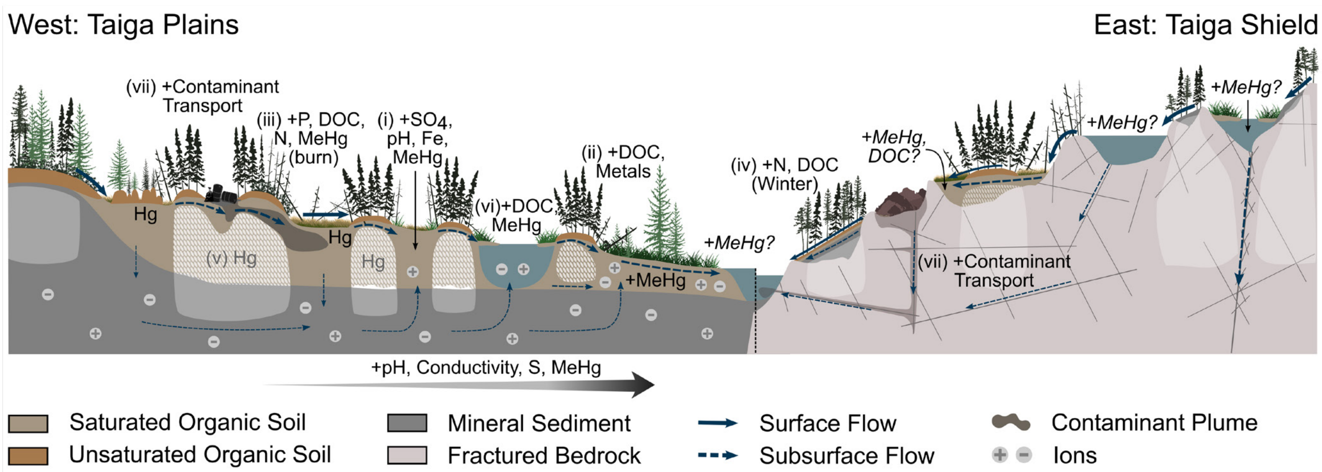


Figure 6. Conceptual cross-section of the impacts to water quality in the Taiga Plains and Taiga Shield following progressive permafrost thaw from climate warming and/or land disturbance. Refer to Part I for initial permafrost conditions and landcover descriptions. The '+' before text indicates an increase 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. Figure from Wright et al. (2022).

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 Mansou, 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 Consulting Ltd. 2016).

## 5.3. Groundwater Biogeochemistry

The activation of groundwater systems as permafrost thaws poses new risks to high latitude water quantity and quality (McKenzie et al. 2021). Our understanding of Arctic and sub-Arctic hydrology is almost entirely based on surface water observations, but new subsurface pathways activated through thaw often drive surface processes (IPCC 2019; McKenzie et al. 2021). Groundwater knowledge in the southern Mackenzie Basin is largely deficient (Golder Associates 2017; VanGluck 2016), although groundwater quality in the discontinuous permafrost region of western NWT has been described as "of good quality" (Michel et al. 2014). Few studies have measured groundwater biogeochemistry and instead make inferences based on surface waters or spring discharge locations (Michel et al., 2014). For example, high ion concentrations in lakes and rivers of the Taiga Plains (Figure 2g-h) indicate that surface-groundwater connectivity may be currently high in sporadic and discontinuous permafrost regions.

Predicted impacts of permafrost thaw include increased groundwater recharge from runoff, increased area and flow of groundwater discharge to surface waters, and increased surface water-groundwater mixing (Golder Associates 2017; Michel et al. 2014). Increased groundwater discharge and mixing with surface waters may increase conductivity and major ion concentrations (Frey and McClelland 2009). In addition, as the delivery of electron receptors such as iron and sulfate increases with groundwater connectivity, a consequence may be the enhanced methylmercury production (e.g., through iron- and sulfate-reducing bacteria) and thus increased concentrations of methylmercury (Gordon et al., 2016).

McKenzie et al. (2021) noted that northern field programs that address subsurface knowledge gaps are required. Future-facing water management strategies must see groundwater as a potential water resource, an accelerator of landscape change, and a driver of infrastructure damage and water pollution (Figure 5; McKenzie et al. 2021). In areas where groundwater quality is at risk, baseline knowledge of groundwater quality is critical. Many groundwater quality studies are concentrated in the western Canadian Arctic and Alaska and are lacking in peatland-dominated basins (Cochand et al. 2019).

## 5.4. Summary

Potential shifts in physical parameters as thaw advances may include increasing pH and conductivity, while total suspended solids load is unlikely to change because of thaw (Figure 6i). Concentrations of DOC are expected to increase as permafrost thaws in peatland-dominated basins, and some pulses of aged carbon have been observed in the Taiga Plains (Figure 6ii, Figure 6iv). Likewise, increased concentrations of nutrients may be expected as permafrost thaws and wildfire incidence increase (Figure 6iii). However, latitudinal observations of DOC and nutrients (Figure 2) show peak concentrations in the permafrost-free and sporadic permafrost zones; greater increases may be expected in the discontinuous and continuous permafrost zones. Permafrost thaw has additionally been shown to increase the production of methylmercury in wetlands within and external to the transboundary region (Figure 6vi), potentially mobilizing mercury released from permafrost stores (Figure 6v), although elevated concentrations have not been detected in downstream lakes and streams at the permafrost thawing front of the Taiga Plains. Still, increased methylmercury concentrations may be expected as thaw continues, alongside mobilization of other metals bound to organic matter. Therefore, including methylmercury as a parameter in long-term monitoring programs is highly recommended. Expanded groundwater quality monitoring in the region should be implemented as data availability was severely limited. However, the most significant impacts on groundwater are likely within regions transitioning from continuous to discontinuous permafrost. Further focus on linkages between permafrost thaw and mobilization of anthropogenic, point source contaminants such as mine tailings or sewage is an additional area of interest for northern communities (Figure 6vii).

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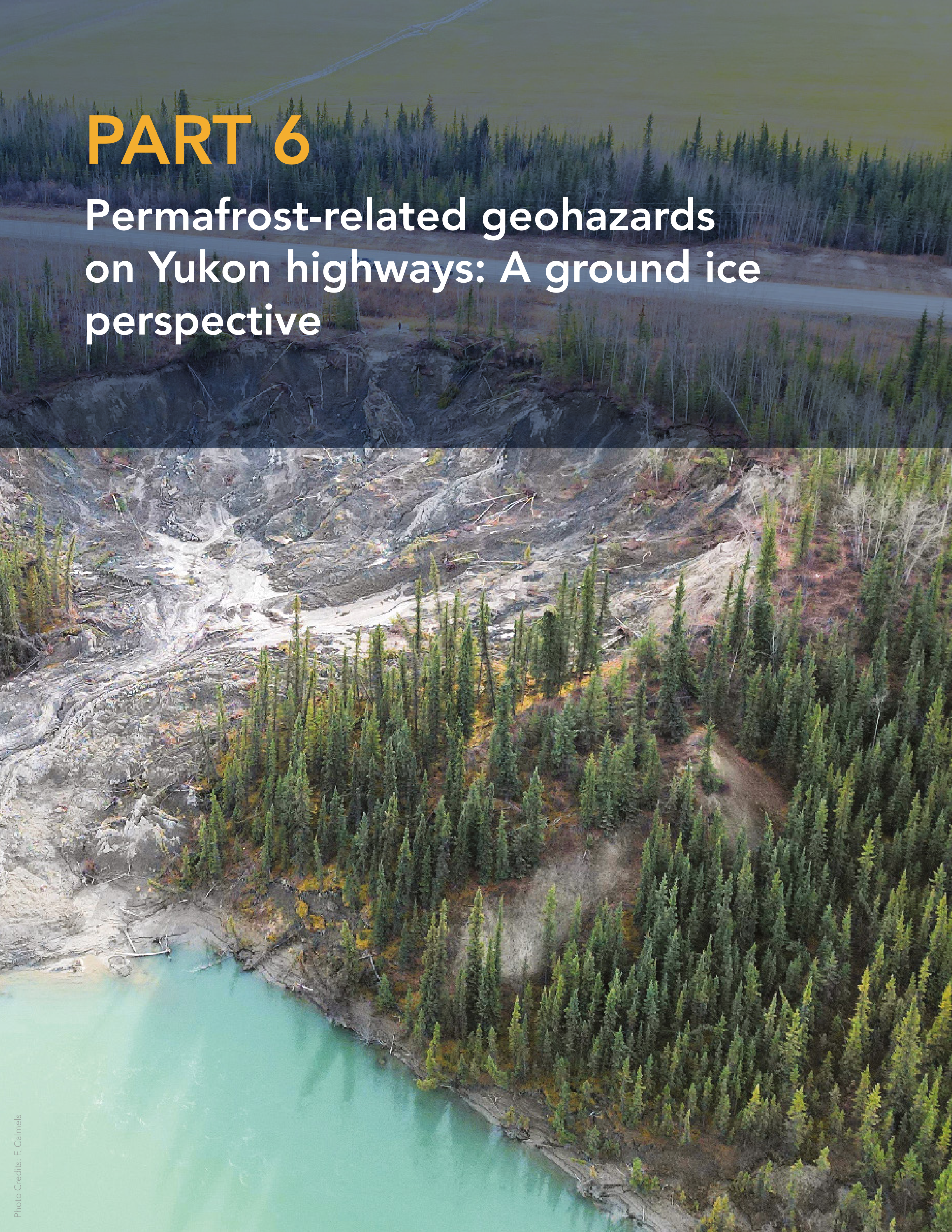
# PART 6

## Permafrost-related geohazards on Yukon highways: A ground ice perspective



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# Abstract

Permafrost-related geohazards, including thaw settlement, sinkholes, and retrogressive thaw slumps, pose an important risk to northern people and infrastructure. As climate change exacerbates permafrost thaw and the melting of ground ice, the instances of permafrost related geohazards are likely to increase. To reduce the risks associated with these hazards, and to plan for appropriate and sustainable remediation, it is essential to better understand the ground and environmental conditions of the infrastructure. This chapter presents a general overview of permafrost-related geohazards in the Yukon, including a summary of the different types of ground ice and their associated geohazards, along with case studies relating to each of these. Special attention is paid to buried glacial ice as a frequently overlooked form of ground ice that causes geohazards, and which is found throughout the Yukon, mirroring the territory's complex glacial history. Attention is also paid to groundwater flow, which plays an important role in the initiation and aggravation of geohazards and is generally poorly understood. This chapter highlights the need for site-specific studies to better understand risks and prevent or mitigate hazards to minimize the impact of permafrost-related geohazards on infrastructure and people.

# Key Recommendations

- To conduct site-specific studies to better understand local environmental conditions;
- To situate these studies within the broader geological and glacial context of the region to account for the glacial history and possibility of buried glacial ice;
- To include groundwater as an important component of permafrost thaw processes, and establish groundwater monitoring practices;
- To create early-warning systems for at-risk infrastructure to increase road user safety.

# 1. Introduction

Geohazards are geological and environmental conditions that involve either long or short-term geological processes and which may lead to widespread damage or risk. Common geohazards include earthquakes, volcanic activity, and landslides. In most northern environments, the most important geohazards result from permafrost thaw and changes in surface hydrology. Permafrost thaw-related geohazards include thaw settlement, sinkholes, and retrogressive thaw slumps, while surface hydrology-related geohazards include icings and flooding. These geohazards often cause damage to or lead to the failure of northern transportation infrastructure. Some of these geohazards can be triggered by thermal disturbances caused by the construction or presence of the infrastructure itself, while other processes occur naturally or as a result of climate change. These thermal disturbances might occur in close proximity to the infrastructure, or they could propagate from further away, ultimately threatening the integrity of the infrastructure.

Currently, this northern transportation infrastructure is critical to connect remote communities to healthcare, goods, and services (Stockton et al. 2021). However, this expansion of the road network to remote areas, often completed without consulting First Nations, also led to consequences for these once isolated communities. The construction of the Alaska Highway is recognized as the impetus of increased alcohol abuse, restricted access to traditional hunting grounds, and an increase in disease among these First Nation communities (Castillo et al. 2020). These involuntarily connected communities must now rely on this transportation infrastructure that brings the potential for increased food security, employment opportunities, and a decrease in household costs (Castillo et al. 2020). To prevent interruption to these important corridors, year-round highway maintenance is required. The expenses linked to climate-related highway maintenance in the Yukon increased from 1994 – 2022 (Schetselaar 2023), and areas of high permafrost presence result in twice the cost for geohazard related maintenance compared to those sections of highway in areas with low permafrost presence (Schetselaar 2023). Characterizing the permafrost underlying Yukon's road network is required to sustain access to these remote communities and reduce costs.

To reduce the risks associated with permafrost-thaw related geohazards, and to plan for appropriate and sustainable remediation, studies of ground and environmental conditions are required. Over the last decade, many such assessments have been carried out throughout the Yukon, along most major highways (Calmels et al. 2015, 2017, 2018, 2021, 2022). These assessments have allowed researchers to better understand how permafrost-related geohazards form, and the effects they have on transportation infrastructure. Often, insight from highway operators and users initiates or augments these studies of permafrost-related geohazards along transportation infrastructure.

This amassed "local knowledge" assists in identifying critical sites, characterizing the processes at work and their timing, and understanding the impacts. This valuable information can be collected at the inception of the studies through workshops and site visits with highway and public works department staff. Regular contact and updates with territorial or government authorities help keep the studies relevant and the partners involved. Project results, future plans, and community feedback can be shared at community workshops, booths at community general assemblies, community meals, and BBQs. These sessions help to foster a meaningful relationship with the communities that depend on this infrastructure. Ultimately, this collaboration paired with the final assessments lead to the development of appropriate remediation strategies for highway operators. In the long term, highway operators can use this information to develop risk management plans and policies to enhance disaster preparedness and mitigation.

This chapter presents how various permafrost-related geohazards are threatening and impacting Yukon highways, based on this extensive research on Yukon highways. This is done by first describing Yukon landscapes including the glacial history and permafrost distribution, then describing the specific types of ground ice that cause geohazards. Finally, these different types of geohazards are presented through a variety of case studies throughout the Yukon.

# 2. A landscape inherited from glaciations

Yukon landscapes are shaped by their glacial histories, where the presence or absence of glacial activity has left lasting legacies on soil and ground characteristics. The properties of permafrost, such as temperature, thickness, and ground ice content, are deeply influenced by this history. Therefore, understanding permafrost-related geohazards requires first understanding the local glacial history.

The Yukon has one of the oldest and most complex glacial histories in North America, that is described in Duk-Rodkin et al. (2004). The southwestern Yukon may have been glaciated as far back as 5 million years ago, like the coastal mountains of Alaska during the Cordilleran glaciation, though stratigraphic records in the central Yukon only date back to the Late Pliocene (< 2.9 Ma). The best documented glacial events are the most recent episodes of the Cordillera glaciation, since evidence of earlier stages of glacial activity were likely cleared by subsequent glacial advances. Ice advanced northeastward and westward from the lobes of the Cordilleran ice sheet, and westward in northern Yukon from the continental Laurentide ice sheets. The stratigraphic records suggest that though the older glaciation was more extensive than the newer glaciations, the general pattern of ice distribution was the same (Figure 1) (Yukon Ecoregions Working Group 2004)

## 2.1. Unglaciated Vs. Glaciated

Large areas of the Yukon remained unglaciated through the last glacial period such as the Klondike Plateau, part of the North Ogilvie Mountains, the Eagle Plains, and the Old Crow Basin and Flats. Yukon roads mostly pass through valleys and plains in both previously glaciated and unglaciated areas (Duk-Rodkin et al. 2004; Yukon Ecoregions Working Group 2004).

In unglaciated areas, valleys are narrow, and slopes are usually covered by colluvial veneers that thicken downslope into aprons of organic debris, reworked loess (which in this case, is silt blown by katabatic winds from broad outwash plains (Froese and Schweger 1999; Muhs and Budahn 2006), bedrock fragments and fine-grained slope wash. Permafrost is most prevalent in the apron deposits and on north-facing slopes. Alluvial deposits are linked to active stream channels and to sporadic alluvial terraces. The areas adjacent to the Pleistocene glaciers received loess from these glaciers (Froese and Schweger 1999). The thickest permafrost in the Yukon has been established in these ice-free areas where ground surface was subjected to the coldest climate for the longest periods of time. Ice-rich permafrost is most likely to be encountered in these areas in sediment deposited by wind or water.

In formerly glaciated areas, valleys are wide and u-shaped, with steep sides and bottoms filled with silt, sand, and gravel. Common landforms include kame terraces in mountainous regions, drumlins, and crag and tail glacial features in lower lying land (Trenhaile 2016). Site elevation has an important influence on soil formation and characteristics since depressions can be covered by tens of meters of till deposits while only a thin till cover or exposed bedrock is found on summits. In some places, proglacial lakes deposited fine-grained lacustrine sediments. As glaciers retreated, hummocky moraine, glaciolacustrine and glaciofluvial plains and esker complexes remained in valley bottoms (Trenhaile 2016). Eventually, stagnant glacier ice would melt resulting in a chaotic landscape with no clear stratigraphic record, where kettle lakes and hollows formed within sand and gravel ridges. Such environments can preserve buried glacier ice if permafrost develops when the glaciers retreat. If drainage outlets in valleys were blocked by ice, glacial lakes would form, such as the glacial Lake Champagne that filled many of the valleys in the Southern Lakes regions of the Yukon. Sections of cliffs in this region, such as in Whitehorse, expose cuts where the sedimentary layers of the silt deposited at the bottom of glacial Lake Champagne are exposed. These silts are very frost-susceptible, meaning they are likely to become ice-rich permafrost upon freezing.

### 2.2. Implication for Yukon roads

The Alaska, Klondike, and Dempster Highways all pass through both glaciated and unglaciated terrain. Most of the Alaska Highway is built in areas that were glaciated during the McConnell glaciation (ca. 22ka), with the glacial limit located around kilometer 1840 (Duk-Rodkin 1999; Duk-Rodkin et al. 2004; Yukon Ecoregions Working Group 2004). The northernmost section, from about km 1840 to km 1902, was glaciated during the pre-Reid and Reid glaciations. Along the Klondike Highway, the McConnell glacial limit is located near Carmacks (km 354), the road passes through pre-Reid and Reid glaciated terrain towards the North before reaching unglaciated regions near kilometer 690, some 20 km east of Dawson City (Duk-Rodkin et al. 2004; Yukon Ecoregions Working Group 2004). The glacial history of the southernmost section of the Dempster Highway is complex, where pre-Reid, Reid, and McConnell glacial limits are entangled from about km 0 to km 160; though the road is built on unglaciated terrain thereafter (Duk-Rodkin et al. 2004; Yukon Ecoregions Working Group 2004).

This varied glacial history can provide general guidelines for permafrost conditions along the road network. In areas that were glaciated during the McConnell glaciation, permafrost tends to be relatively thin (< 20 m) and warm (T > -2 °C); with the possibility of ice-rich ground near the surface. Unglaciated terrains host older, thicker, and colder permafrost, with massive ice of various origins spreading from near the surface to tens of meters in depth. Areas that are between glacial limits are considered transition zones, where the potential for buried massive ice remains.

## 3. Permafrost in the Yukon

Permafrost is defined as any soil or rock that remains at or below 0 °C for two or more consecutive years. It is a phenomenon that is defined solely on the thermal properties of the ground. Between the permafrost and the ground surface is the active layer, which freezes and thaws seasonally. The thickness of the active layer varies greatly depending on the soil type, water content, vegetation, and climate. On a local scale, the active layer is usually relatively thick in dry, well-drained soils and it is thinner in wet soils and where peat and moss layers are present. At a regional scale, active layer thickness decreases as latitude increases.

Based on data from permafrost maps from Brown et al. (1997), continuous permafrost zones represent approximately 34% of the land, while extensive and sporadic discontinuous permafrost zones represent around 66% of the remaining land in the Yukon (Figure 2). The thickness of the permafrost ranges from only a few meters in the south to over 250 m in the north. Although the distribution of permafrost depends primarily on climate, site specific conditions such as soil texture, vegetation, snow cover, and surficial hydrology lead to variability in active layer thickness and ground temperature within a climatic region. For example, wet or shaded sites are typically cooler than drier, more exposed sites, which favors the development of permafrost. Aspect can also have a major impact on permafrost conditions, as shaded north-facing slopes could have permafrost, while sunny south-facing slopes may not have any. Valley bottoms also tend to have colder permafrost than higher hillslopes because cold air tends to sink and stagnate in valley bottoms during the winter.

Several environmental factors may disrupt the thermal equilibrium of permafrost, notably forest fires and snow cover (Mackay 2000). In the Yukon, forest fires are one of the most important drivers of permafrost thaw (Burn 1998; Calmels and Froese 2009; Huscroft et al. 2003; Lipovsky and Huscroft 2006). This is because fires destroy

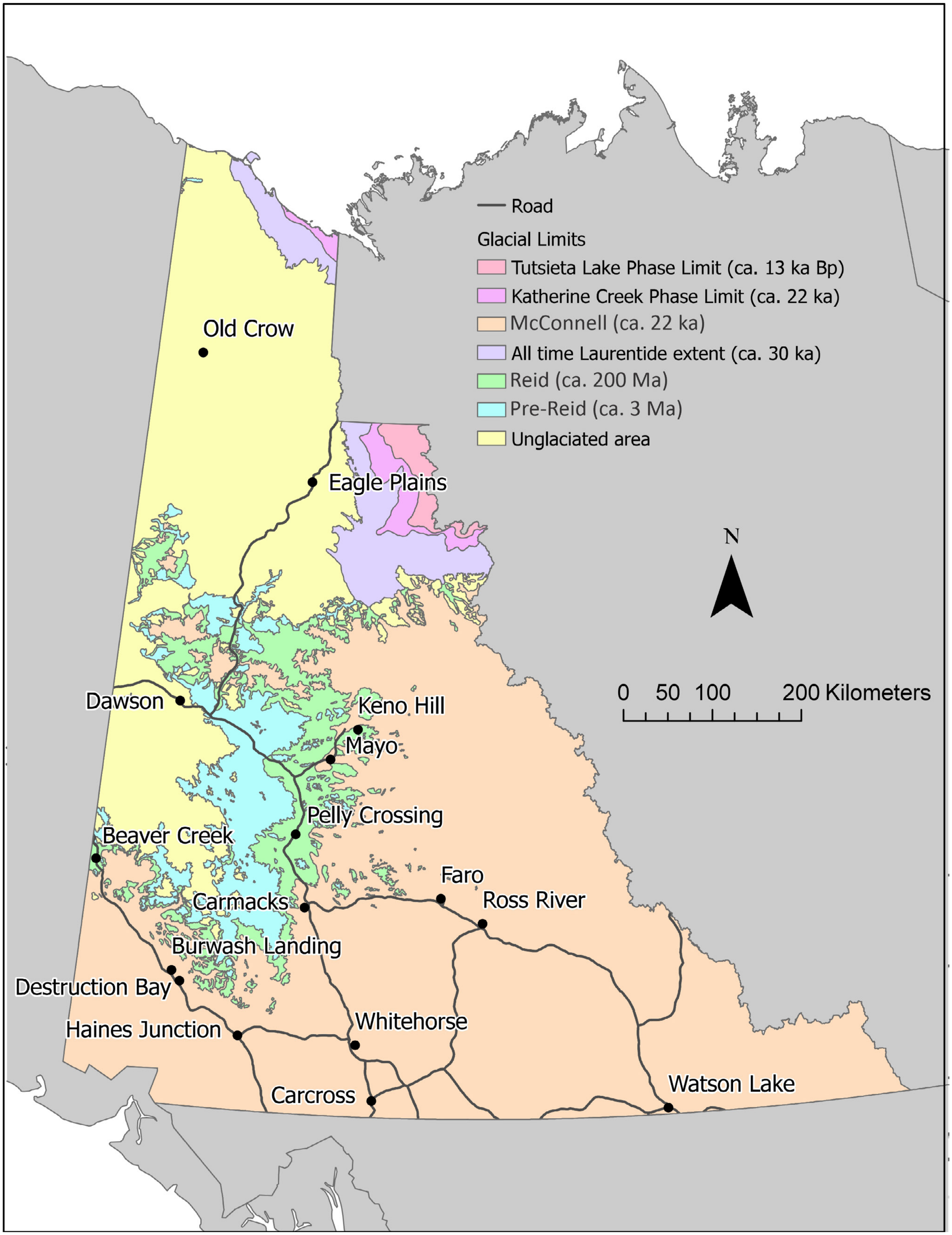


Figure 1. Glacial limits of the Yukon with data from (Duk-Rodkin, 1999; Yukon Geological Survey, 2020).

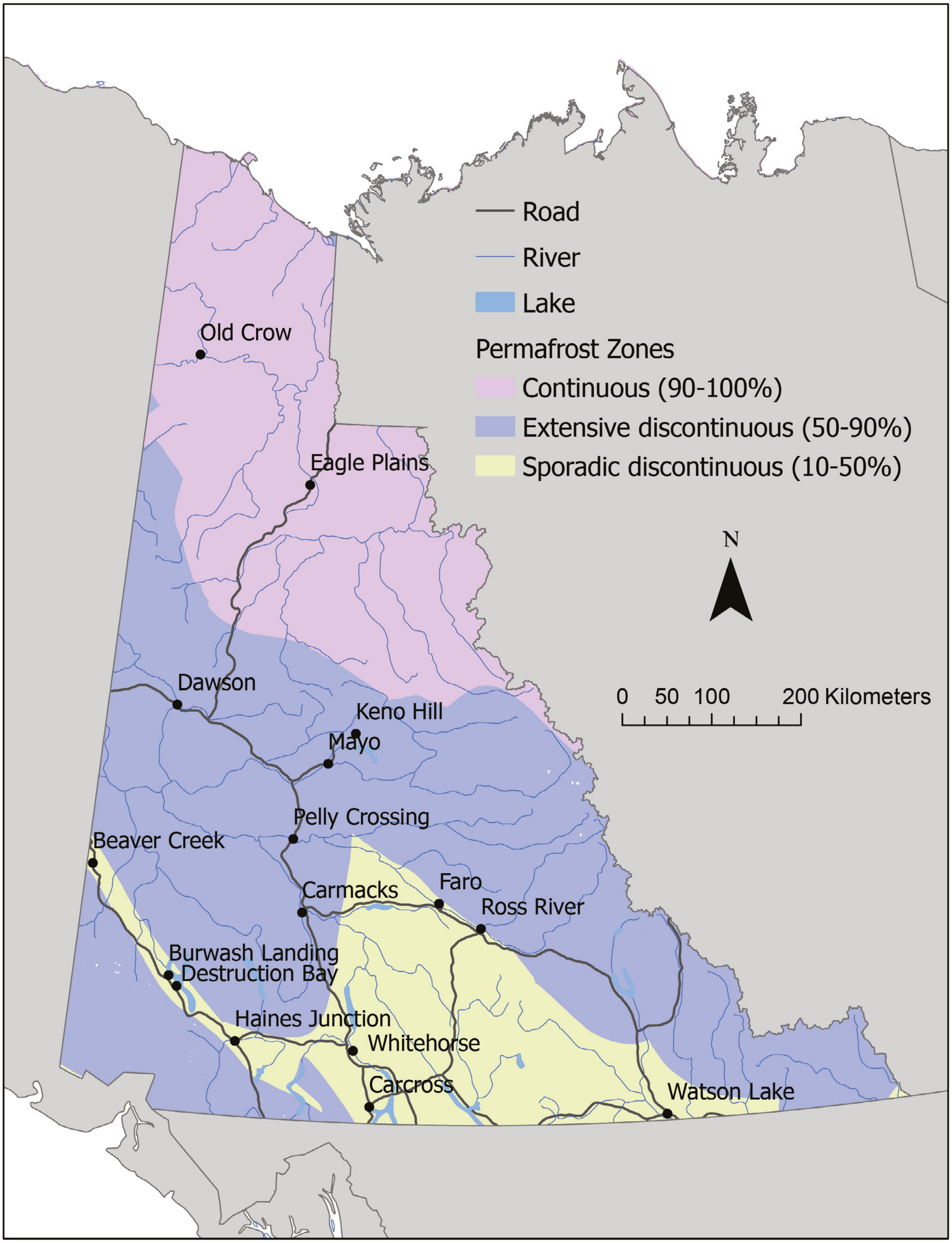


Figure 2. Yukon permafrost zone (adapted from Brown et al. (1997)).

vegetation, including trees and mosses, which results in the loss of protective cover (Calmels and Froese 2009; Grandmont et al. 2015). The loss of tree canopy results in increased solar radiation, and the burnt vegetation leaves behind a dark ground surface with low albedo that further increases heat absorption. Moss and peat protect permafrost by insulating it in the summer when it is dry and promoting frost growth in the winter. The loss of this protective layer therefore results in permafrost thaw (French 2017). Finally, the loss of tree canopy also leads to increased snow accumulation on the ground since there is no foliage to intercept snow. Thick snow accumulation on the ground can act as an insulator and prevent heat extraction during the winter, thereby increasing the ground temperature and potentially thawing permafrost (French, 2017). Ground temperatures are generally colder (as low as -5°C) and more variable north of the tree line in tundra environments, where snow is often blown away, keeping snow depths relatively shallow (20-40 cm). South of the tree line, in wooded environments, permafrost temperatures tend to be warmer and vary less (between -2 and 0° C), partly because trees protect the snow from being blown away by wind, allowing it to accumulate between 40-50 cm (French 2017; Palmer et al. 2012).

