Influences of Source Waters on Alpine River Systems in Tongait KakKasuangita SilakKijapvinga (Torngat Mountains National Park), Nunatsiavut, Labrador

by

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Author's Declaration

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

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

Abstract

Tongait KakKasuangita SilakKijapvinga (Torngat Mountains National Park) encompasses the northern tip of Labrador and is situated at the southernmost limit of the Arctic Cordillera. This region is an integral part of the homeland for Inuit from Nunatsiavut and Nunavik and hosts the only remaining glaciers in continental northeastern North America. Like other high-latitude regions, glacial melt is currently a key source of streamflow in the summer months and provides refugia for cold-water species. Continued climate warming is expected to make streamflow warmer, slower, and less turbid, putting stream function and culturally significant species such as *ikKaluk* (Arctic char) at risk. Future glacial loss is also expected to transition downstream habitats to resemble those of more barren non-glacial fed watersheds, further affecting ecosystem services, connected habitats, and community resources. This research aims to examine the impacts of cryospheric (ice) and hydrological (water) systems on ecohydrology by exploring glacial and late-lying snow influences on stream composition and riverine habitats. Stream composition and ecological function is examined through a stable isotopic analysis of oxygen and hydrogen and measurements of aqueous dissolved organic and inorganic carbon from stream water samples collected from three watersheds with different dominant water sources: glacial meltwater, snowmelt, and rain and groundwater. As this area has not undergone water sampling in the past this work also established a baseline for future research. With continued climate warming projected to shift the contribution of water sources it is important to know the unique influence each of these have to better predict how upstream and downstream systems will respond to continued change. This will further our understanding of how changes in the cryosphere and hydrosphere impact northern ecosystems and human livelihoods in support of future environmental monitoring, adaptation, and conservation.

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List of Abbreviations

BMD	Blow Me Down Mountains
CMB	Cooperative Management Board
DIC	Dissolved Inorganic Carbon
DOC	Dissolved Organic Carbon
EC	Electrical Conductivity
NVB	Nakvak Brook
TBB	Torr Bay Brook
TMBC	Torngat Mountains Base Camp
TMNP	Torngat Mountains National Park

Chapter 1: Introduction and Background Information

1.1 Background and Rationale

The effects of climate change are impacting the Arctic more rapidly than anywhere else on the globe, transforming the land and placing northern communities at the forefront of new environmental challenges and uncertainty (Harris et al., 2020; Malik & Ford, 2025). Remote alpine river systems in the Arctic are among the few pristine features left in the world but will also face lasting and severe changes in the coming decades (Slemmons et al., 2013). This is largely the consequence of altered water resources caused by global-scale glacier retreat, decreased snow accumulation, and the development of post-glacial ecosystems (St. Pierre et al., 2019). Expected changes for stream morphology include a reduction in sediment load, increased streamflow variability, warmer water temperatures, increased channel stability, and changes in nutrient content (Bourquin et al., 2025). For freshwater biotic communities, this may constrict the distribution of cold-specialized species, shift the composition of local flora and fauna, and introduce invasive species (Bosson et al., 2023). The unprecedented nature of ongoing Arctic warming challenges our understanding of how Arctic communities will respond and persist into the future (Wilkes et al., 2023).

In Northern Canada, impacts resulting from climate change are manifesting in the form of changing hydrology and vegetation cover (Giesler et al., 2014). These changes threaten riverine ecosystems which are well accustomed to the natural variation and timing of stream discharge that comes with seasonal ice and snow accumulation and melt (Wang et al., 2024). Watersheds governed by meltwater are forecasted to experience elevated summer flow as glacier and snow contributions increase with warming (Liu et al., 2023). Increased flow is predicted to occur until a maximum rate of flow, known as “peak flow”, is reached. Past peak flow, the ability of meltwater to sustain water levels through the dry seasons is lost resulting in a shift towards rain and groundwater driven watersheds. As water supply dwindles and weather patterns shift, the timing of peak flow is also expected to occur earlier in the season

with potential impacts including extended dry seasons and more variability in newly precipitation-dominated flow regimes (Liu et al., 2023).

Warmer conditions, longer growing seasons, and habitat expansion in proglacial zones have already contributed to greening trends across the Arctic as shrubs take advantage of improved growing conditions in a phenomenon known as "shrubification" (Wrona et al., 2016). Due to their size, shrubs are capable of strongly influencing their environments, altering carbon storage, out-competing low-lying vegetation, changing habitat availability and access to forage, and limiting the ability to travel through the land for animals and people alike (McDowell et al., 2023). For northern communities, these landscape transformations have implications for community health, well-being, and sense of place (Norton et al., 2021). The ramifications of climate change in the Canadian Arctic are gaining increasing recognition and study though only a small portion of the existing literature addresses how changing landscapes will affect ecosystems and livelihoods (Malik & Ford, 2025).

Northern protected areas are particularly useful for understanding how climate change can impact Arctic ecosystems because changes can be isolated from other anthropogenic drivers. *Tongait KakKasuangita SilakKijapvinga* (Torngat Mountains National Park [TMNP]) is Canada's 42nd National Park and encompasses the southernmost limit of the Arctic Cordillera (Figure 1.1). This fretted glacier-rich mountain chain extends from northern Labrador to Ellesmere Island which possesses the largest concentration of ice in Canada (McDowell et al., 2023). There are 105 small mountain glaciers scattered throughout TMNP, preserved by temperate maritime summers and frigid, dry winters due to the Labrador Current, which transports cold water southwards along the coast of the Atlantic Provinces (Way et al., 2014). The Torngat Mountains are part of the ancestral homeland for Inuit from Nunatsiavut and Nunavik, who have stewarded this land since at least 1400 AD (Lemelin et al., 2016; Brice-Bennett et al., 2023). This area is an important cultural and spiritual space for Inuit, with the name "Torngat" derived from the Inuktitut word "Tongait", meaning "place of spirits" (Brice-Bennett et al., 2023). Today, the Torngat Mountains National Park is cooperatively managed

between Parks Canada and the Cooperative Management Board (CMB), all of whose current seven members are Inuit (Lemelin et al., 2015).

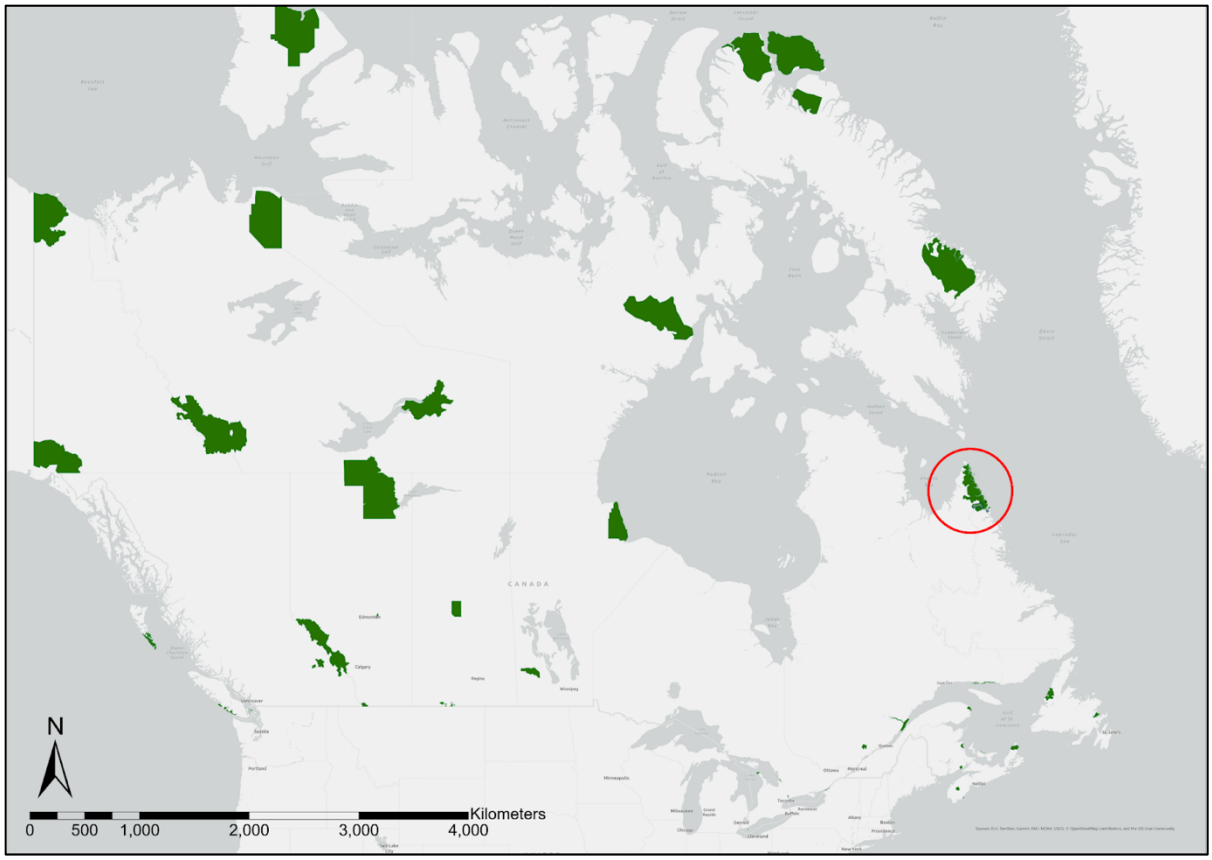


Figure 1.1: Map showing the distribution of Canada's National Parks (green) with Torngat Mountains National Park circled in red (basemap imagery from ESRI ArcGIS and National Parks overlay from EsriCanadaContent, created by the author in 2023).

Despite an extensive history of human use, TMNP remains a pristine wilderness area and home to iconic Canadian species such as polar bears, barren-ground black bears, caribou, minke whales, ringed-seals, Arctic char, and numerous bird species including species-at-risk such as harlequin ducks, peregrine falcons, barrows golden-eye, and short-eared owls (Government of Canada, 2023). This rich biodiversity can be mainly attributed to the region's remoteness as TMNP has no roads, no year-round settlements, and very little infrastructure, rendering direct human impact in this area incredibly low (estimated less than 600 visitors per

year) (Patterson, 2020). Inuit knowledge and the limited science available tell us that the ecosystems in TMNP are healthy with no immediate known threats (Parks Canada Agency, 2008). The most recent federal report on ecological integrity in Canada's National Parks published in 2023 concluded that ecosystems in TMNP are currently "stable" and are closely monitored. However, this report also noted that the two ecosystem types experiencing the greatest declines in their condition across Canada are glaciers and freshwater systems (Environment and Climate Change Canada, 2023). As such, the greatest risk to the long-term viability of TMNP is likely climate change.

Impacts of climate change in TMNP have been heavily felt in recent decades with decadal temperature increases of 2.0℃ in the winter and 0.5℃ in the summer since the 1980's (Davis et al., 2021). Land cover hindcasts estimate a 235% increase in shrubs from 1985 to 2015, mainly in southern and low elevation areas, with an additional 51% increase in relative shrub cover expected by 2039/43 (Figure 1.2). Hindcasts also show a 105% increase in wet vegetation from 1989 to 2019 with wet vegetation anticipated to continue expanding from low-elevation areas into previously dry mid-elevation areas following increasing summer precipitation, permafrost degradation, and glacier melt. The last glacier inventory for TMNP conducted by Barrand et al. (2017) reports a regional glacier loss of 27% from 1950-2005 and suggests that this may be due to trends of decreasing winter precipitation and increasing summer and autumn atmospheric warming since the early 1990s. It is hypothesized that like other semi-arid mountain regions, glacier melt and snowmelt in TMNP are key sources of streamflow in summer months (Ohlanders et al., 2013). Previous work in TMNP by Ritcey and Culp (2008) further suggests that the greatest influencers of stream composition and function in the Torngat Mountains are source water contribution, glacial extent, and the quality and quantity of vegetation. With glacier mass loss, changing snow dynamics, and shifting precipitation and evapotranspiration patterns altering source water contributions, water temperature, sediment load, and nutrient levels (Immerzeel et al., 2019), the main focus of this study will be on source water contribution to provide a more holistic view on the current state of freshwater systems in this region. As these environmental factors change it may hinder the

ability of alpine river systems in TMNP to support terrestrial, freshwater, and marine ecosystems and the Inuit communities who have long relied on them.



Figure 1.2: Repeat photography from Ramah Bay (58.5°N, 63.2°W) in Torngat Mountains National Park of shrub growth and ecosystem change from 1991 to 2021 (photographed by Angus Simpson,1991, and Andrew Trant, 2021).

1.2 Structure and Objectives

My research examines how different types of source water influence alpine river systems in TMNP, affecting stream composition and ecological function. My thesis is divided into four chapters: Chapter 1, which introduces my topic and provides the background information and context in which my research takes place; Chapter 2, which is a synopsis of current literature on the importance of meltwater for alpine river systems and the challenges riverine habitats may face as a result of climate change; Chapter 3, which is a spatial analysis of stream composition and ecological function between glacier, snow, rain and groundwater fed watersheds in TMNP; and Chapter 4, which synthesizes research outcomes and identifies opportunities for further research.

On its own, Chapter 2 is intended to serve as both a literature review and as self-contained report that will be shared with Parks Canada, the TMNP Cooperative Management Board (CMB), and the Nunatsiavut Government. This chapter will summarize the current state of knowledge on glacier influence on alpine river systems and how climate change is altering these areas and their connected environments. This chapter will compile observed changes from similar Arctic and alpine regions including the North American Rocky Mountains, European Alps, and South American Andes, and compare them to the Torngat Mountains to help assess whether local ecosystems are changing in similar ways. Finally, Chapter 2 will help identify knowledge gaps and areas for further exploration to assist with future management plans and ecological monitoring practices for TMNP.

Chapter 3 examines the impacts of cryospheric (ice) and hydrological (water) systems on ecohydrology and physio-chemical properties by exploring glacier and late-lying snow influences on alpine river systems. This study contributes to furthering our understanding of

the hydrological regimes in TMNP and potential future threats they may face by asking the questions:

1. *How influential is source water for stream composition and ecological functioning of alpine rivers systems in Arctic Cordillera landscapes?*

2. *What role does meltwater play in shaping the physio-chemical properties of riverine habitats in the Torngat Mountains?*

These research questions are answered through an analysis of stream water samples collected in TMNP in August of 2024 (Figure 1.3). Stream composition and ecological function are examined through a stable isotopic analysis of oxygen and hydrogen and measurements of aqueous dissolved organic and inorganic carbon from stream water samples collected from three watersheds with different dominant water sources: glacier meltwater, snowmelt, and rain and groundwater. Physio-chemical properties, taken from the same locations, included pH, electrical conductivity, and water temperature. As this area has not undergone water sampling in the past, this work will also establish a baseline for future research and set the structure for long-term monitoring of climate-driven hydrological change.



Figure 1.3: Water sample collection in Nakvak Brook (58.6°N, 63.3°W) (photographed by Nhu Le, August 2024).

Finally, Chapter 4 will summarize research outcomes, placing them into a local context. This concluding chapter will also identify knowledge gaps and provide directions for future research.

This research is part of a larger interdisciplinary project under the Canada-Inuit Nunangat-United Kingdom Arctic Research Programme (CINUK) titled IMpacts of Cryosphere-Hydrosphere ChAnGe on Ecosystems and LIvelihoods in NorthErn Nunatsiavut, Canada (IMAGINE). The goal of the IMAGINE Project is to improve our understanding of how changes in the cryosphere and hydrosphere impact northern ecosystems and livelihoods in support of developing community-based mitigation and adaptation efforts (CINUK, 2023). This research has been supported by Park's Canada, the Nunatsiavut Government, the CMB,

the Torngat Mountains Base Camp, and local community members. This collaborative approach aims to deepen our understanding of Arctic environments in hopes of protecting Torngat Mountain National Park's unique ecological and cultural heritage for generations to come.

Freshwater environments cover less than 1% of the Earth's surface, yet these often-overlooked features serve as important links between the land and water (Isaak & Rieman, 2013). As the sources that feed these streams change under continued warming conditions so does their ability to provide for downstream ecosystems and communities (McDowell et al., 2023). This makes it vital to understand the unique influence source water has for regional ecosystems upon which Inuit depend. My thesis brings together information on alpine river systems and adds to our collective knowledge by providing new information on the current state of freshwater systems in TMNP and provides a baseline for future research. By quantifying the impacts of climate change on glaciers, rivers, and ecosystems in the Torngat Mountains, we can address this existing knowledge gap to better direct conservation efforts in TMNP and foster resilience in the North.

Chapter 2: Summary of Knowledge on Alpine River Systems in Torngat Mountains National Park

2.1 Alpine River Systems and the Cryosphere

Alpine river systems are often referred to as the "water towers of the world" because they originate in the uppermost catchments of the globe, storing and transporting water to an endless number of downstream environments (Immerzeel et al., 2019). The role of rivers and the ecosystem services they offer are influenced by the natural landscape and the ways in which it has been transformed by human use. In remote alpine regions, where there are few direct human influences, rivers are mainly governed by the cryospheric and hydrological processes connected to their watersheds (Milner et al., 2009; McMillan et al., 2025). This puts the current state of alpine river systems and their downstream environments at risk as climate change transforms the cryosphere and hydrosphere.

2.1.1 The Role of Glacial Meltwater

Glaciers are important water reservoirs for alpine systems and critical for maintaining streamflow throughout the year especially during the drier, warmer months late in the melt season (Sepúlveda et al., 2022). Globally, alpine glaciers have been responding strongly to climate change and are expected to experience significant mass loss throughout this century (Huss & Hock, 2018). The general consensus is that as glaciers recede, stream flow will decrease, becoming warmer, slower, and less turbid (Sudlow et al., 2023). These effects will be greatest once the "peak water" threshold is crossed. This refers to the point at which glacier shrinkage results in a surface area too small for the glacier to sustain its previously increasing meltwater contributions from warming conditions (Figure 2.1). Following "peak water" rivers begin to experience a steady decline in water supply as annual runoff decreases and eventually ceases altogether once the glacier becomes functionally extinct (Clarke et al., 2015). Current projections suggest larger glaciers may reach peak water closer to the end of the century while many small alpine glaciers (<5km^2) may have already passed their peak water threshold or will reach it in the next few years (Huss & Hock, 2018). Reduced glacier meltwater contributions

to streamflow will be most obvious in late summer, when contributions of snow and rainwater are also low (Bliss et al., 2014). Ecosystem shifts also occur following glacier loss as previously glacier fed systems transition to perennial and seasonal snowpatch fed systems, and then much later potentially more barren rain and groundwater fed systems (Sudlow et al., 2023). However, prior to reaching "peak water" glacier discharge will increase resulting in an influx of water and material to downstream environments (Milner et al., 2009). Resulting shifts in source water contribution before and after "peak water" will have a number of dynamic effects for alpine river systems, including modified streamflow, sediment and nutrient transport, thermal regimes, and freshwater biodiversity (Milner et al., 2009; Huss & Hock, 2018; Michelutti et al., 2020).

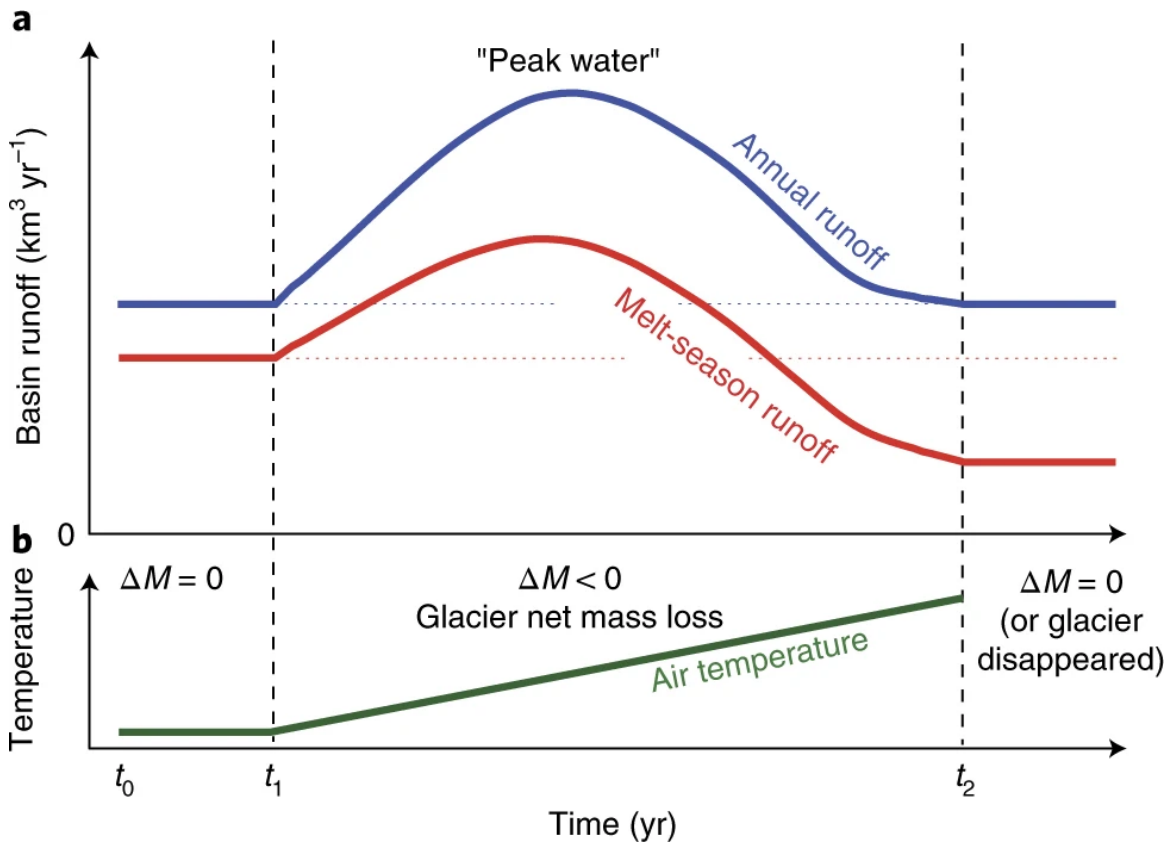


Figure 2.1: Schematic illustration of changes in annual and melt-season runoff for a glacier fed watershed in response to increasing atmospheric temperatures and glacier net mass loss. Retrieved from Huss & Hock (2018).