# 4. The significance of ground ice to Yukon roads

Permafrost has important impacts on the Yukon's road network. As permafrost degrades, the melting of ice within the permafrost causes ground subsidence and damage to road infrastructure. The type and amount of ice in the permafrost (ground ice content) impacts the potential for subsidence. Therefore, knowing the nature and distribution of ground ice along Yukon transportation corridors is essential, as it allows for a better understanding of permafrost thaw-related geohazards, and the development of suitable remediation strategies.

This section describes the different types of ground ice that are most common along Yukon roads, and which are mostly likely to be involved in permafrost related geohazards, such as sinkholes and thaw slumps.

## 4.1. Segregated ice

Segregated ice is one of the most common forms of ground ice found in the Yukon. It is mainly found in the uppermost layers of permafrost where there are unconsolidated, fine-grained sediments, or coarser sediment within a silty or clayey matrix (French 2017). When there is sufficient moisture supply, and the temperature conditions (freezing rates) are suitable, segregated ice lenses (Figure 3) can form as pore water migrates to the freezing front via cryosuction (Mackay 1972; Mackay and Dallimore 1992). The formation of segregated often results in frost heave as the volume of ice is greater than the equivalent volume of water, as seen in Figure 3.

This type of ground ice can be epigenetic, meaning it develops downward as permafrost propagates in pre-existing material (French and Shur 2010; Mackay 1972), which is common in discontinuous permafrost regions. This ice can also be syngenetic, developing near the top of permafrost and remaining there if the permafrost table rises because of sedimentation and aggradation of the surface, or the rise of the permafrost table in response to periods of colder climate (French and Shur 2010; Mackay 1972). One can expect vertical thaw-driven subsidence to decrease over the long term because segregated ice is mostly constrained to the top of permafrost and is likely to be more diffuse downward. However, if horizontal thermal erosion is involved, such as with retrogressive thaw slumps, the degradation may be ongoing if there is additional ground ice available to continue the lateral erosion. Segregated ice is typically clear, but can sometimes include sediment (Pollard 1990).

## 4.2. Ice wedges

Ice wedges are a type of massive vein ice that are characterized by a V-shaped body of ice. Ice wedges develop when the thermal contraction of the ground in the winter causes it to crack due to a rapid decrease in ground temperature. Networks of cracks subsequently fill with melting snow, rain, or surface runoff in the spring, which then freeze as a vertical vein of ice. This sequence is repeated over hundreds of years, as the width of the ice

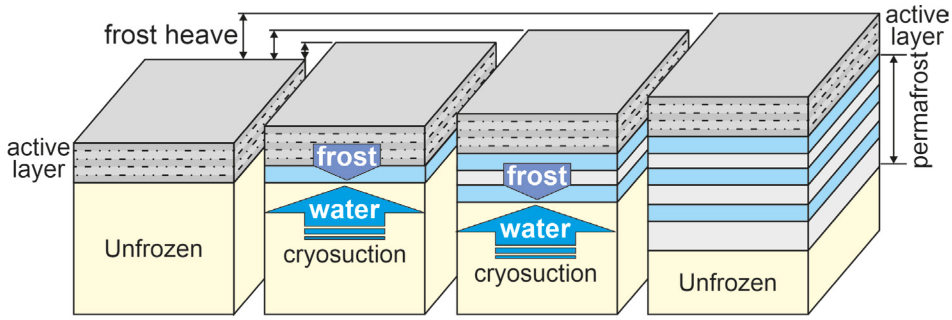


Figure 3. Ice segregation process.

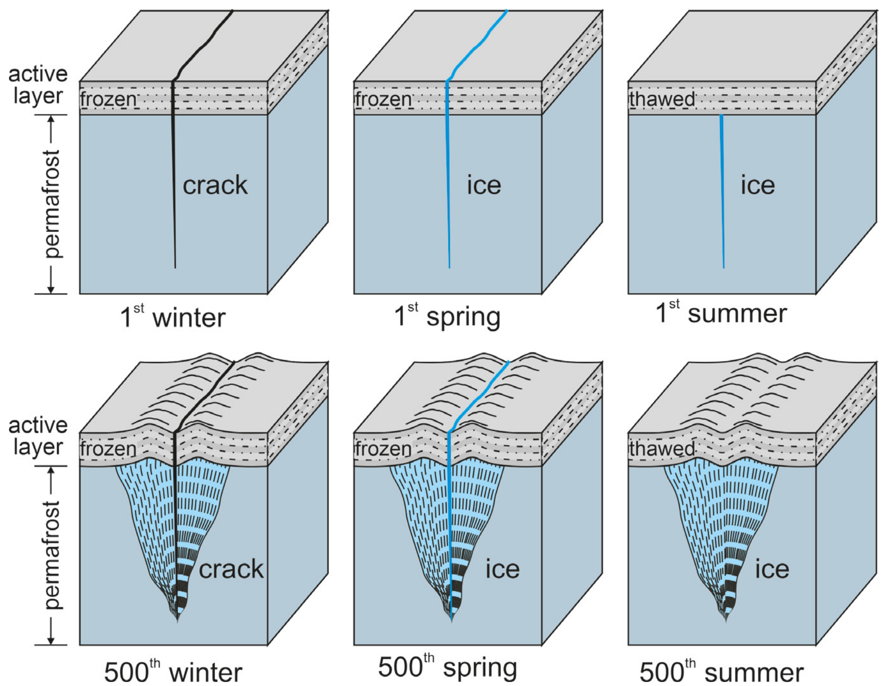


Figure 4. Ice wedge formation.

increases forming the characteristic V-shape or wedge shape (Figure 4) (French 2017; Mackay 1972). As a consequence of this type of growth, wedge ice is typically foliated or vertically banded and is commonly white in colour (Pollard 1990).

Ice wedges eventually connect into what are called ice-wedge polygons, a type of patterned ground (French 2017) shown in Figure 5. Ice wedges can either be active, inactive, or degrading. Active ice wedges that are still growing are typically found in areas of continuous permafrost and can be differentiated based on the raised rim and low center of the polygons (Mackay 2000). Inactive ice wedges can remain stable for many centuries without changing, even in discontinuous permafrost. In the Yukon, ice-wedge polygons are typically present in valley floors, mostly in tundra sites, like in the U-shaped valley floor along the Dempster Highway (Calmels et al. 2022). These polygons tend to have slight depressions above the wedges and can be difficult to see because of vegetation and slow ground surface creep. When they are degrading the troughs will be filled with water (Mackay, 2000). Ice wedges can degrade because of thermal erosion that is induced by surface water flow which can cause sinkholes, or by slumping. Both processes can have major impacts on the transportation network and cause road failure.

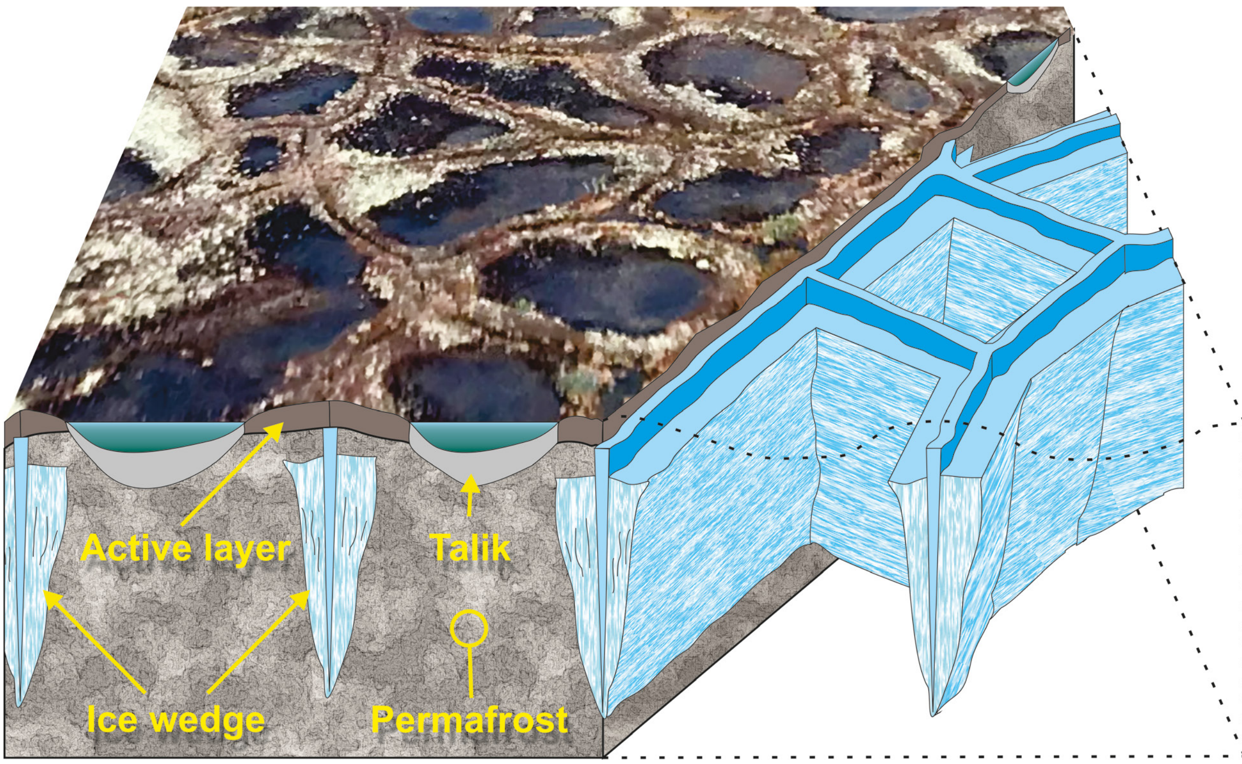


Figure 5. Ice wedge polygons (adapted from (Martin et al., 2009).

## 4.3. Buried Ice

An often overlooked, but important type of ground ice in the Yukon is buried ice, which consists of surface ice or snow that has been buried. The ice is typically buried glacier ice or snowbanks, or even sometimes icings or lake, river or sea ice (French and Harry 1990; Mackay 1989; Pollard 1990) . Much of the buried ice in the Yukon is ice from the last ice sheet that has been buried and preserved for 14,000 years.

When considering a relict glacial landscape, landforms such as kettle ponds and kettle holes are the most common geomorphic indicators of the past and present occurrence of buried glacier ice. These kettles are fluvioglacial landforms that occur as a result of blocks of ice calving from the front of a receding glacier, that became buried by glacial outwash (Figure 6). Over time, these blocks of ice melt leaving depressions, or kettle holes on the surface (French 2017). When they are filled with water, the depressions are called kettle lakes or ponds. Most kettles are deep depressions with steep slopes, and they are often circular in shape as melting blocks of ice tend to become rounded. Small kettles may be formed from ice blocks that were not left as the glacier retreated, but rather floated into place by shallow meltwater streams. Kettles may occur by themselves or in groups.

Several kettles have been observed in the Yukon, in areas where the presence of buried ice has been identified (Johnson 1992). In some cases, the thermokarst process is still active, as the ground surface continues to subside because buried ice is still melting in thawing permafrost. In these cases, the steep edge of the ponds shows signs of ongoing collapse with longitudinal cracks forming around the pond. As the ponds expand and the banks collapse, trees lean into and topple toward the pond. This is a process that has been observed throughout the Yukon, and has important impacts the integrity and safety of roads, most notably at kilometer 1840 of the Alaska Highway at the Dry Creek rest area, as discussed in section 4.3.3.

## 4.4. Intrusive ice

Intrusive ice is ice that is formed from the injection of water into soils or rocks. The injected water freezes, which normally results in the uplifting of the overlaying ground. Intrusive ice bodies can be dome-shaped, generating landforms such as frost blisters and pingos; or tabular, resulting in massive ice veins, filling cracks or fissures in the ground (Figure 7) (Mackay 1972).

Intrusive ice can develop in porous unconsolidated sediments and in jointed or fractured bedrock, where fractures will be enlarged by hydraulic fracturing or frost wedging processes. The phenomenon is most significant when water is trapped in the joints or fractures and is subjected to rapid freezing. Intrusive ice is usually clear with little to no mineral or gaseous inclusions, though dyke ice may be brown (Pollard 1990).

While landforms such as pingos and frost blister exist in the Yukon, the only type of intrusive ice found along roadways in the Yukon are ice veins (Figure 7B), which are generally found in valley floors or on the bottom of hills.

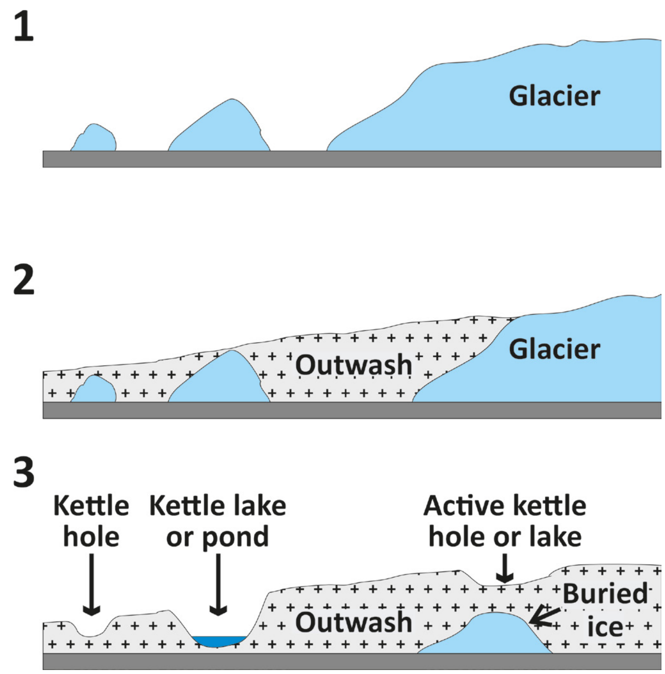


Figure 6. Illustration of the process of kettle formation.

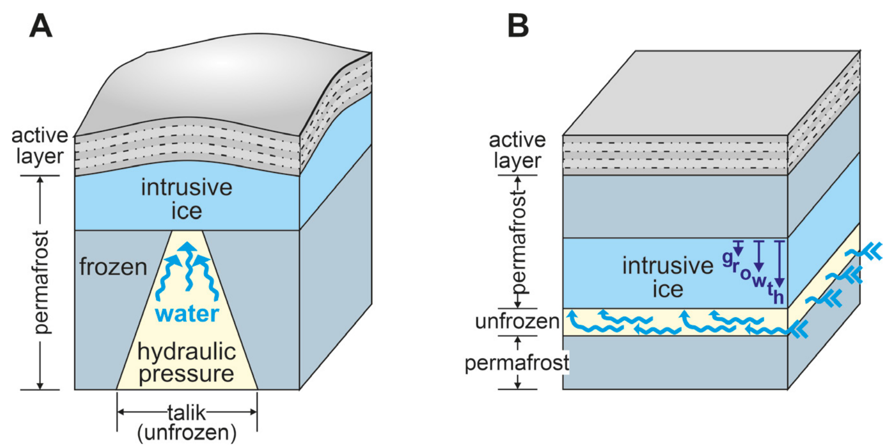


Figure 7. Illustration of the formation of intrusive ice. A- Dome-shaped ice; B- ice vein.

# 5. Permafrost-related geohazards and ground ice

As mentioned, permafrost-related geohazards are the result of ground ice degradation, and the type of geohazard depends on the type and amount of ground ice present. Different forms of thaw settlement, slope failure, and thermal erosion are responsible for infrastructure failures along many sections of Yukon highways built on permafrost. These geohazards pose an important risk to road safety and can disrupt travel for extended periods of time, in what is often the only road access to communities. As such, it is important to study permafrost conditions to anticipate geohazards, and closely monitor existing hazards.

Many studies have been conducted identifying several critical sites along the Alaska and Dempster Highways where the formation of sinkholes, intense subsidence, or the occurrence of retrogressive thaw slumps (RTS) are impacting road safety.

The most common forms of thaw settlement impacting road embankments are general subsidence and tension cracks resulting from shoulder rotation (Figure 8). Since most transportation infrastructure consists of an elevated surface with steep embankments, they tend to accumulate blowing snow on the shoulders and intercept surficial water drainage. The accumulated snow prevents heat extraction in the winter, when the permafrost should be cooling, which can cause an increase in the active layer over time, thawing the top of the permafrost that tends to be ice-rich (French 2017). The resulting ground subsidence is mostly concentrated in the shoulders which induces a rotational movement and the formation of tension cracks (Figure 9) (Ladanyi and Andersland 2004). When the snow melts, water can accumulate at the foot of the embankment, causing additional warming to the permafrost. Surface water runoff also tends to pool along the embankment, unless it is able to flow through the embankment, either of which will result in thaw settlement, tension cracks and/or sinkholes (Figure 10).

Sinkholes pose a particular challenge for maintenance and safety as they may form almost instantly and can be expensive to repair. In some cases, snow accumulation on the embankment due to snow plowing may increase the active layer thickness and open new pathways through the soil for groundwater to flow though, which

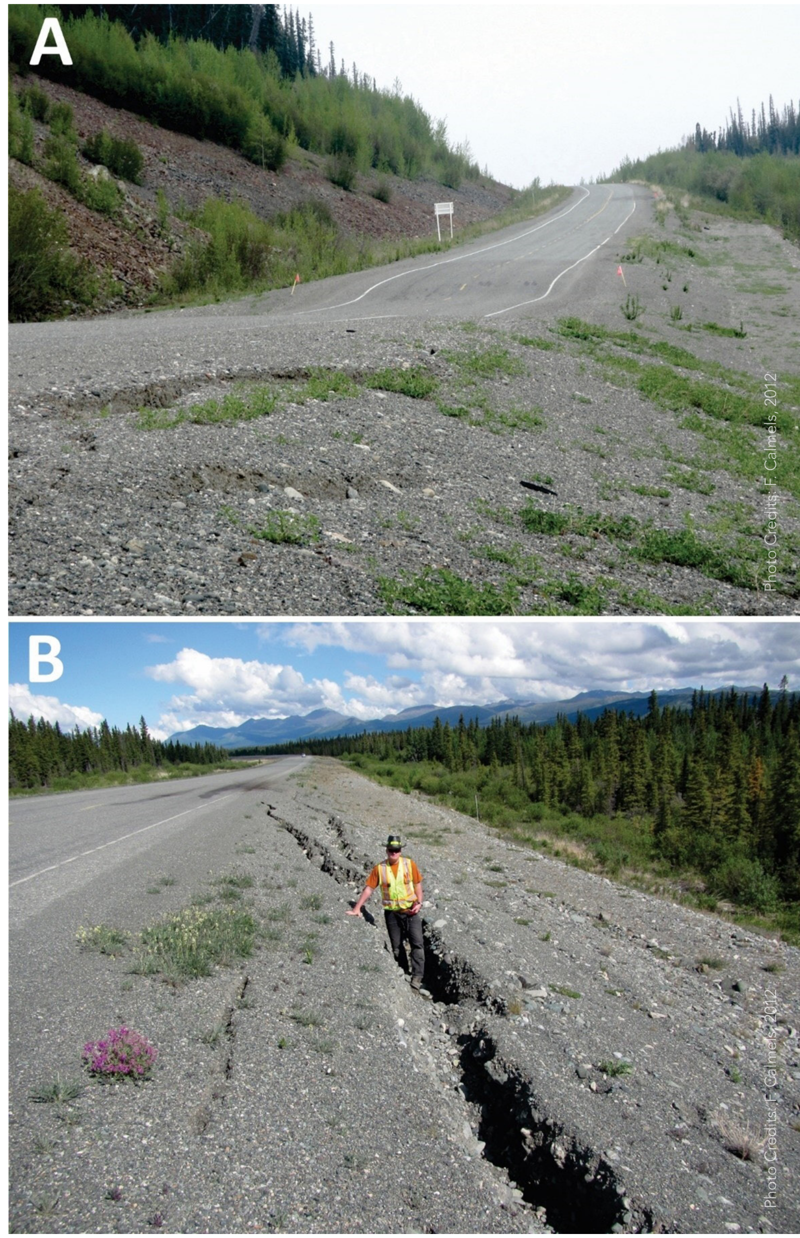


Figure 8. Some of the most common forms of permafrost thaw settlement. A-General subsidence; B-Tension cracks in shoulder (Alaska Highway, YT).

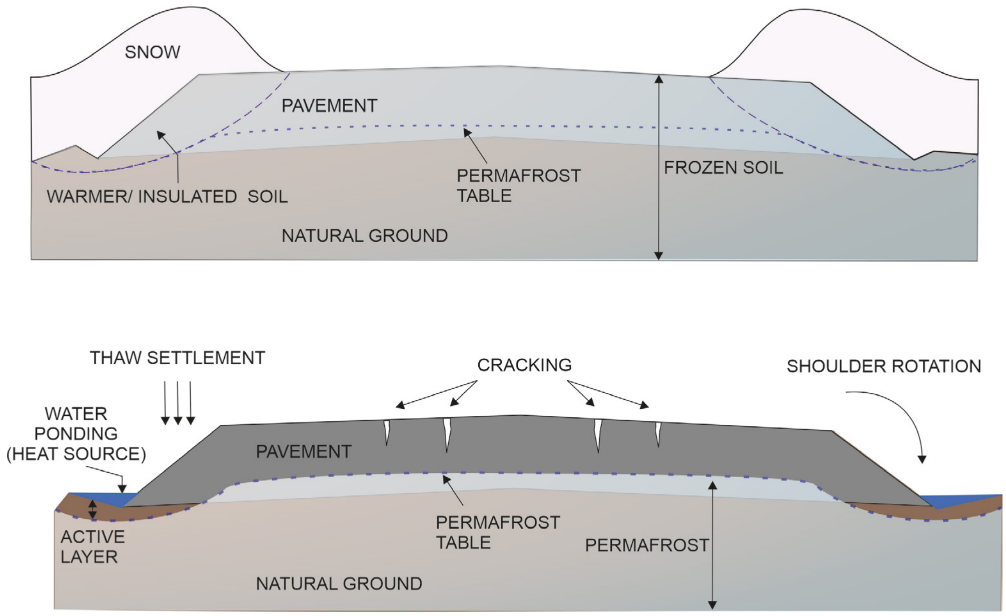


Figure 9. The impact of snow accumulation on roads built on permafrost (adapted from McGregor et al. (2010)).

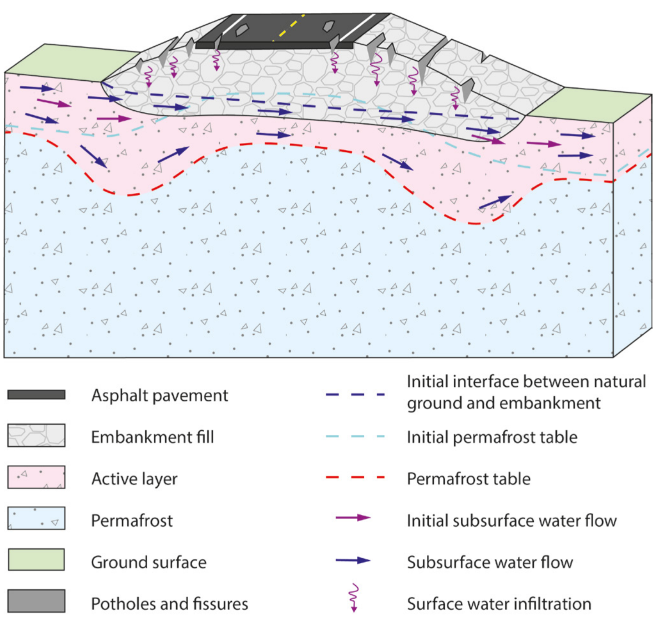


Figure 10. Damages resulting from drainage within and beneath a linear infrastructure (Modified from Chen et al. 2020).

would induce thermal erosion processes (Ladanyi and Andersland 2004). The loss of fine material and ground ice due to this groundwater flow creates a cavity that can collapse, forming a sinkhole. An example of this process is presented in Section 4.2.1.

Retrogressive thaw slumps (RTS), or thaw slumps, are erosional landforms that form in ice-rich areas, usually on hillslopes along the shores of lakes, rivers, or coastlines. RTS develop when the melting of ground ice exposes a vertical section of the ground that leads to a crescent-shaped retreating headwall, and a tongue of debris made up of melted ice and sediment on the slump flood. The slump grows as additional ice melts and the headwall retreats. A headwall may be eroded by many meters in a single summer, and over time a slump can impact several hectares of terrain (Calmels et al. 2021; Jones et al. 2019). The rate of headwall movement is linked to several environmental and physical factors, but generally, rates of slump growth are most rapid when the temperature is warmest and/or there is considerable precipitation (Jones et al. 2019). There are two main RTS impacting Yukon Highways, the Takhini Slump at km 1456 of the Alaska Highway, and the Chapman Lake slump at km 116 of the Dempster Highway. Both slumps are encroaching on the highway and threaten to cut off the road, and are discussed in further detail in sections 4.1 and 4.2.2.

Following the discussion of these case studies, mitigation methods that can be used to slow or prevent permafrost thaw and subsequent geohazards on transport infrastructure are examined in section 4.4.


Figure 11. Retrogressive Thaw Slump along the Takhini River at km 1456 of the Alaska Highway.

## 5.1. Segregated ice: Retrogressive thaw slump along the Takhini River at km 1456 of the Alaska Highway

The retrogressive thaw slump (RTS) located at km 1456 of the Alaska Highway was likely initiated by erosion of the Takhini River bank (Figure 11). Though it was first studied in the spring of 2019, satellite and aerial imagery show the RTS to have been active since at least 2014.

At this location in the Ibex Valley, Glacial Lake Champagne deposited up to 75 m of silt and clay between 9,000 and 10,000 years ago (Yukon Ecoregions Working Group 2004). After the drainage of the lake, permafrost was able to aggrade in this sediment. In the Ibex Valley, glaciolacustrine silt and clay often contains massive ice bodies, which are prone to RTS and general thermokarst degradation when disturbed by river erosion, forest fires, or other changes in surface conditions (French 2017). When the site was first assessed in May 2019, the 50 m wide and 5 m high RTS headwall provided an outstanding natural exposure of ice-rich permafrost with segregated ice lenses that were up to 20 cm thick (Figure 12).

Given its proximity to the Alaska Highway and the risk this poses to road safety, the slump has been monitored monthly during the thaw season since the spring of 2019. Monthly surveys include high resolution unmanned aerial vehicle (UAV) surveys as well as benchmark surveys using differential GPS. With these tools, combined with satellite imagery and LiDAR data from as early as September 2016, it has been possible to monitor the retreat of the RTS headwall since 2016. Between the beginning of summer 2017 and November 2021, the headwall of the RTS progressed 70 m towards the highway, for an average of 14 m/year in those five

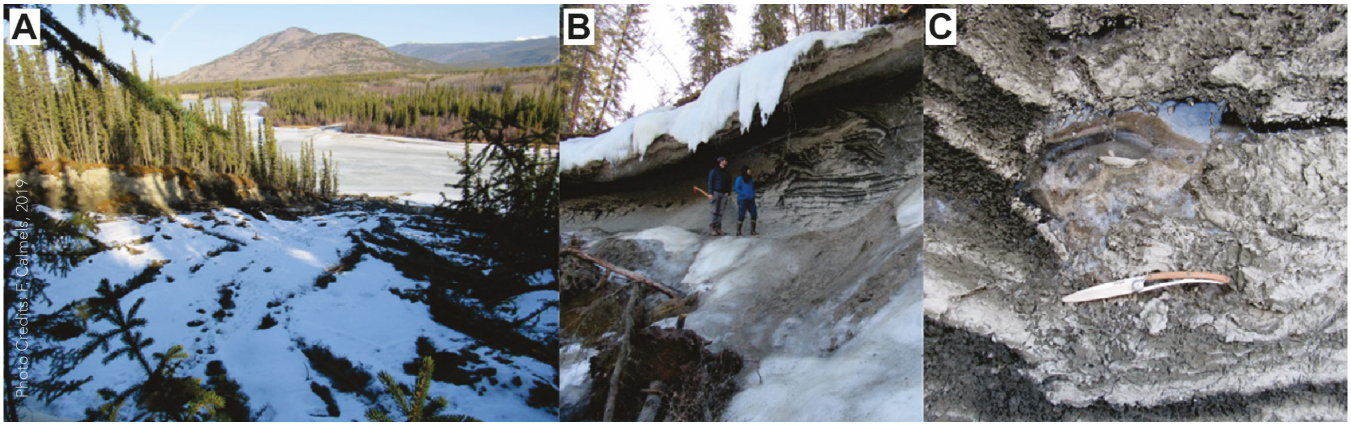


Figure 12. A- View of the RTS; B- Headwall of the RTS exposing ice-rich permafrost; C- 10 cm thick ground ice lenses.

consecutive summers. The headwall progressed by 24.9 m in the 2017-2018 period (avg. 12.5 m/yr), by 12.1 m in 2019, by 12.9 m in 2020, and by 19.3 m in 2021. The headwall retreated 49.6% faster in 2021 compared to 2020, and 51.3% faster compared to the previous 4-year period (Figure 13 and Table 1).

Using UAV photogrammetry, it was possible to create digital elevation models (DEM) from the aerial imagery of the Takhini RTS. When compared over time, these DEMs can be used to calculate the volume of sediment and ice that is eroded by the slumping processes into the Takhini River. The estimated volume of eroded sediment and ice from 2019 to 2021 is presented in Table 2. Approximately 17,024 m³ was eroded in the five years leading up to 2019; 9,497 m³ in 2019-2020, and 15,252 m³ in 2020-2021, with a potential error of approximately 3% for all volumes. The total volume lost is equivalent to the volume of over 16 Olympic-sized pools (2500 m³). These results emphasize the increasing amount of sediment that has flowed into the river as the headwall retreats over time.

The rapid erosion of the headwall in 2021 could be related to extraordinary weather events that occurred during the summers of 2020 and 2021. Whitehorse had its ninth-rainiest summer in the weather records in 2020, with 157.8 mm over the course of the summer (Oakes 2020). Because of inertia in the system, the impact of this significant input of heat may have only been felt during summer 2021. In summer 2021, the "heat dome", a mass of hot air sitting over the Pacific Northwest, occurred in June and July which resulted in warmer than average temperatures in the Yukon (Desmarais 2021), and could also have contributed to rapid erosion.

Groundwater flow is considered a crucial control on the RTS progression. While the thaw slump processes were likely initiated by bank erosion on the Takhini River, the thermal effect of groundwater flow paired with the high ground-ice content has exacerbated the process. In addition to groundwater frequently seen seeping from the headwall of the slump (Figure 14), geophysical and borehole data have revealed the presence of flowing groundwater and confirmed the ice-rich nature of the ground. Similarly, a UAV survey of the site using a thermal camera was conducted in November 2021 and showed groundwater flowing from the headwall and slump floor (Figure 15). During the winter months, this flowing groundwater can generate icings. Although speculative at this point, summertime irrigation of farmland, located directly adjacent to the southern edge of the highway, may provide an additional water source contributing to the degradation processes.

The RTS at kilometer 1456 of the Alaska Highway is closely monitored by researchers and highway operators to ensure the safety of the road users and uninterrupted use of this critical corridor. In 2023, with the headwall of the slump nearly encroaching on the right-of-way, risk mitigation measures were considered including putting rip-rap on the headwall and rerouting a roughly one-kilometer section of the highway approximately 70 m to the south. This latter, more cost-effective undertaking was decided upon after consideration of other possible remediation or mitigation strategies.

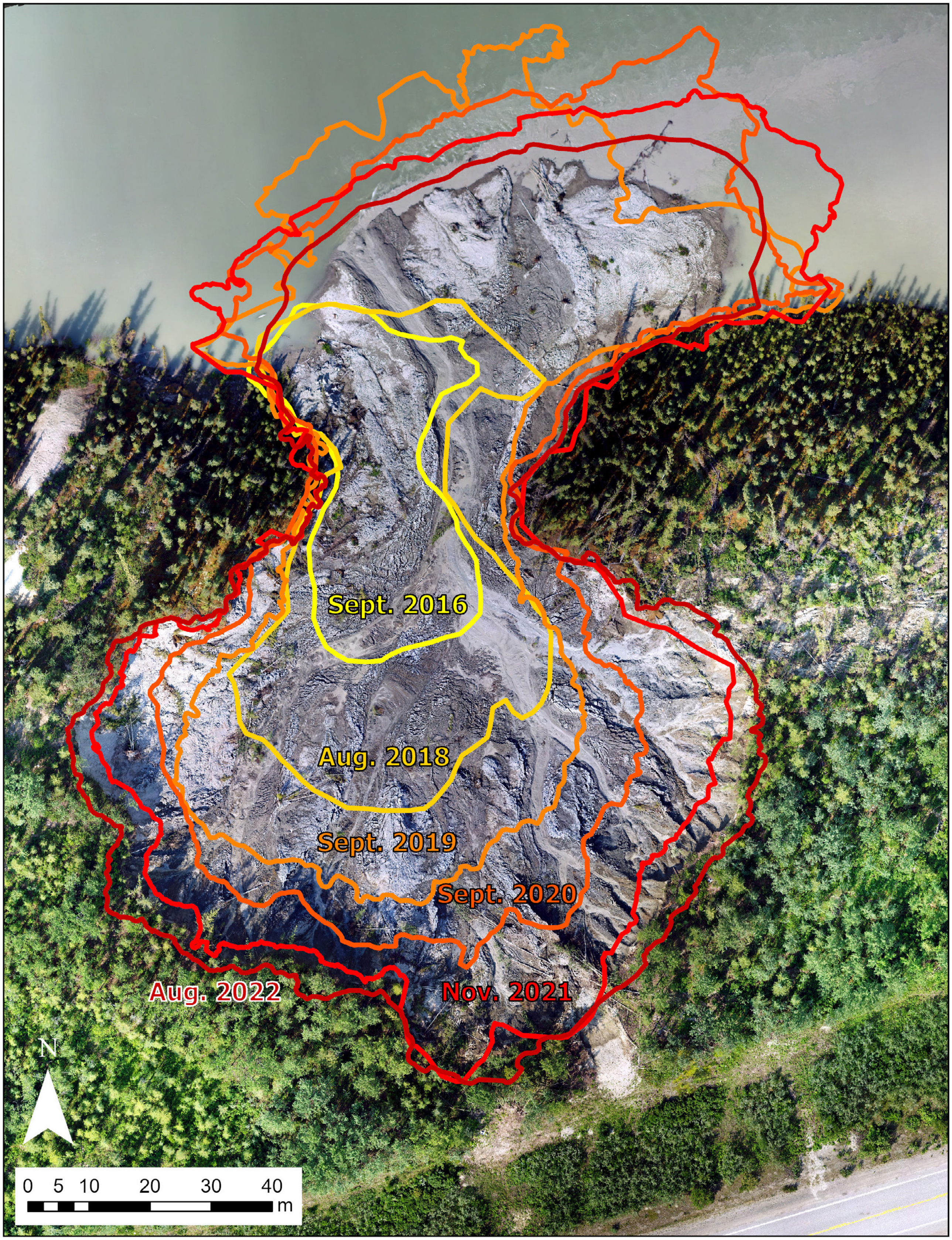


Figure 13. Evolution of the Ibex Valley RTS from September 2016 to August 2022 based on UAV imagery.

Table 1. Evolution of the Ibex Valley RTS based on aerial imagery from September 2016 to November 2021.

| DATE | Distance to road (m) | Length (m) | Width (m) |
|---|---|---|---|
| September 28, 2016 | 105.8 | 53.5 | 27.3 |
| August 18, 2018 | 80.9 | 78 | 41.2 |
| May 16, 2019 | 80.9 | 78 | 52.6 |
| August 22, 2019 | 71.8 | 88.7 | 63.7 |
| September 11, 2019 | 69.7 | 91.8 | 63.7 |
| September 25, 2019 | 68 | 93 | 65.3 |
| October 30, 2019 | 68.8 | 93 | 65.3 |
| May 20, 2020 | 68 | 93 | 65.4 |
| August 26, 2020 | 57.5 | 102.2 | 74.8 |
| September 29, 2020 | 55.1 | 102.8 | 78.5 |
| May 6, 2021 | 55.1 | 107.5 | 78.5 |
| June 4, 2021 | 53 | 107.5 | 83.2 |
| July 6, 2021 | 53 | 107.5 | 88.8 |
| July 30, 2021 | 47 | 116.7 | 96.2 |
| August 31, 2021 | 39.5 | 122.1 | 100.7 |
| October 7, 2021 | 39.3 | 122.3 | 103.7 |
| November 3, 2021 | 35.8 | 125.8 | 103.8 |


Figure 14. Groundwater spring seeping from the headwall at various locations.

Table 2. Volume of lost soil at the Takhini RTS.

| Date | Volume | Equivalent |
|---|---|---|
| Initiation of slump until Sept. 2019 | 17,024m³ | 6.8 swimming pools |
| Sept. 2019 to Sept. 2020 | 9,497m³ | 3.8 swimming pools |
| Sept. 2020 to Nov. 2021 | 15,252m³ | 6 swimming pools |
| Total | 41,773m³ | 16.6 swimming pools |

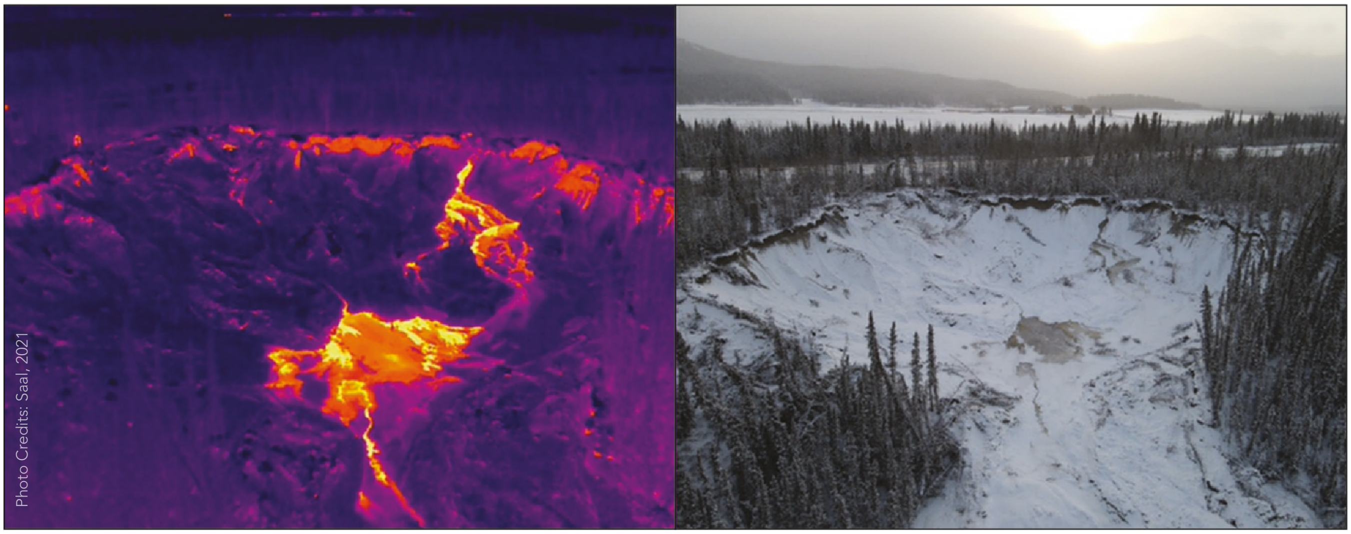


Figure 15. (November 24, 2021) Oblique air photo of the Takhini RTS using thermal (left) and RGB imagery (right) at the Takhini Slump. In the thermal image, the red-yellow hues represent warmer areas, where groundwater was flowing.

## 5.2. Ice Wedges: Sinkholes and retrogressive thaw slumps on the Dempster Highway

### 5.2.1. Sinkholes along the Dempster Highway

Since the mid-2010s, recurring sinkholes have formed along the Dempster Highway from approximately kilometer 90 to kilometer 123, within and just beyond the limits of Tombstone Territorial Park. In recent years, maintenance staff of the Yukon Government's Highways and Public Works (HPW) have noted an increasing frequency of sinkhole development (Yukon Government HPW, personal communication), possibly as an impact of climate change. Several sites, including km 93 and 97, have been extensively studied to better understand the processes involved. Surveys included UAV photogrammetry, electrical resistivity tomography, shallow borehole drilling and core sampling, and the installation of ground temperature monitoring instruments.

Though sinkholes can form for a variety of reasons, at kilometers 93 and 97 of the Dempster Highway, degradation was initiated near culverts that were jammed by icings in the winter (Figure 16) which prevented water from flowing through the culvert, and led to ponding on the upslope side of the culvert, leading to thermal erosion of the ground adjacent to the embankment and the embankment itself (Figure 17A, B and C). In some cases, the culvert can collapse, like at km 97 (Figure 17D). At both of the sites, the thermal erosion process has been so extreme that water has been channelized through ice wedges extending far away from the road and into the adjacent natural ground, exposing ice wedges within the permafrost (Figure 17E and F).

Generally, intra- or supra-permafrost groundwater flow induces the formation of sinkholes through thermal erosion or mineral-leaching water. At the Dempster Highway sites, high-resolution imagery has shown that sinkholes tend to be located in the pathway of surface water drainage (Figure 18). Thermal erosion of ice


Figure 16. Remains of an icing that blocked the culvert at km 97.

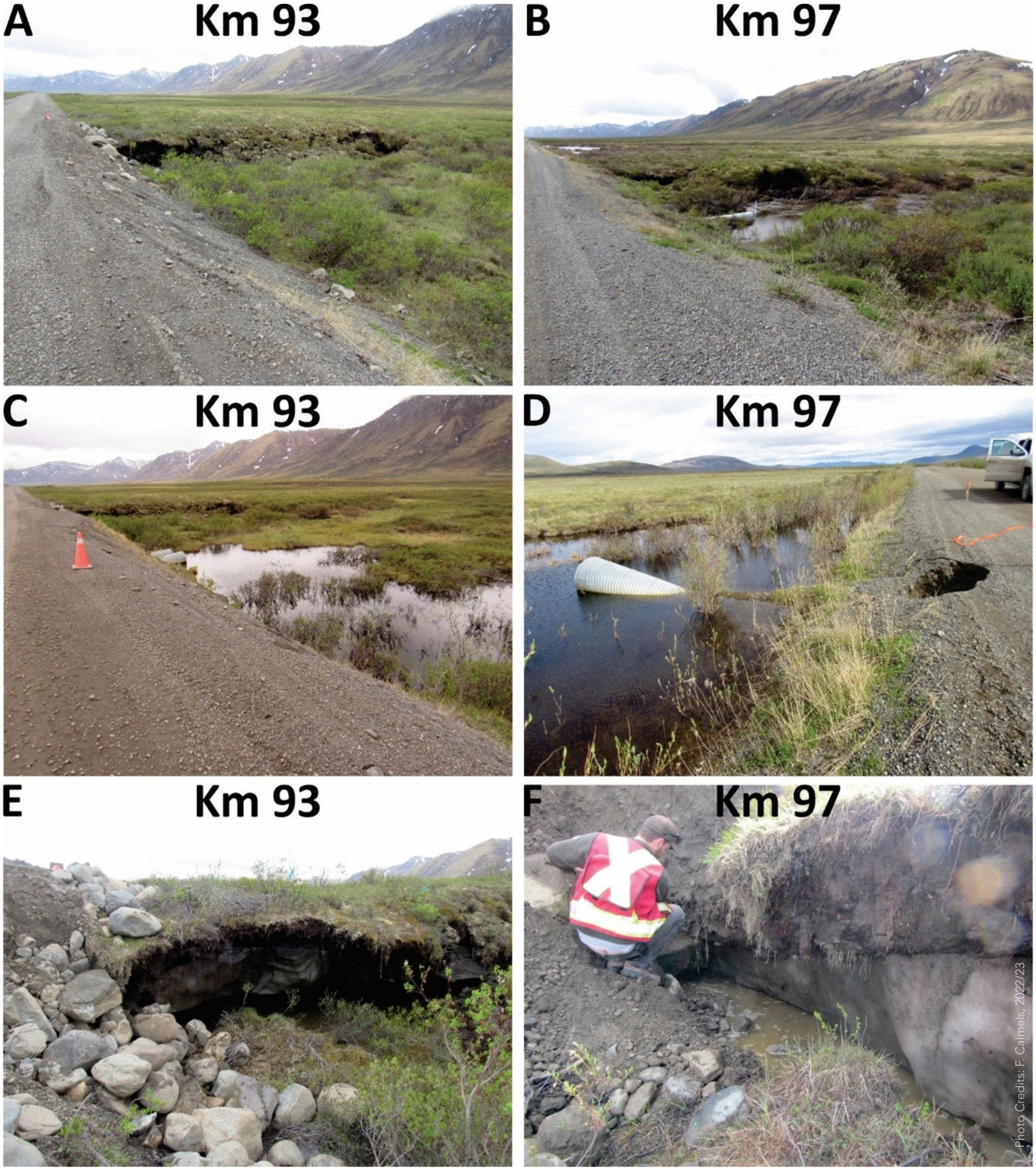


Figure 17. Sinkholes forming at km 93 and 97 of the Dempster Highway. A and B) thermal erosion of the natural ground encroaching on the embankment; C and D) water ponding at the foot of the embankment resulting in culverts failing to provide adequate drainage; E and F) ice wedges showing as a result of thermal erosion.

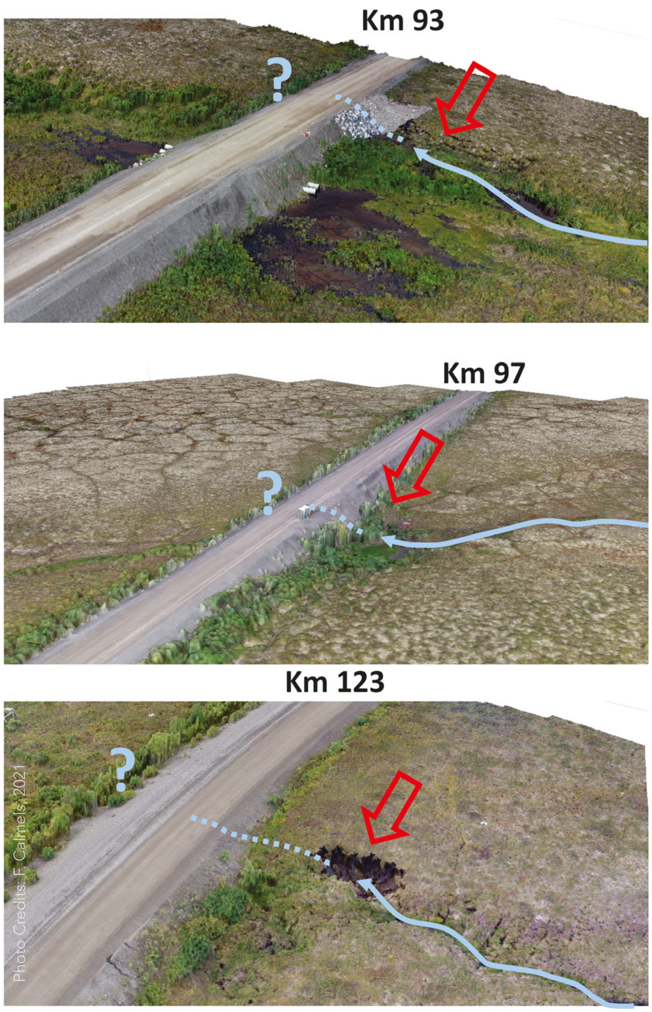


Figure 18. Photogrammetric model from UAV imagery showing the link between sinkholes and flowing water at km 93, 97 and 123 of the Dempster Highway.

wedges beneath the road leads to tunnels under the embankment, such as at km 93 and 97 (Figure 17E and F). While the erosion is directly linked to disturbances from the road at kilometers 93 and 97, in other cases the process is initiated on the land away from the road, like at kilometer 123 (Figure 18 and Figure 19).

Water flow and pooling is intricately linked to the formation of sinkholes, and therefore the increasing frequency of sinkholes reported by highway foremen could be the result of an increase in precipitation in the region that they've also reported (Yukon Government HPW, personal communication).

### 5.2.2. Retrogressive thaw slump at Chapman Lake, km 116 of the Dempster Highway

This site, referred to as Chapman Lake, is located at km 116 of the Dempster Highway on the traditional territories of the Tr'ondëk Hwëch'in First Nation. The Chapman Lake area was first studied in 2017 during the development of a climate-resilient functional plan for the Dempster Highway that was completed for Yukon Highways and Public Works (HPW) (Calmels et al. 2018).

The original assessment detected several issues in this area. In addition to major subsidence occurring along some sections of the highway, several landslides occurred close to the road embankment, where the road passes between Chapman Lake (north) and the Blackstone River (south). HPW was forced to realign the highway to the north as a result of RTS that occurred along the steep riverbank of the Blackstone River in 2006 and 2017 (Figure 20).


Figure 19. General degradation and sinkholes forming a few hundred meters away from km 123 of the Dempster Highway, in the undisturbed tundra across the Blackstone River.

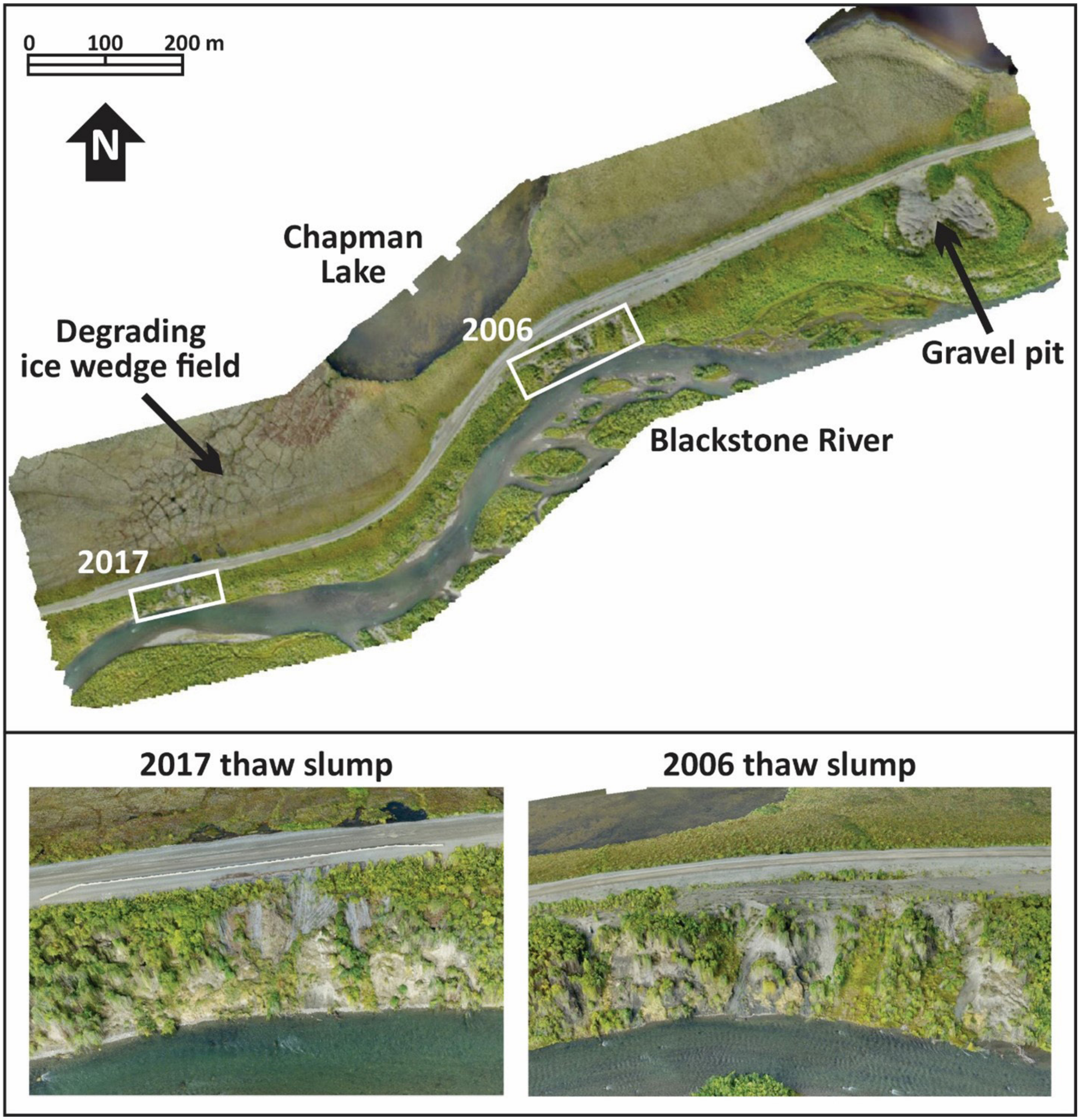


Figure 20. UAV imagery and multi-dimensional model from 2022 showing 2006 and 2017 landslides in the Chapman Lake area.

The first landslide and realignment occurred in 2006, and the slumping process was reactivated during the summer of 2017 when a second slump occurred. In 2017 ground ice was visible on the headwalls of both slumps, indicating that the thawing of ice-rich permafrost was responsible for the slumping process. It was possible to determine the type of ground ice when the embankment was moved in 2006 showing that the surface runoff-induced thermal erosion that caused tunnelling below the road was following an ice-wedge complex (Figure 21). The process was similar to the one explained in the previous section describing the sinkholes


Figure 21. Degradation observed in summer 2006 along the newly built embankment at km 116. A) thermal erosion along the left-hand side shoulder; and B) water tunneling under the embankment along an ice-wedge.

from km 90 to km 123. The exposed ice wedges on the headwalls of both slumps showed that the ice wedges were approximately 3 m wide and 6 m high (Figure 22).