2.1.2 The Role of Snowmelt

Alongside glacier retreat, climate change is also impacting snow deposition and snow melt processes in alpine areas due to rising air temperatures and larger proportions of atmospheric precipitation occurring as rain rather than snow, affecting the magnitude and timing of water availability (Immerzeel et al., 2019). Satellite imagery has shown a multidecadal decrease in snow cover duration and snow depth across portions of Canada's Subarctic and low-Arctic (McDowell et al., 2023). Further, future climate projections show snowlines retreating higher in altitude throughout many major alpine catchments along with earlier and faster seasonal snowmelt (Bavay et al., 2013). This is a major concern for alpine river systems as spring snowmelt is often the largest hydrological event of the year, determining the start of the growing season, recharging depleted groundwater stores, and mobilizing nutrients (Perdrial et al., 2014; Rixen et al., 2022; Hille et al., 2024). Changing patterns in snow cover may lead to more variable hydrological regimes and weaken the relationship between snowmelt and streamflow as spring discharge rates decline (Dyer, 2008).

2.2 Seasonal Shifts and Expanding River Networks

2.2.1 Seasonal Discharge

Seasonal variations in streamflow are common for alpine rivers and often coincide with regional climatic patterns of temperature and precipitation (Gibson et al., 2020). Alpine rivers traditionally experience low flows in the winter when a majority of precipitation falls as snow and peak flows in late spring or early summer with the onset of snowmelt, followed by a return to low flow conditions in the summer once the snowpacks have been depleted (Hille et al., 2024). However, glacier fed watersheds can maintain more consistent stream levels throughout the dry season and even have a greater base flow in the winter in comparison to snow fed and rain fed systems as their flow is sustained by glacier melt (Slemmons et al., 2013; Ohlanders et al., 2013). Meltwater from alpine glaciers is also vital for maintaining river flow in years of low flow or drought, buffering flow variability from extreme rainfall events, and recharging groundwater storage (Milner et al., 2009; Huss & Hock, 2018). With glacier retreat and shifting

climate patterns resulting in earlier melt, seasonal discharge is likely to eventually evolve towards earlier spring peaks and lower summer flows (Milner et al., 2009).

Shifting precipitation patterns are further changing flow patterns due to an increased frequency of large rainfall events. This will lead rain fed systems, whose streamflow's peak and ebb throughout the dry season echoing rainfall events, to become further dominated by rain (Déry et al., 2009). In addition, higher volumes of rainfall will lead to thinner snowpacks, increased slumping events, and shallower frozen upper soil layers, allowing for higher soil moisture contents and the mobilization of solutes within the active layer (Wang et al., 2024). Between increasing rainfall and ongoing cryospheric change, alpine river systems are moving towards a more intensified hydrological cycle affecting the volume, timing, and pathways water will take through a watershed (Wrona et al., 2016).

2.2.2 Development of Proglacial Zones

The environment situated directly in front of a glacier is known as the proglacial zone. Ecological succession of newly established proglacial zones is currently one of the fastest ongoing ecosystem shifts taking place around the globe with around 78% of areas emerging from glacier retreat expected to be terrestrial (Bosson et al., 2023). As glaciers continue to retreat, more proglacial zones will be revealed, and river networks are expected to expand into these newly emerged higher elevation zones at a rate of 1% per decade (Wilkes et al., 2023). This may result in reorganization of river routes and sediment transport in the upper catchments of watersheds with the growth of proglacial zones and shrinkage of glacier headwaters (Shugar et al., 2017). The expansion of proglacial ecosystems and different stages of ecological succession between them can diversify local habitat conditions, increase ecological connectivity, and help generalist species adapt (Bosson et al., 2023). However, how and at what rate proglacial zones will develop depends on relative contributions of ice and snow, proximity to glacier sources, and local climatic conditions (Slemmons et al., 2013).

2.2.3 Sediment Transport

The presence of unconsolidated sediment and glacial till in emerging proglacial zones allows for a greater length of active channel braiding and high sediment loads in streams (Slemmons et al., 2013). The hydraulic intensification of watersheds leading to more frequent flooding events and increased weathering processes can further contribute to higher sediment loads (St. Pierre et al., 2019). This can reduce stream stability, light penetration, and oxygen content, making downstream conditions difficult for some aquatic organisms by impacting photosynthesis, primary production, and visibility (Slemmons et al., 2013).

The effects of increasing sediment transport are expected to be greatest prior to "peak water". Following "peak water" lower streamflow will reduce turbidity and weathering processes, decreasing sediment transport and allowing for stream bed stabilization (Sudlow et al., 2023). Reductions in suspended sediments will then allow for greater light penetration and better stream clarity, leading to increased biotic activity in freshwater environments and the greening of stream channels (Bourquin et al., 2025). Enhanced greening of proglacial zones is predicted to further alter hydrological, nutrient, and carbon cycles by elevating evapotranspiration rates, increasing the uptake of water and nutrients for plant growth, and stabilizing stream channels (Hou et al., 2022; Milner et al., 2009).

2.3 Alpine River Systems and the Carbon Cycle

2.3.1 The Role of Rivers in the Global Carbon Budget

River systems have been historically overlooked when investigating global carbon budgets due to the small portion (<1%) of the Earth's surface they cover and the difficulty in determining their carbon contributions as seasonal changes in streamflow make carbon balances highly variable (Schrope et al., 2000; Isaak & Rieman, 2013; Perdrial et al., 2014). However, recent studies have shown that rivers play an important role in regional and global carbon cycles due to their unique influence as both net sources and sinks of dissolved carbon (Schrope et al., 2000; Zhang et al., 2024). Carbon input to river systems can occur in various ways such as flushing through decomposing organic matter in soils from surrounding terrestrial

landscapes, erosion from carbon-containing rock, soil respiration beneath waterways, and biological functioning of freshwater habitats such as aquatic plant respiration (Slemmons et al., 2013). The abiotic and biotic processes occurring in alpine rivers mean they typically become supersaturated with carbon dioxide (CO_2) (St. Pierre et al., 2019). While some CO_2 remains in streams, or is stored in the ocean, a large fraction of it enters back into the atmosphere through degassing (Schrope, 2000). Hou et al. (2022) estimate that rivers release ~40% of their CO_2 into the atmosphere through outgassing, store ~20% through sediment burial, and deliver the remaining ~40% to marine environments. Further work by Kerins et al. (2024) suggests that though alpine rivers tend to be small, they are so abundant that they may contribute to a third of global stream CO^2 contributions through degassing, an amount equivalent to 16% of the annual global land carbon sink. This contribution is predicted to increase in the future as warmer water temperatures allow for less CO_2 storage (Schrope, 2000).

2.3.2 Dissolved Organic and Inorganic Carbon

Rivers transport both organic and inorganic forms of carbon. Organic carbon occurs as carbon compounds found in living organisms and contributes to primary production and respiration in rivers. Inorganic carbon occurs as carbon dioxide (CO_2), carbonic acid (H_2CO_3), bicarbonate (HCO_3^-), and carbonate (CO_3^{-2}) and regulates the acidity and buffering capacity of rivers and is needed for photosynthesis (Cole & Prairie, 2014). The two most investigated forms of carbon in streams are dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC), which are defined as the fraction of organic and inorganic carbon able to pass through a 0.45 μm filter (Kerins et al., 2024). Both DOC and DIC are important for aquatic food webs and ecological functioning in riverine habitats as they provide the basis for primary production, regulate pH balance, and influence the overall biogeochemistry of streams (Zhang et al., 2024). The main sources of DOC come from the degradation of terrestrial vegetation releasing organic matter into soils and root exudates while the main sources of DIC are physical and chemical weathering, biotic respiration processes, and the oxidation of DOC into CO^2 (Kerins et al., 2024; Zhang et al., 2024). Proportions of DOC and DIC in a river are governed by climatic

factors such as air temperature and precipitation, biological factors such as vegetation growth stage, type, decomposition, and proportion of wetland cover, and physical characteristics such as watershed area, sediment depth, underlying geology, and rates of stream discharge (Hou et al., 2022). For alpine rivers, glaciers can be an important source of DOC and DIC concentrations (Liu et al., 2023).

Glacial catchments typically have low amounts of DOC due to sparse vegetation cover and poorly developed soils (Slemmons et al., 2013). However, water stored in glaciers can hold a large amount of DOC due to years of biologic carbon sequestration, accumulation of soil and plant matter blown onto glacial surfaces, and the biological activity of supraglacial microbial communities on glaciers (Milner et al., 2017; Liu et al., 2023). As glaciers retreat and stream flow increases, DOC concentrations in alpine river systems are predicted to increase as stored DOC is free to enter into river systems and increased streamflow will lead to greater flushing of DOC from surrounding ecosystems (Slemmons et al., 2023; Kerins et al., 2024). While DOC may increase under an intensified hydrological cycle, DIC is predicted to decrease due to dilution (Giesler et al., 2014). This is due to DOC being produced in younger, shallow soils which are more easily flushed out during high flows. Meanwhile, DIC is more abundant in older, deeper groundwater stores that take longer for water to penetrate and seep back out of (Battin et al., 2023; Kerins et al., 2024).

Changes to the carbon cycle in alpine systems are also expected from regional warming. For example, the decomposition of alpine litter mainly occurs in winter, which is then covered by snow and ice and will not enter streams until the snowmelt season (Hou et al., 2022). As snowmelt advances earlier in the year due to warming winter temperatures, this will lead to an earlier influx of DOC with potential impacts on the timing of biological activity downstream (Ejarque et al., 2021). Heavier runoff from increased precipitation events can also increase riverbank scouring and weathering, raising both DOC and DIC concentrations (Hou et al., 2022). Regional warming will also increase active layer thicknesses where permafrost is present, leading to more pronounced subsurface flow and transport of carbon stored in soil (Zhang et al., 2024). Cumulatively, these changes will likely shift the ratio of DOC and DIC

in alpine river systems, though the timing and outcomes of this are still largely unknown. This presents a challenge in predicting how regional and global carbon balances will be affected and how future conditions for riverine habitats may adapt (Hou et al., 2022).

2.4 Alpine River Biodiversity and Habitat Change

2.4.1 Changes in Community Composition

The strongest determinant of biodiversity and community composition in alpine regions is the ability of a species to tolerate extreme physical and chemical conditions in an unstable environment (Ritcey & Culp, 2008). However, being highly specialized for these conditions can also restrict many of these species to specific areas, making it hard for them to adapt to changing climate conditions (McDowell et al., 2023). For freshwater species, branching networks of river systems creates an additional challenge as rivers can be easily fragmented leading to the isolation of populations, separation from resources and habitats, and potential to be trapped by warm temperatures and upstream limits of watersheds (Brown et al., 2007; Isaak & Rieman, 2013). Currently, the greatest threat to alpine river biodiversity is expected to come from the loss of suitable habitat space for cold-water species and the range expansion of warm-water species that may outcompete cold-water species (Culp et al., 2019; Wrona et al., 2016).

The predicted upward expansion of warm-water species in alpine river systems is attributed to declining influences of cryospheric processes. Rivers fed by glaciers have unique characteristics compared to snow and rain fed streams due to colder temperatures, channel instability, large sediment loads, seasonal ice cover, and highly turbid flows (Brown et al., 2007; Kosek & Ruman, 2021; Wilkes et al., 2023). Climate change projections suggest alpine river systems will experience an increase in average stream water temperature and electrical conductivity, and a decrease in turbidity and pH levels, allowing for more favourable conditions for generalist species to emerge (Bourquin et al., 2025). Furthermore, longer growing seasons are likely to enhance plant growth and biological productivity (Milner et al., 2009; Griffiths et al., 2017). Longer growing seasons and earlier meltwater peaks will also

allow stream channels to stabilize earlier in the year leading to fewer disturbance events and more opportunities for plant biomass to accumulate (Sudlow et al., 2023). As a result, it is likely that shifts in biodiversity patterns of freshwater ecosystems will occur, including an increase in species richness and species turnover, as cold-water species are outcompeted (Culp et al., 2019). The arrival of certain species from the south may further alter regional hydrological regimes. For example, species such as dam-forming beavers, nitrogen fixing alder, algae, and mat-forming cyanobacteria can alter streamflow levels, evaporation and runoff processes, and nutrient cycling. For people living in northern communities, ecosystem changes following the arrival of southern species raise concerns about water quality and drinking water safety, and alterations to ecologically and culturally important habitats (Wrona et al., 2016).

2.4.2 Threats to Cold-Water Species

Water temperature in streams is strongly correlated to air temperature, and it is expected that climate change will lead to a rise in both water temperature and air temperature. A decline in the contribution of cold glacier and snow meltwater, and reduced streamflow limiting the thermal capacity of rivers to buffer against heating will also contribute to increased water temperatures (Milner et al., 2017). Warmer conditions would then be expected to favour more warm-water species over cold-water species who may have a more difficult time adjusting to changing temperature regimes. This is a special concern for people living in northern communities as it may impact economically and culturally important species, such as fish (Milner et al., 2009).

Salmonid species such as *ikKaluk* (Arctic char; *Salvelinus alpinus*) can be found throughout the Canadian Arctic but in northern parts of Quebec and Labrador they are endemic to alpine rivers due to specific thermal tolerance levels (McDowell et al., 2023). This species requires moderate water temperatures between 5°C and 9°C, with overwintering temperatures between 0-2°C, and optimal spawning temperatures estimated to be at 7°C (Harris et al., 2020). A recent study centered on rivers in Nunatsiavut, Labrador, demonstrated that during warm

water events, habitat for *ikKaluk* is constricted and results in behavioural changes. These changes include reduced or ceased feeding and growth, less territorial behaviour during spawning season, and movement to cooler river sections to escape thermal stress. In some rivers premature mortality of *ikKaluk* has been reported following warm water events along with delays in upstream migration and altered habitat use due to low water levels (Geissinger et al., 2024). However, it is possible that *ikKaluk* and other cold-water species may adapt to changing conditions and find refuge in colder upstream catchments where glaciers and perennial snow patches persist (MacMillan-Kenny et al., 2025).

Predicting where and how long suitable habitats may persist proves a challenge as it is unclear how ecological communities will adapt and how transportation corridors may be affected by changing streamflow levels and thermal regimes. Wilkes et al (2023) suggest that riverine habitats will change dynamically in the future rather than linearly due to the unique geographical characteristics of individual catchments and the size of resident glaciers leading to non-uniform ecosystem development. Due to this, a better understanding of how resilient these environments are to warming conditions and shifts in source water contributions is needed to understand how change will occur in order to protect at-risk species (Michelutti et al., 2020; Wilkes et al., 2023).

2.4.3 Pollutants and Contaminants

There are concerns surrounding whether glaciers and perennial snowpacks can act as repositories for pollutants and contaminants due to their long-term storage capabilities (McDowell et al., 2023). Glaciers can harbour bacteria, fungi, viruses, and chemicals transported by long-range atmospheric processes, such as perfluorinated chemicals (PFCs), mercury, and persistent organic pollutants (POPs), the release of which can impact the integrity of downstream ecosystems and alter freshwater chemistry (Slemmons et al., 2013; Wrona et al., 2016). In addition, changes in the hydrosphere in alpine areas may mobilize contaminants from terrestrial ecosystems and distribute them throughout watersheds (Wrona et al., 2016). River sediments and aquatic organisms can act as sinks for pollutants and contaminants, allowing for these to accumulate in alpine environments and food webs over time (Kosek &

Ruman, 2021). This poses risks to the health of alpine river systems and even in some cases northern communities (Wrona et al., 2016). Community observations of microplastics in fish and increased precipitation of contaminants affecting air and water quality in Nunatsiavut confirm that pollution is already occurring, raising concerns about food and water security (Nunatsiavut Government, 2024).

2.5 Alpine River Systems in Torngat Mountains National Park

2.5.1 History and Establishment

Human occupation of northern Labrador dates back nearly seven thousand years with archaeological evidence such as tent rings, stone caribou fences, food caches, and burial sites present throughout the region (Brice-Bennett, 1977). The direct ancestors of Nunatsiavut and Nunavik Inuit have continuously used this region for hunting, gathering, fishing, and the collection of raw materials for tools, oil lamps, and jewelry and carvings (Government of Canada, 2023). This region is a place of deep spiritual connection for Labrador Inuit with the name "*Torngat*" hailing from Inuttitut meaning "*place of spirits*" (Brice-Bennett et al., 2023). This word is derived from "*Torngarsoak*", a master spirit from Inuit mythology who controls the life of sea animals and takes the form of a huge polar bear believed to reside in the Torngat Mountains (Brice-Bennett, 1977). For over 500 years, the Torngat Mountains were continuously inhabited by Nunatsiavut and Nunavik Inuit, also known as *Avanimiut* or "people of the North". However, between 1956 and 1959, *Avanimiut* were forcibly relocated south from the Okak Bay (Nutak) and Hebron regions by the provincial government to what the government considered to be more "established and centralized" communities (Figure 2.2). This permanent displacement resulted in monumental social and cultural harm for *Avanimuit*, disrupting their way of life, traditional practices, and depriving them of their ancestral homeland (Brice-Bennett et al., 2023).

Research to identify a possible national park for northern Labrador began in 1969 and a prospective spot in the Torngat Mountains was quickly found. In the 1970s, before park development could be pursued further, the recently formed Labrador Inuit Association (LIA),

the political representation for Inuit in Labrador, indicated their intent to file a land claim with the Government of Canada and suggested any negotiations about a national park be included then (Brice-Bennett et al., 2023). The land claim was filed to the federal government in 1977 and accepted for negotiation the following year but would take several decades before coming to fruition. Initially, the land claim involved plans to reconstruct a community in the North; however, due to pressure from the federal and provincial governments this idea was abandoned and instead compensation and a formal apology from the provincial government were given to the displaced families (Brice-Bennett et al., 2023). In 2005, the Nunatsiavut Government and Torngat Mountains National Park Reserve were established under the Labrador Inuit Land Claim Agreement. On July 10th, 2008, *Tongait KakKasuangita SilakKijapvinga* (Torngat Mountains National Park [TMNP]) officially became Canada's 42nd National Park when the Nunavik Inuit Land Claims Agreement came into full legal effect (Brice-Bennett et al., 2023).

The management of TMNP follows an integrated management structure between Parks Canada and an all-Inuit Cooperative Management Board in recognition of the connection Nunatsiavut and Nunavik Inuit have to this land (Brice-Bennett et al., 2023). The CMB advises the federal Minister of Environment and Climate Change Canada (ECCC) on all TMNP related matters and ensures Inuit traditional knowledge is incorporated in all decisions. The CMB is made up of seven members: two members from the Nunatsiavut Government, two members from the Makivik Corporation who represent Nunavik's Inuit, two members from Parks Canada, and an independent Chairperson. The CMB also provides advice to the Torngat Wildlife and Plant Cooperative Management Board, the Torngat Joint Fisheries Board, the Nunatsiavut Government, and other agencies operating in the area on all matters related to management and conservation (Lemelin et al., 2015). *Tongait KakKasuangita SilakKijapvinga* serves as an important symbol of Inuit legacy and identity in Labrador and protects a land rich in culture and beauty (Brice-Bennett et al., 2023).

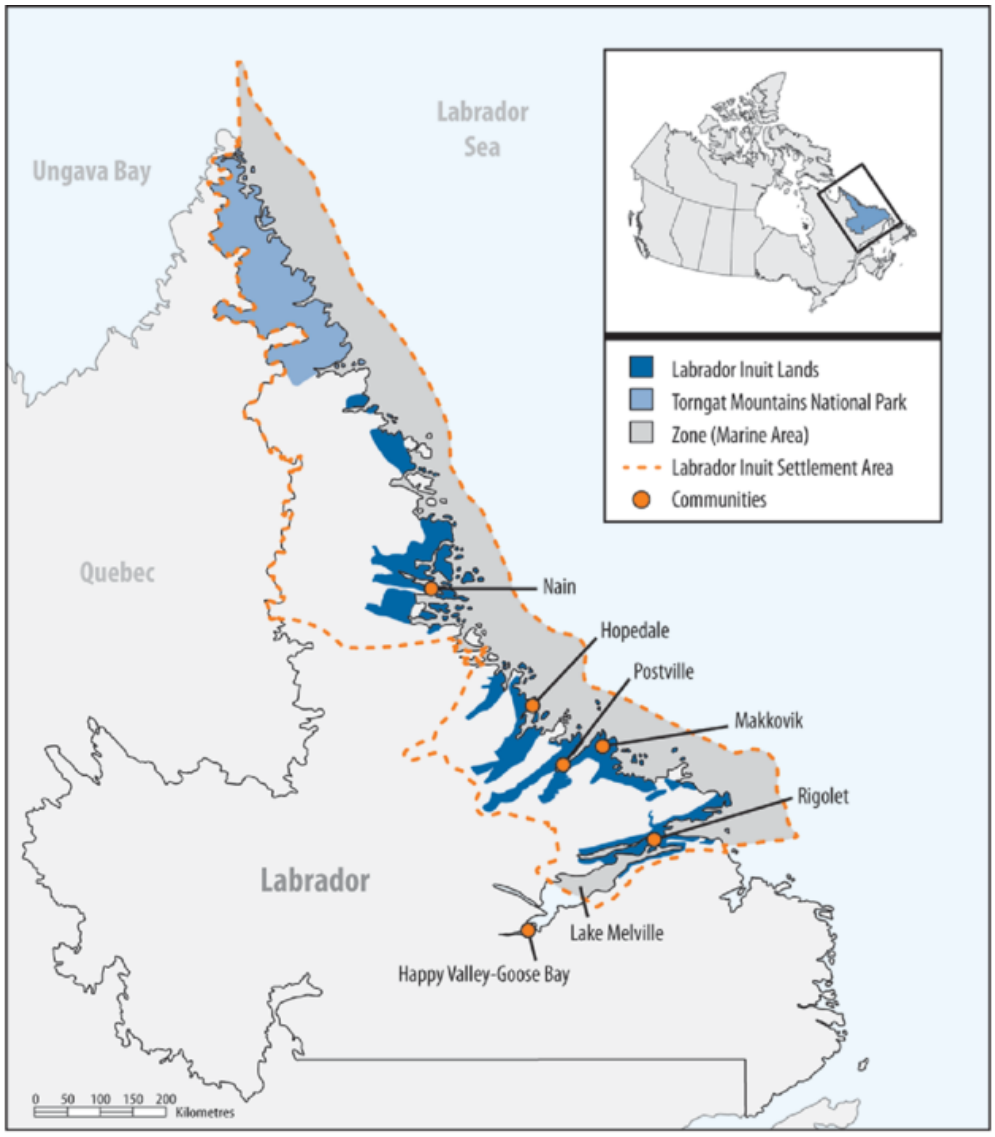


Figure 2.2: Map of Nunatsiavut and Labrador Inuit Settlement Area showing Nunatsiavut communities and Torngat Mountains National Park. Map retrieved from Ortenzi et al. (2024).