The preliminary assessment showed that the thaw slumps posed a significant threat to the highway infrastructure. To determine the best remediation plan, further investigation was required. A combination of geophysical surveys and geotechnical drillings was used to characterize the ground ice distribution across the area, and a prototype for an early warning alarm system was developed for the slump, to alert HPW of impending risk.

Several Electrical Resistivity Tomography (ERT) surveys were conducted following the embankment over 1600 m, which allowed for the mapping of the ice wedge complex as well as deeper massive ice bodies (Figure 23) (Calmels et al. 2022). A total of 5 sampled boreholes as deep as 20 to 25 m deep were drilled at selected locations along the ERT lines to validate the findings from these surveys, as well as to sample both ice wedges and deeper massive ice bodies (Calmels et al. 2022). Two general massive ice complexes were identified across the site: an ice wedge complex spreading from 1.5 to 10 m in depth, and buried massive ice, likely of glacial origin, from 14 m down to over 24 m (discussed further in section 4.3.1). The sediment was sandy silt and silty sand with gravel and was generally coarser with increased depth. Coarse sediments could be the result of deposition from glaciofluvial melt water (section 3.3), which can quickly bury relict glacial ice during glacier retreat.

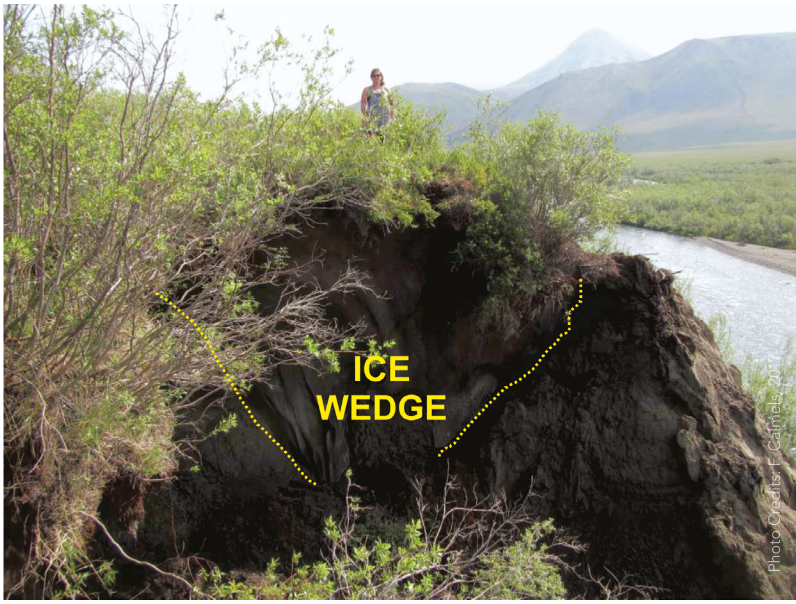


Figure 22. Headwall of the 2017 thaw slump with a visible ice-wedge in June 2017.

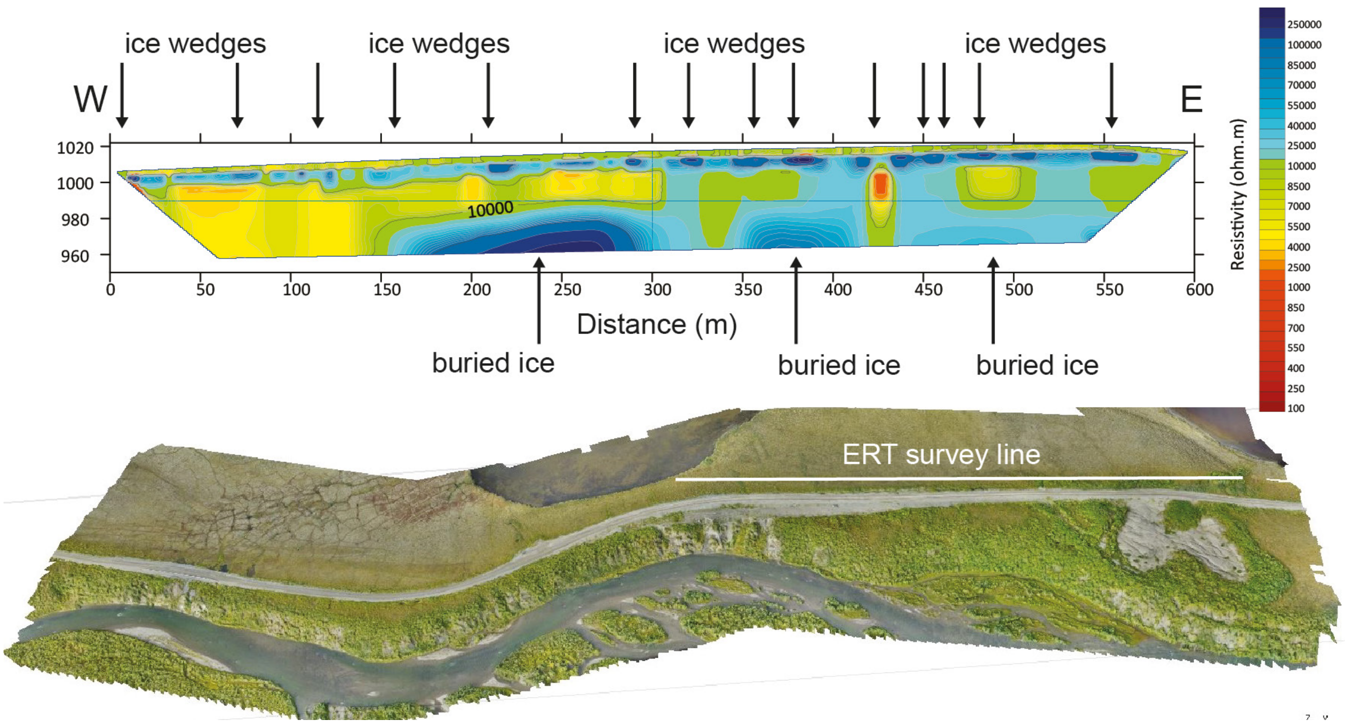


Figure 23. Example of ERT surveys at Chapman Lake site showing the presence of ice wedges and deeper massive ice bodies.

## 5.3. Buried ice

### 5.3.1. Chapman Lake, Dempster Highway km 116

The investigations aiming to characterize the retrogressive thaw slumps at km Chapman Lake led to the discovery of massive, buried ice at this location (section 4.2.2). This was not entirely unexpected, because buried glacier ice had previously been found and described in moraine sediments at km 110, only 6 km from Chapman Lake (Lacelle et al. 2007). The massive ground-ice body at km 110 was exposed following a retrogressive thaw slump on a hill along the highway. The age of the glacier ice in this location is not known, but as previously mentioned, the Blackstone uplands were likely glaciated on numerous occasions during the Pleistocene but prior to the Cordilleran glaciation.

Crystallographic observations on ice samples collected from the geotechnical boreholes confirmed that the buried ice was of glacial origin, based on the large crystal size and the homogenously distributed bubbles (Figure 24) (Calmels et al. 2022).

The ERT surveys and geotechnical investigations show that beneath an ice wedge complex extending down to approximately 10 m in depth, massive ice is present much deeper than 10 m, starting at about 15-20 m in depth and potentially extending below 25 m in depth. Observations from boreholes suggest that the thickness of this massive ice is at least 6 m in some places. When the log of the geotechnical boreholes are compared to Blackstone River and Chapman Lake water levels, the elevation of the deeper massive ice contact is almost below the water level in Chapman Lake (Figure 25). Unfrozen soil sections (orange and red areas in the ERT profile, Figure 23) were discovered in the ERT between the ice wedge complex and buried massive ice, likely representing underground water infiltration between the two ground ice complexes.

This geocryological structure suggests that, in addition to the current threat caused by the retrogressive thaw slump, the possibility exists for additional thaw by various processes. For example, ice wedges could rapidly degrade if surface water was to initiate catastrophic ice wedge thermal erosion on the surface or on the top of the slump headwall, where thermal erosion already occurs. Tunneling and gullying could quickly reach the ice-wedge network below the road and erode down

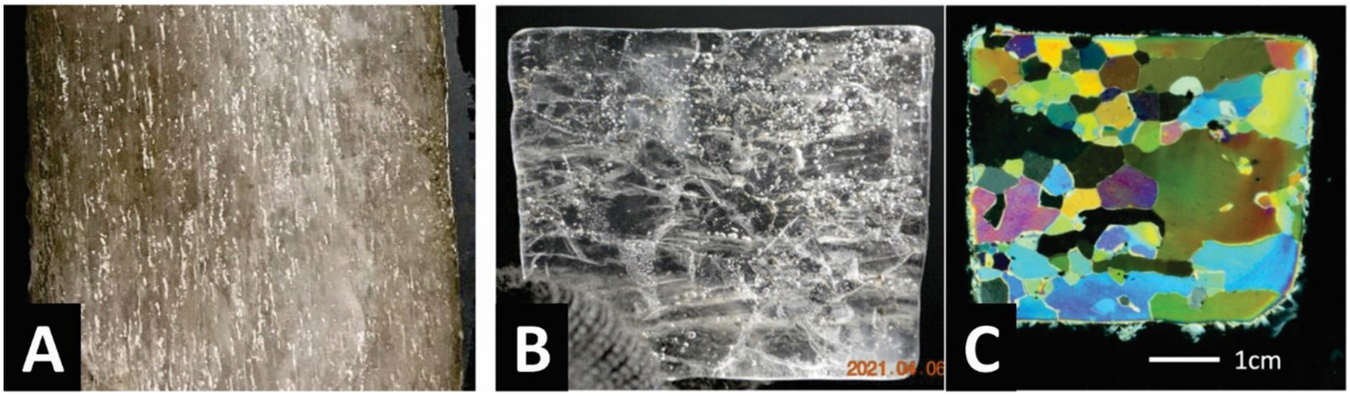


Figure 24. A) Wedge ice, B) buried glacial ice (natural light) and C) buried glacial ice (polarized light), figure from (Calmels et al., 2022).

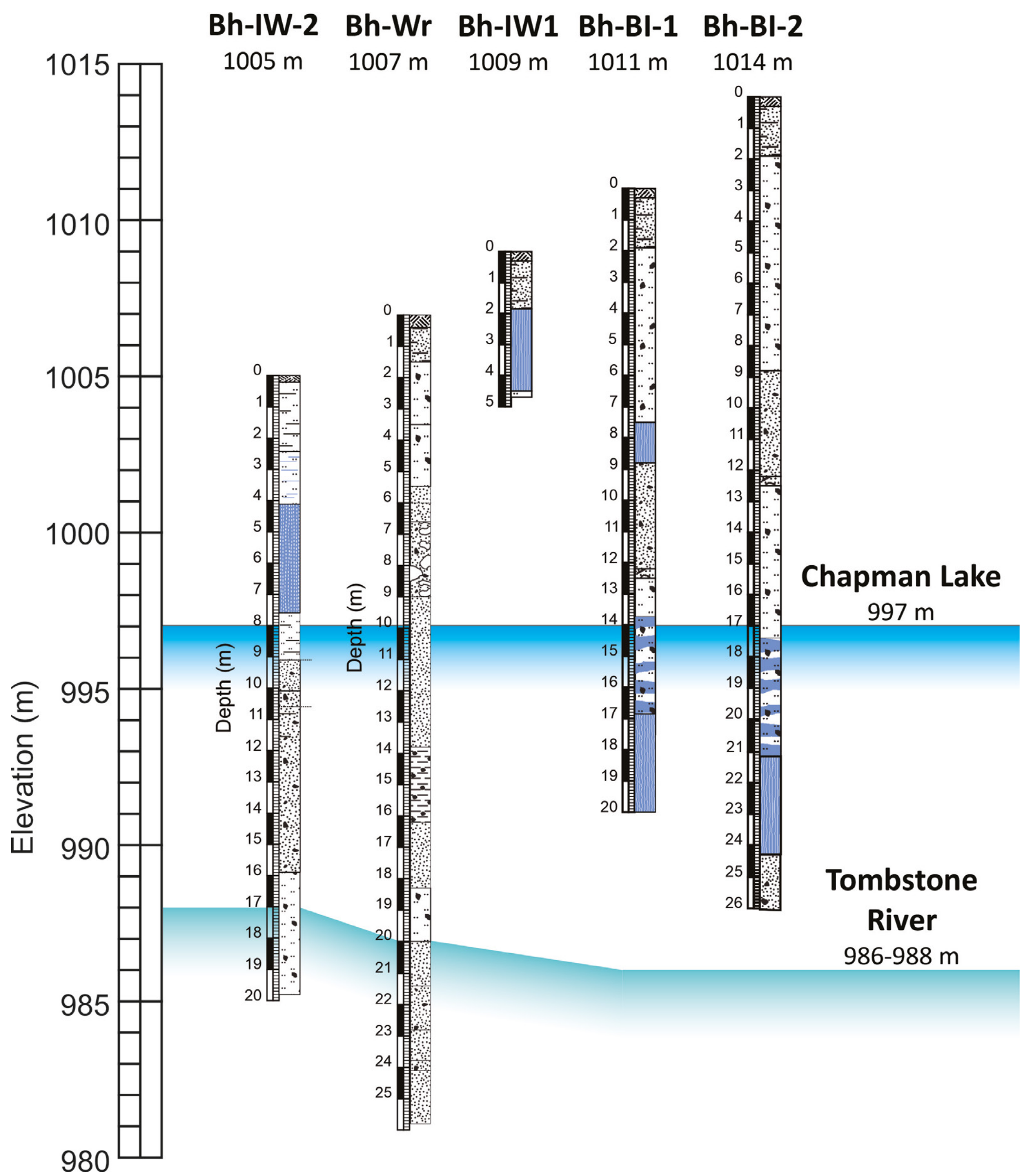


Figure 25. Borehole logs compared to Blackstone River and Chapman Lake water levels.


Figure 26. Top: Aerial image of the Carmacks bypass road; and bottom: excavated massive ground ice bodies.

to the local base level, which could be lower than the wedge ice level. Another possibility is the initiation of permafrost degradation from within and beneath the thaw slump. ERT observations suggest that sub- and intra-permafrost groundwater flow exists, first between the lake bottom and the riverbed where there might be a talik, and second between both ground ice complexes. Therefore, it is possible that this groundwater can contribute to the decay of the buried ice from the top and bottom of the ice bodies.

The combined thicknesses of upper wedge ice (up to 8 m) and of deeper massive ice bodies (> 6 m) may exceed 14 m at some locations. The difference in elevation between the lake surface and the ground surface at Bh-BI1 is 14 m (Figure 25). Should the ice melt or be removed and underground water seepage occur, the possibility of the lake draining cannot be excluded.

The combination of all these results highlights the need for ongoing monitoring at this site to anticipate or prevent a catastrophic road collapse caused by permafrost degradation, surface-ground water interactions, and potentially lake drainage.

### 5.3.2. Carmacks bypass road, km 2

Massive ground ice bodies were uncovered near Carmacks in the summer of 2022 during construction of the road for mining traffic that will bypass the town of Carmacks (Figure 26). An ERT survey was conducted based on HPW's initial

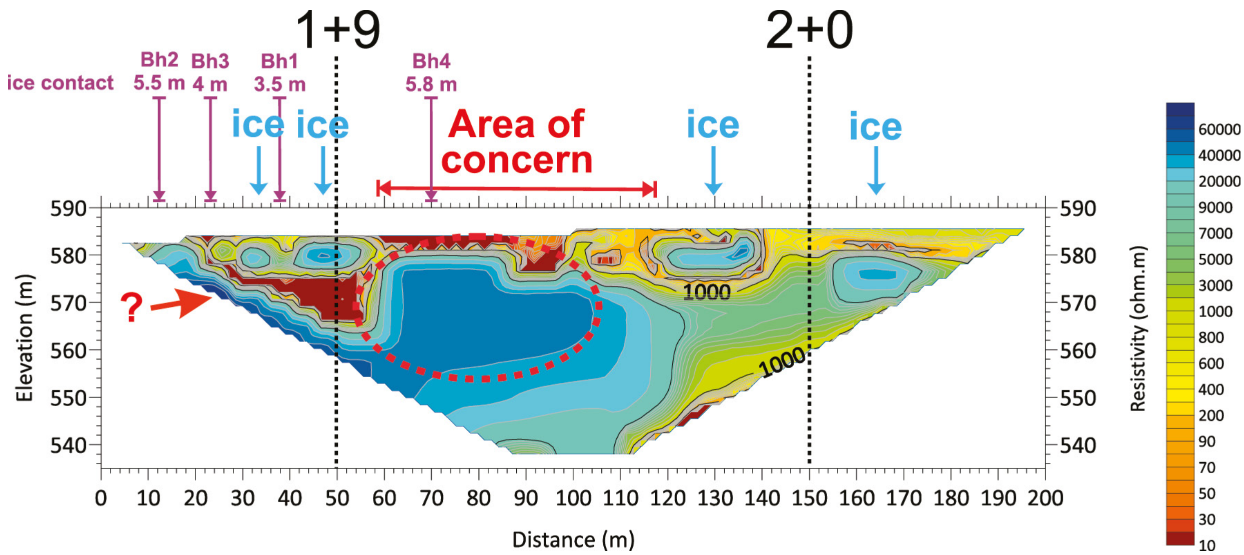


Figure 27. Electrical resistivity tomography survey on the Carmacks bypass road, (black numbers represent road chainage).

observations, to characterize the distribution of the massive ice bodies. These findings helped direct permafrost thaw mitigation efforts along the road (section 4.4.4).

Geomorphic observations confirmed that the site is located near the glacial boundary of the last glacial period (Figure 1). For example, kettle lakes, the periglacial landforms typically found in these ice contact environments, are present just 250 m southeast of the site (Figure 26). As discussed in section 3.3, kettle lakes, ponds, and holes often are present near sites of buried glacial ice. The results of the ERT surveys show that the massive ice complex spreads almost entirely along the 200-m survey line (Figure 27). The survey also shows that, from approximately 70 m to 120 m, one of the ice bodies reaches well over 10 m in depth. Several boreholes contracted by HPW confirmed the upper ice contact observed in the ERT profile but were not able to go through the ice bodies. The geomorphic context along with the ground ice distribution pattern from the ERT survey that shows clusters of ice with different horizontal and vertical extents, supports the notion that this ice is of glacial origin. Ice samples that were collected during drilling will be analyzed to confirm this hypothesis. This type of buried ice is also seen in the Dry Creek rest area at kilometer 1840 of the Alaska Highway.

### 5.3.3. Dry Creek rest area, Alaska highway km 1840

The last 200 km of the Alaska Highway in Canada, from Burwash Landing (km 1701) to the Yukon/Alaska border (km 1902) has been heavily impacted by permafrost thaw and has thus been the subject of many research and remediation studies in recent times (Calmels et al. 2015, 2016; M-Lepage et al. 2012; Reimchen et al. 2009; Stephani 2013; Stephani et al. 2010). The Dry Creek area has been extensively studied as part of a vulnerability assessment that spanned from 2012 to 2016 investigating multiple sites (Calmels et al. 2015, 2016). The Dry Creek site was the only one from the study for which issues were addressed through a three-step approach including a vulnerability assessment, adaptation strategies tailored to the site, and implementation of the adaptation design (Calmels et al., 2016).

This section of the road has frequently been damaged due to subsidence (Figure 28), in response to which multiple survey methods were used to assess the situation. These survey types included permafrost coring, geocryological analyses, ground temperature and climate monitoring, electrical resistivity tomography and remote sensing. The results showed that a 400 m section of the road is


Figure 28. Example of thaw subsidence occurring at Dry Creek, km 1840 of the Alaska Highway.

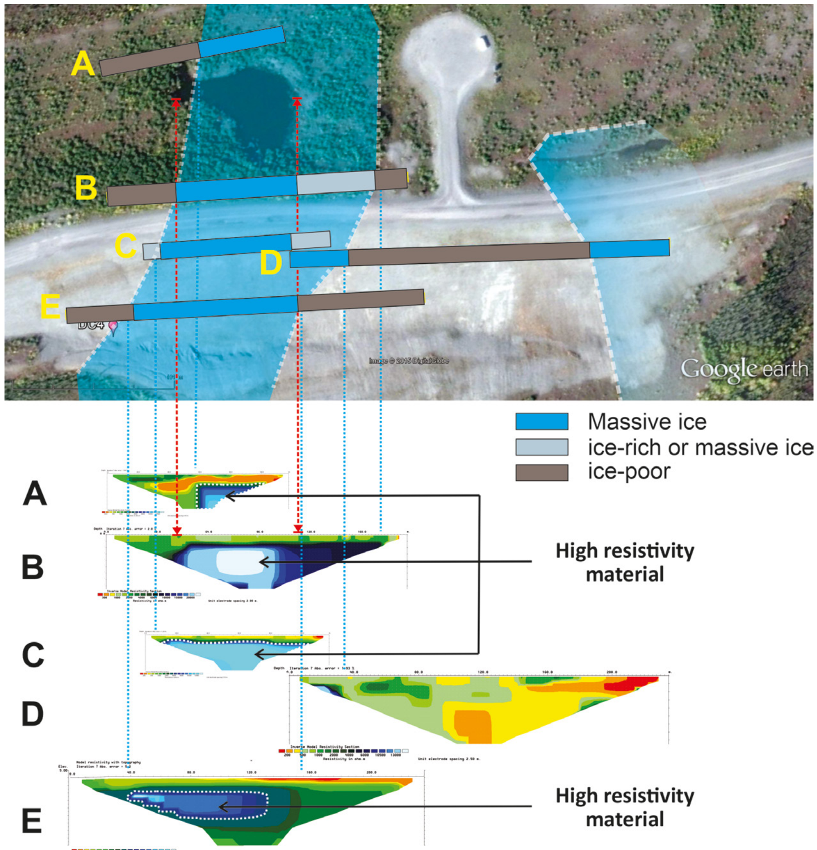


Figure 29. Massive ground ice distribution mapped using ERT figure adapted from (Calmels et al., 2015).

underlain by very-thaw sensitive permafrost. This section overlaps with a glaciofluvial unit that is highly vulnerable to thaw settlement due to the presence of massive ice observed 10 m below the ground surface.

This massive ice body is believed to be of glacial origin based on three factors. First, the site is located within the boundaries of the McConnell glaciation. Second, the massive ice is overlain by glaciofluvial material, whose quick deposition would be able to bury glacial ice quickly and effectively. Finally, there are several kettle lakes and ponds in the area, including one that is still active near the road, which suggests that there is buried ice in the area (Figure 30). ERT surveys were used to map the distribution of this massive ice, as shown in Figure 30. Multiple cored boreholes were used to validate the ERT surveys and confirm the distribution and thickness of the ice.

Based on the results from the study, three remediation options were suggested, including an air convection embankment, thermosyphons, and a heat drain coupled with a high-albedo surface. These techniques are examined further in section 4.4. Ultimately, HPW chose to implement the broad-scale use of 58 thermosyphons in 2020 (Figure 30) (Calmels et al. 2016; Stevens et al. 2019), which have stabilized this section of the highway (Elmer and Muhammad 2021). Ultimately, this eight-year project underscored the importance of considering the distribution of permafrost, how the permafrost might react to environmental changes before designing adaptation strategies, and the need for ongoing monitoring to closely assess the performance of these strategies once they are implemented.


Figure 30. Thermosyphons implemented at the Dry Creek rest area, km 1840 of the Alaska Highway.

## 5.4. Mitigation

The detrimental impact of thawing of permafrost and melting of ground-ice was a challenge to manage since the early days of the Yukon transportation infrastructure networks. When the Alaska Highway was built in 1942 by the Army Corps of Engineers, the thawing permafrost of muck bogs or muskegs necessitated the development of mitigation methods which included using available nearby trees to create a corduroy road.

More recently, diverse mitigation techniques have been tested and/or implemented throughout the Yukon. The most noticeable effort is the Beaver Creek experimental road site, an experimental road site that has been constructed on the Alaska Highway near Beaver Creek at km 1865. It was implemented to better understand permafrost degradation on transport infrastructure. The test site was constructed along a 600m length of highway in April-June 2008 approximately 8 km south of Beaver Creek and 30 kilometers south of the Canada-United States border. The site is divided into 12 different sections 50 meters in length and 40 meters wide. These sections are used to test one or several combined methods of thermal stabilization, such as convection air embankments, snow/sun sheds, grass-covered embankments, reflecting surfaces and snow clearing on embankment slopes. Those approaches aim to slow or stop permafrost degradation underneath the embankment. The choice of a technique is mostly based on site factors that vary between each location, but cost is also an important consideration.

Site factors will vary depending on the climate and geological conditions. The general climatic conditions that influence the equilibrium of the thermal regime at a place depend on its position – latitude, altitude, aspect, and slope angle- since this influences the amount of incoming solar radiation and the air temperature. These climatic conditions include air temperature, wind velocity and direction, snow depth, precipitation, and solar radiation. These data can be obtained from a site-specific climate monitoring station or a nearby climate data station. Local ground surface conditions, such as surfical vegetation, snow accumulation, terrain relief, and drainage condition, have a strong influence on the thermal energy balance at the interface between the atmosphere and ground. The level of detail required for a site description depends on the types of analysis desired for a given construction or rehabilitation project.

To protect an embankment in permafrost regions, several mitigation techniques are proposed for consideration. All have been tested on field sites and shown to mitigate either the thaw of permafrost or the effects of permafrost degradation (Goering 1998; Zarling et al. 1984). These mitigation methods can be classified into four categories:

1. Preventing heat absorption into the permafrost underneath the embankment;
2. Extracting heat to prevent additional heat absorption underneath the embankment;
3. Reinforcing the embankment, using geogrids and geotextiles; and
4. Other methods, such as pre-thawing, snow removal, and subsurface permafrost excavation and replacement.

The embankment thickening technique is based on increasing thermal resistance to protect the underlying permafrost. However, this method cannot compensate for the effects of climate warming. For the other mitigation techniques, there are different thermal effects from "passive cooling" to "active cooling". Passive mitigation methods preventing heat absorption. These methods prevent heat from entering the embankment and do not actively remove heat from the system. Active heat extraction methods provide the ability to actively remove heat from the embankment. Methods in categories (3) and (4) are mainly used to ensure and enhance mechanical stability and are used before and after the construction of transportation infrastructures. Some methods that have been tested or implemented in the Yukon are described below.