2.5.2 Geology and Climate

Spanning over 9,700 km^2, TMNP encompasses the northernmost tip of Labrador and the southernmost limit of the Arctic Cordillera ecozone, which extends from northern Labrador to Ellesmere Island. This region is bracketed to the east by the Labrador Sea and to the west

by the Quebec-Labrador watershed divide. The Torngat Mountains range includes the tallest mountains in mainland Canada east of the Rocky Mountains and possess the only remaining glaciers in continental northeast North America (Way et al., 2014). The underlying geology of this region is amongst the oldest on Earth with formations such as the Nanok gneiss in Saglek Bay dating back 3.9 billion years. Bedrock is mainly composed of orthogneiss and granite near the coast, undifferentiated gneiss further inland, and sections of sedimentary rocks in the south and igneous intrusions present in the north (Way et al., 2014). The physical landscape of TMNP is composed of two distinct landscapes, the George Plateau and Torngat Mountains. The George Plateau is characterized by sweeping bedrock plains cut deep by massive U-shaped river valleys that run west to east through the Torngat Mountains (Figure 2.3). The Torngat Mountains are steep and rugged, rising from the ocean and reaching over 1000 meters in height, with the highest peak being Mount Caubvick at 1652 m.a.s.l., and forming towering cliffs along the coastline. This whole region is littered by evidence of past glaciation, such as drumlin fields, kame terraces, erratics, eskers, and cirques (Riley et al., 2013).



Figure 2.3: Towering cliffs and U-shaped valleys of Torngat Mountains National Park (photographed by author, 2023).

This region is classified as polar tundra and is heavily influenced by the Labrador Current, which keeps summers mild and winters cold and dry. The region's proximity to a coastal moisture source and its steep topography have allowed for the preservation of over one-hundred alpine glaciers scattered throughout the mountain's small cirque basins (Way et al., 2014). Seasonal air temperature models for 2000-2014 for the Labrador-Ungava region show a mean summer air temperature of 7°C, a mean winter air temperature of -17°C, and a mean annual precipitation of 400-700 mm for TMNP (Way et al., 2017). In recent decades however, the effects of climate change have become noticeable with recorded winter temperatures trending to an increase of approximately 2°C and summer temperatures of 0.5°C per decade

since the 1980s. Summer sea ice has also been estimated to be declining by 30% each decade (Barrette et al., 2020; Davis et al., 2021).

2.5.3 Flora and Fauna

Despite the extensive history of human use, TMNP is a relatively pristine wilderness area rich in biodiversity. Much of the vegetation in the northern extent of TMNP is sparse tundra, but in the south a variety of boreal, coastal, alpine, and Arctic plant and animal species can be found (Trant et al., 2022). Foraging animals here survive off of lichen, grasses, low-lying berry plants, and palatable shrubs. These mountains are also home to many iconic Canadian species, such as *nanuq* (k; *Ursus maritimus*), *adlak* (black bear; *Ursus americanus*), *tuttuk* (caribou; *Rangifer tarandus*), *pamiuligak* (minke whale/grumpus; *Balaenoptera acutorostrata*), *kaiguliatsuk* (ringed-seal; *Pusa hispida*), and *ikKaluk*, along with a multitude of bird species, including species-at-risk such as *kotsiutik* (harlequin duck; *Histrionicus histrionicus*), peregrine falcons (*Falco peregrinus*), barrows golden-eye (*Bucephala islandica*), and short-eared owls (*Asio flammeus*) (Government of Canada, 2023).

The Arctic Cordillera is above the latitudinal limit for trees, so dominant woody vegetation is composed of deciduous shrub species which respond quickly to improved growing conditions (McDowell et al., 2023). The most notable ecological change for this landscape has come from the rapid expansion of shrubs, especially in valleys and along river corridors, in a phenomenon coined as “shrubification” (Myers-Smith et al., 2011; Davis et al., 2021). A recent time series of Normalized Difference Vegetation Index (NDVI) in the Nakvak Brook watershed, located in the southern portion of TMNP, shows a significant greening trend over the past four decades. Land cover hindcasts record a 235% increase in shrubs and a 105% increase in wet vegetation cover over the past three decades while forecasts expect an additional 51% increase in shrubs by 2039/43 (Figure 2.4) (Davis et al., 2021). Enhanced shrub trapping of snow has been implicated in observations of permafrost thaw and carbon release across the circumpolar north (Davis et al., 2021; Larking et al., 2021). Shrub expansion can also encroach on other low-lying plants such as berry plants, an important food resource for people and animals, and lichens, which is a primary food source for *tuttuk*, whose numbers

appear to be in decline across Canada (Johnson et al., 2025). Shrubification also offers a new complexity to the relationship *tuttuk* have with forage availability as *tuttuk* may eat the palatable shrubs, such as birch and willow, keeping their expansion under control but leave non-palatable shrub species to flourish (Johnson et al., 2025). Another primary concern is that taller and denser shrubs make it more difficult for Inuit and visitors to travel through the land and harder to spot *nanuq* and *adlak*, raising human-wildlife safety concerns (Davis et al., 2021).

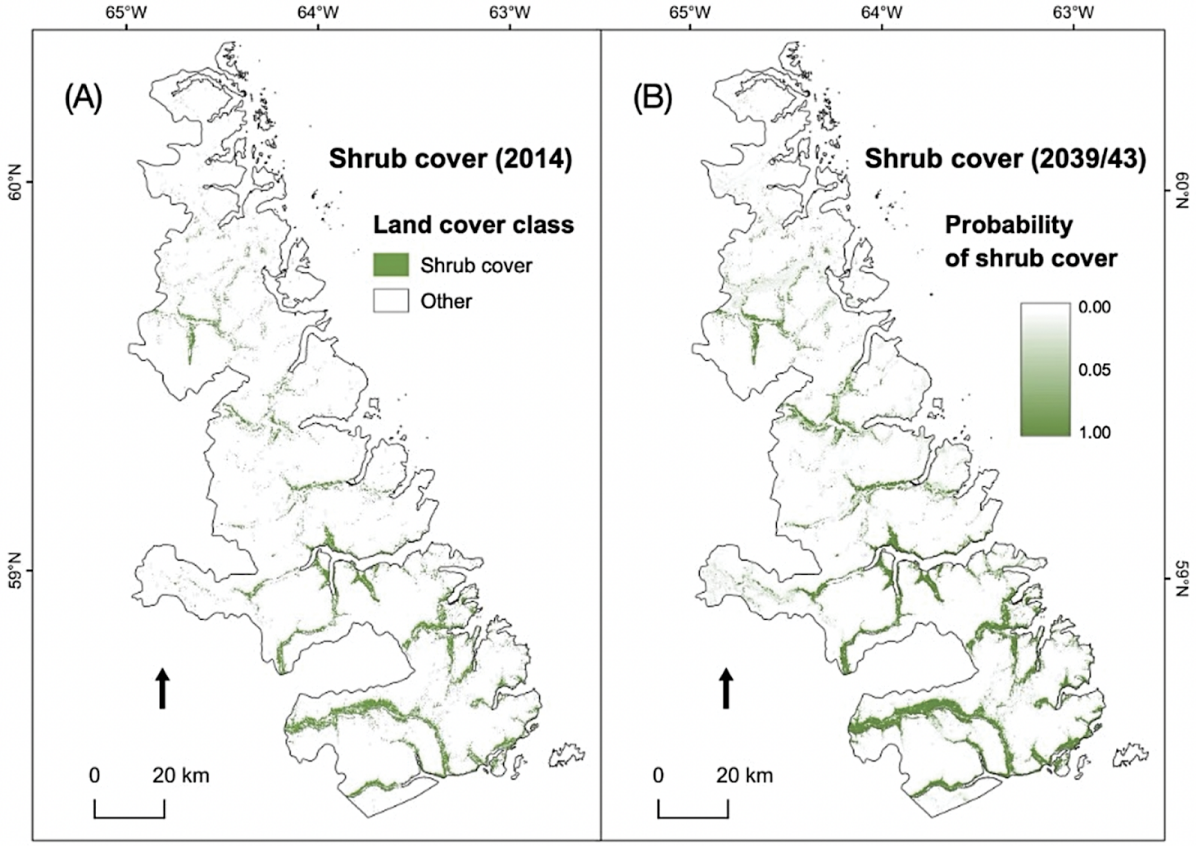


Figure 2.4: Map of Torngat Mountains National Park and the distribution of shrubs in 2014 (A) and projected shrub expansion in 2039/43 (B). Retrieved from Trant et al. (2022).

2.5.4 The Cryosphere and Hydrosphere

Ecosystem change in TMNP is expected to be modified by changes in the cryosphere as glaciers and snowpacks shrink leading to major shifts in source water (Brown et al., 2007).

Modelling by Way and Lewkowicz (2016) suggests that the southern portion of TMNP falls within the extensive discontinuous permafrost zone with the northern portion of TMNP residing in the continuous permafrost zone. Thawing permafrost in this region could affect regional hydrology and vegetation cover through the release of stored water, carbon, and nutrients (Giesler et al., 2014). However, little work has been done to understand the extent and changes of permafrost in this area, though current research efforts aim to fill in these knowledge gaps (CINUK, 2023).

While the impacts of permafrost thaw in TMNP are largely understudied, there is at least some knowledge about the region's glaciers. TMNP is home to 105 small alpine glaciers which all occur within 50 kilometres of the coastline and span just over 1° of latitude from 58.6°N to 59.9°N (Figure 2.5) (Way et al., 2017). Observed changes reveal that these are in steady decline with a regional glacier loss of 27% recorded from 1950 to 2005 and a 52.5% reduction in ice extent since the Little Ice Age (LIA) maxima (Barrand et al., 2017). These studies have linked glacial decline to trends of decreasing winter precipitation and increasing summer and autumn atmospheric warming since the early 1990s. Ongoing changes to the region's glaciers likely have downstream effects on the region's freshwater ecosystems which are an integral part of the cultural landscape for Nunatsiavut and Nunavik Inuit (Barrand, et al., 2017).

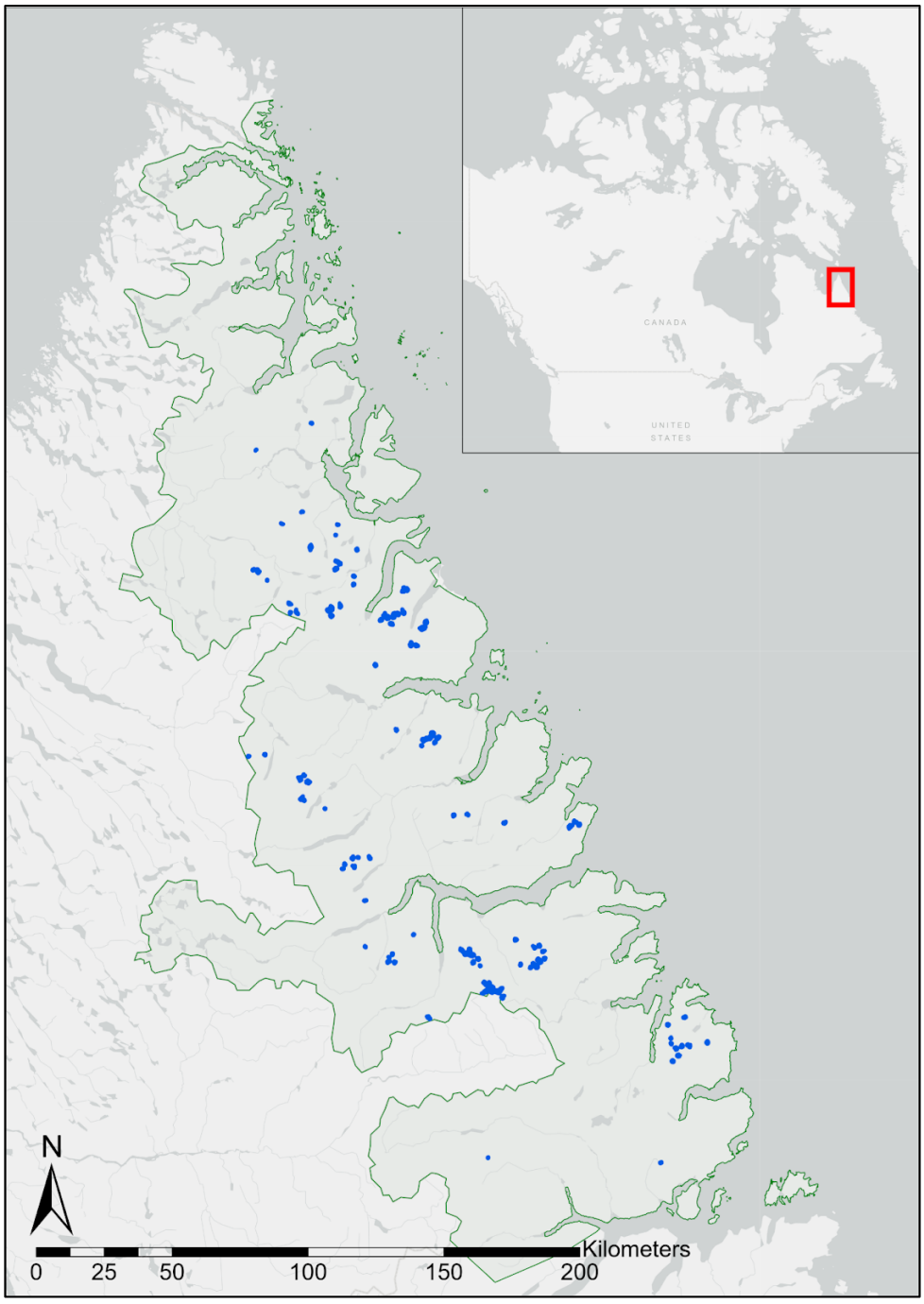


Figure 2.5: Map of glaciers in Torngat Mountains National Park with glaciers represented in blue and the park boundary outlined in green (basemap imagery from ESRI Canada and Parks Canada's open database, created by the author in 2025).

Similar to other alpine areas the hydrological regimes in TMNP can be categorized as glacier-dominated, snow-dominated, rain-dominated, groundwater-dominated or a hybrid of these systems (McDowell et al., 2023). Changes in glacier extent, source water contribution, and the quantity and quality of riparian vegetation are likely to have the greatest influence on stream function and structure in this area (Ritcey & Culp, 2008). Future warming is expected to make stream flow warmer, slower, and less turbid, with glacier loss altering downstream environments to resemble those of more barren non-glacial systems in the future (Sudlow et al., 2023). Prior to reaching "peak water" a wetter climate is anticipated to become a major impact of increased glacier melt due to higher rates of discharge impacting downstream ecology (Slemmons et al., 2013). Future changes to TMNP's alpine river systems and their habitats are anticipated which raises environmental and cultural conservation concerns.

2.5.5 Implications for Ecosystems and Livelihoods

TMNP supports a diversity of plants, animals, and waters, and fosters a sense of place and culture. The protection of TMNP ensures the protection of diverse and remarkable landscapes and sustainability for Inuit homelands (Brice-Bennett et al., 2023). Though protected areas can guard against habitat and species loss, they are still at the mercy of climate change and associated environmental transformations (Holsinger et al., 2019). Continued warming will continue to change freshwater systems in the region, altering local climate and weather patterns, snow accumulation, species distribution, nutrient cycles and carbon balance, and posing a threat to northern ecosystems and communities (Thorne et al., 2024).

The effects of climate change have already begun to impact the way of life for the people of Nunatsiavut. The Silavut Asianguvalliajuk Nunatsiavut Climate Change Workshop hosted in Nain in 2024 included extensive discussion of the ways in which Inuit have seen the land change and how it has impacted their way of life, identity, and ability to use and connect to the land. Examples of ongoing changes included shifts in migration patterns for birds and locations of edible berry patches, unpredictable seasonal sea ice formation making winter travel more dangerous, increases in polar bear encounters as sea ice declines, more intense storm and weather events, and previously unseen southern wildlife species being spotted. One

consistent theme throughout the workshop was that despite these challenges, Nunatsiavummiut are resilient and ready to take on the uncertainty climate change presents (Nunatsiavut Government, 2024). Today, there is both a need and a will for more standardized and consistent environmental monitoring in TMNP in order to produce meaningful research and help communities design effective conservation and adaptation strategies (Isaak & Rieman, 2013).

2.5.6 Hydrological Monitoring and Knowledge Gaps

Alpine river systems are ideally suited for studying the hydrological effects of climate change due to minimal direct human influence and their sensitivity to temperature change (Slemmons et al., 2013). The management and conservation of alpine river systems requires knowledge on how water moves and changes through a watershed. Unfortunately, due to limited resources there are few long-term hydroclimatological monitoring stations across northern Canada (Gibson et al., 2020). This is a fundamental challenge for stream hydrology research as it is difficult to explain and predict how water will flow through a landscape without long-term records. Each watershed also has its own unique characteristics, making it impossible to generalize river processes (McMillan et al., 2025). Still, developing a solid understanding on the current state of alpine river systems will help future monitoring and conservation efforts (Wrona et al., 2016).

Past hydrological monitoring in TMNP has been limited but this area has been identified as a priority by the CMB to better understand how changes in stream temperature and flow may affect local fish populations, biodiversity, and ecological functioning of aquatic and riparian ecosystems (Nunatsiavut Government, 2025). To begin to address this challenge, the IMAGINE team, an interdisciplinary research project investigating changes in the cryosphere and hydrosphere and their impacts on northern ecosystems and livelihoods, began collecting stream water samples in TMNP in August of 2024. Water samples were collected for the purposes of stable isotope tracing and aqueous carbon measurement and analyses. Stable isotopic tracers add value to hydrological monitoring and the prediction of future conditions in TMNP as they can track streamflow mixing and sources, estimate evaporation and water residence times, and gain knowledge of local water cycle variability (Gibson et al.,

2020). Regular isotopic sampling can help detect early evidence of climate change impacts to alpine river systems, allowing us to better protect freshwater resources and habitats (Gibson et al., 2020). Monitoring of aqueous carbon in alpine rivers also provides a wealth of knowledge on the ecological functioning and material transport processes of alpine watersheds (Milner et al., 2017). Continued use of these methods can help establish reliable baseline hydrological data for TMNP to guide management decisions and safeguard alpine ecosystems and resources (Immerzeel et al., 2019). As we embark towards a warmer world, it is important to consider what the future holds for alpine river systems as the sources that feed them disappear, and how we can best inform stewardship of these landscapes for generations to come.

2.6 References

Barrand, N. E., Way, R. G., Bell, T., & Sharp, M. J. (2017). Recent changes in area and thickness of Torngat Mountain glaciers (northern Labrador, Canada). The Cryosphere 11, 1, 157-168. https://doi.org/10.5194/tc-11-157-2017

Barrette, C., Brown, R., Way, R., Mailhot, A., Diaconescu, E.P., Grenier, P., Chaumont, D., Dumont, D., Sévigny, C., Howell, S., et al. (2020). *Nunavik and Nunatsiavut Regional Climate Information Update*. ArcticNet Inc.

Battin, T. J., Lauerwald, R., Bernhardt, E. S., Bertuzzo, E., Gener, L. G., Hall, R. O., Hotchkiss, E. R., Maavara, T., Pavelsky, T. M., Ran, L., Raymond, P., Rosentreter, J. A., & Regnier, P. (2023). River ecosystem metabolism and carbon biogeochemistry in a changing world. Nature, 613(7944), 449–459. https://doi.org/10.1038/s41586-022-05500-8

Bavay, M., Grünewald, T., & Lehning, M. (2013). Response of snow cover and runoff to climate change in high Alpine catchments of Eastern Switzerland. Advances in Water Resources, 55, 4–16. https://doi.org/10.1016/j.advwatres.2012.12.009

Bliss, A., Hock, R., & Radić, V. (2014). Global response of glacier runoff to twenty-first century climate change. Journal of Geophysical Research: Earth Surface, 119(4), 717–730. https://doi.org/10.1002/2013JF002931

Bosson, J. B., Huss, M., Cauvy-Fraunié, S., Clément, J. C., Costes, G., Fischer, M., Poulenard, J., & Arthaud, F. (2023). Future emergence of new ecosystems caused by glacial retreat. Nature, 620(7974), 562–569. https://doi.org/10.1038/s41586-023-06302-2

Bourquin, M., Peter, H., Michoud, G., Busi, S. B., Kohler, T. J., Robison, A. L., Styllas, M., Ezzat, L., Geers, A. U., Huss, M., Fodelianakis, S., & Battin, T. J. (2025). Predicting climate-change impacts on the global glacier-fed stream microbiome. Nature Communications, 16(1), 1264. https://doi.org/10.1038/s41467-025-56426-4

Brice-Bennett, C. (1977). *Our Footprints Are Everywhere*. Labrador Inuit Association.