### 5.4.1. Air convection embankment

Air convection embankments (ACE) use a highly porous, poorly graded material like boulders or cobbles with a low fine content, to construct significant portions of the embankment. During winter, cold temperatures cool the surface and upper portion of the embankment, while the temperature at the base remains relatively warm due to heat accumulation in the ground during summer (Figure 31). The temperature difference between surface and the base results in an unstable air density gradient, which is balanced by air circulation in the pore space between the grains. This method enhances winter heat transfer in a porous embankment with sufficient air permeability. During summer, the embankment air density gradients are stable and air circulation will not occur. The rock layer begins to function as a thermal insulation barrier due to the low thermal conductivity of air and relatively small contact area of

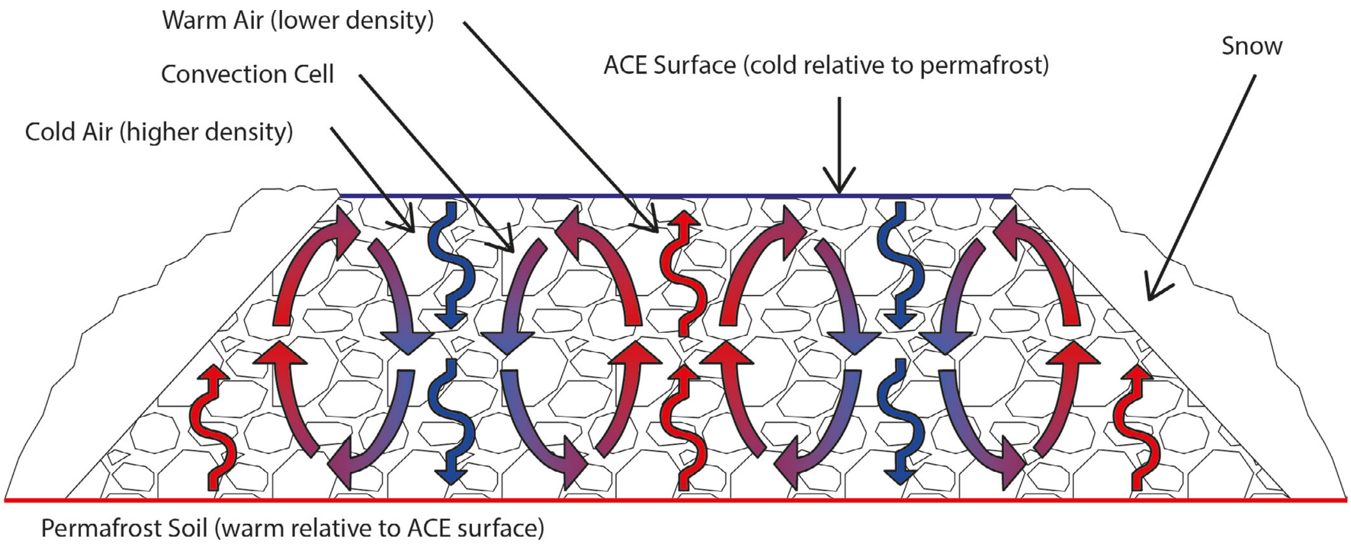


Figure 31. Pattern of winter-time pore air circulation (Jensen 2015).

the stones (Goering 1998). It is a promising technique (López et al. 2024) that has been successfully implemented at the Beaver Creek experimental road site.

### 5.4.2. High albedo surface

A high albedo surface (HAS) is a passive mitigation method, which is based on reducing heat intake on the surface of embankment. This method was tested at km 1786 of the Alaska Highway and at the Beaver Creek experimental road site (km 1865). A HAS is typically created by coating the road surface with a high-albedo treatment or using a light-colored aggregate in a bituminous surface treatment (BST). Weaknesses of HAS include the costs of initial coating application, the potential for decreased traction, and possible high maintenance costs due to frequent recoating. To overcome these, it is necessary to respect the technical specifications for coating products made for northern regions.

### 5.4.3. Insulation

Thermal insulation is a passive method to protect permafrost by increasing thermal resistance (Cheng et al. 2004; Stockton et al. 2021). Although insulation may not stop the rise in the mean annual ground temperature and the deepening of the permafrost table, it may delay or stabilize permafrost degradation. In summer, thermal insulation acts as "cold preservation", which can reduce heat absorption. However, in winter, permafrost is warmer than the atmosphere, and the thermal insulator has the effect of "heat preservation", which can decrease heat extraction. It is more effective if used in combination with heat extraction methods, such as ACE or HD. It was most recently implemented at km 2 of the Carmacks bypass road site discussed in section 4.3.2.

### 5.4.4. Snow/Sun sheds

Snow/sun sheds are both an active and passive mitigation method used as a physical barrier to protect embankment slopes during winter and summer (Figure 32). They are constructed of plywood and metal braces, with a reflective roof that rests less than a metre off the surface of the embankment slope. In the winter, these structures protect embankment slopes from snow accumulation causing thermal insulation and they promote cold air circulation beneath them, cooling the permafrost. In the summer months, the reflective roof reduces solar radiation on the embankment slopes. The snow/sun shed has been effective at reducing the ground temperature at the Beaver Creek experimental road site (López et al. 2024; Stockton et al. 2021).

### 5.4.5. Thermosyphons

Thermosyphons are an active thaw mitigation method to remove heat from the soil and decrease the subsurface temperature in permafrost regions. This method is most suitable for severe localized issues like that of the Dry Creek rest area site, at km 1840 of the Alaska Highway, presented in section 4.3.3. Typically, thermosyphons consist of a sealed, fluid filled tube with an upper part above the ground working as a condenser and a buried part in the ground functioning as an

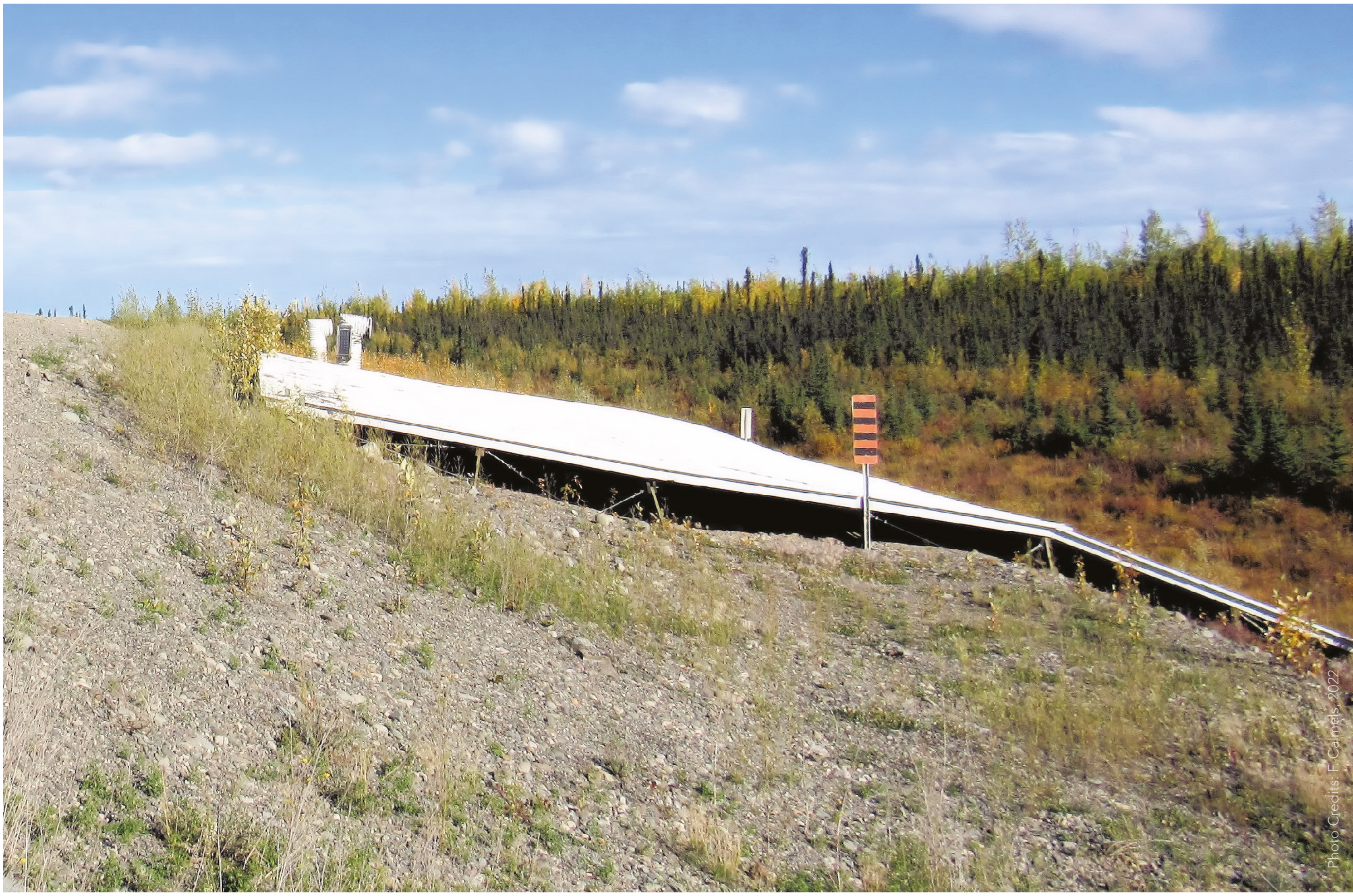


Figure 32. Snow/Sun shed built at the Beaver Creek Test section of the Alaksa Highway.

evaporator. Most condensers have fins to create a better surface area available for cooling. The most commonly used working fluid is carbon dioxide ($CO_2$), while ammonia and butane are also used. The advantages of $CO_2$ thermosyphons are that they have low maintenance costs, no operating cost, and are environmentally friendly. To trigger heat transfer, a temperature difference of at least 1°C between the condenser (air) and the evaporator (underground) is needed. Heat transferred from the ground exposes the fluid contained in the evaporator to warmer temperatures. The liquid evaporates and vapor rises along the pipe. When the vaporized fluid reaches the condenser and is exposed to colder air (outside), condensation takes place. The condensed fluid is then pulled down to the evaporator by gravity and the cycle is repeated. Whenever air temperature is warmer than the soil temperature, the cycle stops.

### 5.4.6. Snow compaction

Snow compaction is a passive mitigation method that attempts to lower the thermal resistance of the overlying snowpack. Deep, less dense snow insulates the ground and prevents release from the ground. In contrast, by compacting the snow and creating a thinner, denser layer of snow, the thermal resistance of the snowpack decreases, and heat can be released. Jardine and Burn (2024) tested this mitigation method with snowmobiles compacting the snow once a month throughout winter. The test-site ground surface temperatures were reduced by approximately 1°C, although the effect on subsurface temperatures were not tested in this study. This is a simple effective method with a low-cost, however, the large-scale viability is yet to be tested.

# Conclusion

The studies of permafrost along Yukon Highways that are described in this chapter illustrate how the geohazards impacting terrain stability are often directly linked to the melting of ground ice within permafrost. This melting has the potential to cause infrastructure failure, as illustrated in the previous examples.

Although the disturbance caused by the roads themselves may be sufficient to induce degradation, climate change has the potential to increase the quantity and scale of many disturbances on permafrost. While permafrost may thaw gradually, extreme events such as heavy rain, heat waves, and unusually warm summer temperatures exacerbate and accelerate the phenomenon. As ground temperature increases, the mechanical properties of permafrost change, especially as ground temperature approaches 0 °C. As a result, processes such as landslides tend to increase in frequency, notably after heavy rain or heat waves.

The examples described in the chapter highlight the important role that two specific features have on road stability, which have previously been underestimated: groundwater and buried ice. Groundwater flow is a relatively new consideration for the management of transportation infrastructure in permafrost environments, yet it may be at the root of many of the problems caused to the infrastructure (McKenzie et al. 2021). Therefore, assessments and ongoing monitoring of hydrogeomorphology should be taken into consideration when assessing sites and creating mitigation plans. Buried glacier ice has been exposed and described along all major Yukon highways. These massive ground-ice bodies have typically been exposed following retrogressive thaw slumps or excavations, mainly on hillsides near the highways. The age of glacier ice can vary based on the glacial limit at these locations, and the complex glacial history in the Yukon makes it difficult to draw conclusions on the age without chemical analyses. Though the ice tends to be difficult to detect before degradation occurs, knowledge of the local glacial history and an understanding of geomorphic landforms can help predict its presence. Therefore, mapping ground ice types and amounts is essential for infrastructure design, repair, and maintenance. This action is especially important for choosing engineering solutions to keep the permafrost frozen and to stabilize the infrastructure for as long as possible.

Finally, many permafrost-induced geohazards, such as retrogressive thaw slumps, are preceded by pre-conditioning processes such as localized heat flow, ground water flow, thaw settlements, and deformation. Therefore, it is possible to anticipate the failure, notably by installing arrays of sensors connected to a warning system at vulnerable sites. The nature and configuration of such an array must be based on proper site characterization where the permafrost conditions are analyzed, the potential hazard identified, and related preconditions and processes considered.

In the last decade, many applied research projects, including the studies presented in this chapter, were funded by Transports Canada's Northern Transportation Adaptation Initiative (NTAI) and presented in the Compendium of Permafrost Reports: Northern Transportation Adaptation Initiative (NTAI) 2011-2021. These works are instrumental to establish resilient northern transportation infrastructure built in the permafrost environment that are being increasingly challenged by the growing impacts of climate change. More recently Transports Canada's National Trade Corridors Fund program has continued to help northern agencies to prepare for the development to develop resilience for northern transportation infrastructure.

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# PART 7

## Recent hydrological extremes provide insight on the impact of climate change on watersheds of Yukon

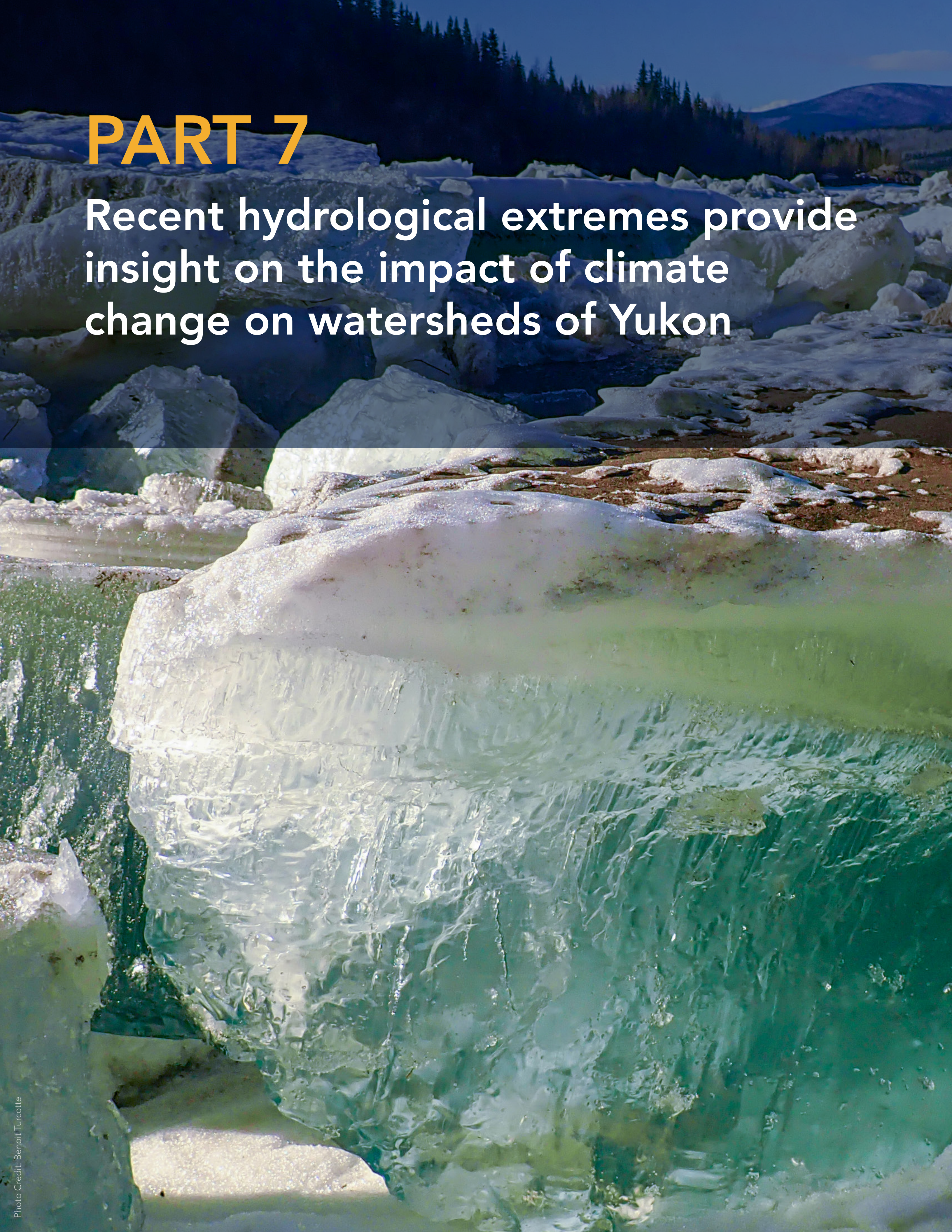
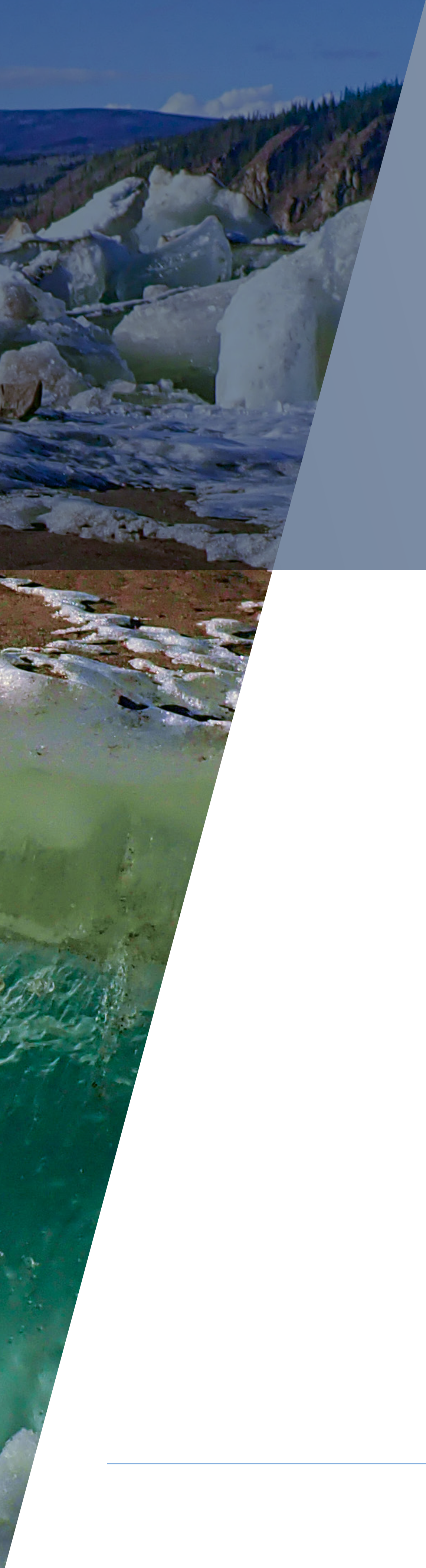


Photo Credit: Benoit Turcotte



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# Abstract

Life in the North has always been intimately linked to water. Rivers and lakes provided food and facilitated transportation for millennia before Europeans explored the region, and surface water continues to play a central role in the life of Yukoners today. Traditional ways of living, healthy ecosystems, energy production, transportation of goods, the mining industry, and recreational activities all depend, at different levels, on an understanding of the hydrological regime of watersheds.

Climate change affects several components of the water cycle, but the net impact on river flows and lake levels remains largely unknown. This may sound surprising in a northern context where changes to the landscape and rising average air temperatures have been reported for decades. However, hydrological responses to a changing climate are complex, resulting in a lack of statistical trends in hydrometric datasets on a variety of watercourses and water bodies. Warmer temperatures and altered precipitation patterns affect several variables of the water cycle through positive and negative feedback loops with net effects that are difficult to understand or predict. The occurrence of more frequent weather extremes also obscures the expected, gradual shift in hydrological conditions.

This chapter proposes a simple approach to evaluate the impact of climate change on the quantity of water in Yukon river systems. It identifies a few confirmed trends in historical data sets but emphasizes extreme events for a simple reason: they cause more damage and socio-ecological concerns than changing average conditions.

This chapter describes unusual hydrological events that have occurred throughout the Yukon in recent years. The knowledge obtained from the analysis of these events is used to develop two prototype, conceptual models that can evaluate the impact of climate change on several hydrological hazards, with a focus on flooding processes.

# Recommandation

Future steps for this research, in Yukon and in other cold regions, would include:

- Accurately documenting extreme hydrological events, especially those informing land use and infrastructure design.
- Conducting more research on the morphological impact of extreme weather and hydrological events on river channels.
- Investigating the hydrological impact of climate change on small creeks.
- Proposing tangible water management and infrastructure design adaptation measures for industrial sites such as active and decommissioned mines.
- Supporting studies about the frequency and intensity of atmospheric rivers (intense rainstorms from the Pacific Ocean) and their future impact on coastal and inland watersheds.

# 1. Introduction

Yukoners are fortunate to live in an environment with relatively pristine water. Groundwater, wetlands, glaciers, streams, rivers, and lakes support all forms of life and are essential to northern communities. With changing climate conditions resulting from global greenhouse gas emissions, different components of the water cycle are adjusting, and this materializes in a spaciotemporal redistribution of water in small and large catchments. For instance, in several areas of Yukon, the porosity and hydraulic conductivity of the ground is increasing as permafrost thaws, consequently opening new, slower flow paths towards streams and lakes (e.g., Painter et al. 2022). In the southwest corner of the territory, the surface of glaciers becomes exposed to sun radiation earlier in the summer, resulting in a significant ice mass loss through melting before a new snow season begins (Painter et al. 2022).

It could be expected that observed and measured changes in weather and the landscape translate into a progressive (statistically detectable) shift in hydrological conditions (such as average annual flow) in most watersheds of the territory. However, identifying, understanding, and foreseeing these shifts in northern watersheds may be challenging for several reasons:

- **The many frequencies of climate**: Climate is defined by weather conditions over long periods. In addition to the progressively changing climate induced by humans over decades, multi-year cycles (such as El Niño / La Niña), year-to-year variability, and seasonal patterns all define weather conditions that are influencing elements of the hydrological cycle. These patterns can be considered as waves of distinct amplitude traveling at their own speed, with possibilities to cancel one another or to become superimposed at specific locations and times. As a result, hydrological events such as floods or droughts may depend on several climatic components coinciding.

- **Multiple hydrological drivers**: The amount of water that reaches the outlet of a river at any given time is the result of a sequence of interconnected drivers that either accentuate or attenuate specific hydrological processes. Climate change may bring unexpected outcomes in particular contexts due to contrasting effects and the response may be far from linear. For instance, winters may become warmer and therefore shorter, which would tend to reduce the occurrence of snowmelt spring floods. However, increased precipitation yields can have the opposite effect, resulting in a significant end-of-season snowpack that promotes high snowmelt runoff rates.

- **Unique hydrological dynamics**: Each watershed in Yukon is unique in terms of gradient, elevation, presence of glaciers, vegetation coverage (and vulnerability to forest fires), permafrost distribution, and aspect (i.e., alignment). Therefore, specific climate trends or general shifts in weather patterns should not be expected to generate uniform hydrological responses over large areas.

- **Performance of hydrological models**: The capacity of deteministic hydrological models to calculate the amount of water entering or exiting a river system (i.e., water balance and runoff routing models) is restricted by two factors: the poor availability of quality input parameters and the lack of cold regions-adapted equations meant to calculate energy fluxes and water balance components. In the short term (e.g., up to 10 days), the performance of hydrological forecasts is limited by the availability of measured weather data (e.g., precipitation) as well as by the accuracy of weather forecasts. It is therefore not surprising that, for the long term (e.g., over the next decades), models fed by uncertain or inaccurate future weather scenarios produce incorrect hydrological projections. In addition, hydrological models are often calibrated for a range of common flow conditions, which may reduce their performance when simulating extreme events associated with rare or unseen weather patterns. Finally, most models are not developed to emphasize winter processes such as the freeze-up discharge depression or the occurrence of ice jam release waves (Turcotte and Rainville 2022), and this means that hydrological models are largely inaccurate from October to May in most Yukon watersheds.

- **Post-Little Ice Age adjustments**: Parts of the Yukon are considered young from a fluvial geomorphology perspective, with major landscape adjustments that took place following the Little Ice Age (which chronology was re-questioned and redefined, e.g., Clague et al. 2010). For example, the current location of the community of Haines Junction was under Alsek Lake, dammed by the Lowell Glacier, less than two centuries ago (Clague and Rampton 1982). In addition, post-glaciation crustal uplift rates in the St. Elias Range are among the highest in Canada (Simon 2024). This means that some river channels and lakes are not close to reaching equilibrium (i.e. what scientists and engineers may refer to as "normal conditions") independently of climate change, a reality that mostly applies to Southwestern Yukon.

This multifaceted complexity may explain why relatively few statistical trends have been extracted from the analysis of recent hydrometric records (e.g., Government of Yukon 2021; Janowicz 2010; Turcotte 2021) and why opportunities still exist to significantly improve hydrological projections. The occurrence of extreme events, either dry or wet, also prevents the detection of robust trends from hydrological records. It is not uncommon that trends that were statistically significant weaken after the occurrence of an extreme event (e.g., Government of Yukon 2021).

Why should we care about environmental processes with uncertain historical and future trends? Simply because they have a direct impact on multiple aspects of living in the North, from traditional activities (e.g., Southwick and Ballegooyen, 2019) to the design, operation, and maintenance of infrastructure (e.g., Hancock et al. 2022). A significant effect of the warming climate on the risk that hydrological processes represent to people and northern communities comes not only from gradually evolving average conditions that drive progressive (and sometimes irreversible) changes to the land and water, but mostly from the same weather extremes that are blurring the climate change impact signal. Based on Figures 4.20 and 4.21 in Canada's changing climate report (Zhang et al. 2019), the frequency of hydrological events that have morphological and societal impacts on river systems is expected to continue its rising trend, and this represents a serious concern.

This chapter considers the hydrological impact of climate change from atypical angles. After a general presentation of Yukon's watersheds, it reports on the very few robust hydrological trends associated with climate change since the 1970s. The core of the chapter focuses on the present period and describes recent hydrological extremes that align with the expected impact of climate change. Finally, the last part of the chapter contemplates the future of river systems from a science-based, conceptual angle.

# 2. Yukon watersheds

Yukon is dry compared to other areas of Canada, with only 250 to 400 mm of precipitation falling every year at low and mid-altitude, and up to 800 mm in mountain terrain (even more in parts of the St. Elias Range). Based on recent evaluations, a significant fraction of this precipitation (10 to 30%, or more in low gradient and wetland areas) either sublimates, evaporates or is transpired by the vegetation. This means that the quantity of water flowing in streams and rivers divided by the area of the watershed (typically expressed in $m^3/s$ per $km^2$ or mm/year) is low, a statement that applies to annual average flows, minimum flows, and peak flows. In addition, many small (headwater) channels are sensitive to weather extremes, either dry (when evaporation can exacerbate low flow conditions) or wet (when runoff overwhelms stream channels).