Brice-Bennett, C., Onalik, L., Procter, A. (2023). *Avanimiut: A History of Inuit Independence in Northern Labrador*. Nunatsiavut Government.

Brown, L. E., Hannah, D. M., & Milner, A. M. (2007). Vulnerability of alpine stream biodiversity to shrinking glaciers and snowpacks. Global Change Biology, 13(5), 958–966. https://doi.org/10.1111/j.1365-2486.2007.01341.x

CINUK. (2023). *IMAGINE - glaciers, rivers, & ecosystems*. Canada-Inuit Nunangat-United Kingdom Arctic Research Program (CINUK): https://www.cinuk.org/projects/imagine/

Clarke, G. K. C., Jarosch, A. H., Anslow, F. S., Radić, V., & Menounos, B. (2015). Projected deglaciation of western Canada in the twenty-first century. Nature Geoscience, 8(5), 372–377. https://doi.org/10.1038/ngeo2407

Cole, J., & Prairie, Y. (2014). Dissolved CO2 in Freshwater Systems. In Reference Module in Earth Systems and Environmental Sciences. https://doi.org/10.1016/B978-0-12-409548-9.09399-4

Culp, J. M., Lento, J., Curry, R. A., Luiker, E., & Halliwell, D. (2019). Arctic biodiversity of stream macroinvertebrates declines in response to latitudinal change in the abiotic template. Freshwater Science, 38(3), 465–479. https://doi.org/10.1086/704887

Davis, E. L., Trant, A. J., Way, R. G., Hermanutz, L., & Whitaker, D. (2021). Rapid Ecosystem Change at the Southern Limit of the Canadian Arctic, Torngat Mountains National Park. Remote Sensing, 13(11), Article 11. https://doi.org/10.3390/rs13112085

Déry, S. J., Stahl, K., Moore, R. D., Whitfield, P. H., Menounos, B., & Burford, J. E. (2009). Detection of runoff timing changes in pluvial, nival, and glacial rivers of western Canada. Water Resources Research, 45(4). https://doi.org/10.1029/2008WR006975

Dyer, J. (2008). Snow depth and streamflow relationships in large North American watersheds. Journal of Geophysical Research: Atmospheres, 113(D18). https://doi.org/10.1029/2008JD010031

Ejarque, E., Scholz, K., Wohlfahrt, G., Battin, T. J., Kainz, M. J., & Schelker, J. (2021). Hydrology controls the carbon mass balance of a mountain lake in the eastern European Alps. Limnology and Oceanography, 66(6), 2110–2125. https://doi.org/10.1002/lno.11712

Geissinger, E. A., Van Leeuwen, T. E., Kelly, N., Pennell, C., Fitzsimmons, M. G., Duffy, S., Poole, R., Angnatok, J., Dempson, J. B., & Coté, D. (2024). Salmonids in hot water: An unprecedented warm-water event in Labrador, a subarctic region of Canada. Fisheries Management and Ecology, 31(5), e12710. https://doi.org/10.1111/fme.12710

Gibson, J. J., Holmes, T., Stadnyk, T. A., Birks, S. J., Eby, P., & Pietroniro, A. (2020). 18O and 2H in streamflow across Canada. Journal of Hydrology: Regional Studies, 32. Scopus. https://doi.org/10.1016/j.ejrh.2020.100754

Giesler, R., Lyon, S. W., Mörth, C.-M., Karlsson, J., Karlsson, E. M., Jantze, E. J., Destouni, G., & Humborg, C. (2014). Catchment-scale dissolved carbon concentrations and export estimates across six subarctic streams in northern Sweden. Biogeosciences, 11(2), 525–537. https://doi.org/10.5194/bg-11-525-2014

Government of Canada. (2023). *Torngat Mountains National Park*. https://parks.canada.ca/pn-np/nl/torngats

Griffiths, K., Michelutti, N., Sugar, M., Douglas, M. S. V., & Smol, J. P. (2017). Ice-cover is the principal driver of ecological change in High Arctic lakes and ponds. PLOS ONE, 12(3), e0172989. https://doi.org/10.1371/journal.pone.0172989

Harris, L. N., Yurkowski, D. J., Gilbert, M. J. H., Else, B. G. T., Duke, P. J., Ahmed, M. M. M., Tallman, R. F., Fisk, A. T., & Moore, J. (2020). Depth and temperature preference of anadromous Arctic char Salvelinus alpinus in the Kitikmeot Sea, a shallow and low-salinity area of the Canadian Arctic. Marine Ecology Progress Series, 634, 175–197. https://doi.org/10.3354/meps13195

Hille, E., Lafrenière, M., Lamoureux, S. (2024). Multi-year and seasonal trends in the water quality of the Niaqunguk River, Nunavut (2013–2018). International Permafrost Association (IPA). https://doi.org/10.52381/ICOP2024.127.1

Holsinger, L., Parks, S. A., Parisien, M.-A., Miller, C., Batllori, E., & Moritz, M. A. (2019). Climate change likely to reshape vegetation in North America's largest protected areas. Conservation Science and Practice, 1(7), e50. https://doi.org/10.1111/csp2.50

Hou, J., Li, F., Wang, Z., Li, X., Cao, R., & Yang, W. (2022). Dynamics of Dissolved Carbon in Subalpine Forest Streams. Forests, 13(5), Article 5. https://doi.org/10.3390/f13050795

Huss, M., & Hock, R. (2018). Global-scale hydrological response to future glacier mass loss. Nature Climate Change, 8(2), 135–140. https://doi.org/10.1038/s41558-017-0049-x

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde, S., Brumby, S., Davies, B. J., Elmore, A. C., Emmer, A., Feng, M., Fernández, A., Haritashya, U., Kargel, J.

S., Koppes, M., Kraaijenbrink, P. D. A., Kulkarni, A. V., Mayewski, P. A., … Baillie, J. E. M. (2020). Importance and vulnerability of the world's water towers. Nature, 577(7790), 364–369. https://doi.org/10.1038/s41586-019-1822-y

Isaak, D. J., & Rieman, B. E. (2013). Stream isotherm shifts from climate change and implications for distributions of ectothermic organisms. Global Change Biology, 19(3), 742–751. https://doi.org/10.1111/gcb.12073

Johnson, A., Trant, A., Hermanutz, L., Davis, E., Saunders, M., Collier, L. S., Way, R., & Knight, T. (2025). Climate warming impacts tuttuk (caribou) forage availability in Tongait (Torngat) Mountains, Labrador. Arctic Science, 11, 1–14. https://doi.org/10.1139/as-2023-0047

Kerins, D., Sadayappan, K., Zhi, W., Sullivan, P. L., Williams, K. H., Carroll, R. W. H., Barnard, H. R., Sprenger, M., Dong, W., Perdrial, J., & Li, L. (2024). Hydrology Outweighs Temperature in Driving Production and Export of Dissolved Carbon in a Snowy Mountain Catchment. Water Resources Research, 60(7), e2023WR036077. https://doi.org/10.1029/2023WR036077

Kosek, K., & Ruman, M. (2021). Arctic Freshwater Environment Altered by the Accumulation of Commonly Determined and Potentially New POPs. Water, 13(13), Article 13. https://doi.org/10.3390/w13131739

Lemelin, H., Johnston, M., Lough, D., Rowell, J., Broomfield, W., Baikie, G., & Sheppard, K. (2016). Two Parks, One Vision – Collaborative Management Approaches to Transboundary Protected Areas in Northern Canada: Tongait KakKasuangita SilakKijapvinga/Torngat Mountains National Park, Nunatsiavut and le Parc national Kuururjuaq Nunavik. In T. M. Herrmann & T. Martin (Eds.), Indigenous Peoples' Governance of Land and Protected Territories in the Arctic (pp. 71–82). Springer International Publishing. https://doi.org/10.1007/978-3-319-25035-9_4

Liu, D., Wang, T., Liu, X., Ao, J., Tang, H., & Chang, R. (2023). Source, pattern and flux of dissolved carbon in an alpine headwater catchment on the eastern Tibetan Plateau. Hydrological Processes, 37(7), e14941. https://doi.org/10.1002/hyp.14941

MacMillan-Kenny, Z., Denniston, M., Edinger, E., Templeton, A., Côté, D., Limoges, A., & Robert, K. (2025). Associations between iKaluk/Arctic charr (Salvelinus alpinus) and estuarine benthic diatom habitats in nearshore Nunatsiavut waters. Polar Biology, 48(1), 20. https://doi.org/10.1007/s00300-024-03323-z

McDowell, G., Stevens, M., Marshall, S. (2023). *The Canadian Mountain Assessment: Walking Together to Enhance Understanding of Mountains in Canada*. University of Calgary Press.

McMillan, H., Araki, R., Bolotin, L., Kim, D.-H., Coxon, G., Clark, M., & Seibert, J. (2025). Global patterns in observed hydrologic processes. Nature Water, 1–10. https://doi.org/10.1038/s44221-025-00407-w

Michelutti, N., Douglas, M.S.V., Antoniades, D., Lehnherr, I., St. Louis, V.L., St. Pierre, K., Muir, D.C.G., Brunskill, G., Smol, J.P. (2020). Contrasting the ecological effects of decreasing ice cover versus accelerated glacial melt on the High Arctic's largest lake. Proc. R. Soc. B 287: 20201185. http://dx.doi.org/10.1098/rspb.2020.1185

Milner, A. M., Khamis, K., Battin, T. J., Brittain, J. E., Barrand, N. E., Füreder, L., Cauvy-Fraunié, S., Gíslason, G. M., Jacobsen, D., Hannah, D. M., Hodson, A. J., Hood, E., Lencioni, V., Ólafsson, J. S., Robinson, C. T., Tranter, M., & Brown, L. E. (2017). Glacier shrinkage driving global changes in downstream systems. Proceedings of the National Academy of Sciences, 114(37), 9770–9778. https://doi.org/10.1073/pnas.1619807114

Myers-Smith, I. H., Forbes, B. C., Wilmking, M., Hallinger, M., Lantz, T., Blok, D., Tape, K. D., Macias-Fauria, M., Sass-Klaassen, U., Lévesque, E., Boudreau, S., Ropars, P., Hermanutz, L., Trant, A., Collier, L. S., Weijers, S., Rozema, J., Rayback, S. A., Schmidt, N. M., … Hik, D. S. (2011). Shrub expansion in tundra ecosystems: Dynamics, impacts and research priorities. Environmental Research Letters, 6(4), 045509. https://doi.org/10.1088/1748-9326/6/4/045509

Nunatsiavut Government. (2024). *Silavut Asianguvalliajuk Nunatsiavut Climate Change Workshop*. Nunatsiavut Government. https://nunatsiavut.com/research/climate-change/

Nunatsiavut Government. (2025). *Co-Management*. https://nunatsiavut.com/department/lands-natural-resources/co-management/

Ohlanders, N., Rodriguez, M., & McPhee, J. (2013). Stable water isotope variation in a Central Andean watershed dominated by glacier and snowmelt. Hydrology and Earth System Sciences, 17(3), 1035–1050. https://doi.org/10.5194/hess-17-1035-2013

Ortenzi, K. M., Flowers, V. L., Pamak, C., Saunders, M., Schmidt, J. O., & Bailey, M. (2024). Good data relations key to Indigenous research sovereignty: A case study from Nunatsiavut. Ambio. https://doi.org/10.1007/s13280-024-02077-6

Perdrial, J.N., McIntosh, J., Harpold, A., Brooks, P.D., Zapata-Rios, X., Ray, J., Meixner, T., Kanduc, T., Litvak, M., Troch, P.A., Chorover, J. (2014). Stream water carbon controls in seasonally snow-covered mountain catchments: impact of inter-annual variability of water fluxes, catchment aspect and seasonal processes. Biogeochemistry, 118:273-290. https://doi.org/10.1007/s10533-013-9929-y

Riley, J. L., Notzl, L., & Greene, R. (2013). *Labrador Nature Atlas: Ecozones, Ecoregions and Ecodistricts*. Nature Conservancy Canada.

Ritcey, A., & Culp, J. (2008). *Environmental Drivers of Stream Ecosystem Structure and Function in Subarctic Labrador, Canada*. [Master's Thesis, University of New Brunswick].

Rixen, C., Høye, T. T., Macek, P., Aerts, R., Alatalo, J. M., Anderson, J. T., Arnold, P. A., Barrio, I. C., Bjerke, J. W., Björkman, M. P., Blok, D., Blume-Werry, G., Boike, J., Bokhorst, S., Carbognani, M., Christiansen, C. T., Convey, P., Cooper, E. J., Cornelissen, J. H. C., Zong, S. (2022). Winters are changing: Snow effects on Arctic and alpine tundra ecosystems. Arctic Science, 8(3), 572–608. https://doi.org/10.1139/as-2020-0058

Schrope, M. (2000, January 1). Streams and Rivers Breathing Carbon Dioxide. https://environment.yale.edu/news/article/streams-and-rivers-breathing-carbon-dioxide

Sepúlveda, L. D., Echegoyen, C. V., Martin, M. E., Campodonico, V. A., Pasquini, A. I., Temporetti, P., & Lecomte, K. L. (2022). Isotopic signature of a glacial influenced hydrological system in northern Patagonia, Argentina. Hydrological Processes, 36(2), e14504. https://doi.org/10.1002/hyp.14504

Shugar, D. H., Clague, J. J., Best, J. L., Schoof, C., Willis, M. J., Copland, L., & Roe, G. H. (2017). River piracy and drainage basin reorganization led by climate-driven glacier retreat. Nature Geoscience, 10(5), 370–375. https://doi.org/10.1038/ngeo2932

Slemmons, K. E. H., Saros, J. E., & Simon, K. (2013). The influence of glacial meltwater on alpine aquatic ecosystems: A review. Environmental Science: Processes & Impacts, 15(10), 1794–1806. https://doi.org/10.1039/C3EM00243H

St. Pierre, K. A., St. Louis, V. L., Schiff, S. L., Lehnherr, I., Dainard, P. G., Gardner, A. S., Aukes, P. J. K., & Sharp, M. J. (2019). Proglacial freshwaters are significant and previously unrecognized

sinks of atmospheric CO2. Proceedings of the National Academy of Sciences, 116(36), 17690–17695. https://doi.org/10.1073/pnas.1904241116

Sudlow, K., Tremblay, S. S., & Vinebrooke, R. D. (2023). Glacial stream ecosystems and epilithic algal communities under a warming climate. Environmental Reviews, 31(3), 471–483. https://doi.org/10.1139/er-2022-0114

Thorne, R., Walker, B., Tutton, R., Fogal, A., Seto, J., Brocket, M., Dakin, B., Abumazan, N., Marsh, P. (2024). Predicting the future hydrology of western Canadian Arctic watersheds dominated by thermokarst lakes. International Permafrost Association (IPA). https://doi.org/10.52381/ICOP2024.199.1

Trant, A., Davis, E., Hermanutz, L., Cuerrier, A., Laing, R., Knight, T., Lightfoot, H., Siegwart, L., Collier, Whitaker, D., and Way, R. (2022). Past and Future Ecosystem Change in Torngat Mountains National Park. State of the Mountains, Alpine Club of Canada. https://stateofthemountains.ca/state-of-the-mountains-blog/past-and-future-ecosystem-change-in-torngat-mountains-national-park-tongait-kakkasuangita-silakkijapvinga-northern-nunatsiavut-labrador?rq=torngat

Wang, H., Liu, J., Klaar, M., Chen, A., Gudmundsson, L., & Holden, J. (2024). Anthropogenic climate change has influenced global river flow seasonality. Science, 383(6686), 1009–1014. https://doi.org/10.1126/science.adi9501

Way, R. G., Bell, T., & Barrand, N. E. (2014). An inventory and topographic analysis of glaciers in the Torngat Mountains, northern Labrador, Canada. Journal of Glaciology, 60(223), 945–956. https://doi.org/10.3189/2014JoG13J195

Way, R. G. & Lewkowicz, A. G. (2016). Modelling the spatial distribution of permafrost in Labrador–Ungava using the temperature at the top of permafrost. Canadian Journal of Earth Sciences, 53(10). https://doi.org/10.1139/cjes-2016-003

Way, R. G., Lewkowicz, A. G., & Bonnaventure, P. P. (2017). Development of moderate-resolution gridded monthly air temperature and degree-day maps for the Labrador-Ungava region of northern Canada. International Journal of Climatology, 37(1), 493–508. https://doi.org/10.1002/joc.4721

Wilkes, M. A., Carrivick, J. L., Castella, E., Ilg, C., Cauvy-Fraunié, S., Fell, S. C., Füreder, L., Huss, M., James, W., Lencioni, V., Robinson, C., & Brown, L. E. (2023). Glacier retreat reorganizes river habitats leaving refugia for Alpine invertebrate biodiversity poorly protected. Nature Ecology and Evolution, 7(6), 841–851. Scopus. https://doi.org/10.1038/s41559-023-02061-5

Wrona, F. J., Johansson, M., Culp, J. M., Jenkins, A., Mård, J., Myers-Smith, I. H., Prowse, T. D., Vincent, W. F., & Wookey, P. A. (2016). Transitions in Arctic ecosystems: Ecological implications of a changing hydrological regime. Journal of Geophysical Research: Biogeosciences, 121(3), 650–674. https://doi.org/10.1002/2015JG003133

Zhang, Y., Li, X., Shi, F., Zhang, X., Hu, G., Zuo, F., Wang, Z., & Liu, X. (2024). Spatiotemporal variability of dissolved carbon and sources of dissolved inorganic carbon influenced by freeze–thaw and subsurface flow in an alpine headwater catchment of the Qinghai-Tibetan Plateau. Journal of Hydrology, 640, 131740. https://doi.org/10.1016/j.jhydrol.2024.131740

Chapter 3: Investigating the Influences of Source Water on Arctic Cordilleran River Systems in Torngat Mountains National Park

3.1 Introduction

Changes in hydrological and cryospheric conditions collectively contribute to landscape transformation and alteration of the structure and function of Arctic ecosystems (Wrona et al., 2016). Glaciers and snowfields are particularly important water reservoirs feeding stream networks across the Arctic and transporting nutrients, minerals, and species (Milner et al., 2009). With high latitude regions experiencing accelerated rates of warming compared to lower latitudes, the ability of glaciers and snowpacks to continue supplying stream networks and their dependent ecosystems is at risk (Griffiths et al, 2017; St. Pierre et al., 2019; Geissinger et al., 2024).

Glacier and snowmelt contributions to rivers are predicted to decline globally in the coming decades, leading to a reduction in locally available meltwater. This has the potential to reorganize regional hydrological processes with subsequent implications for downstream environments and the people who depend on them (Giesler et al., 2014). Prior to a decline in meltwater contributions, current climate projections anticipate that alpine river systems will experience an initial rise in streamflow levels due to increased glacier runoff under continued warming conditions and an intensified hydrological cycle (Milner et al., 2009; Wrona et al., 2016). This is predicted to be followed by a decrease as the glaciers surpass their “peak water” threshold, the point at which glacier shrinkage results in a surface area too small for the glacier to sustain its increasing meltwater contributions, and becomes functionally extinct (Clarke et al., 2015). These systems would then be expected to transition to snowpack fed systems, and eventually more barren rain and groundwater fed systems with continued warming (Slemmons et al., 2013; Sudlow et al., 2023). For rivers, the consequence of warming includes earlier melt and spring freshet and lower summer flows as glacier retreat and shifting climate patterns alter the timing, volume, and pathways water takes through a watershed (Milner et al., 2009; Wrona et al., 2016). This will result in subsequent changes in the timing and availability of material

and nutrients transported downstream, potentially impacting the timing of biological activity for freshwater species (Harris et al., 2020). Recent work by Wilkes et al. (2023) also projects that river networks are expanding into higher elevations at a rate of 1% per decade as proglacial zones increase following glacier retreat, with corresponding effects on ecosystems and species range. The ecological succession of expanding proglacial ecosystems will allow for the establishment of new habitats, increased ecological connectivity and biological activity, and allow more generalist species to adapt. Though, how and at what rate this will occur depends on the local characteristics of individual watersheds (Slemmons et al., 2013; Bosson et al., 2023). River habitat availability is also forecasted to change dynamically rather than linearly depending on local topography and regional climate, decreasing our ability to understand how and at what rate change will occur (Wilkes et al., 2023). Stream ecosystems are especially vulnerable to climate warming as many freshwater species are sensitive to temperature change. Warmer conditions are expected to benefit warm-water species over cold-water species which may find it hard to adapt to warming water temperatures and experience increased competition for habitat and resources with warm-water species (Milner et al., 2009). Further, frequent stream branching can easily lead to ecosystem fragmentation, making it difficult to predict how species will adapt and where refugia for cold-water species may persist (Isaak & Rieman, 2013; MacMillan-Kenny et al., 2025).

Ongoing changes to glacio-hydrological systems are likely occurring in *Tongait KakKasuangita SilakKijapvinga* (Torngat Mountains National Park [TMNP]) which is located at the southern limit of the eastern Canadian Arctic and the northernmost tip of Labrador and hosts the only remaining glaciers in continental northeastern North America (Way et al., 2014; Barrand et al., 2017). This region is an integral part of the homeland for Inuit from Nunatsiavut and is home to a variety of boreal, coastal, alpine, and Arctic plant and animal species, including culturally significant species such as *ikKaluk* (Arctic char; *Salvelinus alpinu*s), *aKiggik* (Ptarmigan; *Lagopus* spp.), and *tuttuk* (caribou; *Rangifer tarandus*). For this region, it is expected that glacier melt is a key source of streamflow in the summer months similar to other high latitude regions (Ohlanders et al., 2013). As climate change is expected to make

stream flow warmer, slower, and less turbid, cold-water species such as *ikKaluk* may experience a decrease in suitable habitat conditions and increased competition from the expansion of warm-water species (Sudlow et al., 2023). Additionally, enhanced vegetation growth due to warmer and wetter conditions from an intensified hydrological cycle may lead to amplified shrub growth encroaching on low-lying berry plants (Myers-Smith et al., 2015). This may change the type and availability of habitat for animals, including *tuttuk* and *aKiggik*, and impact Inuit by altering food source availability and the ability to travel over the land. Enhanced vegetation growth also increases safety concerns for people as it becomes harder to see *nanuk* (polar bear; *Ursus maritimus*) and *adlak* (black bear; *Ursus americanus*) in tall vegetation (Davis at el., 2021b).

The remote location of TMNP has kept this region's ecosystems largely intact and minimally influenced by anthropogenic change. However, the remoteness of TMNP has also contributed to a knowledge gap on the impacts of climate change on regional hydrology. According to Hanly et al (2023), glacio-hydrological research in Canada has grown in the past couple decades but this research has been clustered in western Canada (specifically the Canadian Rockies) and glacier ecohydrology, human vulnerability, and adaptation are underrepresented. Correspondingly, the Torngat Mountains were identified as one of the least studied mountain ranges in Canada (Hanley et al., 2023) with no glacio-hydrological research in the region in over 15 years. The most recent investigation in TMNP was undertaken by Ritcey and Culp (2008) during the last International Polar Year (2007) who focused on taxonomic composition of freshwater species by sampling for benthic macroinvertebrates and stable isotopes of carbon and nitrogen. This study also proposed that source water contribution, glacial extent, and the quality and quantity of vegetation have the greatest influence on local stream composition and ecological function for this region.

To improve our understanding of the implications of climate change on regional freshwater and terrestrial ecosystems, this study examines the impacts of cryospheric and hydrological change on downstream ecology by exploring different source water influences on

alpine river systems in TMNP (Figure 3.1). The main objectives of this study are to: (1) assess differences in stream composition between glacial and non-glacial watersheds; (2) examine the influence various contributions of source water have on the physical and chemical aspects of a watershed; and (3) investigate how source water affects the ecological functioning of downstream ecosystems. To address these objectives, stream water samples were collected in glacially and non-glacially fed watersheds for a stable isotopic analysis of oxygen (δ18O) and hydrogen (δ2H) and measurements of aqueous carbon for dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC). The stable isotope analysis was used to evaluate source water contributions and water mixing through watersheds. Measurements of aqueous carbon were used to evaluate how source water contributions influence the ecological functioning of streams. As this geographic area has not undergone stream water sampling in the past, this work also establishes a baseline for future research and sets the groundwork for long-term monitoring initiatives. This work will further our understanding of how cryospheric and hydrological changes impact northern ecosystems and human livelihoods in support of ecological integrity monitoring and conservation.

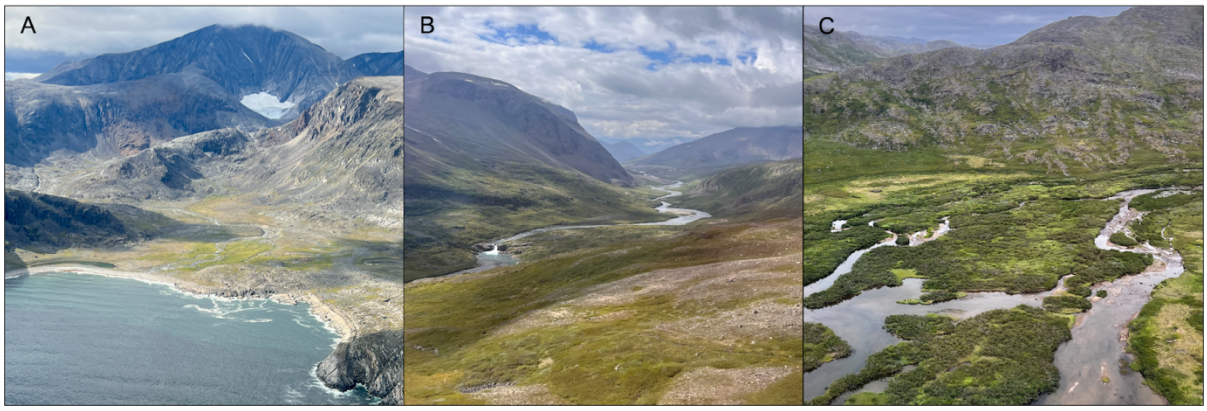


Figure 3.1: Photography of three valleys in TMNP fed by different source waters. (A) Glacier fed Blow Me Down Mountains (58.8°N, 62.9°W). (B) Snow fed Nakvak Brook (58.6°N, 63.3°W). (C) Rain and groundwater fed Torr Bay Brook (58.4°N, 62.8°W). (photographs by Andrew Trant in August 2022, and the author in August 2024).

3.2 Study Area

3.2.1 Torngat Mountains National Park

TMNP, spanning 9,700 km^2, is an Arctic Cordilleran national park that was established in 2005 with the signing of the Labrador Inuit Land Claims Agreement. TMNP is bordered by the Labrador Sea to the east and the Quebec-Labrador watershed divide and George Plateau to the west. This culturally significant area is the ancestral homeland for Nunatsiavut and Nunavik Inuit who have stewarded this land since at least 1400 AD, until between 1956 and 1959 when they were forcibly removed from the Okak Bay (Nutak) and Hebron regions by the provincial government and relocated to more southern and centralized communities of Hopedale, Makkovik, and Nain (Lemelin et al., 2016; Brice-Bennett, 2023). Recognizing the connection Nunatsiavut and Nunavik Inuit have to northern Labrador, TMNP stands as a symbol of Inuit legacy and identity and is cooperatively managed by an all-Inuit Cooperative Management Board which oversees all matters related to the management and conservation of TMNP (Brice-Bennett, 2023).

TMNP is made up of two distinct landscapes, the George Plateau; an expansive bedrock plain with deep U-shaped river valleys and abundant glacial formations, and the rugged Torngat Mountains; which are the tallest mountains in mainland Canada east of the Rocky Mountains reaching over 1500 m a.s.l. (Way et al., 2014). This region is heavily influenced by the Labrador Current which provides cool summer temperatures and cold, dry winters. Seasonal air temperatures modeled by Way et al. (2017) for the Labrador-Ungava region from 2000-2014 show a mean summer air temperature of 7°C and mean winter air temperature of -17°C, with a mean annual precipitation of 400-700 mm. Since the 1980s, the effects of climate change have been felt in the region with recorded winter temperatures having increased by approximately 2°C per decade and summer temperatures having increased by 0.5°C per decade (Barrette et al., 2020; Davis et al., 2021a; Nunatsiavut Government, 2024). The region's coastal proximity, mild summer conditions, and fretted topography have allowed for the preservation of 105 small mountain glaciers. Since the 1990s, Torngat glaciers have been inferred to be in a steady decline due to decreasing winter precipitation and increasing summer and autumn

atmospheric warming (Barrand et al., 2017). As warming trends and glacier retreat are projected to continue, it is important to quantify the influence glacier meltwater and other source waters have on the composition and function of alpine river systems in TMNP. To investigate stream composition and ecological function, data collection and stream water sampling took place across three watersheds: Blow Me Down Mountains (glacier fed), Nakvak Brook (late-lying snowpack fed), and Torr Bay Brook (rain and groundwater fed) (Figure 3.2). These watersheds are located in the southern portion of TMNP, apart from Torr Bay which is included in this analysis with TMNP sites but is actually located a few kilometres outside the park boundary in the Labrador Inuit Settlement Area (Nunatsiavut).

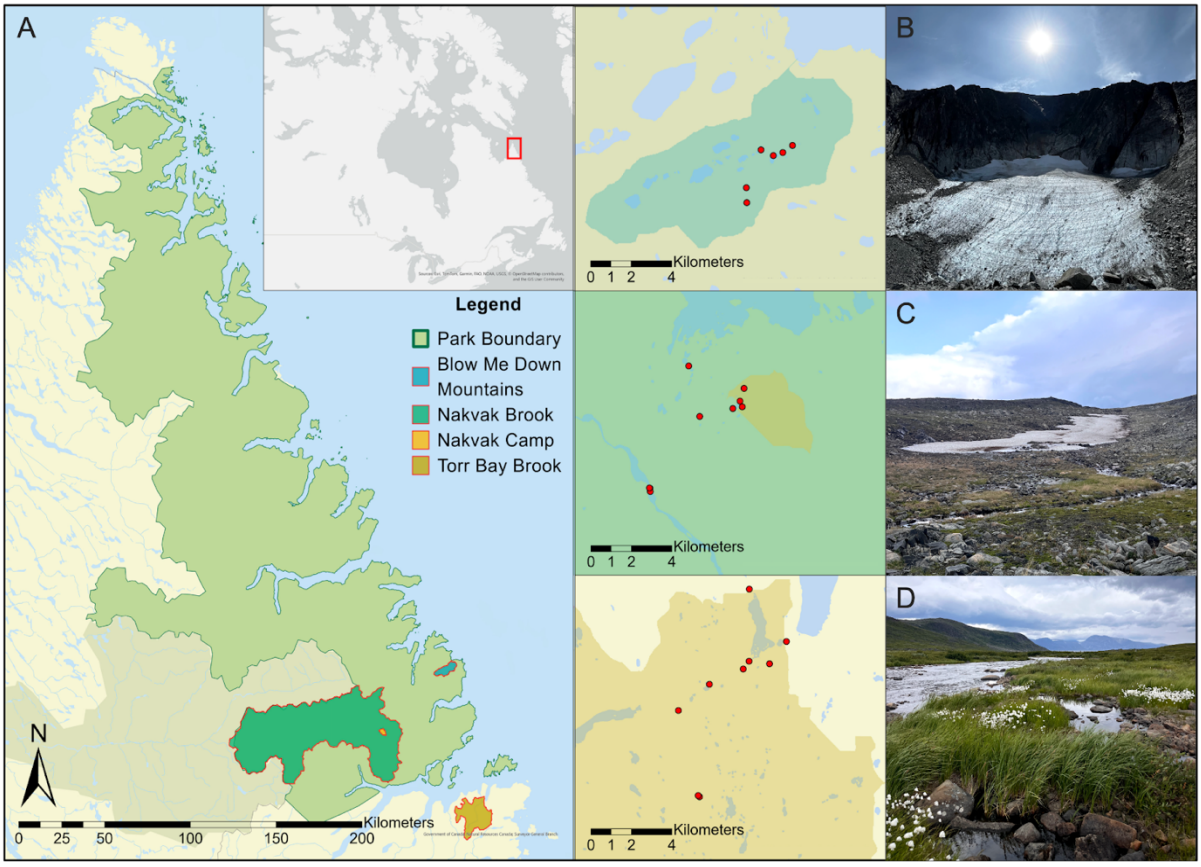


Figure 3.2: (A) Sampled watersheds in Torngat Mountains National Park (left) with inserts showing individual sampling locations (right). (B) Unnamed Glacier sampled in the Blow Me Down Mountains (58.8°N, 62.9°W, 400 m a.s.l). (C) Late-laying snowpack in Nakvak Brook (58.6°N, 63.3°W, 427 m a.s.l). (D) Riparian vegetation at the mouth of Torr Bay Brook (58.4°N, 62.8°W, 7 m a.s.l). Basemap imagery obtained from ESRI Canada, photographs taken by the author.

3.2.2 Blow Me Down Mountains

The Blow Me Down Mountains (BMD) (58.8°N, 62.9°W) research site is located in a narrow east trending valley (~15 km^2) along the Labrador Sea coastline surrounded by prominent ridgelines. BMD is home to four small cirque glaciers situated in north and eastern facing cirques and has a total glacier cover of ~4%. Meltwater from these glaciers' feed into a series of small alpine lakes before draining into the Labrador Sea 5 km to the northeast. The

upper valleys of this watershed are dominated by barren and exposed rocky ground. Low tundra vegetation (*Cladonia* spp., *Bryophyte* spp.) begins to appear below 200 m a.s.l. with the establishment of deciduous shrub communities (*Betula glandulosa* [*AvaˆlaKiak* in Inuttitut], *Salix* spp., *Vaccinium uliginosum*) at valley bottoms.

3.2.3 Nakvak Brook

Nakvak Brook (NVB) (58.6°N, 63.3°W) is the largest and farthest inland of the sampled watersheds, covering 850 km^2 of sloping plateau and deep fjords. Late laying snowpacks are present above 400 m a.s.l throughout the watershed, providing a year-round water source and relief from heat and flies in the summer for species such as *tuttuk* and *adlak* (McDowell et al., 2023). Sampling took place in the eastern portion of this watershed, approximately 25-30 km inland from the coast and 16 km north of Saglek Fjord, which drains east to west into the Labrador Sea. Water samples taken at higher elevations were surrounded by predominantly low (roughly below knee height) deciduous shrub communities and tundra vegetation. In the lower portion of the watershed at elevations below 100 m a.s.l vegetation was dominated by tall (above knee height) deciduous shrubs with wildflowers (*Chamerion latifolium* [*Paunnak*]) flanking watercourses.

3.2.4 Torr Bay Brook

Torr Bay Brook (TBB) (58.4°N, 62.8°W) covers an area of 82 km^2 and is located 5 km south of TMNP and 2 km west of the Torngat Mountains Base Camp (TMBC). This watershed is located 10 km inland from the outer coast and drains north into Saglek Bay which opens to the east into the Labrador Sea. Much of the land cover in this watershed consists of low deciduous shrubs and berry plants (*Arctous alpina* [*Kallak*], *Vaccinium vitis-idea* [*Kimminak*], *Empetrum nigrum* [*Paungak*]). Along watercourses at the lowest elevation sites (<50 m a.s.l) the shrub communities grow to a couple meters in height and are accompanied by sedge (*Carex* spp.) and wet graminoids (*Eriophorum angustifolium* [*Suputaujak*]). Satellite imagery from Google Earth Engine from the sampling period from August 9th to August 13th, 2024, revealed no ice or snow sources present at the time of sampling in this watershed.

3.3 Methods

3.3.1 Water Sample Collection and Processing

Water samples were collected over five days from August 9th to 13th, 2024, coinciding with the middle of the summer melt season, which extends from June to September (Way et al., 2014). Samples were taken from the center of streams at 60% depth from the water surface following freshwater sampling procedures set by Lloyd et al. (2022). When reaching the centre of the stream was not possible (e.g. safety, inaccessibility), samples were collected along the stream bank in areas visually determined to be well-mixed. Water samples were collected for a stable isotopic analysis of oxygen (δ18O) and hydrogen (δ2H) and aqueous carbon measurements of dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC). Samples for stable isotopes were collected by filling 2 ml capacity syringes and transferring them into Whatman® Mini-UniPrep® 0.45 µm syringeless filters. Samples for aqueous carbon measurements were collected by filling 50 ml capacity syringes and passing the water through a 0.45 µm syringe filter into a 40 ml amber glass vials with silicon septum caps. All syringes and sample vials were rinsed three times with local stream water prior to sample collection to avoid cross-contamination. Endmember samples of primary water sources such as ice and snow were collected using a clean metal trowel and stored in resealable plastic bags to melt. Once melted, they were transferred into syringeless filters and amber glass vials using the same methods as above.

A total of 24 samples were obtained between the three watersheds, the boundaries of which were delineated using a digital elevation model (DEM) from publicly available satellite imagery from Google Earth Engine and historical air photos of the region. Six stream water samples were collected from BMD in an altitude range of 144-509 m a.s.l. An additional endmember sample of glacial ice was taken from a small cirque glacier covering 0.19 km^2 of the watershed. Eight stream water samples were collected from the eastern portion of NVB in an altitude range of 76-427 m a.s.l (Figure 3.3). An additional endmember sample was taken from the surface of a late laying snowpatch. Eight stream water samples were collected from TBB in an altitude range of 7-124 m a.s.l, with an additional water sample being taken from a

nearby stagnant pond with no inlets or outlet used to represent endmembers of rain and groundwater.



Figure 3.3: Photograph of water sampling team including the author and Inuit Youth Research Technician (IYRT) team (Ella, Melissa, and Jessica) collecting water samples and field observations in Nakvak Brook (58.6°N, 63.3°W) (photographed by Robert Way in August 2024).

All samples were stored in the dark and refrigerated at 4 ℃ at TMBC within 24 hours of collection. Samples were then transported in an electric cooler kept at 4 ℃ throughout travel for sample processing at the Environmental Isotope Lab located at the University of Waterloo, Ontario. Isotopic water samples were placed in an autosampler and analyzed for oxygen and hydrogen-stable isotopes with a 20% duplication analysis using an LGR-OA-ICOS Laser System with precisions of $\delta 2H = \pm 0.8‰$ and $\delta 18O = \pm 0.2‰$. Aqueous carbon water samples were processed by extracting part of the sample through the septum cap and injecting it into a helium-flushed 12 ml Labco Exetainer vial. DIC and DOC were measured separately with a

20% duplication analysis and a determination result of ≤0.3‰. Measurements for DIC were acid ingested before being analyzed through a Thermo Scientific Delta V Plus Isotope Ratio Mass Spectrometer while samples for DOC were oxidized before analysis from headspace in a MicroGas-IsoPrime Mass Spectrometer. Water sample results and the full water sampling protocol used for field collection can be found in Appendix A.

3.3.2 Collection of Field Observations

Field measurements for physio-chemical, geomorphological, and atmospheric characteristics were recorded in the field at each stream water sampling site at the time of sampling (Figure 3.4). Measurements included pH, electrical conductivity (EC), water temperature, stream velocity, air temperature, average wind speed, and general descriptions of terrestrial vegetation and depositional processes. Measurements for pH levels were recorded with a Hanna Instruments pH Checker (±0.2 pH). Measurements for EC (±1%) and water temperature (±0.5°C) were both recorded with a Fieldscout EC 450 Meter Data Logger. Stream velocity was recorded with a Global Water Flow Probe FP111 (±0.1 FPS) and measured by continuously moving the probe vertically up and down the height of the water column for one minute to obtain average stream velocity (Figure 3.4). Atmospheric characteristics for average air temperature (±0.5°C) and average wind speed (±3%) were measured using a Kestrel 2500. Other relevant site information was interpreted qualitatively and included the last precipitation event and type, dominant vegetation, and depositional environment.



Figure 3.4: IMAGINE team and Parks Canada research partners collecting water samples and conducting stream discharge measurements near the mouth of Torr Bay Brook (58.4°N, 62.8°W) (photographed by Nhu Le, August 2024).

3.3.3 Atmospheric Reanalysis and Satellite Observations

Atmospheric reanalysis data was used to reconstruct past climate conditions due to the lack of long-term meteorological infrastructure in the region (Davis et al., 2021a). Climate data covering 2014-2024 was obtained from ERA5 atmospheric reanalysis from Copernicus Climate Change Service for grid cells (31km by 31 km) covering the sampled watersheds. Daily mean air temperatures were averaged for each month from 2014-2023 and compared to the monthly average temperatures for the sampling year to gauge antecedent climate conditions. Total rainfall was also calculated for each month and then averaged from 2014-2023 and compared to the sampling year. Air temperature and rainfall data in Tables 3.1 and 3.2 below both show that the sampling year was warmer and wetter than average, especially in

the colder months. Annual averages for air temperature and rainfall separated by year from 2014 to 2024 can also be found in Appendix A.

Table 3.1: Average monthly temperatures (°C) for the sampled watersheds from 2014-2023 compared to the sampling year (2024). Data derived from ERA5 atmospheric reanalysis data.

Torr Bay Brook			Nakvak Brook			Blow Me Down Mountains		
Month	**2014–2023 Average (°C)**	**2024 Average (°C)**	**Month**	**2014–2023 Average (°C)**	**2024 Average (°C)**	**Month**	**2014–2023 Average (°C)**	**2024 Average (°C)**
January	-21	-18	January	-25	-22	January	-20	-17
February	-24	-19	February	-27	-22	February	-23	-19
March	-16	-14	March	-19	-16	March	-16	-14
April	-8	-4	April	-10	-6	April	-9	-5
May	-2	-1	May	-3	-2	May	-2	-2
June	4	5	June	4	5	June	3	4
July	9	10	July	10	9	July	8	9
August	10	10	August	9	9	August	9	9
September	5	7	September	3	6	September	4	6
October	0	1	October	-3	-1	October	-1	0
November	-9	-4	November	-12	-7	November	-8	-5
December	-15	-12	December	-18	-16	December	-13	-11

Table 3.2: Total monthly rainfall (mm) for the sampled watersheds averaged across 2014-2023 and compared to the sampling year (2024). Data derived from ERA5 atmospheric reanalysis data.

Torr Bay Brook			Nakvak Brook			Blow Me Down Mountains		
Month	2014–2023 Average (mm)	2024 Total (mm)	Month	2014–2023 Average (mm)	2024 Total (mm)	Month	2014–2023 Average (mm)	2024 Total (mm)
January	56	88	January	55	102	January	64	96
February	29	65	February	28	58	February	31	63
March	47	79	March	43	78	March	49	77
April	76	90	April	70	82	April	80	93
May	62	74	May	61	62	May	66	64
June	63	89	June	64	105	June	68	105
July	96	81	July	102	84	July	117	81
August	80	63	August	80	66	August	102	70
September	78	96	September	79	94	September	88	119
October	75	97	October	78	100	October	85	102
November	62	69	November	61	71	November	68	76
December	74	87	December	76	85	December	80	94

To assess snow conditions prior to field sampling, satellite imagery from Sentinel-2 L2A was obtained from Copernicus Browser. Imagery was assessed from the end of May 2024 until the end of July to evaluate snowmelt onset and progression throughout the melt season throughout the sampled watersheds. Unfortunately, imagery throughout August was heavily obscured by cloud cover and therefore not suitable for use. However, mid-July imagery shows there was very little snow cover present in the watersheds, especially in the southernmost catchment of TBB (Figure 3.5).