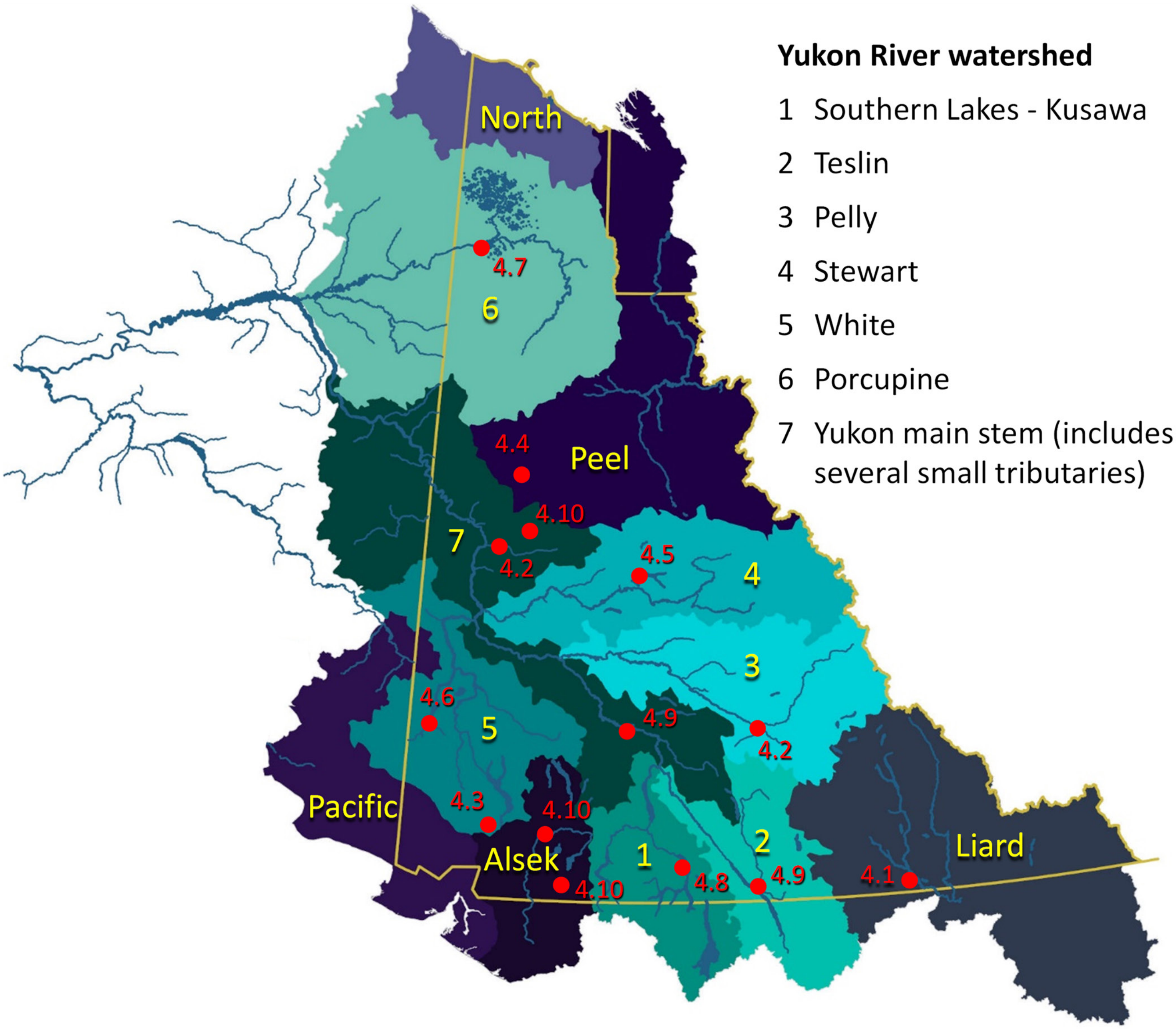


Figure 2.1. Watersheds of the Yukon. The numbered watersheds are part of the Yukon River drainage basin that flows into Alaska. Red dots refer to specific events described in Section 4.

Most watersheds in the Yukon (Figure 2.1), are dominated by a snowmelt regime whereby spring snowmelt generates the highest flows and accounts for a large ratio of the annual cumulative flow. In these watersheds, peak flows generally occur between mid-May and late-June. Some watersheds also present a strong glacier influence (i.e. Pacific drainage, White River, Alsek River, and Southern Lakes and Kusawa drainages; Figure 2.1) with peak flows that occur later during the summer period. All watersheds may also see an increase in flow rates later during the summer or fall as a result of rain events. This is especially true for small (sub) watersheds affected by intense rainstorms. As presented in Figure 2.1, roughly 70% of the territory (480 000 km$^2$) is drained by the Yukon River and its tributaries, including the Porcupine River.

This work attempts to respectfully acknowledge First Nations who have been living on these lands for thousands of years. In a perspective of reconciliating worldview and decolonizing science, known traditional names for rivers and lakes are used in the following sections of this chapter.

# 3. Looking back

Canada's changing climate report (Zhang et al. 2019) summarizes the spatial evolution of annual and seasonal air temperature across Canada during the period 1948-2016. Among the available information, it is reported that the Yukon has warmed by about 2°C to 4°C during that period, and by more than 5°C during winter months (Dec. to Feb.). The main factor influencing hydrological conditions in any given watershed is precipitation, but unfortunately, the statistical link between precipitation data and river flow estimates is unclear and contains inconsistencies. For instance, between 1948 and 2012, Zhang et al. (2019) report an increase in annual precipitation by 10% to 30% in most of the Yukon with the largest rise (30% to 50%) detected during the winter period in the Ch'oodeenjìk (Porcupine River) watershed and Beaufort Sea drainages (North Slope). In the same report, figures derived from Mudryk et al. (2018) state that the maximum snow water equivalent (SWE; the snowpack expressed in mm of water) in the same part of the Yukon decreased (by 2% to 5%) during the period 1981-2015. Looking at flow data from the Water Survey of Canada (WSC) hydrometric station on the Ch'oodeenjìk at the Alaska Border (09FD002), stable streamflow with great variability in both peak flow and average May-June flows (snowmelt period) over the period 1969 (the earliest data on record) to 2016 are detected, but a rising trend (0.5 to 0.6% per year) for the same parameters is obtained when emphasizing the period of 1981-2015.

This means that, based on current records, one could not confidently state that climate change is causing significant modifications to the hydrological regime of the Ch'oodeenjìk. Comparable results are obtained in other corners of the Yukon. This illustrates the need for more consistent monitoring in all parts of the territory (e.g., weather stations and snow courses), but it also confirms the great complexity of a watershed's hydrological response to the multiple components of regional climate. The few robust statistical hydrological trends in the territory that can confidently be attributed to a changing climate are:

- **The period of the year when rivers and lakes are covered with ice is becoming shorter**: Warm air temperatures represent a key driver of this trend, but there is also an indirect link through warmer and more abundant groundwater. Interestingly, though, the ice cover in some Yukon rivers is relatively resilient, which suggests that, at high latitudes, the formation and decay of river ice strongly depends on the energy provided by the sun. For example, the beginning of the river ice formation period in the Chu kon' dëk (Yukon River in Hän) upstream of Dawson has been essentially stable since the 1970s (based on WSC records) and the Chu kon' dëk breakup date at Dawson has only advanced by one day per decade since the 1970s. Based on a record starting in the late 1890s, Jasek (1999) reported a similar shift of 0.5 day per decade. Trends in ice cover season duration, where they exist, do not represent a significant hydrological risk to infrastructure and communities, but they impact traditional activities (e.g., on large lakes), transportation (e.g., ice bridges or ferry operations) and ecosystems.

- **Minimum winter flows are increasing**: The Yukon state of the environment interim report (Government of Yukon 2021) clearly highlights that minimum flows in most watersheds are increasing. Minimum flows in Yukon rivers occur just before the onset of snowmelt. The analysis of hydrometric data from the WSC network reveals that winter flows are consistently increasing over the years in a large majority of watersheds. This is the result of a shorter winter period (as described above), but permafrost degradation (which produces a thicker active layer that can store more water) and increased precipitation during the fall also influence baseflow. Higher winter flows can lead to dynamic river ice formation processes and to intense ground icing (aufeis, ice formed by the freezing of successive overflow events, Turcotte et al. 2023a), two processes that may affect people and communities.

- **Higher summer flows downstream of large glaciers**: Large glaciers are mostly found in the Southwestern corner of the Yukon, in the St. Elias Mountains. A wide range of possible weather conditions are causing high runoff rates downstream of these glaciers, from warm and dry periods to rainstorms. However, very few glacier-fed rivers in the Yukon (or on the British Columbia side of the Yukon River watershed) have been consistently monitored; therefore, this interpretation is derived from statistical trends in Southern Lakes and from a study presented by Rousseau et al. (2020). In the latter case, simulations indicated that the glacier melt contribution to the annual hydrograph would increase until the late 2030s before initiating a decline resulting from a significant cumulative ice mass loss.

Other climate change hydrological trends that are expected and that represent a moderate to significant risk or societal concern, but that are simply not detected in most hydrological records include:

- **An earlier spring freshet (snowmelt period)**: The rising limb of the spring snowmelt flow seems to occur earlier in some watersheds (e.g., 'At'aayaat Chù', White River), but this signal is inconsistent. The freshet tended to occur earlier in several rivers of the territory between the 1960s and the 1990s, but this shift stalled for most hydrometric stations in the 2000s.

- **Higher water levels associated with different hydrological processes**: Turcotte (2021) identified a single case of rising peak flows over time (Ch'oodeenjìk, Porcupine River), but generally, either declining peak flows or no trends were identified. The Government of Yukon (2021) observed similar results for peak flow (open water events).

- **Higher annual average (or total) flow**: This trend is only detected in some watersheds (e.g., Ch'oodeenjìk and Tr'ondëk (Klondike River)) as well as in rivers with a summer flow dominated by glacier melt (as described above). In turn, areas of shrinking or vanishing glaciers are associated with declining or low summer flows, respectively.

- **The occurrence of mid-winter breakup events**: Beyond a higher rate of traffic accidents resulting from icy road surfaces, rain events during winter can cause runoff events that trigger ice cover breakup, ice jams, and floods. Fortunately, these events are not yet affecting Yukon watersheds. The mid-winter breakup event reported by Janowicz (2010) in the Tr'ondëk was likely a freeze-up jam that was not caused by a runoff event (Turcotte and Nafziger, 2021).

In the end, despite obvious changes in weather patterns over recent decades, most Yukon watersheds are demonstrating an unexpected statistical resilience. Even if gradual changes were observed in all corners of the territory, they would represent a moderate concern in terms of hydrological risk compared with an increased dispersion, range, or envelope of possible flow and water level scenarios. Understanding average hydrological conditions can be useful in specific circumstances (e.g., planning annual hydroelectric production); however, hydrological extremes and associated hazards represent, by far, the primary incentive for adaptation.

# 4. Looking at current conditions: recent hydrological extremes

Different approaches exist to describe hydrological hazards. The analysis of Yukon hydrometric records, as presented in the previous section, does not offer much insight, and could even mislead adaptation efforts. Presenting annual water-related damage data effectively reflects the evolving flood risk over time, but this information is rarely collected consistently and cannot be easily accessed. This section focuses on reading the present. It describes current hydrological risks by telling the story of recent significant hydrological events.

## 4.1. Southern Yukon floods of 2012

In June 2012, an unusually intense rain-on-snow event took place in southeastern Yukon. This caused washouts along the Alaska Highway and the interruption of the supply of goods to Yukoners for several days. As Allan Nixon, Yukon's assistant deputy minister of highways, expressed (CBC 2012a): "*As people know, we've had a fairly unprecedented event right across the Yukon. […] Our crews have been working non-stop here to get the roads reopened.*" Damage, including the impact of a breached dike, was reported to reach \$8M, mostly because of washouts, mudslides, and damage in Upper Liard (CBC 2016).

Figure 4.1.1 shows how the June 2012 runoff event was exceptionally high for the Liard River at Upper Liard (watershed area of 32,600 km$^2$) and for the Rancheria River near its mouth (5,100 km$^2$) compared to the historical range (62 years of data for the Liard River, 38 years for the Rancheria River). Interestingly, the snowpack in the Liard watershed was not historically high at the end of winter 2012 (estimated between 130% and 150% of normal, based on data

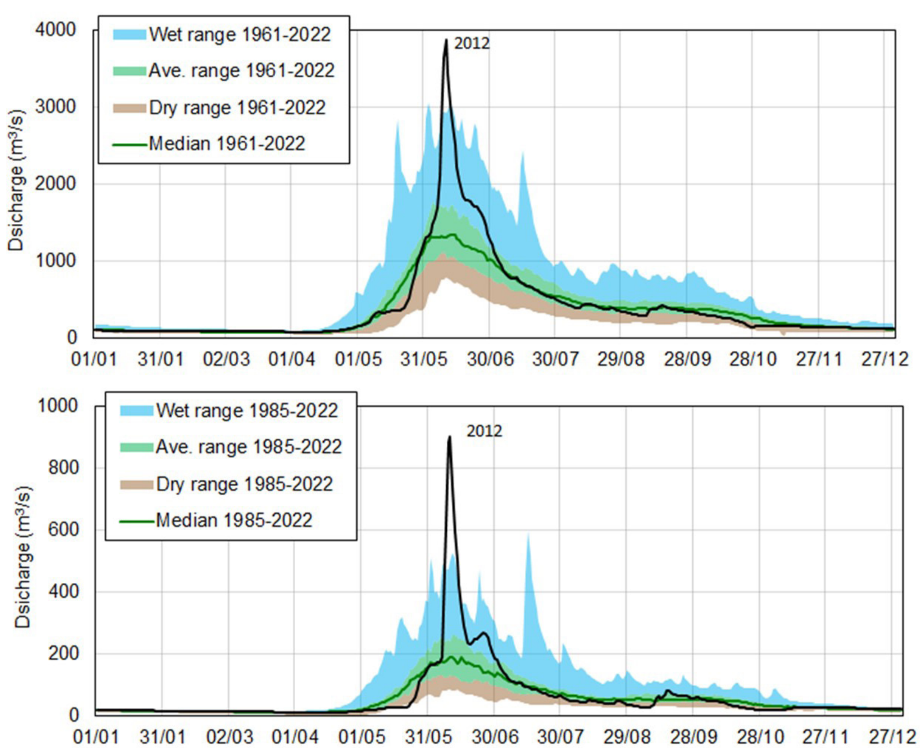


Figure 4.1.1. Historical hydrograph ranges and 2012 hydrograph of the Liard River (top, Water Survey of Canada station 10AA001) and Rancheria River (bottom, 10AA004). Daily average data is presented.

provided by the Yukon Government 2012). It seems that the rain event of June 5-7, with a total accumulation of 50 to 70 mm in 72 hours in Watson Lake, including 35 mm in 24 hours (more rain might have fallen at remote locations), played a significant role in this record flood.

Based on the analysis of hydrometric data, this flood is associated with a return period of 100 years (which means that a higher flow has an annual probability of less than 1%) for the Liard River and 200 years for the Rancheria River. Although this assessment implies some form of engineering judgment, the event certainly represents one of the greatest open water (flow) anomalies in the recent history of Yukon.

In 2022, the late winter snowpack in the Liard River watershed was estimated to be twice the normal (200%, Yukon Government, 2022), and this snow melted later than usual. The resulting instantaneous peak flow in the Liard River was only 3000 $m^3/s$ (compared with almost 4000 $m^3/s$ in 2012), and 550 $m^3/s$ (compared with almost 1000 $m^3/s$) for the Rancheria River. What are the 2012 and 2022 events telling us? That nature has the potential to produce even higher flows if a winter with a significant snowpack (like in 2022) is followed by a sudden rise in air temperature with heavy rain (like in 2012).

## 4.2. Rock Creek floods of 2023

The community of Rock Creek and the nearby Hamlet of Henderson Corner were significantly impacted by two consecutive floods in May 2023. These floods were preceded by a winter characterized by a very dynamic freeze-up in the Tr'ondëk (Klondike River, located in the Traditional Territory of the Tr'ondëk Hwëtch'in First Nation) in November and December (2022) and by above-average snowfalls in the Dawson region. The snowpack continued to thicken until the end of April, resulting in a 200% SWE anomaly on May 1 (twice the normal, Yukon Government 2023).

The first flood was caused by a series of breakup ice jams that remained in place under a surprisingly high discharge (in the range of the average annual peak flow, 450 $m^3/s$). Tens of properties were flooded or isolated, and the Klondike Highway, the only ground transportation link to Dawson, was temporarily closed. The flood response was a real challenge, with the presence of several ice jams over a short distance of the Tr'ondëk, with a release sequence that was hard to predict, in addition to backwater through drainage culverts affecting areas where water accumulation was not anticipated. The last ice jam was finally mobilized on May 13, causing a wave with an estimated peak flow of 600 $m^3/s$ at the WSC station 09EA003 (daily averaged flows are presented in Figure 4.2.2).

The second, open water, flood took place on May 24-25 (Figure 4.2.2). It was caused by a rain-on-snow event in central Yukon, including the headwaters of the Tr'ondëk, and it produced a record high flow (since WSC station 09EA003 started to be operated in 1965). The peak discharge, estimated at 940 $m^3/s$ (the daily-averaged flow presented in Figure 4.2.1 is about 760 $m^3/s$ for two consecutive days because the peak occurred at 21:00 on May 24), was associated with a return period of 100 years. Water levels in multichannel reaches of the Tr'ondëk were higher during this second flood whereas ice jams between May 10 and May 13 produced higher water levels in single-channel sections where the flow cannot easily by-pass the jam.

Several observations can be made about these two Tr'ondëk floods:

- Warmer winters can still lead to severe ice jam flooding if preceded by dynamic freeze-up conditions, at least in relatively small and steep river systems. During the winter of 2022-2023, about 2900 degree-days of freezing were cumulated at the Dawson airport compared with the historical average of 3400 degree-days of freezing. Late-winter snowfalls and overcast conditions definitely played a role in delaying the degradation of the ice cover, therefore maintaining its resistance to the increasing spring flow.

- Grounded ice jams (involving ice slabs or intact ice cover sections anchored to the bed of the river) can sustain high hydrodynamic forces. The release of the largest ice jams in the Tr'ondëk, between May 12 and May 14, occurred under warm conditions while a significant amount of heat had been absorbed by the water flowing towards, through, under, and above portion of those jams. It seemes that, in steep, multi-channel reaches, the concept of an ice jam mobilization discharge threshold does not apply, and that *in-situ* melt is needed to reduce the ice jam resistance prior to its release.

- A positive snowpack anomaly supports the occurrence of both types of floods (ice jam and open water). However, other factors, those influencing snowmelt rates (i.e., warm conditions) and those adding to the amount of potential runoff (i.e., rainstorms), may play a more decisive role in freshet floods. In 2022, the snowpack anomaly in the Tr'ondëk watershed


Figure 4.2.1. Aerial view of a portion of Rock Creek (far side of Tr'ondëk) on May 9, 2023. Flow is from left to right. The main channel is blocked by a grounded ice jam on the right and most of the water flows in the secondary channel as well as near residences and private properties.

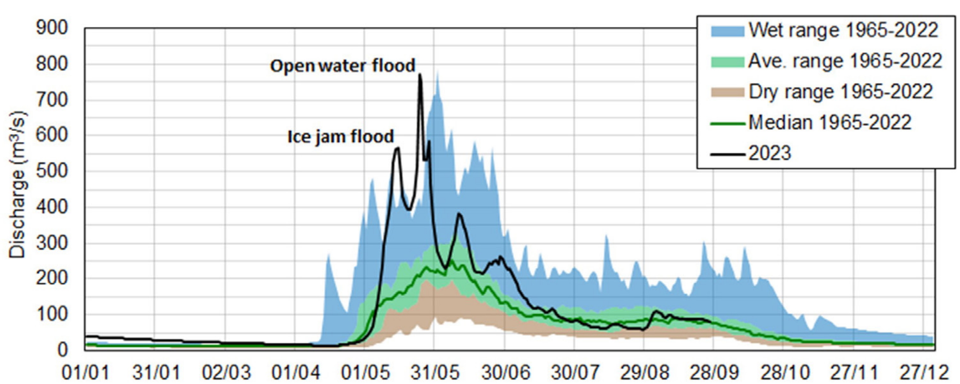


Figure 4.2.2. Historical hydrograph ranges and 2023 hydrograph of the Tr'ondëk (Klondike River, Water Survey of Canada station 09EA003). Daily average data is presented.

was even greater than in 2023, but the snow melted progressively, the peak flow only reached 450 $m^3/s$ at station 09EA003, and no flooding occurred.

This was not the first time that two floods in a row happened in Rock Creek. In 2013, a similar hydrological scenario occurred: the preceding winter brought more snow than usual to the watershed, the snowmelt period was delayed, and spring weather conditions generated two significant runoff events, one causing major ice jams and the other producing a peak flow of about 840 $m^3/s$.

Tu Lidlini (which means “two salmon rivers meeting” in Kaska), the community of Ross River, home of the Ross River Dena Council, was also flooded twice in 2013. The first flood was caused by an ice jam at the Ferry Ramp on the Pelly River on May 15, and it ended when an ice run from the Ross River (a major tributary) pushed the ice accumulation downstream of the community. The following week was cool, which preserved the watershed’s snowpack. When above-normal air temperatures returned, at the end of May, the flow quickly rose again, reaching more than 1500 $m^3/s$ on June 1. The resulting water level surpassed the preceding ice jam flood by about 0.5 m at the WSC station 09BC002 and caused further damage.

## 4.3. Kaskawulsh Glacier diversion of 2016

The most remarkable climate change-induced hydrological event in the recent history of Yukon is the diversion of the Tänshį̄ (Kaskawulsh glacier in Southern Tutchone) outflow. This water used to flow through the Ä’äy Chù (Slims River) towards Łù’àn Män (Kluane Lake), the largest waterbody in the Yukon and home of the Kluane First Nation (KFN), then feeding into the Kluane River, the Dän Zhǘr (Donjek River), the ’At’aayaat Chù’ (White River), and ultimately, the Chu Nìikwän (Yukon River) towards the Bering Sea. This water is now flowing into the Kaskawulsh River, which feeds the Àłsêxh (Alsek River) and drains into the Gulf of Alaska (Figure 4.3.1). While it used to take months to years for any droplet of water from the glacier to reach the ocean, it now takes roughly 3 days.

The Tänshį̄ and Ä’äy Chù diversion process, which is described in Shugar et al. (2017), is not only a singular geological-scale event, it also produces several tragic downstream impacts, ranging from altered air quality (dust is constantly blown from the dry bed tothe Ä’äy Chù towards the lake and the surrounding forest, Figure 4.3.2), changes in water quality, modification of fish habitats and unusual ice cover formation and thickening patterns on Łù’àn Män (e.g., McKnight 2021), all of which continue to impact ancestral KFN activities and culture. Southwick and Ballengooyen

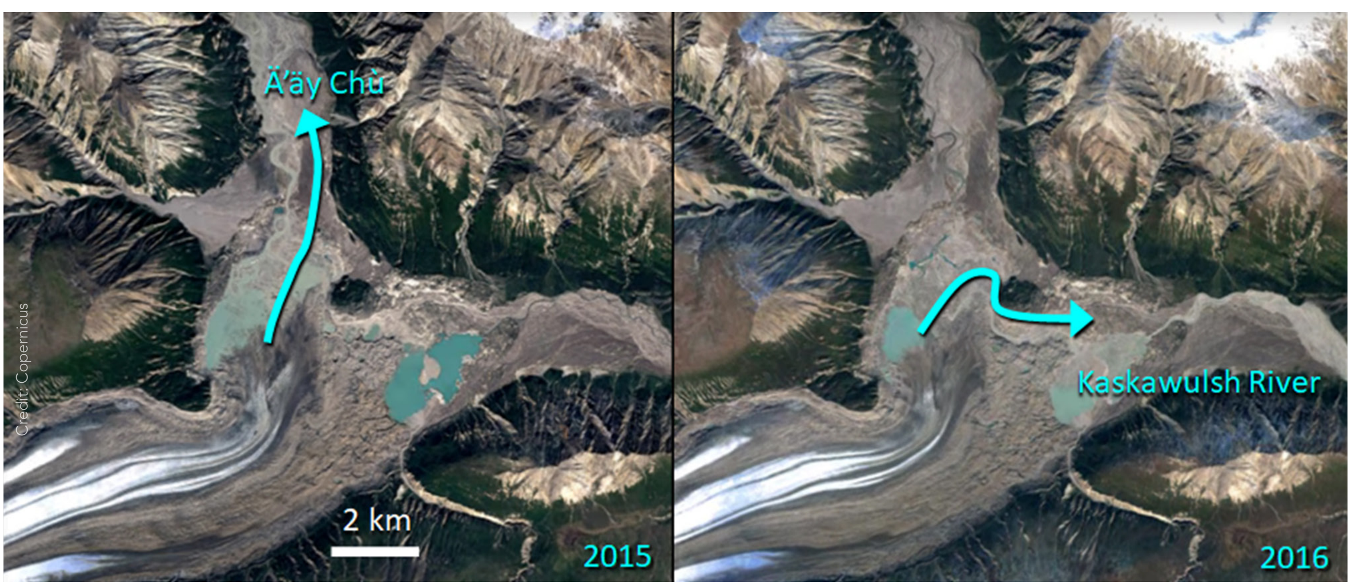


Figure 4.3.1: Sentinel 2 satellite images of the Tänshį̄ (Kaskawulsh glacier) terminus and head of the Ä’äy Chù (Slims River) and Kaskawulsh River in 2015 (left) and 2016 (right).

(2019) express: “We have to relearn the lake and our Traditional Territory for it is irrevocably changed, and that means the way we interact with our Traditional Territory must be adapted”. Other impacts include the need to redesign boat launches, which was informed by a hydrological assessment involving water balance simulations (Loukili and Pomeroy 2018).

The most obvious impact of this dramatic event for Kluane Park visitors is the now desertic Ä’äy Chù delta. Figure 4.3.3 presents the historical range of water levels in Łù’àn Män prior to 2016 as well as the averaged water levels for 7 years following the diversion. Winter water levels are not significantly lower, although they are consistently near or below the historical dry range (they are controlled by the elevation of the lake outlet). However, summer water levels are about 2 m below their historical average, resulting in almost 1 $km^3$ less water stored in the lake and 2.5 $km^3$ less water flowing into and out of the lake each year.

On the new downstream side of this morphological phenomenon, Figure 4.3.4 presents the 1975 – 2015 flow records for the Àłsêxh at WSC station 08AB001. Streamflow from subsequent years (2016-2019, black lines) show consistently higher-than-average or record summer discharges. Average peak flows at that station increased from 1000 $m^3/s$ prior to 2016 to 1700 $m^3/s$ after 2016, and the pre-2016 record flow (1550 $m^3/s$ in 1989) was exceeded four times in four years (with a new record established at 2050 $m^3/s$ in 2021). This change is directly linked with the new Tänshį̄ contribution, a clear reminder that the effects of global green-house gas emissions may be far from gradual or episodic, with major consequences.


Figure 4.3.2. Delta of the Ä’äy Chù (Slims River) at the southern tip of Łù’àn Män (Kluane Lake) in May 2019. Wind blowing from the river valley is lifting fine sediment.

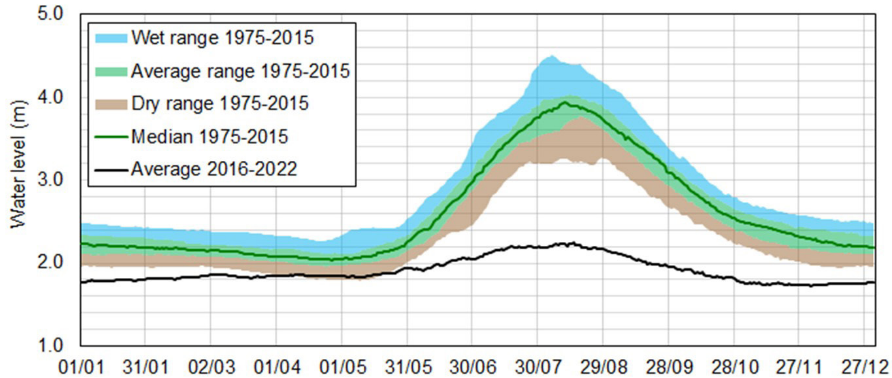


Figure 4.3.3. Historical (1975-2015) water level range and post Ä'äy Chù (Slims River) piracy (2016-2022) average water level Łù'àn Män (Kluane Lake, Water Survey Canada station 09CA001).

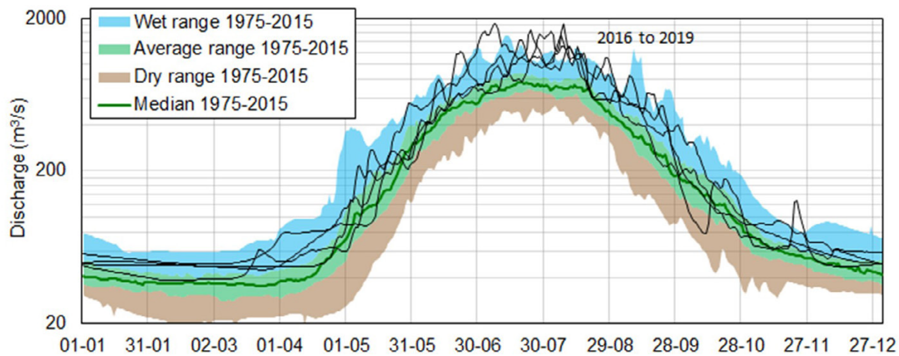


Figure 4.3.4. Historical (1975-2015) hydrograph and post Ä'äy Chù (Slims River) diversion hydrographs for the Àłsêxh (Alsek River; Water Survey of Canada station 08AB001). Daily average data is presented.