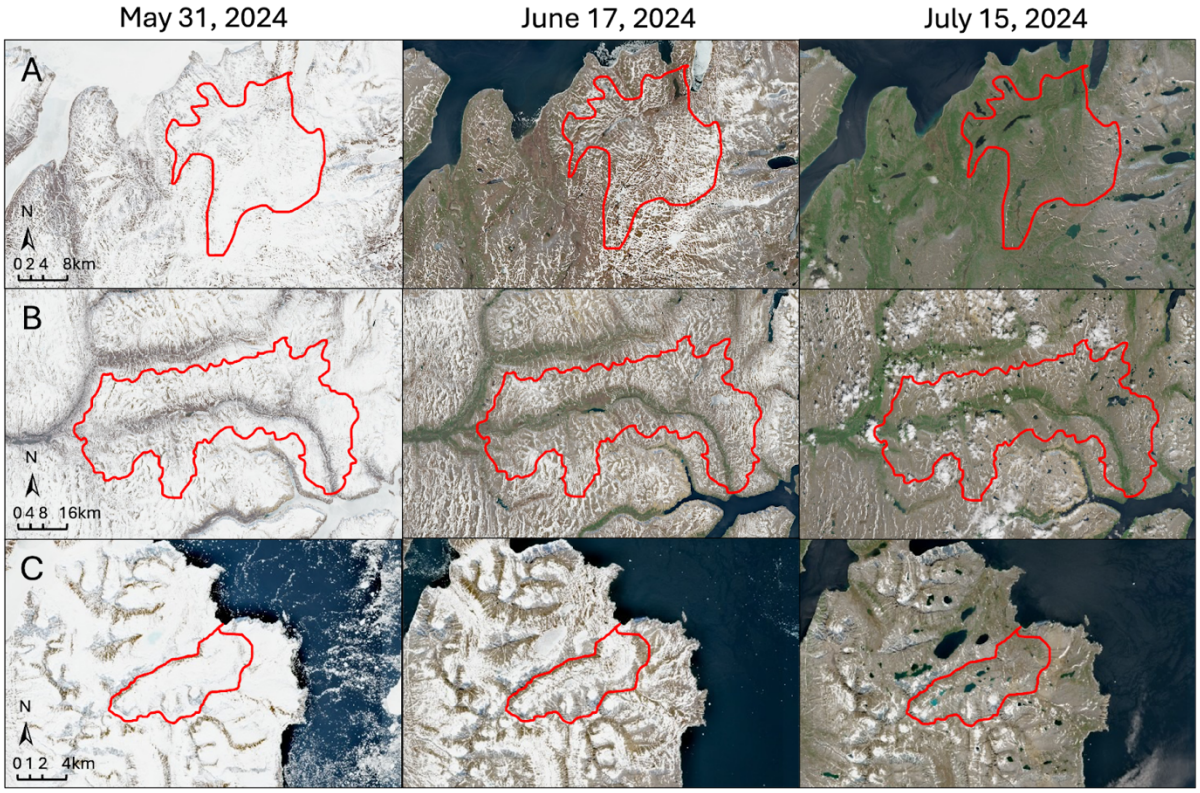


Figure 3.5: Satellite imagery from Sentinel-2 L2A accessed through Copernicus Browser for each of the sampled watersheds (outlined in red). (Row A) TBB, (Row B) NVB, and (Row C) BMD. Images from left to right are for May 31, 2024, June 17, 2024, and July 15, 2024.

3.3.4 Data Analysis

To assess differences in stream composition between glacier and non-glacier watersheds (research question #1), an analysis of variance was conducted for stable isotopes of δ18O and δ2H, aqueous carbon concentrations of DOC and DIC, and field measurements of pH, EC, and water temperature. Endmembers were excluded from this analysis to avoid potential outlier effects. A Shapiro-Wilk test was first conducted to test for normality, and all variables were determined to have a normal distribution ($p > 0.05$). Analysis of variance across watersheds used ANOVA and a post-hoc test using a Tukey Honestly Significant Difference (HSD) to determine statistically significant differences between variables, as identified by a compact letter display (CLD).

Contributions of source water across the watersheds (research question #2) was explored through stable isotopic analysis and isospace plotting to evaluate relationships between water sources and water samples. Stable isotopes of δ18O and δ2H are natural tracers of water reflecting differences in composition between different source waters, such as rain, groundwater, snowmelt, and glacier melt. As such, stable isotopes are useful for estimating source water contributions and the mixing of waters throughout watersheds (Ohlanders et al., 2013; Sepúlveda et al., 2022). While the composition of stable isotopes of δ18O and δ2H can be influenced by source water it can also be affected by regional geography and weather conditions such as latitude, elevation, distance inland, and air temperature (Gibson et al., 2020). To assess whether these factors influenced isotopic compositions in TMNP, a Generalized Linear Model (GLM) was used to test for correlation between predictor variables of elevation, latitude, distance inland, and air temperature and response variables of δ18O and δ2H. The GLM used a Gaussian family distribution as the variables were continuous and relatively normally distributed.

To investigate how source water affects ecological functioning (research question #3), the three watersheds were divided into upper and lower sections to see whether DOC and DIC concentrations changed with distance downstream and increased mixing from other water sources. Watersheds were divided into upper and lower portions according to elevation. The upper portions of the watershed had higher elevation sites and low order streams, resulting in less water mixing and closer proximity to head waters. Lower portions of watersheds had lower elevation sites and higher order streams, which would likely result in more water inputs from the whole watershed and thus a greater amount of water mixing. A linear regression for predictor variables of elevation and stream order for response variables of DOC and DIC found that both elevation and stream order elevation had a significant correlation ($p < 0.05$) to concentrations of DOC, and elevation had a significant correlation to concentrations of DIC. Amounts of DOC and DIC were then averaged for the upper and lower portions of each watershed for comparison.

All statistical tests and plotting used RStudio version 2024.09.0 with the "ggplot2" (Wickham, 2016) and "multcompView" (Graves, 2024) packages. All maps were created in ArcGIS Pro version 3.5.1.

3.4 Results

3.4.1 Analysis of Variance Between Watersheds

ANOVA results showed statistically significant differences between watersheds for all variables apart from DOC and water temperature (Figure 3.6) and all raw ANOVA test results can be found in Appendix A. The stable isotope analysis of δ18O and δ2H showed values from NVB (δ18O mean = 14.49‰, δ2H mean = 109.53‰) to be statistically different ($p < 0.05$) from TBB (δ18O mean = 12.39‰, δ2H mean = 96.55‰) and BMD (δ18O mean = 11.70‰, δ2H mean = 91.78‰), while TBB and BMD were statistically similar to each other ($p > 0.05$).

Concentrations of DOC were not found to have any statistical differences between TBB (0.34 mg/L), NVB (mean = 0.42 mg/L), and BMD (mean = 0.43 mg/L). However, concentrations of DIC were found to be statistically different for BMD (mean = 0.91 mg/L) when compared to TBB (mean = 1.87 mg/L) and NVB (mean = 1.30 mg/L), though TBB and NVB were not statistically different from each other.

For field measurements, pH levels for TBB (mean = 7.6) and BMD (mean = 6.7) were found to be statistically different from each other, with the waters in TBB being more basic and BMD being more acidic. The pH levels for NVB (mean = 7.1) were relatively neutral and this watershed was found to not be statistically different from either TBB or BMD. Of all measured variables, EC levels showed the most variation with TBB (mean = 93.0µS/cm), NVB (mean = 53.4µS/cm), and BMD (mean = 3.7µS/cm) all being statistically different from one another. Finally, water temperatures were not found to have statistical differences between TBB (mean = 10.4°C), NVB (mean = 9.1°C), and BMD (mean = 8.8°C).

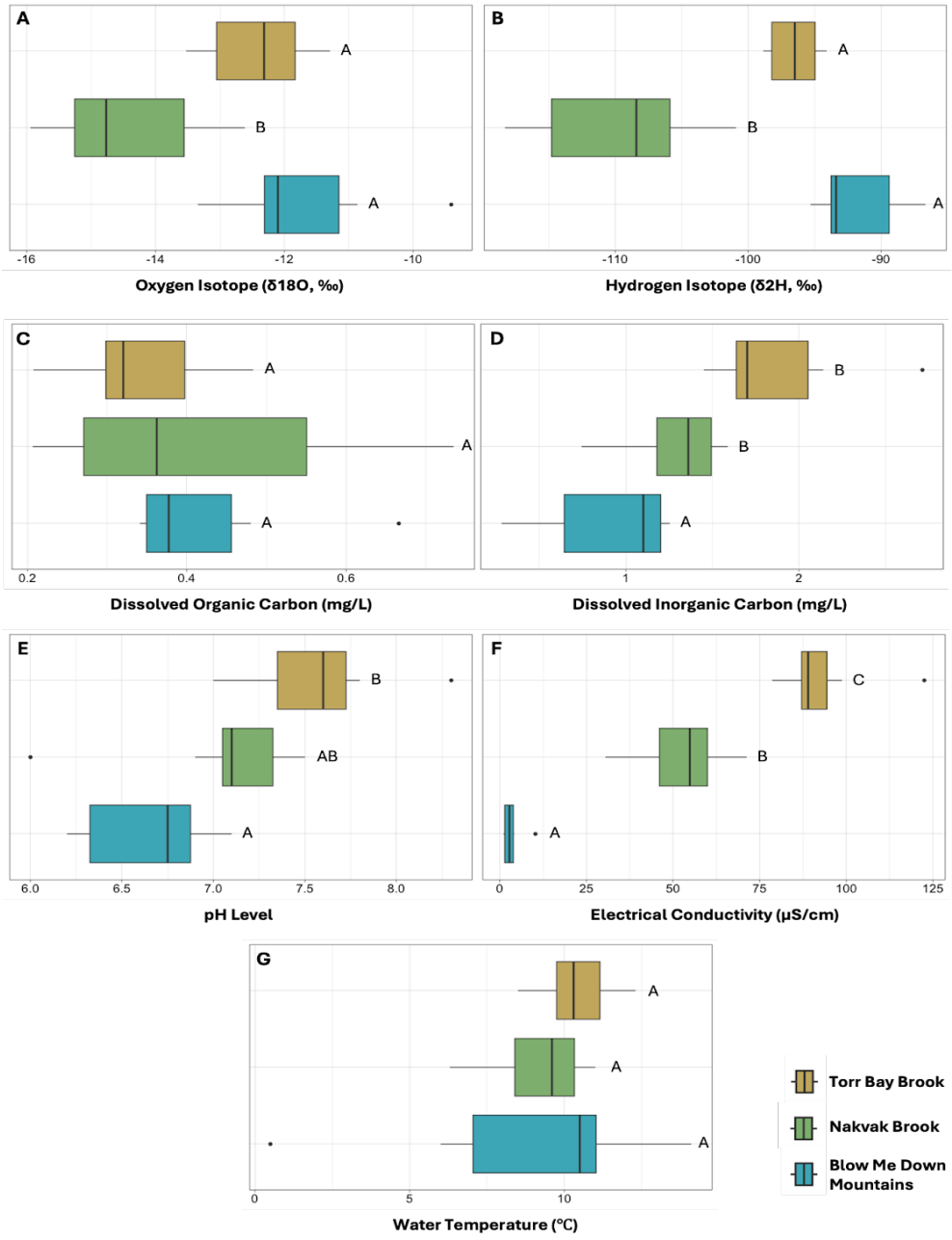


Figure 3.6: Boxplots for ANOVA results for variables of (A) δ18O, (B) δ2H, (C) DOC, (D) DIC, (E) pH, (F) EC, and (G) water temperature, stratified by watershed. Groupings that are not statistically different from each other share the same letters according to post hoc comparisons. Boxes indicate the 25th, 50th (median), and 75th percentile of the data with the range of the whiskers indicating minimum and maximum values.

3.4.2 Isospace of δ18O and δ2H Across Watersheds

The isospace plot revealed distinct grouping for the three watersheds, with water samples from TBB clustered in the center of the plot, NVB at the bottom, and BMD at the top (Figure 3.7). Sample points for TBB formed the tightest cluster, due to having the smallest range in values (δ18O = -11.29‰ to -13.52‰, δ2H = -94.10‰ to -98.86‰). Sample points for both NVB (δ18O = -12.61‰ to -15.94‰, δ2H = -100.92‰ to -118.30‰) and BMD (δ18O = -9.41‰ to -13.34‰, δ2H = -86.67‰ to -95.31‰) had a larger range in values, with NVB having a larger range of δ2H and BMD having a larger range of δ18O.

Isotopic values for endmembers for the stagnant pond in TBB (δ18O = -7.89‰, δ2H = -80.00‰) and the glacier ice in BMD (δ18O = -15.24‰, δ2H = -109.74‰) vary significantly from the water samples in their respective watersheds. The endmember sample for TBB shows much more enrichment than the other samples in TBB. The endmember in BMD has a similar isotopic signature to the perennial snowpatch in NVB (δ18O = -13.46‰, δ2H = -107.77‰) but is more depleted than the rest of the water samples in BMD.

Two meteoric water lines were included in the isospace plot, the Global Meteoric Water Line (GMWL), which represents the global average relationship for δ18O and δ2H in freshwaters, and the Local Meteoric Water Line (LMWL) for Fort Smith (60.0° N, 111.9° W) (Baer et al., 2016). As there is no known LMWL for TMNP, Fort Smith was chosen as it is located at a similar latitude and elevation and therefore may be more representative of isotopic values in northern Labrador. When utilizing meteoric water lines for a stable isotope analysis sample points occurring below meteoric water lines are colloquially believed to have been influenced by evaporation (Kosek & Ruman, 2021). During processes of evaporation lighter isotopes evaporate more readily, leaving behind heavier isotopes, resulting in water samples that tend to be above meteoric water lines as their composition becomes heavier than average (Gibson et al., 2020). According to the GMWL this would include nearly all samples taken which may not be fully representative of the evaporation processes occurring in this region since high latitude environments tend to have lower rates of evaporation in comparison to global averages due to cooler air temperatures (Kosek & Ruman, 2021). According to the

LMWL it would appear that TBB experiences the highest rates of evaporation out of the three watersheds. This corresponds to what we would expect to see as out of the three sampled watersheds TBB is the southernmost watershed and has the lowest elevation sites, resulting in higher rates of evaporation.

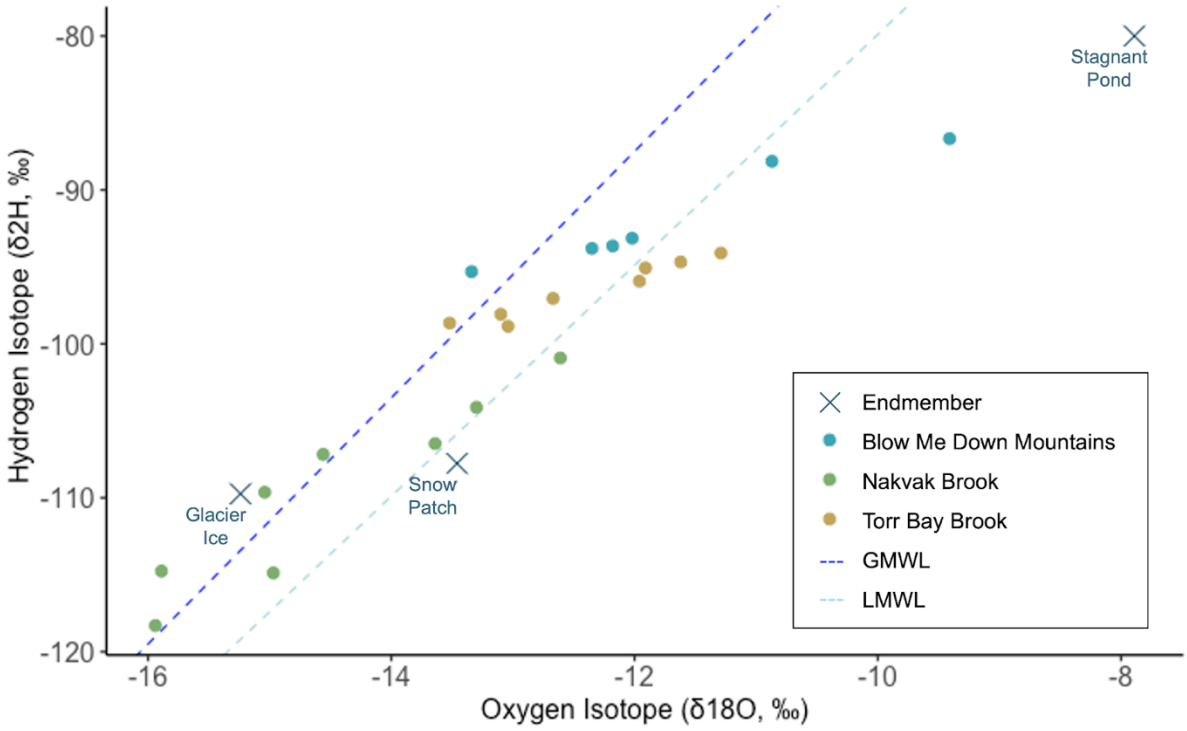


Figure 3.7: Dual isospace plot of stream water samples for stable isotopes of δ18O and δ2H. Samples are stratified by watershed and endmembers are represented by an 'X'. The dark blue dashed line represents the Global Meteoric Water Line (GMWL), and the light blue dashed line represents the Local Meteoric Water Line (LMWL) for Fort Smith (60.0° N, 111.9° W, 205 m.a.s.l.). An annotated version of this plot can be found in Appendix A.

3.4.3 Influences of Geography and Temperature on Isotopic Composition

The Generalized Linear Model (GLM) used to test between response variables of elevation, latitude, distance inland, and air temperature and response variables of δ18O and δ2H found the only predictor variable to have any significant correlation ($p < 0.05$) to the stable

isotopes was “distance inland”. For δ18O, “distance inland” was found to be statistically significant ($p = 0.00589$), with δ18O decreasing by 0.13‰ with every 1 km increase in distance from the coast. For δ2H, “distance inland” was found to be statistically significant ($p = 0.00013$), with δ2H decreasing by 0.81‰ with every 1 km increase in distance from the coast.

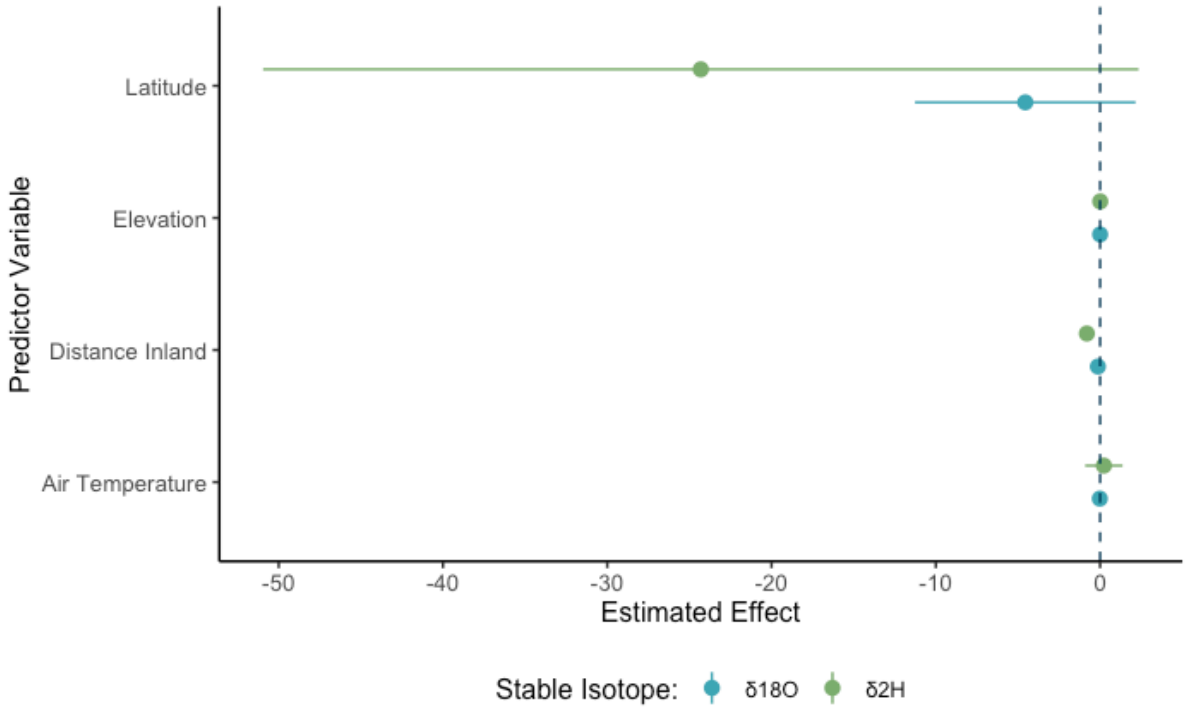


Figure 3.8: Forest plot of GLM model coefficients results for δ18O and δ2H showing the estimated effect sizes of the predictor variable (latitude, elevation, distance inland, and air temperature) with error bars representing the 95% confidence intervals. The dashed horizontal line at “0” represents no statistically significant effect for that predictor at the 95% confidence level.

3.4.4 Changes in Aqueous Carbon Concentrations with Distance Downstream

A linear regression model was used to determine whether there was a statistically significant (p-value < 0.05) trend between response variables of DOC and DIC and predictor variables of elevation and stream order. For DOC, both “elevation” ($p = 0.01533$) and “stream order” ($p = 0.00047$) were found to be statistically significant. For DIC, only “elevation” ($p =$

0.00046) was found to be statistically significant. Concentrations of DOC were found to increase with distance downstream in all three sampled watersheds (Figure 3.9). For TBB concentrations of DOC in the upper watershed had a mean of 0.28 mg/L and concentrations for the lower watershed had a mean of 0.37 mg/L. For NVB concentrations of DOC in the upper watershed had a mean of 0.34 mg/L and concentrations for the lower watershed had a mean of 0.55 mg/L. For BMD concentrations of DOC in the upper watershed had a mean of 0.40 mg/L and concentrations for the lower watershed had a mean of 0.46 mg/L.

For TBB concentrations of DIC in the upper watershed had a mean of 2.14 mg/L and concentrations for the lower watershed had a mean of 1.71 mg/L. For NVB concentrations of DIC remained relatively constant throughout the watershed, with both the upper and lower portions of the watershed having a mean of 1.30 mg/L. For BMD concentrations of DIC for the upper watershed had a mean of 0.67 mg/L and concentrations for the lower watershed had a mean of 1.15 mg/L. In this case only TBB was found to have decreasing concentrations of DIC with distance downstream, whereas NVB remained fairly constant and BMD increased (Figure 3.9).

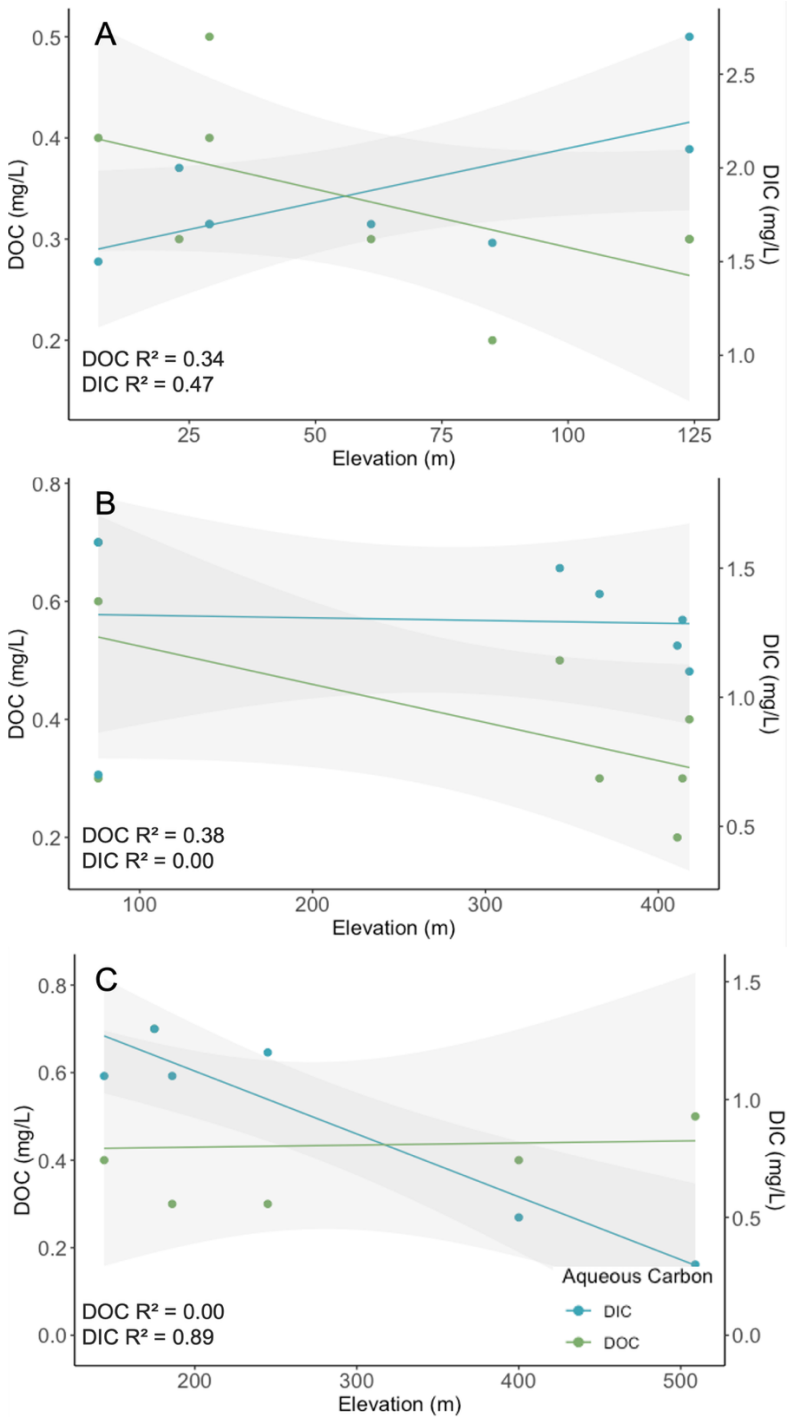


Figure 3.9: Double-axis scatterplots with linear regression lines showing change in DOC and DIC with elevation for the sampled watersheds, (A) TBB, (B) NVB, (C) BMD. Shaded areas represent the 95% confidence interval.

3.5 Discussion

3.5.1 Effects of Source Water and Geography on Stream Composition

The stable isotopic analysis of δ18O and δ2H showed grouping by watershed under the influence of source water contribution and geographic setting. Ranges in recorded values by watershed can be used to approximate amount of source waters contributing to each watershed, with more sources resulting in more mixing and isotopic variability. Isotopic values in TBB, which is rain and groundwater fed, had the least variability out of the three watersheds in comparison to NVB, which had inputs of snow melt in addition to rain and groundwater, and BMD, which had additional inputs of snow melt and glacier melt. Isotopic values for NVB (snow fed watershed; δ18O mean = 14.49‰, δ2H mean = 109.53‰) were also similar to those from a snow-dominated high-altitude watershed presented by Ohlanders et al (2013) in the Central Andes, which recorded mean values of 15.32‰ for δ18O and 110.2‰ for δ2H. Isotopic values measured at BMD (glacier fed watershed; δ18O mean = 11.70‰, δ2H mean = 91.78‰) were also similar to those observed elsewhere in glacier fed alpine streams. For example, Stern and Bliskiuk (2002) recorded mean values of 12.5‰ for δ18O and 93.0‰ for δ2H in the Southern Patagonia Andes, and Sepúlveda et al (2022) recorded mean values of 10.5‰ to 11.2‰ for δ18O and 79‰ to 83‰ for δ2H in northern Patagonia.

Influences of source water contributions are evident in the distributions of water sample results for NVB and BMD. In NVB, evidence of mixing between source water occurred between the samples results that fall above and below the endmember for the perennial snowpatch. The snowpatch endmember sampled at NVB is considered to be “old” snow, which has a more enriched isotopic signal than “new” snow due to processes of melt and re-freezing, evaporation, and rainfall occurring on its surface over multiple melt seasons. Water sample results below this endmember are more depleted and correspond to samples taken from the main river channel in the valley bottom which is influenced by a larger area of the surrounding watershed. From this we can infer that there are likely newer snowpatches elsewhere in the watershed contributing melt to the main river channel resulting in more depleted isotopic values. For BMD, the most depleted water sample from this watershed corresponds to a sample

taken at the outflow of a small alpine lake that had multiple small snowpatches located around it. Since snow has a lighter isotopic signature than other water sources, contributions from the snow patches are a likely cause for this water sample's more depleted isotopic signal relative to the remainder of samples from the rest of the watershed (Ohlanders et al., 2013).

Large-scale geographic factors including distance from the coast, elevation and latitude were considered to evaluate which had the largest influence on isotopic composition in TMNP. The measured δ18O and δ2H values in each watershed suggested an influence of processes of isotopic depletion that occur as water vapour is affected by the landscape. Higher latitudes tend to have more depleted isotopes than lower latitudes due to cooler average air temperatures resulting in lower evaporation rates (Clark & Fritz, 1997). Regions that have a higher elevation or are located further inland also tend to have more depleted isotopes due to fractionation processes of evaporation and condensation causing heavier isotopes to precipitate out as water vapour moves inland (Winnick et al., 2014). Of all geographic factors assessed only "distance inland" was found to have any statistically significant correlation with isotopic composition in TMNP. As seen in Figure 3.7 NVB had the most depleted isotopic values and was also located the furthest inland with sample sites located 25-30 km inland. The most enriched values were seen in BMD which had sample sites located 5 km inland. Between these is TBB, which has sample sites located 10-15 km inland.

The lack of statistical significance for other geographic factors in the stable isotope samples could be influenced by the relatively limited variation between watersheds. For example, all sampled watersheds were within 0.5°N of each other (58.4°N to 58.8°N) and the elevation range in sample sites was less than 500 m. Daily air temperatures throughout the sampling period ranged from a low of 8.1°C (recorded on August 12th in TBB) to a high of 18.6°C (recorded on August 13th in BMD). However, when air temperatures were averaged across all sample sites for each watershed mean air temperature values varied by less than 4°C (TBB = 12.4°C, NVB = 11.1°C, and BMD = 14.5°C).

3.5.2 Factors Influencing DOC and DIC Ratios in Alpine Rivers

For most river systems, concentrations of DOC typically increase with distance downstream due to increased inputs from other water sources, flushing of terrestrial vegetation and soils, and freshwater biotic processes (Giesler et al., 2014). Concentrations of DIC, on the other hand, tend to decrease as DIC is consumed by aquatic communities for biotic processes such as photosynthesis (Xu et al., 2021). In all sampled watersheds in TMNP, concentrations of DOC increased with distance downstream as expected. Out of the three sampled watersheds, BMD had the highest mean value of DOC, which was unexpected as glacier fed watersheds typically have lower concentrations of DOC than non-glacier watersheds due to a lack of vegetation and poorly developed soils (Slemmons et al., 2013). These relatively higher values may be attributed to contributions of glacier melt given that the local endmember glacier ice sample had the highest concentration of DOC out of all samples in TMNP. We interpret this as being because glacier ice can store large amounts of DOC from years of sequestering biologic carbon, soil and plant matter that is being blown onto glacier surfaces, and from biological activity of supraglacial microbial communities (Milner et al., 2017; Liu et al., 2023). The relatively minimal organic matter in Arctic Cordilleran glacier fed rivers also means that there is less ability for these systems to absorb DOC released from glacier melt which would increase concentrations of DOC comparatively (Slemmons et al., 2013).

Concentrations of DIC were also found to decrease with distance downstream in TBB, following the assumption that DIC would be taken up by aquatic communities for biotic processes (Xu et al., 2021). However, this was not the case for NVB or BMD. For NVB, the cause for the consistency in DIC concentrations is unknown but could potentially be influenced by the fjord and valley topography of the watershed which would allow for DIC to be replenished through weathering processes as rivers descend the steep valley walls to lower elevations. The increasing concentrations of DIC in BMD may be attributed to the lack of vegetation in the watershed available to absorb DIC, allowing for higher concentrations of DIC to accumulate through the watershed. Increases could also be due to the higher rates of weathering characteristic of glacier fed streams, further increasing DIC concentrations. This

follows similar observations made by Liu et al. (2023) in the alpine headwaters of the Tibetan Plateau, which found high DIC concentrations in glacial watersheds being delivered downstream due to increased weathering.

Overall, for all three sampled watersheds a greater concentration of DIC (mean = 1.40 mg/L) in comparison to DOC (mean = 0.39mg/L) were measured. Concentrations of DIC are typically higher than DOC during low flow conditions from contributions of DIC-rich groundwater seepage, whereas concentrations of DOC are dominant under high flow conditions from the flushing shallow soil water (Keirn et al., 2024). As water sampling took place in the middle of the summer dry season it can be safely assumed that all sampled watersheds were experiencing low flow conditions. While light rain periodically occurred throughout the field sampling period it was likely not enough to stimulate leaching of DOC from soils (Hou et al., 2022).

3.5.3 Importance of Cryospheric Contributions to Alpine River Systems for Cold Water Species

The analysis of variance tests between watersheds showed that mean water temperatures were not statistically different between watersheds; however, the range in water temperature for each watershed did show influences of source waters. For TBB (rain/groundwater fed watershed), water temperatures ranged from 8.5℃ to 12.3℃, for NVB (snow fed watershed) water temperatures ranged from 6.3℃ to 11.0℃, and for BMD (glacier fed watershed) water temperatures ranged from 0.5℃ to 14.1℃. In all cases, water temperatures increased with distance downstream with the lowest temperatures recorded nearest to endmembers for the perennial snowpatch in NVB and glacial ice in BMD. This aligns with observations by Brown et al (2005) and Sudlow et al (2023) who found that near glaciers water temperatures rarely exceed 2℃ year-round. Our results highlight the important influence of perennial snowpatches and glaciers on stream water temperature heterogeneity in TMNP.

Cold-water species endemic to alpine river systems have specific thermal tolerance levels and require cooler water temperatures for proper biological functioning and reproduction (McDowell et al., 2023). For example, *ikKaluk* (Arctic char; *Salvelinus alpinus*), a culturally and economically important species, requires summer water temperatures between 5°C and 9°C (Wrona et al., 2016; Harris et al., 2020). In this case, NVB and BMD would provide the more suitable habitat conditions for ikKaluk than TBB. The major limitation here is that the cooler water temperatures were mainly in the upper portion of the watersheds, meaning that suitable habitat conditions for cold-water species may be constrained to higher elevations that are more difficult to access. Future declines in snowpatch and glacier area may cause a reduction in habitat suitability and force cold-water species to either adapt to warmer temperatures or migrate farther upstream. This change poses a threat to cold-water species in TMNP as the increased branching of rivers and streams upstream would be more prone to habitat fragmentation and isolated communities. In addition, the mountainous landscape can result in populations becoming trapped by topography as species reach the upstream limits of watersheds (Brown et al., 2007; Isaak & Rieman, 2013). As warmer water temperatures begin to increase further upstream, this will also allow for warm-water species to expand their ranges upwards, shifting the biodiversity of freshwater ecosystems and increasing competition for habitat and resources with cold-water species (Culp et al., 2019). This raises concerns for Northerners on the long-term sustainability of these ecologically and culturally important freshwater habitats and species (Wrona et al., 2016).

3.6 Limitations

The remote location and designation as protected land makes TMNP an ideal place to study the effects of climate change as changes can be isolated from other anthropogenic drivers. However, the remote location also means that there has historically been little research here resulting in large knowledge gaps on the state of freshwater systems in TMNP. TMBC only operates for approximately two months each summer and is only accessible via charter aircraft. Travel to field sites can only be completed by helicopter, boat, or on foot, which are all subject to weather conditions and delays. In 2024, there was only a short weather and

logistical window available for collecting stream water samples resulting in a small sample size and no opportunity for repeated sampling through time. Thus, the results of this study provide a single snapshot in time of the hydrological conditions that existed during the field sampling period. To remedy this sampling over the course of a longer field season, repeat site visits, and instrumentation of river systems for year-round hydrological monitoring is needed.

The restricted nature of this field season also meant that only three watersheds could be visited, all of which were in close proximity to TMBC and had other ongoing environmental monitoring projects going in by fellow team members. Due to this, the three watersheds chosen all vary in catchment size, topographic features, and distance from the coast, making it difficult to isolate influences of source water from influences of geography. This complicates data interpretation as the patterns observed in these watersheds may differ both temporally and spatially. Further sampling of these watersheds as well as additional watersheds through TMNP is needed to better understand the influence of individual watershed characteristics in comparison to source water.

Additionally, the low number of endmember samples meant that it is difficult to assess whether these are the most representative of their watersheds. For example, the stagnant pond sampled in TBB is believed to be fed by rain and groundwater but was so heavily impacted by evaporation processes that its isotopic composition was significantly more enriched than the other water samples taken in TBB. The endmember of glacier ice taken in BMD also had a different isotopic signal than the other water samples taken from the watershed. As isotopic signatures of glaciers can be variable since glacier ice tends to have enriched summer layers and depleted winter layers, it is possible the ice sample was taken from a depleted winter layer whereas the water samples were more influenced by melt coming from the enriched summer layer (Clark & Fritz, 1997).

Further water sampling is needed to gain a clearer understanding of the hydrological processes that exist in TMNP and how source water contributions shift throughout the year. Despite these limitations, the patterns we document here show that water sampling for stable isotopes and aqueous carbon can be a promising tool for investigating alpine river systems in TMNP.

3.7 Conclusion

Hydrological monitoring in TMNP has been identified as a priority by the Inuit-led Torngat Mountains Cooperative Management Board in order to better understand how changes in the cryosphere and hydrosphere will impact downstream ecosystems and northern livelihoods (Nunatsiavut Government, 2025). Stream water samples for a stable isotopic analysis and measurements of aqueous carbon were collected across three glacier and non-glacier watersheds to investigate the influence of source water on stream composition and ecological function. Statistical analysis revealed differences between watersheds in isotopic composition and DIC, and in physio-chemical characteristics of pH and EC. Stable isotope tracing was also used to assess source water contributions and mixing of waters through the watersheds. Results showed distinct grouping for each watershed and evidence of water mixing though geographical influences were also found to play a large role in determining isotopic composition in the region. However, a larger sample size of watersheds is needed to quantify how influential source waters are on isotopic composition across a broader geographic area.

Variations in aqueous carbon concentrations were compared both between watersheds and within watersheds. Results showed concentrations of DOC increased with distance downstream, but concentrations of DIC varied between the watersheds. Overall, DIC concentrations were found to be greater than DOC concentrations in all watersheds, which may be attributed to the time of year water sampling occurred. Further sampling, preferably over the course of an entire melt season, could improve understanding the drivers of carbon concentrations between watersheds and how ratios of DOC and DIC shift in high and low flow conditions. Finally, optimal habitat conditions for culturally important cold-water species were observed in watersheds fed by snow melt and glacier melt, though suitable conditions were limited to the upper portions of the watersheds. Further measurements of water temperature throughout watersheds are needed to identify where suitable habitat conditions for cold-water species exist to better inform conservation efforts and species monitoring.

Though more information is needed to quantify the influences of source water on alpine river systems in TMNP, this research has aided in establishing a baseline for future

studies and setting the groundwork for addressing long-term research objectives. Continued stream water sampling for future field season by current and future team members and research partners from Parks Canada and the Nunatsiavut Government are planned for this, which will build on this work. Understanding the current state of freshwater systems in TMNP will allow us to investigate how future changes in the hydrosphere and cryosphere may transform Arctic ecosystems and impact human livelihoods. This will be fundamental to developing effective adaptation and conservation strategies in the North in order to best steward this culturally and ecologically remarkable landscape with an eye to the future.

Data Availability Statement

All data will be made publicly available in Nordicana D upon submission of the manuscript. Data can be made available upon reasonable request.

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3.8 References

Baer, T., Barbour, S.L., Gibson, J.J. (2016). The stable isotopes of site wide waters at an oil sands mine in northern Alberta, Canada. Journal of Hydrology 541, 1155-1164. http://dx.doi.org/10.1016/j.jhydrol.2016.08.017

Barrand, N. E., Way, R. G., Bell, T., & Sharp, M. J. (2017). Recent changes in area and thickness of Torngat Mountain glaciers (northern Labrador, Canada). The Cryosphere 11, 1, 157-168. https://doi.org/10.5194/tc-11-157-2017

Barrette, C., Brown, R., Way, R., Mailhot, A., Diaconescu, E.P., Grenier, P., Chaumont, D., Dumont, D., Sévigny, C., Howell, S., et al. (2020). *Nunavik and Nunatsiavut Regional Climate Information Update*. ArcticNet Inc.

Brice-Bennett, C., Onalik, L., Procter, A. (2023). *Avanimiut: A History of Inuit Independence in Northern Labrador*. Nunatsiavut Government.

Brown, L. E., Hannah, D. M., & Milner, A. M. (2007). Vulnerability of alpine stream biodiversity to shrinking glaciers and snowpacks. Global Change Biology, 13(5), 958–966. https://doi.org/10.1111/j.1365-2486.2007.01341.x

Clark I.D., & Fritz, P.F. (1998). *Environmental Isotopes in Hydrology*. Lewis Publishers.