## 4.4. Dempster Highway 2016 washouts

On August 10, 2016, intense summer precipitation affected several catchments in the Tth'oh zraii njik (Blackstone River in Gwich'in, and Ttth'oh zrąy in Hän) and Gwazhàl Njik (Ogilvie River in Gwich'in) watersheds (including Engineer Creek, e.g., Figure 4.4.1). Resulting high streamflows damaged 14 road segments (PECG, 2018) which took several days to repair. These road closures affected many tourists in addition to the supply of provisions to Eagle Plains and Inuvik.

The lack of meteorological stations in the area makes it difficult to evaluate the exact amount of rain that overwhelmed the various creek and river channels. A weather station at Windy Pass (Engineer Creek headwaters) operated by Yukon Government, Department of Environment, in collaboration with McMaster University, registered 60 mm of rain in 36 hours, and more importantly within this period, 40 mm in 12 hours. This represents a significant rainstorm for the area. WSC stations on the Tth'oh zraii njik (10MA003) and Gwazhàl Njik (10MA002) measured what could be their second highest and highest flow on record, respectively (Figure 4.4.2; it is uncertain if the peak flow was missed). From this hydrological data, back-calculated precipitation values for this event corresponded to less than 40 mm of watershed-averaged runoff. It is possible that some areas were affected by twice that amount whereas other areas received less.

An assessment of flood damage (PECG 2018) stated that flow events of similar or greater magnitude than the August 2016 floods are anticipated to occur along the Dempster Highway over the coming decades. Interestingly, the Dempster Highway was washed out at two locations by the Gwazhàl Njik during the spring of 2023. In this case, a dynamic river ice breakup event (that may have caused erosion) was immediately followed by high snowmelt runoff rates (peak flow estimated to 850 m$^3$/s), leading to a multi-day closure of the highway.


Figure 4.4.1. Photograph of a damaged road segment on the Dempster Highway at Km 165.5. The damage was caused by high flows in Engineer Creek.

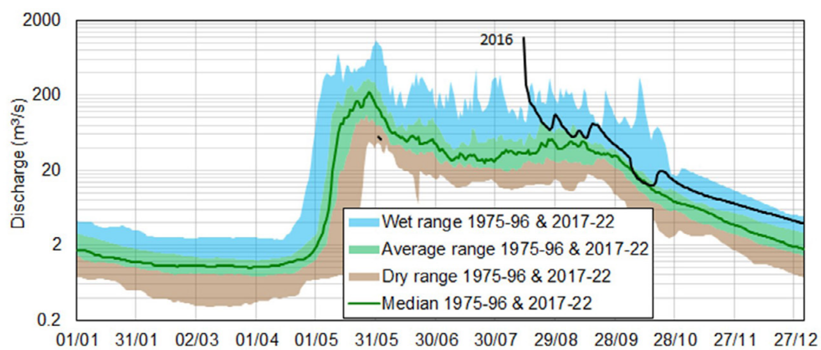


Figure 4.4.2. Historical (1975-1996 and 2017-2022) hydrograph of the Gwazhàl Njik (Ogilvie River, Water Survey of Canada station 10MA002) with the 2016 partial data set (station measurements were apparently restored at a record flow, which is unusual). Daily average data is presented.

## 4.5. Extreme dry winter conditions in 2019

Snow accumulation in southern and central parts of the Yukon during the winter of 2018-2019 were particularly low. In early May 2019, several snow courses (24 out 54 stations) reported no snow (Yukon Government 2019a), which means that the thin snowpack had already melted at most low altitude locations. This early melt was largely driven by the dramatically dry and warm month of March 2019 (with anomalies as high as 11 degrees above normal for the entire month; Yukon Government 2019b).

Dry conditions persisted in the following months in several watersheds. Since most rivers in the Yukon present a spring snowmelt regime, several low summer flow records were broken. The Ts'agro Mǟn (Mayo Lake) situation was among the most dramatic: from June onward, the water level was lower than it had been in the last 40 years by 0.5 m (and 1.5 m below normal, Figure 4.5.1).

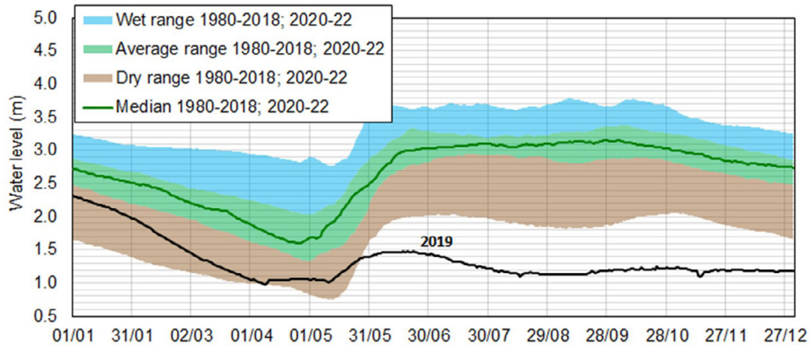


Figure 4.5.1. Historical water level range (1980-2018 and 2020-22) and 2019 water levels at Ts'agro Mǟn (Mayo Lake; Water Survey of Canada station 09DC005). Daily average data is presented.

Ts'agro Mǟn is used as storage for hydroelectric production during the coldest period of the year. Active storage usually happens during the freshet period for the next winter's high energy demand. Dam operations by the Yukon Energy Corporation (YEC) are constrained by a Water License granted by the Water Board (an independent regulatory body) and a set of water level and flow thresholds have to be respected, some of which are seasonal. During that summer, YEC could no longer maintain minimum flows in the Tadzę Nyäk (Mayo River) to support downstream habitats, including the Chinook Salmon run, and minimum water levels in Ts'agro Mǟn to support lake habitats. YEC had no other choice than to apply for a Water License amendment, which was approved in August (Yukon News 2019).

During the following winter, the lack of water available for hydroelectric production (not only from Ts'agro Mǟn) was likely compensated for by higher-than-average fossil fuel-derived electricity production, as identified by the Yukon Bureau of Statistics (2021). The 2018-2019 dry sequences, with hydrological impacts extending into 2020, is a reminder that despite an observed and projected increase in precipitation across most of the Yukon (Zang et al. 2019), extreme droughts and dry records should still be expected.

## 4.6. White River peak flow events

Floating woody debris were reported at the surface of the Chu kon' dëk (Yukon River) at Dawson on August 16, 2020. Data from the WSC station 09EB001 confirmed the occurrence of a 0.7 m-high wave, or surge, that lasted several hours. Two days earlier, at the WSC station 09CB001 on the 'At'aayaat Chù' (White River) at the Alaska Highway (some 330 km upstream of Dawson), a rather intense and short-lived runoff event (light blue in Figure 4.6.1) was recorded, with an amplitude of 2.2 m. Its shape contrasted with normal, daily snowmelt and glacier melt flow variations. A comparable historical event was identified in September 2014 (with a similar amplitude of 2.0 m) at the 'At'aayaat Chù' station (dark blue in Figure 4.6.1). It was initially hypothesized that these hydrological anomalies were caused by the drainage of an ice-dammed lake within the 'At'aayaat Chù' watershed.

Recent observations shared by scientists from the National Oceanic and Atmospheric Administration (NOAA) based in Alaska (Johnson, pers. com. 2023) helped identify the lake at the terminus of Russell Glacier, located some 100 km upstream of the Alaska Highway (and station 09CB001). Figure 4.6.2 presents two Sentinel 2 images of the area prior and after the most recent lake drainage event (2023). Interestingly, though, this event generated a more gradual downstream hydrological response (presented in green in Figure 4.6.1). The size of that lake is relatively small (about 2 km$^2$); however, based on a simple analysis of the 2014, 2020 and 2023 hydrographs, it probably stores about 20 million m$^3$ of water, which corresponds to an average lake depth of approximately 10 m.

An analysis of post-2014 satellite images (Sentinel 2 and Landsat 8) reveals that this lake also emptied dramatically in 2015 (early-September) and partially in 2017 (July). Other lakes located at glacier terminus in the St. Elias Range are known to release at varying frequencies. For instance, a lake located just below the Dań Zhùr (Donjek) Glacier drains less frequently (Kochtitzky et al. 2019), but the phenomenon causes a major hydrological event that can be felt down the Chu kon' dëk at Dawson.

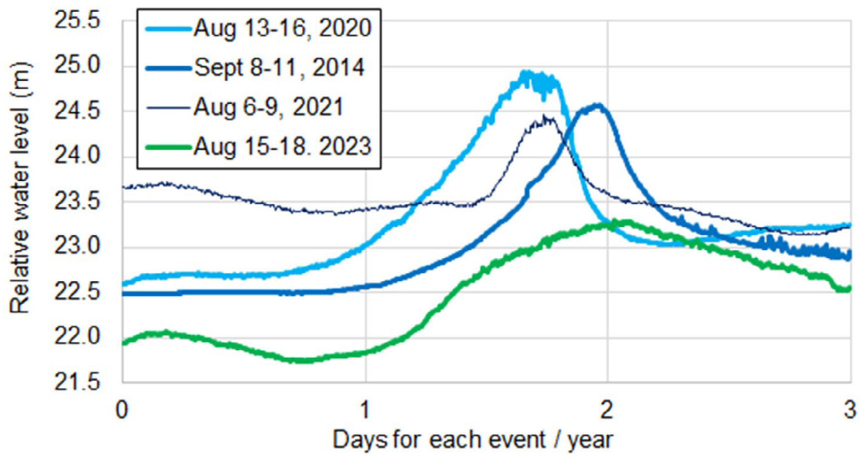


Figure 4.6.1. Three-day hydrographs from four different hydrological events in the 'At'aayaat Chù' (White River). The 5-minute data is provided by the Water Survey of Canada for station 09CB001.

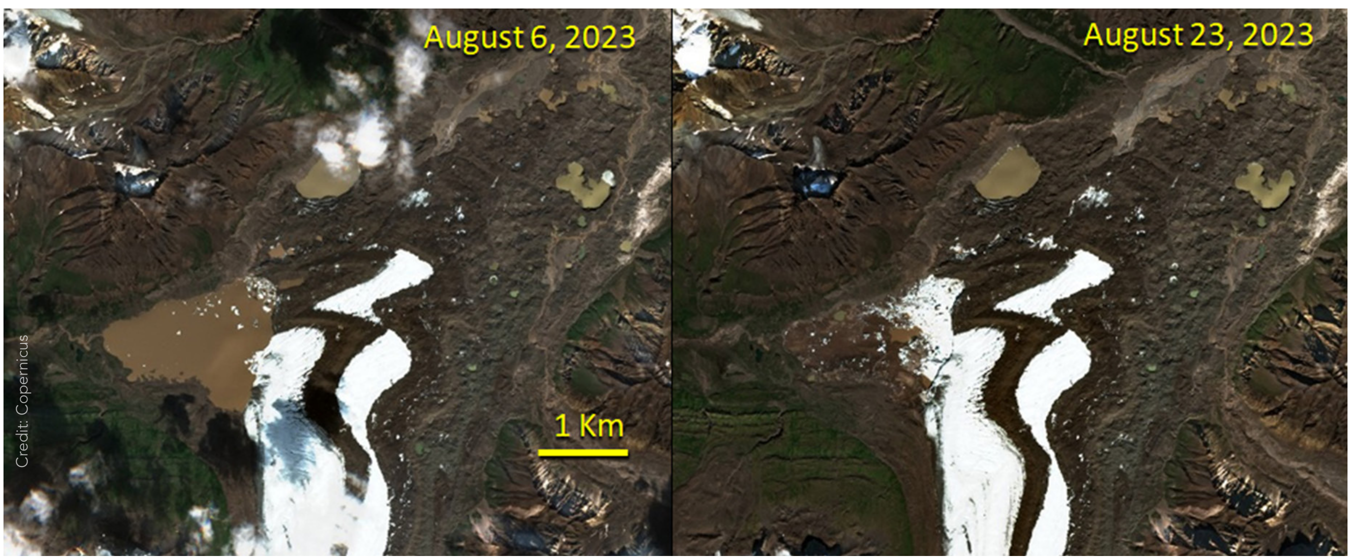


Figure 4.6.2. Satellite images (Sentinel 2) of the foot of Russell Glacier showing a full (left) and empty (right) lake. In this case the release took place between August 15 and 18, 2023.

Other hydrological anomalies do occur in the 'At'aayaat Chù' watershed that are independent of the ice-dammed lake identified in Figure 4.6.2. For example, in August 2021, a rather distinct runoff event was recorded at station 09CB001 (black line in Figure 4.6.1). Since a hydrological response was simultaneously monitored at the nearby Koidern River station 29CB007 (operated by Yukon Government) as well as at the Shą̈́r Ndü Chù (Duke River) WSC station 09CA004, it was probably caused by a regional rainstorm. What if a rainstorm was to occur at the same time as (or initiate) the drainage of an ice-dammed lake? This is apparently precisely what happened in August 2020, which explains the significant volume associated with the event (about 50 million $m^3$ of water) as well as the second highest flow on record at station 09CB001 since 1975 (1,500 $m^3$/s).

Why is this lake drainage phenomenon important? From a hydrological perspective, it can produce the peak flow of the year (e.g., the 'At'aayaat Chù' event of 2020), especially in the reach located immediately downstream of its associated glacier. Therefore, it represents a noteworthy hazard, but also a criterion for the design of downstream structures such as bridges. Moreover, the fast release of water stored in such lakes can generate what fluvial morphologists call "channel forming events", which means that the power of the flowing water contributes to defining the shape of the river channel through massive sediment transport. Finally, the dramatic drainage of a lake may bring downstream consequences to ecosystems, affecting aquatic and riparian habitats, just like when a beaver dam cedes.

## 4.7. Ch'oodeenjìk (Porcupine River) ice breakup

The community of Old Crow, home of the Vuntut Gwitchin First Nation, has been flooded relatively regularly over the past few decades by the Ch'oodeenjìk. Most of these events occurred in the presence of a local or downstream breakup ice jam. Figure 4.7.1 presents the results of a flood frequency analysis corroborating that ice jams are usually associated with the highest annual water levels. This figure also reveals that the community can see minor flood damage from ice jams on average every 8 years, and from open water (mostly snowmelt-driven) events every 20 years. Turcotte and Saal (2022) provide more specific data about the flood return periods (or annual flood probabilities) for different assets in the community and also present flood extent maps for a 2-year, a 20-year, and a 200-year flood (water levels that respectively have 50%, 5% and 0.5% chance to occur on any given year).

Questions may arise about the potential for an ice jam to generate water levels that are significantly higher than those that occurred during the 1991 ice jam flood (water surface elevation estimated at 246.9 m above sea level, using the most recent WSC datum). The simple river model presented by Jasek (1997) provides additional answers, despite being based on an approximate topography. In 1991, the Ch'oodeenjìk ice jam was initiated at the Sriinjìk (Bluefish River), a typical ice jam anchor point located some 40 km downstream of Old Crow. The head of the ice jam (its upstream limit), however, was not visible from the community; it was located some 5 km downstream, a distance over which the water surface had a lower gradient than if the jam had extended all the way to Old Crow. If an additional ice run had been intercepted by the jam prior to its release on May 8, 1991 (or if the jam toe had been closer to Old Crow), and if the discharge had remained constant (at about 3500 $m^3/s$), the water level in Old Crow could have theoretically been 1 m higher (Figure 14 in Jasek 1997). Although the extreme flood scenario (i.e., with a return period of 200 years) presented by Turcotte and Saal (2022) is less pessimistic, it still suggests that the Ch'oodeenjìk can produce fairly higher water levels than those of 1991.

On May 11, 2020, the ice cover in the Ch'oodeenjìk was still relatively intact over hundreds of kilometers while tributaries were flowing at full capacity further south (about 900 $m^3/s$ at the Whitestone River WSC station 09FA001, draining only 12% of the Ch'oodeenjìk watershed at Old Crow). On the following day, a major ice run produced a water level that reached the minor flood level (245.1 m) and was associated with a flow of about 4000 $m^3/s$. If an ice jam had formed downstream of Old Crow at that time, the resulting flood could have been

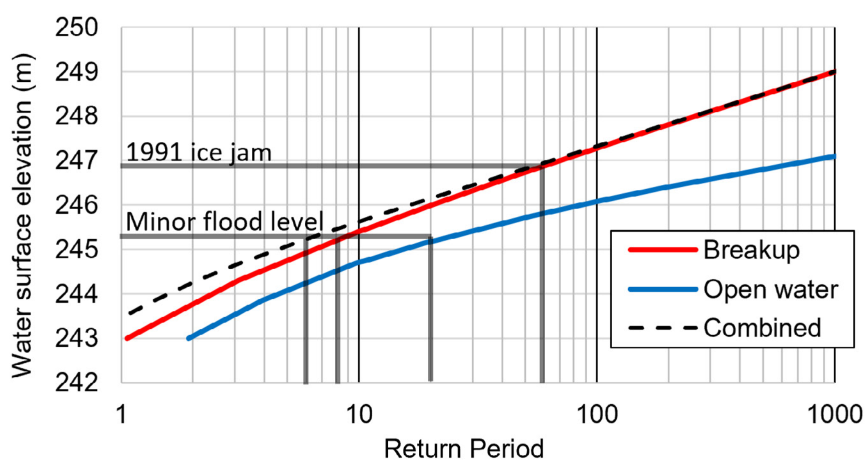


Figure 4.7.1. Water surface elevation (above sea level) at the Water Survey of Canada hydrometric station 09FD003 corresponding to different return periods for two flooding processes as well as for a combination of both processes for the Ch'oodeenjìk (Porcupine River) at Old Crow.

worse than that in 1991. A similar breakup pattern was observed in May 2024, but the river ice cover offered less resistance than in 2020, and the flood potential was therefore lower.

Multiple factors may affect the probability of ice jam floods in Old Crow, some of which seem to be positively correlated with climate change:

- The occurrence of unusual freeze-up patterns caused by dry and wet anomalies during the previous fall (it seems that high flows in the fall represent the condition that would exacerbate ice jam issues during the following spring, but this still needs to be confirmed).

- The formation of a large river aufeis (Turcotte et al. 2023a) at the mouth of the Sriinjìk could become more common in the future. Figure 4.7.2 presents a false color satellite image that suggests the presence of a massive ice accumulation on May 9, 2022, at the Sriinjìk mouth (or delta), which indicates that this phenomenon still occurs, occasionally blocking the entire Ch'oodeenjìk channel.

- A significant snowpack in the headwaters (south) also contributes to elevated flood risks in Old Crow by increasing the potential for a fast-rising spring flow (like in 2024, with a record snowpack at several snow courses, Yukon Government 2024).

- Warming conditions in the headwaters can contribute to a dynamic breakup scenario (Janowicz 2017), with a high ice jam potential in the Ch'oodeenjìk downstream of Old Crow.

Fortunately, other factors protect Old Crow from ice jam floods, including:

- The existence of a dominant ice jam location just upstream of the community delays downstream breakup and allows the downstream ice cover to degrade and become less resistant.

- The distance between the Sriinjìk outlet or the tightest Ch'oodeenjìk meander and the community is significant (30 to 40 km), which means that the river system may run out of ice rubble before the ice jam extends to Old Crow, especially if the ice cover becomes thinner as a result of warmer winter air temperatures. (However, there is currently no correlation between the winter coldness and the thickness of the ice cover measured by the Water Survey of Canada in the Ch'oodeenjìk at Old Crow.)

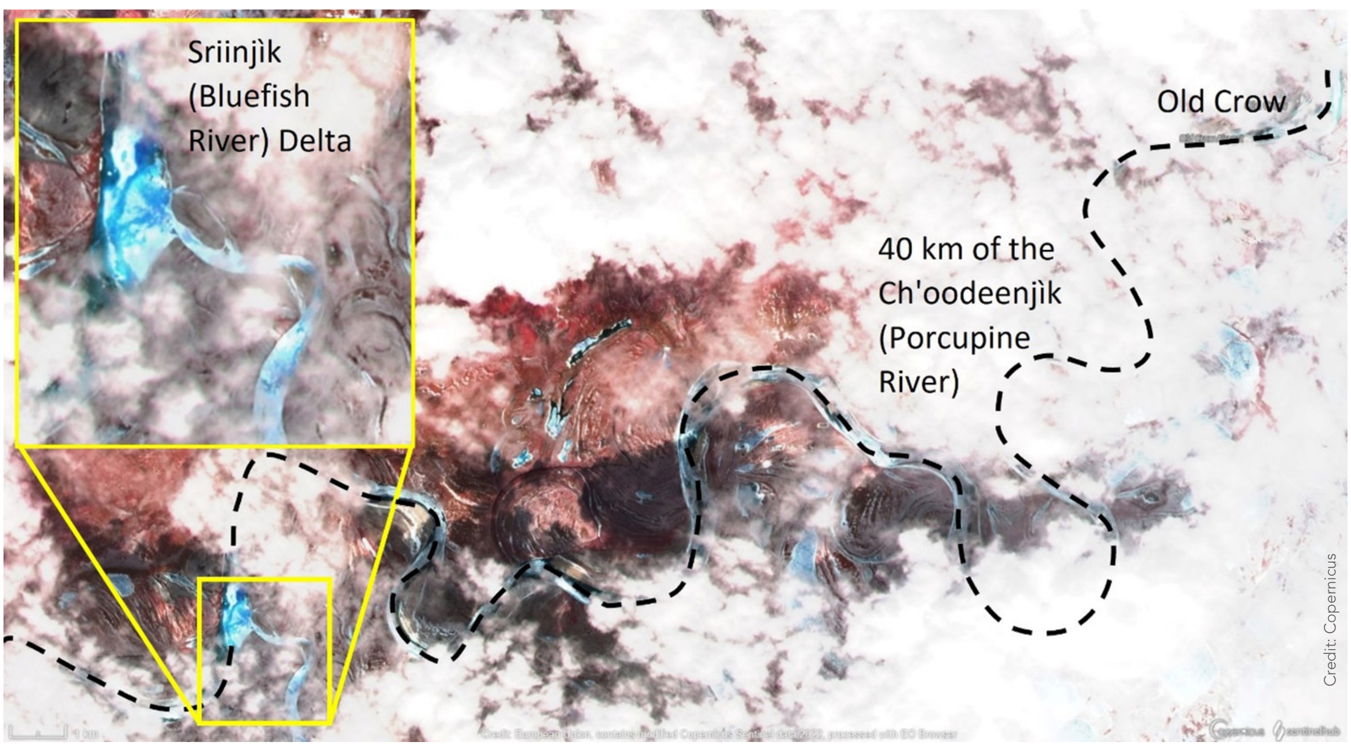


Figure 4.7.2. Partially cloudy, False color satellite image (Sentinel-2) showing the Sriinjìk (Bluefish River) delta ice accumulation (in bright blue) on May 9th 2022.

## 4.8. Floods in Southern lakes in 2021 and 2022

Southern Lakes are one of the main sources of the Yukon River. They are the home of several First Nations that have been living in this corner of Turtle Island (North America) for thousands of years including Ta'an Kwäch'än Council (TKC), Kwanlin Dün First Nation (KDFN), Carcross Tagish First Nation (CTFN), and Taku River Tlingit First Nation (TRTFN). Several communities and subdivisions are established around the Bennett-Tagish-Marsh Lake complex, including Carcross, Tagish, Army Beach, and McClintock, with multiple low elevation, flood-prone properties.

Log Cabin is a National Historic Site located in the White Pass, a part of the Southern Lakes headwater at the border between Alaska and British Columbia. Since 1960, the late-winter snow water equivalent (SWE) at the Log Cabin snow course averaged 380 mm, and rarely exceeded 600 mm. In April 2021, the SWE at this location was 800 mm. Inevitably, Southern Lakes had the potential to peak above their usual average level during the following summer. However, when a heat dome was forecast for the end of June, flooding in Southern Lakes became a real possibility. Lake levels rose fast (up to 12 cm per day), suggesting that lake inflows were more than twice Marsh Lake outflows (for a total net gain of about 800 $m^3/s$). A new water level record was established on July 10 (657.90 m, compared to the preceding 2007 record of 657.65 m, using the 2021 WSC datum). The resulting flood lasted several weeks, and the combination of wind waves against temporary dikes, along with groundwater infiltration, represented a major concern for property owners. The date of the event itself was also remarkable, as it was the earliest peak in more than 100 years of (WSC and White Pass) record (matching the early July peak of 1959).

Figure 4.8.1 presents the natural (unaffected by dam operations) peak water surface elevations for Marsh Lake from 1990 to 2024, including three very high-level years: 2007, 2021, and 2022. It also exposes the results of a 40-year moving window frequency analysis for maximum annual water levels associated with return periods of 2, 20, and 200 years. Whereas the water surface elevation associated with the 2-year event remains stable over the years, the 200-year water surface elevation increased from 657.5 m in 2006 to 657.7 m in 2007, then up to 658.3 m in 2021.

Figure 4.8.2 presents similar information but tied to the 2021 peak water surface elevation: it evaluates the return period of this water level from 1990 to 2024. The key message is that, back in the 1990s and early 2000s, a 2021 flood was largely improbable (statistically happening once every 10,000 years). In 2022, and including the 2021 peak in the record, the return period was down to 50 years, a remarkable increase in frequency.

It could be argued that records are meant to be broken, that extreme events have always happened, and that the 2021 flood could have occurred without human-induced climate change. However, other reasons support the likelihood of the role played by climate change in Southern Lakes water levels. For example, the following winter was characterized by a higher-than-average snowpack and late-summer rainstorms contributed to produce the 3rd highest water level on record in Southern Lakes. The peak itself was not the most impressive (some 0.6 m lower than in 2021), especially considering that it was influenced to some degree by 2021 wet conditions through groundwater storage, as indicated by Yukon Government (Mulligan, pers. com., 2022) and demonstrated in Figure 4.8.3. What was striking about this event is that it established a new record for the latest natural peak to occur in Southern Lakes (October 20). The earliest annual peak level (2021) followed by the latest peak in a 100-year record is exceptional as it represents a notable expansion of the annual envelope of historical water levels in only two years.

Other aspects of the 2021 event suggest that Southern Lakes can collect and store even more water under similar weather conditions:

- The largest tributary of the Bennett-Tagish-Marsh Lake complex is Atlin River, from Áa Tlein (Atlin Lake in Tlingit), the largest unregulated water body in British Columbia with a glacier melt and high-altitude snowmelt-dominated regime (similar to Tagish Lake). In 2021, Áa Tlein peaked on August 18, some 40 days after Tagish Lake. Had those lakes been better synchronized (as they were in 2007), higher water levels would have resulted.
- After August 15, 2021, cold temperatures brought glacier melt in the Áa Tlein and Tagish Lake watersheds to a rather abrupt ending. This was not accompanied by severe rain (as was the case in 2022) or followed by a subsequent warm spell (as was the case in 2007). Any comparable weather pattern could have generated a higher water level in Southern Lakes in August or September (a more typical peak period).

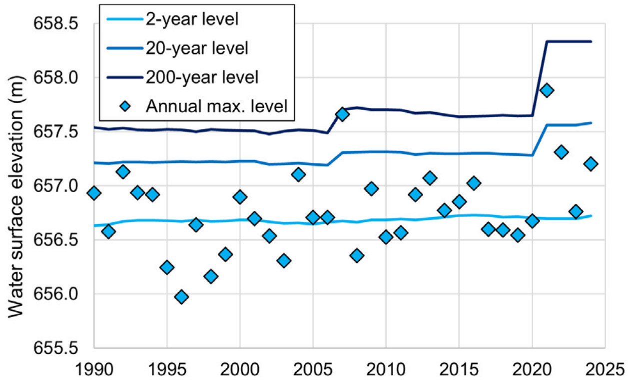


Figure 4.8.1. Unregulated Marsh Lake (Water Survey of Canada station 09AB004) peak water surface elevation from 1990 to 2023 and water surface elevations associated with three specific return periods, each considering the 40 preceding years (1950-1990 to 1983-2023).

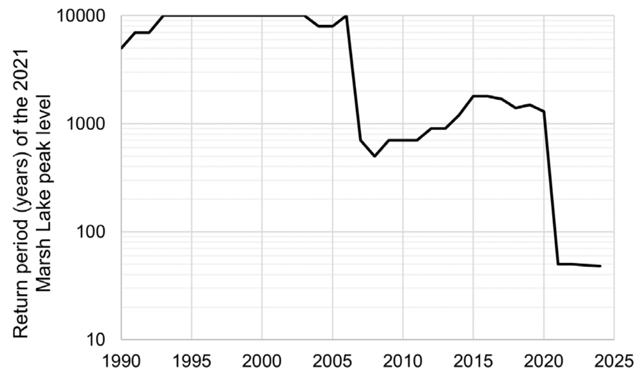


Figure 4.8.2. Estimated return period (on a logarithmic axis) of the 2021 flood level from 1990 to 2023, based on a 40-year running frequency analysis.

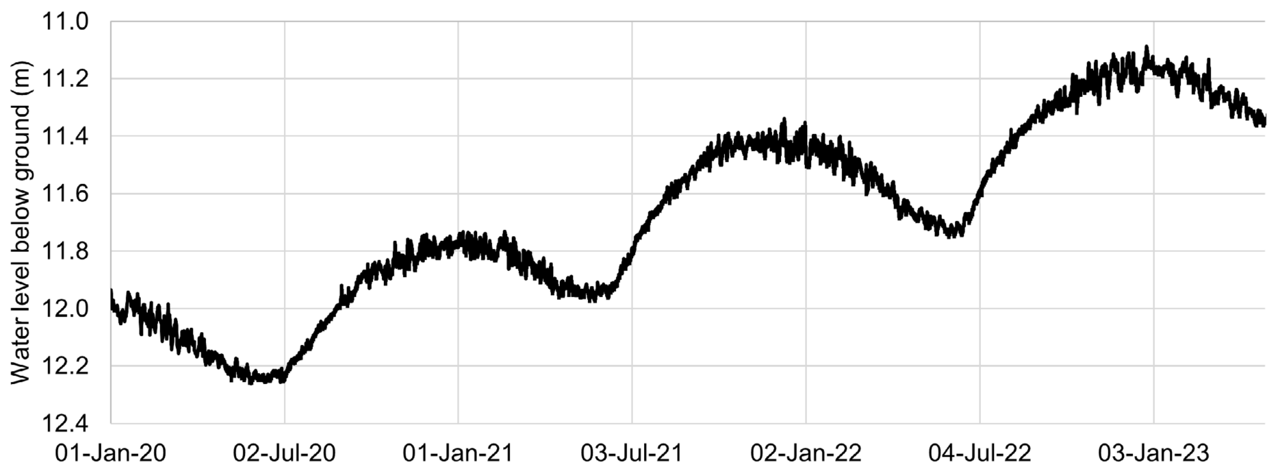


Figure 4.8.3. Groundwater level (expressed in meters below ground surface) at Yukon Government well YOWN-1901 located in Tagish, Yukon, from January 1, 2020 to April 30, 2023.

Flooding events are likely to become more frequent in Southern Lakes (at least until the 2030s; Rousseau et al. 2020) simply because a wide range of common and less common weather conditions are associated with high runoff rates: warm periods trigger intense snow and glacier melt whereas cool periods are often accompanied by rain. In this case, infiltration contributes to rising groundwater levels well into the following year (e.g., Figure 4.8.3), increasing the probability of high water levels (especially during wet periods that could result from La Niña years). Overall, the 2021 and 2022 sequence in Southern Lakes justifies somewhat urgent infrastructure and community adaptation actions.

## 4.9. Floods in Teslin and Carmacks in 2021 and 2022

At their confluence in Hootalinqua, Yukon, the Délin Chú (Teslin River in Southern Tutchone, Deisleen Héeni in Tlingit) drains a larger watershed than the Tàgé Cho (Yukon River in Northern Tutchone). It is therefore not surprising that water levels in the Tàgé Cho downstream of that point are largely influenced by those of the Délin Chú, with its mid-altitude, snowmelt-dominated regime. Figure 4.9.1 reveals a good correlation between the peak level in Teslin Lake at Teslin (WSC station 09AE002, drainage area of 18,000 km$^2$), home of the Teslin Tlingit Council, and the peak open water level (and therefore the maximum flow) at Carmacks (09AH001, drainage area of 82,000 km$^2$). There is also a fair correlation between the early May snowpack at three snow courses in the Délin Chú watershed (data provided by the Government of Yukon) and peak levels in Tás Ten (Teslin Lake in Tlingit, Figure 4.9.2). Therefore, a significant late-winter snowpack in the Délin Chú watershed can indicate that the communities of Teslin and Carmacks (280 km apart) may be affected by high water levels in the weeks following peak snowmelt rates.

The significant snowpack in the Délin Chú watershed in May 2021 and 2022 (estimated to 250 mm and 300 mm, respectively) generated extreme water levels in both Teslin and Carmacks (Table 4.9.1). Emergency flood

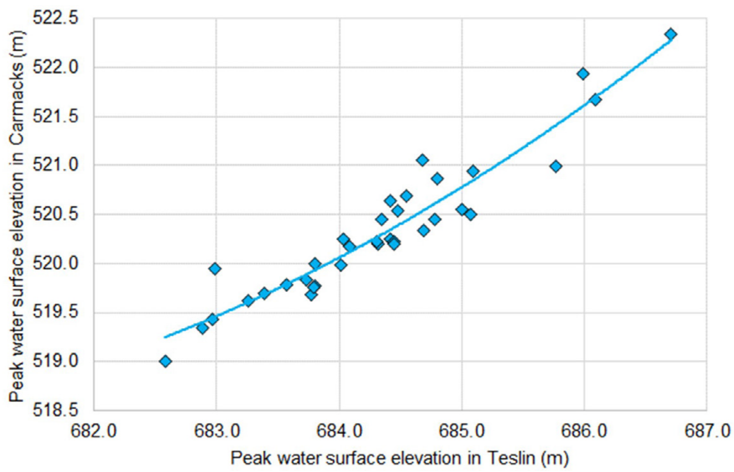


Figure 4.9.1. Peak water surface elevation in the Tàgé Cho (Yukon River) at Carmacks (Water Survey of Canada station 09AH001) expressed as a function of peak water surface elevation in Tás Ten (Teslin Lake, Water Survey of Canada station 09AE002). The data presented is from 1970 to 1996 and from 2014 to 2023.

Table 4.9.1. Data and statistics associated with peak water levels in Tás Ten and Tàgé Cho during the summers of 2021 and 2022.

| | Teslin (Teslin Lake) | Carmacks (Tàgé Cho) |
|---|---|---|
| WSC station | 09EA002 | 09AH001 |
| Record | 1953-2023 | 1952-1995 & 2015-2023 |
| 2021 | 686.0 m (5th highest) | 521.9 m (3rd highest) |
| | (20-year event) | (30-year event*) |
| 2022 | 686.7 m (2nd highest) | 522.3 m (2nd highest) |
| | (70-year event) | (60-year event*) |

*For open water conditions

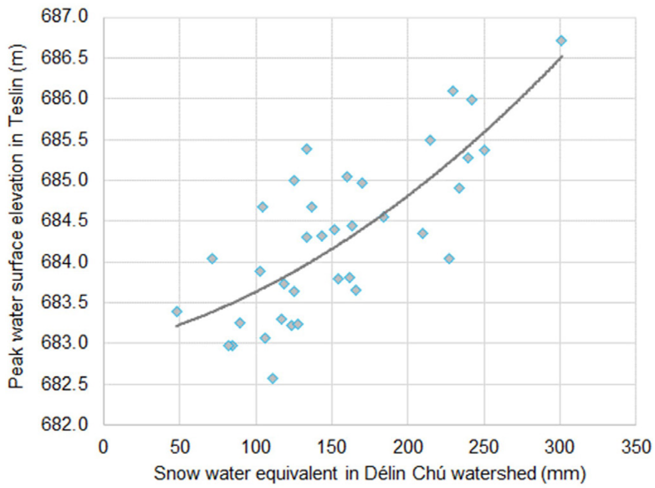


Figure 4.9.2. Peak water surface elevation in Teslin (Water Survey of Canada station 09AE002) expressed as a function of May snow water equivalent (SWE) at three locations in the Délin Chú watershed (using data from 1987 to 2023).

defenses were deployed during both years, but particularly in 2022, to protect citizens and infrastructure from high water levels. Waves generated by high winds caused further damage along the lake edge, including to the WSC station (Figure 4.9.3).

These events are related to the conditions reported in Southern Lakes during the same summers (Section 4.8) through regional weather patterns; they were substantially influenced by high (or record high) snowpacks in their respective watersheds. However, it is interesting to note that the floods occurred in different climate regions, geographies, and hydrological regimes.

## 4.10. Late-2022 rainfall events

The last events described in this section were caused by high precipitation anomalies in southwestern and central Yukon in September and October 2022. These conditions produced high flows in several watersheds, including in the Tatshenshini River (WSC station 08AC002) and in the Tth'oh zraii njik (in Gwich'in or Ttth'oh zrąy in Hän, Blackstone River, WSC station 10MA003), setting new records for the season, and significantly expanding the envelope of historical flows (Figures 4.10.1 and 4.10.2).

These rainfall events and their associated high flow anomalies had the probable or known following consequences:


Figure 4.9.3. Fallen Water Survey of Canada hydrometric station (09EA002) shelter on Teslin Lake during summer 2022.

- They generated significant sediment transport as bedload, therefore affecting salmon spawning.
- They caused the groundwater table to rise prior to the cold season, leading to unusually intense ground icing along the Dempster Highway (Highway 5) in November (Turcotte et al. 2023b)
- The resulting high, late-season water levels in Southern Lakes (Section 4.8) were a few days away from affecting the application of a freeze-up flood control protocol downstream of the Whitehorse Rapids Generating Station in Kwanlin (Yukon River at Whitehorse) through Water License regulation imposed by a Water License owned by YEC.

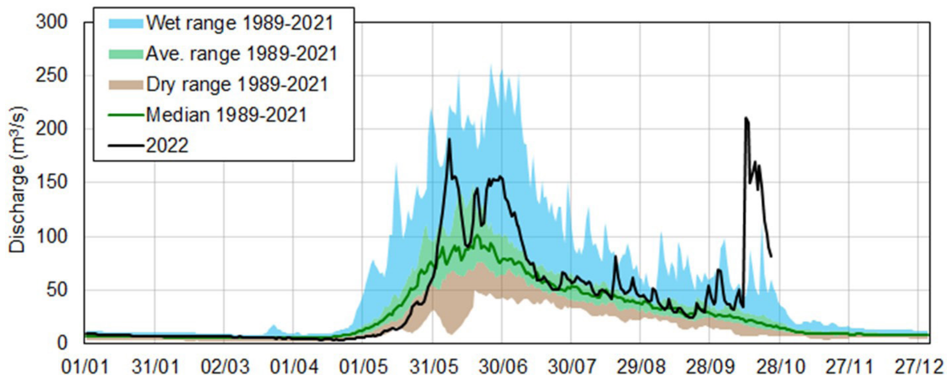


Figure 4.10.1. Historical water level range (1989-2021) and uncorrected 2022 water levels in the Tatshenshini River (Water Survey of Canada station 08AC002). Daily average data is presented.

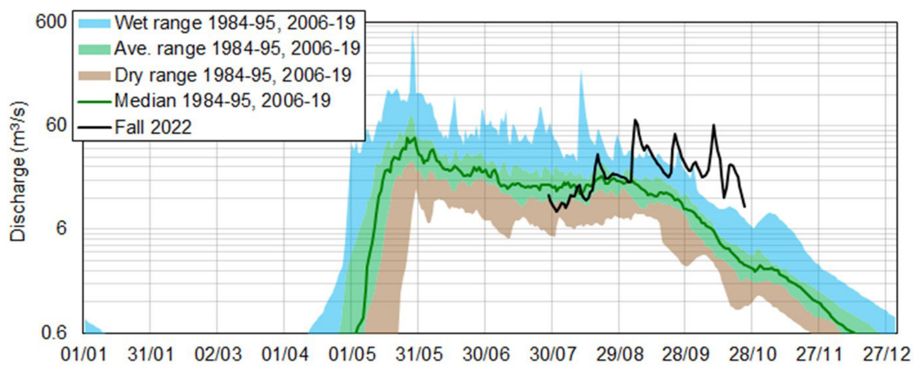


Figure 4.10.2. Historical water level range (1984-1995 and 2006-2019) and 2022 levels in the Tth'oh zraii njik or Ttth'oh zrąy (Blackstone River; Water Survey of Canada station 10MA002). Daily average data is presented.

- They contributed to producing absolute high record levels during the period of river ice formation in several rivers, including the Dezadeash River at Haines Junction (WSC station 08AA003), where the structural integrity of a bridge was threatened on Highway 3 in December.

This demonstrates how late-season runoff events in Yukon watersheds, which may increase in frequency in a changing climate (they are linked with the occurrence of atmospheric rivers) can produce challenging hydrological conditions for aquatic habitats, infrastructure, communities, and flow management authorities.

# 5. Looking forward

Scientists and engineers usually rely on complex deterministic water balance models to generate runoff or flow time series that are meant to be representative of future hydrological conditions. These tools are useful, even when they do not provide accurate projections because their outputs represent a step towards a better understanding of the impact of climate change on the water cycle. They also promote critical thinking and stimulate expert judgment. However, as mentioned in Section 1, these models are rarely calibrated to simulate extreme events, and a similar consideration may apply to the representativeness of future weather simulations (e.g., Coupled Model Intercomparison Project, Phase 6, or CMIP6) which outputs are used in hydrological models.

The unusual hydrological events described in Section 4, some of which are associated with long return periods (or low probabilities), took place in the last 12 years in most of the main watersheds of the Yukon (Figure 2.1). Beyond statistics, these extremes alone reveal that climate change is adding stress on northern watersheds, communities, and infrastructure framed around watercourses and lakes. This section takes advantage of this learning to introduce two types of conceptual or zero dimensional models (0D; this type of model have an undefined or flexible spatial dimension) that provide insight on the impact of climate change on the future or Yukon watersheds.

The first model is presented in the form of a table (Table 5.1) and involves a qualitative analysis of the impact of known and expected climate change outcomes on hydrological controls (some of which are presented in Canada's Changing Climate Report by Bush and Lemmer, 2019) in decades to come. For example, higher winter flows are well supported (++ and dark green in Table 5.1) by three distinct runoff controls (warmer winters, fall rainstorms, and permafrost thaw) whereas higher annual flows are negatively (-, red) or slightly positively (+, light green) affected by several controls. The net effect of climate change on different hydrological

Table 5.1. Conceptual model evaluating how different impacts of climate change on hydrological controls will affect the behaviour of Yukon watersheds in the next decades. Grey-shaded columns represent collateral consequences of climate change that also influence the water cycle.

| | Expected or known impacts of climate change | | | | | Intermediate impacts | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Hydrological consequences and hazards** | Warmer winters | Altered winter precipitation patterns | Warm spring anomalies | Warm and dry summer anomalies | Summer and fall heavy rainstorms | Vegetation migration and growth | Increase in burnt areas | Permafrost thaw | **Simulated net effect*** |
| Higher winter flows | ++ | + | | | ++ | - | | ++ | ++++++ |
| Mid-winter ice jams and floods | + | + | | | +/- | - | + | +/- | +++ |
| Spring ice jam floods | - | + | A + | | | | +/- | - | A ++ |
| High spring flow anomalies in small streams | A - | ++ | A + | | | - | + | D - | A ++ |
| High spring flow anomalies in large rivers | A - | + | A + | | | - | + | D - | A +/- |
| Low summer flow anomalies | | +/- | + | ++ | | +/- | + | - | +++ |
| Low flows downstream of small glaciers | + | - | + | ++ | - | | | | ++ |
| High flows downstream of large glaciers | - | + | + | ++ | ++ | | | | +++++ |
| Summer and fall floods in small streams | | | | +/- | ++ | +/- | ++ | - | +++ |
| Higher annual flows | | + | +/- | - | ++ | - | + | + | +++ |
| Freeze-up floods | D | | | | D ++ | +/- | | D + | DDD +++ |

A stands for advanced, D stands for delayed

* Not considering morphological adjustments

++: Strong increase + : Increases, - : Decreases, A : Advanced, D : Delayed, * Assuming no morphological channel adjustment.

processes and hazards, presented in the last (right) column of Table 5.1, is simply the sum of all impacts, and it can be interpreted as a level of certainty or a level of expected alteration and intensity. For example, higher winter flows and higher flows downstream of large glaciers are very likely (++++++, dark green, and actually already verified, as presented in Section 3) whereas ice jam floods at the end of winter may become more or less severe (+/-, yellow) in the future, depending on the location. The model also includes an assessment of the timing of different processes, with the letter "A" associated with an *advanced* date (e.g., earlier spring freshet) and the letter "D" meaning a *delayed* process (e.g., river ice formation, or freeze-up, in the fall).

The main advantage of this conceptual model, beyond its rapid development (it took a couple of hours to create, as opposed to months or years for water balance type of hydrological models), is its versatility: it can emphasize a diversity of processes and be applied in many geographical contexts. Moreover, just like any model, it can be calibrated using known climate change impacts, and it can be applied to a specific watershed. This model represents a learning tool for undergraduate students and communities, and it can help structure discussions and develop research strategies among hydrology experts.

A refinement of the model presented in Table 5.1 would involve including more climate change impacts (e.g., evapotranspiration), including additional hazards (e.g., drainage of ice-dammed lakes) confirming the assumption of linearity between hydrological controls (considering the outcomes of studies that emphasize energy and water budgets), and presenting results over defined and varying time scales.

The second 0D model is developed by considering the recently reported hydrological anomalies listed in Section 4. It is presented in Figure 5.1 for the Tr'ondëk (Klondike River), located in central Yukon. Rather than relying on the automated simulation of hundreds of climate change scenarios that consider different future greenhouse gas emission intensities, it takes advantage of what nature has already produced, including in regionally nearby watersheds that present a comparable hydrological regime. Reported hydrological extremes, or anomalies, can be converted in % increase (e.g., roughly 200% in the case of Figure 4.10.2) to generate a future envelope and a median condition for a full hydrological year.

One weakness of this model is that it does not provide seasonal probabilities or return periods (the idea would be to produce a wet and dry 200-year envelope that can inform adaptation). However, it can still inform prefeasibility studies for engineering structure and land development. This visual tool offers an accessible complement to more sophisticated hydrological models, especially for the identification of future extreme events. It can also offer a useful alternative to foresee hydrological conditions during the winter period, including the river ice formation and breakup periods during which most physics-based hydrological models commonly underperform. The 0D model proposed in Figure 5.1, provides useful information for a little resource investment and the results are supported by what has been directly documented in neighbour watersheds.

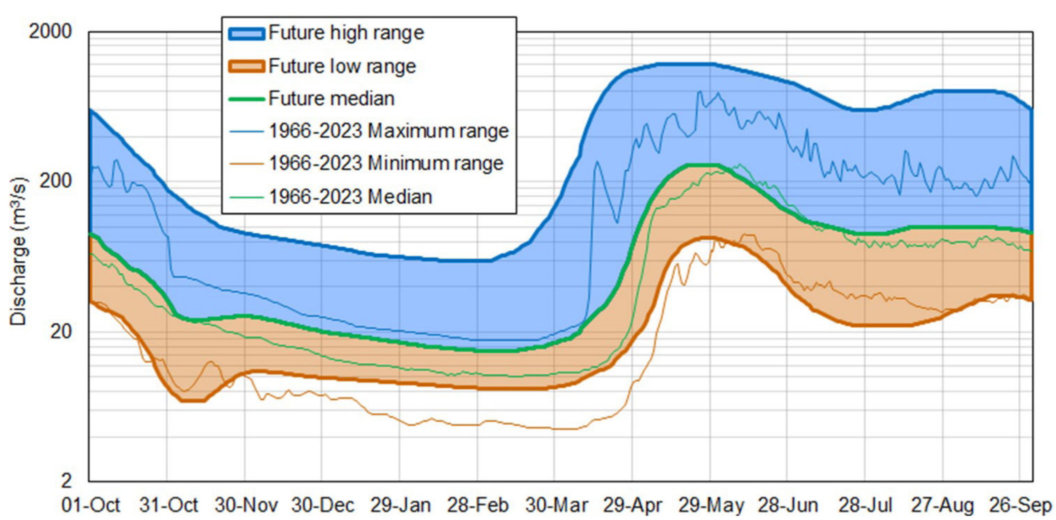


Figure 5.1. Conceptual model of the range of future flows for the Tr'ondëk (Klondike River) at Bonanza Creek (Water Survey of Canada station 09EA003) considering the known and expected impacts of climate change and taking into account extreme events that have recently occurred locally as well as in nearby watersheds.

# 6. Conclusion

Climate conditions are changing faster in the North than in most other parts of Canada (Bush and Lemmens, 2019). However, the impact of climate change on cold region watersheds remains largely unclear, with very few high-confidence trends extracted from historical records (e.g., Turcotte 2021). It could be stated that climate change has been statistically gentle on most river systems, at least so far. Several reasons may explain the lack of statistically significant hydrological tendencies (as presented in Section 1), including the alteration of hydrological controls, with effects that cancel one-another, and the occurrence of extreme dry and wet conditions that affect correlations. Section 3 listed only three (statistically supported) trends in historical records: a shorter ice season, higher winter discharge, and higher summer discharge in rivers fed by large glaciers. Even when the analysis of hydrometric records and the consideration of First Nation Knowledge indicate the existence of a robust historical trend, it cannot be simply extrapolated into the future without an understanding of the factors driving the identified change. Major, sometimes hard-to-predict geological phenomena can drastically (even irreversibly) affect the hydrological regime of rivers and lakes. In the case of the Ä'äy Chù (Slims River) diversion of 2016 (reported in Section 4.3), the process had been anticipated (e.g., Clague et al. 2006).

Section 4 of this chapter has presented several examples of hydrological extremes taking place in all corners of the Yukon, covering most climate zones and a diversity of ecoregions, and affecting Yukoners on multiple levels, from forcing travelers and tourist agencies to change their itineraries to the complete loss of properties and transportation infrastructure. Figure 4.8.1 is an example showing how average conditions (return period of 2 years) may remain somewhat unchanged over time while extremes (return period of 200 years) represent an increasing concern. From a probabilistic point of view, it seems impossible that the hydrological extremes presented in Section 4 for different watersheds could be caused by a transient, decade-long, climate pattern (which would imply that fewer hydrological anomalies would occur from now on and for some time). Indeed, nature is sending a clear warning message, and our leaders need to bring flood and drought adaptation up their priority list and proactively invest in science-based adaptation. The climate change awareness-action gap (e.g., Hochachka, 2024) needed to be tackled more than a decade ago, and the discomfort it brings keeps intensifying.

Research projects that attempt to foresee how the hydrological regime of cold region watersheds may evolve in decades to come often present results that i. are largely uncertain, ii. only cover a fraction of hydrological processes that affect communities, infrastructure, and ecosystems, iii. do not emphasize extreme events and conditions or iv. present results in a format that is only understandable by peer researchers. Since no flow forecast model can predict hydrological extremes more than a few months (e.g., for snowmelt dominated regimes) to a few days (e.g., rainstorms in small watersheds) ahead, questions may arise about how to adapt our northern communities and infrastructure to a future that remains largely uncertain.

Section 5 presented two examples of original, conceptual (zero dimensional) models that attempt to foresee the future of small and large river systems by taking advantage of current knowledge and the most recent observations and data about hydrological extremes (mostly floods) in multiple watersheds of the Yukon. The model presented in Table 5.1 indicates that the frequency and/or intensity of most hydrological hazards will increase in the future. Figure 5.1 combines hydrological observations at a regional level to define a future range (or envelope) of flows for a specific watershed (the Tr'ondëk, or Klondike River, in this case). A similar graph could be developed to include ice-induced flooding processes; it would emphasize water levels rather than flows and would only be valid at specific locations (since the impact of ice processes, such as ice jams, on water levels only apply to relatively short river segments). These easily-affordable models can be used in different contexts:

- Stimulate hazard and adaptation discussions among leaders, scientists, and knowledge keepers.
- Summarize observations, projections, and assumptions in an easy-to-understand format.
- Inform the development of tools such as flood hazard or flood risk maps, and flood response protocols.
- Support the design of industrial (e.g., hydropower, water treatment plants), community (e.g., schools, hospital), and transportation (e.g., bridges) assets.

Several research avenues exist to improve these conceptual models. Other cold region hydrology topics that warrant further investigation include:

- The morphological impact of extreme weather and hydrological events on river channels (their rate of lateral migration, for instance, may increase with permafrost degradation and higher runoff rates, but this could be partially counteracted by the growth of riparian vegetation (Lelpi et al. 2023) or the presence of entrainment-limited material (Douglas and Lamb 2024))

- The hydrology of small creeks (there are hundreds of culverts along highways of the Yukon, some of which are occasionally overwhelmed by ice, snowmelt and rainstorm)

- The hydrology of mining sites (the release of untreated water in the environment is not uncommon and could be further mitigated through adapted design) that better captures climate-change affected runoff rates

- The impact of heat domes and atmospheric rivers on watersheds (these phenomena have caused major floods and have triggered landslides in British Columbia, Yukon, and Alaska in recent years) in addition to destructive forest fires.

Readers may have noticed that none of the hydrological extremes presented in this Chapter occurred in Whitehorse, where more than 75% of the Yukon population is established. Even the 2021 Southern Lakes flood reported in Section 4.8 did not significantly impact Yukon's capital. Beside the temporary unavailability of goods, food, and internet caused by washouts along key transportation corridors (e.g., 2012, 2022, 2024), is the vulnerability of Whitehorse residents to water-related extremes low and/or stable? The short answer is no. Even though some hydrological processes and their consequences are not impressive enough to make the national news, flood damage and insurance coverage is also increasing in the Whitehorse area. In 2021 and 2022, the fast melt of a well-above-average snowpack led to water infiltration and damage to multiple properties, including the basement of residences that are out of reach of any small or large watercourse. Urban flooding also affected Whitehorse in July 2023 when an intense rainstorm transformed streets in streams. Erosion damage was also observed; in this case, nature is generous enough to leave obvious clues of inadequate drainage capacity or under-designed erodible surfaces, including gravel roads, ditches, and embankments (e.g., Figure 6.1). Municipal workers and decision makers (as well as property owners) can take advantage of the gullies or gravel accumulations to promptly redesign and fix public (and private) assets before the next major rainstorm.

Hydrological extremes are also taking place beyond the Yukon borders. Flood hazards represent a concern year after year in several small communities of Alaska. In Northwest Territories, major ice jams floods have recently been reported in Fort Simpson (2021), Hay River (2022), and Fort MacPherson (2023). Each event has a unique origin and sequence, but the potential influence of climate change is impossible to ignore, and lessons should cross borders.

Finally, it is important to remind readers that the impact of climate change, beyond adaptation, can still be attenuated through the political and consumption choices that are made in the present.


Figure 6.1. (left) Embankment erosion along a paved bike path in Whitehorse and (right) erosion gully on a gravel trail in Whitehorse (hockey puck on the right for scale, the gully is almost 1 m-deep).

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