Clarke, G. K. C., Jarosch, A. H., Anslow, F. S., Radić, V., & Menounos, B. (2015). Projected deglaciation of western Canada in the twenty-first century. Nature Geoscience, 8(5), 372–377. https://doi.org/10.1038/ngeo2407

Culp, J. M., Lento, J., Curry, R. A., Luiker, E., & Halliwell, D. (2019). Arctic biodiversity of stream macroinvertebrates declines in response to latitudinal change in the abiotic template. Freshwater Science, 38(3), 465–479. https://doi.org/10.1086/704887

Davis, E. L., Trant, A. J., Way, R. G., Hermanutz, L., & Whitaker, D. (2021). Rapid Ecosystem Change at the Southern Limit of the Canadian Arctic, Torngat Mountains National Park. Remote Sensing, 13(11a), Article 11. https://doi.org/10.3390/rs13112085

Davis, E., Trant, A., Hermanutz, L., Way, R. G., Lewkowicz, A. G., Siegwart Collier, L., Cuerrier, A., & Whitaker, D. (2021b). Plant–Environment Interactions in the Low Arctic Torngat Mountains of Labrador. Ecosystems, 24(5), 1038–1058. https://doi.org/10.1007/s10021-020-00577-6

Geissinger, E. A., Van Leeuwen, T. E., Kelly, N., Pennell, C., Fitzsimmons, M. G., Duffy, S., Poole, R., Angnatok, J., Dempson, J. B., & Coté, D. (2024). Salmonids in hot water: An unprecedented warm-water event in Labrador, a subarctic region of Canada. Fisheries Management and Ecology, 31(5), e12710. https://doi.org/10.1111/fme.12710

Gibson, J. J., Holmes, T., Stadnyk, T. A., Birks, S. J., Eby, P., & Pietroniro, A. (2020). 18O and 2H in streamflow across Canada. Journal of Hydrology: Regional Studies, 32. Scopus. https://doi.org/10.1016/j.ejrh.2020.100754

Giesler, R., Lyon, S. W., Mörth, C.-M., Karlsson, J., Karlsson, E. M., Jantze, E. J., Destouni, G., & Humborg, C. (2014). Catchment-scale dissolved carbon concentrations and export estimates across six subarctic streams in northern Sweden. Biogeosciences, 11(2), 525–537. https://doi.org/10.5194/bg-11-525-2014

Griffiths, K., Michelutti, N., Sugar, M., Douglas, M. S. V., & Smol, J. P. (2017). Ice-cover is the principal driver of ecological change in High Arctic lakes and ponds. PLOS ONE, 12(3), e0172989. https://doi.org/10.1371/journal.pone.0172989

Hanly, K., Marshall, Shawn, & and McDowell, G. (2023). The state of glacier hydrology research in Canada. Canadian Water Resources Journal / Revue Canadienne Des Ressources Hydriques, 48(4), 475–496. https://doi.org/10.1080/07011784.2023.2289805

Harris, L. N., Yurkowski, D. J., Gilbert, M. J. H., Else, B. G. T., Duke, P. J., Ahmed, M. M. M., Tallman, R. F., Fisk, A. T., & Moore, J. (2020). Depth and temperature preference of anadromous Arctic char Salvelinus alpinus in the Kitikmeot Sea, a shallow and low-salinity area of the Canadian Arctic. Marine Ecology Progress Series, 634, 175–197. https://doi.org/10.3354/meps13195Hou, J., Li, F., Wang, Z., Li, X., Cao, R., & Yang, W. (2022). Dynamics of Dissolved Carbon in Subalpine Forest Streams. Forests, 13(5), Article 5. https://doi.org/10.3390/f13050795

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde, S., Brumby, S., Davies, B. J., Elmore, A. C., Emmer, A., Feng, M., Fernández, A., Haritashya, U., Kargel, J. S., Koppes, M., Kraaijenbrink, P. D. A., Kulkarni, A. V., Mayewski, P. A., … Baillie, J. E. M. (2020). Importance and vulnerability of the world's water towers. Nature, 577(7790), 364–369. https://doi.org/10.1038/s41586-019-1822-y

Isaak, D. J., & Rieman, B. E. (2013). Stream isotherm shifts from climate change and implications for distributions of ectothermic organisms. Global Change Biology, 19(3), 742–751. https://doi.org/10.1111/gcb.12073

Kerins, D., Sadayappan, K., Zhi, W., Sullivan, P. L., Williams, K. H., Carroll, R. W. H., Barnard, H. R., Sprenger, M., Dong, W., Perdrial, J., & Li, L. (2024). Hydrology Outweighs Temperature in Driving Production and Export of Dissolved Carbon in a Snowy Mountain Catchment. Water Resources Research, 60(7), e2023WR036077. https://doi.org/10.1029/2023WR036077

Lemelin, H., Johnston, M., Lough, D., Rowell, J., Broomfield, W., Baikie, G., & Sheppard, K. (2016). Two Parks, One Vision – Collaborative Management Approaches to Transboundary Protected Areas in Northern Canada: Tongait KakKasuangita SilakKijapvinga/Torngat Mountains National Park, Nunatsiavut and le Parc national Kuururjuaq Nunavik. In T. M. Herrmann & T. Martin (Eds.), Indigenous Peoples' Governance of Land and Protected Territories in the Arctic (pp. 71–82). Springer International Publishing. https://doi.org/10.1007/978-3-319-25035-9_4

Lloyd, C. E. M., Johnes, P. J., Pemberton, J. A., Yates, C. A., Jones, D., & Evershed, R. P. (2022). Sampling, storage and laboratory approaches for dissolved organic matter characterisation in freshwaters: Moving from nutrient fraction to molecular-scale characterisation. Science of The Total Environment, 827, 154105. https://doi.org/10.1016/j.scitotenv.2022.154105

Liu, D., Wang, T., Liu, X., Ao, J., Tang, H., & Chang, R. (2023). Source, pattern and flux of dissolved carbon in an alpine headwater catchment on the eastern Tibetan Plateau. Hydrological Processes, 37(7), e14941. https://doi.org/10.1002/hyp.14941

MacMillan-Kenny, Z., Denniston, M., Edinger, E., Templeton, A., Côté, D., Limoges, A., & Robert, K. (2025). Associations between iKaluk/Arctic charr (Salvelinus alpinus) and estuarine benthic diatom habitats in nearshore Nunatsiavut waters. Polar Biology, 48(1), 20. https://doi.org/10.1007/s00300-024-03323-z

McDowell, G., Stevens, M., Marshall, S. (2023). *The Canadian Mountain Assessment: Walking Together to Enhance Understanding of Mountains in Canada*. University of Calgary Press.

Milner, A. M., Khamis, K., Battin, T. J., Brittain, J. E., Barrand, N. E., Füreder, L., Cauvy-Fraunié, S., Gíslason, G. M., Jacobsen, D., Hannah, D. M., Hodson, A. J., Hood, E., Lencioni, V., Ólafsson, J. S., Robinson, C. T., Tranter, M., & Brown, L. E. (2017). Glacier shrinkage driving global

changes in downstream systems. Proceedings of the National Academy of Sciences, 114(37), 9770–9778. https://doi.org/10.1073/pnas.1619807114

Myers-Smith, I. H., Forbes, B. C., Wilmking, M., Hallinger, M., Lantz, T., Blok, D., Tape, K. D., Macias-Fauria, M., Sass-Klaassen, U., Lévesque, E., Boudreau, S., Ropars, P., Hermanutz, L., Trant, A., Collier, L. S., Weijers, S., Rozema, J., Rayback, S. A., Schmidt, N. M., … Hik, D. S. (2011). Shrub expansion in tundra ecosystems: Dynamics, impacts and research priorities. Environmental Research Letters, 6(4), 045509. https://doi.org/10.1088/1748-9326/6/4/045509

Nunatsiavut Government. (2024). *Silavut Asianguvalliajuk Nunatsiavut Climate Change Workshop*. Nunatsiavut Government. https://nunatsiavut.com/research/climate-change/

Nunatsiavut Government. (2025). *Co-Management*. https://nunatsiavut.com/department/lands-natural-resources/co-management/

Ohlanders, N., Rodriguez, M., & McPhee, J. (2013). Stable water isotope variation in a Central Andean watershed dominated by glacier and snowmelt. Hydrology and Earth System Sciences, 17(3), 1035–1050. https://doi.org/10.5194/hess-17-1035-2013

Ritcey, A., & Culp, J. (2008). *Environmental Drivers of Stream Ecosystem Structure and Function in Subarctic Labrador, Canada*. [Master's Thesis, University of New Brunswick].

Rixen, C., Høye, T. T., Macek, P., Aerts, R., Alatalo, J. M., Anderson, J. T., Arnold, P. A., Barrio, I. C., Bjerke, J. W., Björkman, M. P., Blok, D., Blume-Werry, G., Boike, J., Bokhorst, S., Carbognani, M., Christiansen, C. T., Convey, P., Cooper, E. J., Cornelissen, J. H. C., Zong, S. (2022). Winters are changing: Snow effects on Arctic and alpine tundra ecosystems. Arctic Science, 8(3), 572–608. https://doi.org/10.1139/as-2020-0058

Sepúlveda, L. D., Echegoyen, C. V., Martin, M. E., Campodonico, V. A., Pasquini, A. I., Temporetti, P., & Lecomte, K. L. (2022). Isotopic signature of a glacial influenced hydrological system in northern Patagonia, Argentina. Hydrological Processes, 36(2), e14504. https://doi.org/10.1002/hyp.14504Slemmons, K. E. H., Saros, J. E., & Simon, K. (2013). The influence of glacial meltwater on alpine aquatic ecosystems: A review. Environmental Science: Processes & Impacts, 15(10), 1794–1806. https://doi.org/10.1039/C3EM00243H

Stern, L. A., & Blisniuk, P. M. (2002). Stable isotope composition of precipitation across the southern Patagonian Andes. Journal of Geophysical Research: Atmospheres, 107(D23), ACL 3-1-ACL 3-14. https://doi.org/10.1029/2002JD002509

St. Pierre, K. A., St. Louis, V. L., Schiff, S. L., Lehnherr, I., Dainard, P. G., Gardner, A. S., Aukes, P. J. K., & Sharp, M. J. (2019). Proglacial freshwaters are significant and previously unrecognized sinks of atmospheric CO2. Proceedings of the National Academy of Sciences, 116(36), 17690–17695. https://doi.org/10.1073/pnas.1904241116

Sudlow, K., Tremblay, S. S., & Vinebrooke, R. D. (2023). Glacial stream ecosystems and epilithic algal communities under a warming climate. Environmental Reviews, 31(3), 471–483. https://doi.org/10.1139/er-2022-0114

Way, R. G., Bell, T., & Barrand, N. E. (2014). An inventory and topographic analysis of glaciers in the Torngat Mountains, northern Labrador, Canada. Journal of Glaciology, 60(223), 945–956. https://doi.org/10.3189/2014JoG13J195

Way, R. G., Lewkowicz, A. G., & Bonnaventure, P. P. (2017). Development of moderate-resolution gridded monthly air temperature and degree-day maps for the Labrador-Ungava region of northern Canada. International Journal of Climatology, 37(1), 493–508. https://doi.org/10.1002/joc.4721

Wilkes, M. A., Carrivick, J. L., Castella, E., Ilg, C., Cauvy-Fraunié, S., Fell, S. C., Füreder, L., Huss, M., James, W., Lencioni, V., Robinson, C., & Brown, L. E. (2023). Glacier retreat reorganizes river habitats leaving refugia for Alpine invertebrate biodiversity poorly protected. Nature Ecology and Evolution, 7(6), 841–851. Scopus.

Winnick, M. J., Chamberlain, C. P., Caves, J. K., & Welker, J. M. (2014). Quantifying the isotopic 'continental effect.' Earth and Planetary Science Letters, 406, 123–133. https://doi.org/10.1016/j.epsl.2014.09.005https://doi.org/10.1038/s41559-023-02061-5

Wrona, F. J., Johansson, M., Culp, J. M., Jenkins, A., Mård, J., Myers-Smith, I. H., Prowse, T. D., Vincent, W. F., & Wookey, P. A. (2016). Transitions in Arctic ecosystems: Ecological implications of a changing hydrological regime. Journal of Geophysical Research: Biogeosciences, 121(3), 650–674. https://doi.org/10.1002/2015JG003133

Xu, J., Ling, H., Zhang, G., Yan, J., Deng, M., Wang, G., & Xu, S. (2021). Variations in the dissolved carbon concentrations of the shallow groundwater in a desert inland river basin. Journal of Hydrology, 602, 126774. https://doi.org/10.1016/j.jhydrol.2021.126774

Chapter 4: Conclusion

4.1 Thesis Summary

Alpine river systems in *Tongait KakKasuangita SilakKijapvinga* (Torngat Mountains National Park [TMNP]) connect the land to the sea, transporting nutrients, materials, species, and people. The rivers here are influenced by cryospheric and hydrological processes, and their integrity may be at risk due to the impacts of continued warming on the cryosphere (Milner et al, 2009; Michelutti et al., 2020; Wilkes et al., 2023). Continued reductions of snow and ice contributions to alpine river systems in TMNP may alter spatial and temporal dynamics of streamflow, decrease sediment load, shift nutrient and carbon cycles, increase water temperatures, and change the community compositions of freshwater ecosystems (Milner et al., 2009). This poses a threat for culturally and economically important cold-water species such as *ikKaluk* (Arctic char; *Salvelinus alpinus*), which may experience a subsequent loss of suitable habitat space due to warming thermal regimes and increased competition from to the range expansion of warm-water species (Culp et al., 2019; Wrona et al., 2016). As the impacts of climate change are increasingly felt across Nunatsiavut, there is need and desire for standardized and consistent environmental monitoring to ensure the sustainability of these ancestral Inuit homelands (McDowell et al., 2023; Nunatsiavut Government, 2024; Thorne et al., 2024). The goal of this research is to investigate the current state of alpine river systems in TMNP and set the groundwork to monitor how changes in the cryosphere and hydrosphere will impact northern ecosystems and livelihoods in support of climate change adaptation and monitoring (CINUK, 2023).

My first research question, as presented in Chapter 1, asked how influential is source water for stream composition and ecological functioning of alpine rivers systems in Arctic Cordillera landscapes? Results presented in Chapter 3 used a stable isotopic analysis of oxygen ($\delta 18O$) and hydrogen ($\delta 2H$) and aqueous carbon measurements of dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC) to compare three different watersheds; glacier fed Blow Me Down Mountains (BMD), snow fed Nakvak Brook (NVB), and rain and

groundwater fed Torr Bay Brook (TBB). An analysis of variance (ANOVA) test showed statistical differences in isotopic composition, DIC, pH, and electrical conductivity (EC) between these three sampled watersheds. The stable isotopic analysis revealed distinct grouping for each watershed; however, the results of a Generalized Linear Model (GLM) also suggested these differences may be due to effects of geography rather than source water contributions, though evidence of source water mixing was still present. Differences in concentrations of DOC and DIC between the upper and lower portions of the watersheds were measured for most watersheds, suggesting that distance from source waters and increased water mixing do have an impact on the ecological function of rivers.

My second question was what role does meltwater play in shaping the physio-chemical properties of freshwater systems in the Torngat Mountains? A literature review presented in Chapter 2 investigated the role snowpacks and glaciers play in alpine river systems. Snowpacks and glaciers act as important reservoirs for the long-term storage and release of water, nutrients, and other materials throughout the year. In addition, meltwater is a key component in determining the biodiversity and distribution of species in freshwater environments as meltwater fed rivers have colder temperatures, greater channel instability, larger sediment loads, seasonal ice cover, and highly turbid flows (Brown et al., 2007; Kosek & Ruman, 2021; Wilkes et al., 2023). Further, Chapter 3 found that rivers fed by snow melt and glacier melt supported optimal habitat conditions for cold-water species due to their ability to maintain cooler thermal regimes than non-meltwater fed rivers, especially at their headwaters. While further water sampling is needed to fully understand the hydrological processes taking place in TMNP and how they shift throughout the year, the results presented provide useful insights to guide future research and established baseline hydrological data for this region.

4.2 Significance

As the ancestral homeland for Nunatsiavut and Nunavik Inuit, TMNP stands as a symbol of Inuit legacy and identity in Labrador, protecting culturally and ecologically important lands and supporting a diversity of plants and animals (Brice-Bennett et al., 2023). As the rivers that feed these lands face an uncertain future there is a need to establish reliable

baseline hydrological data to form robust conservation and management strategies for this region. The next steps needed to accomplish this include the continuation of water sampling in TMNP on a broader spatial scale and as much as possible throughout a whole hydrological year to gain a comprehensive view of the local water cycles and how they shift through the seasons with changing source water contributions. These objectives could be accomplished by the work of future graduate students, our research partners at Parks Canada and the Nunatsiavut Government, or through future Inuit-led research projects. Stream water sampling of the three sampled watersheds in this study will be continued by other team members, with hopes of expanding the sampling range to additional sites within these watersheds as well as other watersheds throughout TMNP to continue building our understanding of the current state of alpine river systems in this region and begin building a long-term dataset. Instrumentation will be placed in streams at select study sites to provide year-round hydrological monitoring of the three monitored watersheds. Research Partners at Parks Canada and the Nunatsiavut Government have also shown interest in assisting with the collection of stream water samples throughout TMNP, and plans have been established for this to take place in future field seasons.

Tangible contributions of my thesis include a summary of the current state of knowledge on alpine river systems and how they may be impacted by climate change, the first stable isotopic analysis of oxygen and hydrogen and measurements of aqueous carbon for freshwater streams in TMNP, the identification of knowledge gaps and proposed directions for future research, and a better understanding of the current state of the hydrosphere in northern Labrador. My thesis also contributed to a larger interdisciplinary project titled IMpacts of Cryosphere-Hydrosphere ChAnGe on Ecosystems and LIvelihoods in NorthErn Nunatsiavut, Canada (IMAGINE) which operates under the Canada-Inuit Nunangat-United Kingdom Arctic Research Programme (CINUK). The goal of the IMAGINE Project is to improve our understanding of changing cryospheric and hydrological process in TMNP and investigate the downstream impacts this has on ecosystems and livelihoods (CINUK, 2023). I plan to communicate the results of my thesis by sharing the self-contained report in Chapter 2 with Parks Canada, the TMNP Cooperative Management Board, and the Nunatsiavut Government,

publishing the manuscript in Chapter 3 to a scientific journal, and ensuring all data is made publicly accessible and presented back to communities whenever possible. My hope is that this work will help inform future management and conservation strategies that will foster the resilience and sustainability of TMNP for years to come.

References

Barrand, N. E., Way, R. G., Bell, T., & Sharp, M. J. (2017). Recent changes in area and thickness of Torngat Mountain glaciers (northern Labrador, Canada). The Cryosphere 11, 1, 157-168. https://doi.org/10.5194/tc-11-157-2017

Bosson, J. B., Huss, M., Cauvy-Fraunié, S., Clément, J. C., Costes, G., Fischer, M., Poulenard, J., & Arthaud, F. (2023). Future emergence of new ecosystems caused by glacial retreat. Nature, 620(7974), 562–569. https://doi.org/10.1038/s41586-023-06302-2

Bourquin, M., Peter, H., Michoud, G., Busi, S. B., Kohler, T. J., Robison, A. L., Styllas, M., Ezzat, L., Geers, A. U., Huss, M., Fodelianakis, S., & Battin, T. J. (2025). Predicting climate-change impacts on the global glacier-fed stream microbiome. Nature Communications, 16(1), 1264. https://doi.org/10.1038/s41467-025-56426-4

Brice-Bennett, C., Onalik, L., Procter, A. (2023). *Avanimiut: A History of Inuit Independence in Northern Labrador*. Nunatsiavut Government.

Brown, L. E., Hannah, D. M., & Milner, A. M. (2007). Vulnerability of alpine stream biodiversity to shrinking glaciers and snowpacks. Global Change Biology, 13(5), 958–966. https://doi.org/10.1111/j.1365-2486.2007.01341.xCINUK. (2023). *IMAGINE - glaciers, rivers, & ecosystems*. Canada-Inuit Nunangat-United Kingdom Arctic Research Program (CINUK): https://www.cinuk.org/projects/imagine/

CINUK. (2023). *IMAGINE - glaciers, rivers, & ecosystems*. Canada-Inuit Nunangat-United Kingdom Arctic Research Program (CINUK): https://www.cinuk.org/projects/imagine/

Culp, J. M., Lento, J., Curry, R. A., Luiker, E., & Halliwell, D. (2019). Arctic biodiversity of stream macroinvertebrates declines in response to latitudinal change in the abiotic template. Freshwater Science, 38(3), 465–479. https://doi.org/10.1086/704887

Davis, E. L., Trant, A. J., Way, R. G., Hermanutz, L., & Whitaker, D. (2021). Rapid Ecosystem Change at the Southern Limit of the Canadian Arctic, Torngat Mountains National Park. Remote Sensing, 13(11), Article 11. https://doi.org/10.3390/rs13112085

Environment and Climate Change Canada. (2023). *Canadian Environmental Sustainability Indicators: Ecological integrity of national parks.* Government of Canada.

https://www.canada.ca/en/environment-climate-change/services/environmental-indicators/ecological-integrity-national-parks.html

Giesler, R., Lyon, S. W., Mörth, C.-M., Karlsson, J., Karlsson, E. M., Jantze, E. J., Destouni, G., & Humborg, C. (2014). Catchment-scale dissolved carbon concentrations and export estimates across six subarctic streams in northern Sweden. Biogeosciences, 11(2), 525–537. https://doi.org/10.5194/bg-11-525-2014

Government of Canada. (2023). *Torngat Mountains National Park*. https://parks.canada.ca/pn-np/nl/torngats

Harris, L. N., Yurkowski, D. J., Gilbert, M. J. H., Else, B. G. T., Duke, P. J., Ahmed, M. M. M., Tallman, R. F., Fisk, A. T., & Moore, J. (2020). Depth and temperature preference of anadromous Arctic char Salvelinus alpinus in the Kitikmeot Sea, a shallow and low-salinity area of the Canadian Arctic. Marine Ecology Progress Series, 634, 175–197. https://doi.org/10.3354/meps13195

Isaak, D. J., & Rieman, B. E. (2013). Stream isotherm shifts from climate change and implications for distributions of ectothermic organisms. Global Change Biology, 19(3), 742–751. https://doi.org/10.1111/gcb.12073

Kosek, K., & Ruman, M. (2021). Arctic Freshwater Environment Altered by the Accumulation of Commonly Determined and Potentially New POPs. Water, 13(13), Article 13. https://doi.org/10.3390/w13131739

Lemelin, H., Johnston, M., Lough, D., Rowell, J., Broomfield, W., Baikie, G., & Sheppard, K. (2016). Two Parks, One Vision – Collaborative Management Approaches to Transboundary Protected Areas in Northern Canada: Tongait KakKasuangita SilakKijapvinga/Torngat Mountains National Park, Nunatsiavut and le Parc national Kuururjuaq Nunavik. In T. M. Herrmann & T. Martin (Eds.), Indigenous Peoples' Governance of Land and Protected Territories in the Arctic (pp. 71–82). Springer International Publishing. https://doi.org/10.1007/978-3-319-25035-9_4

Liu, D., Wang, T., Liu, X., Ao, J., Tang, H., & Chang, R. (2023). Source, pattern and flux of dissolved carbon in an alpine headwater catchment on the eastern Tibetan Plateau. Hydrological Processes, 37(7), e14941. https://doi.org/10.1002/hyp.14941

Malik, I. H., & Ford, J. D. (2025). Understanding the Impacts of Arctic Climate Change Through the Lens of Political Ecology. WIREs Climate Change, 16(1), e927. https://doi.org/10.1002/wcc.927

McDowell, G., Stevens, M., Marshall, S. (2023). *The Canadian Mountain Assessment: Walking Together to Enhance Understanding of Mountains in Canada*. University of Calgary Press.

Michelutti, N., Douglas, M.S.V., Antoniades, D., Lehnherr, I., St. Louis, V.L., St. Pierre, K., Muir, D.C.G., Brunskill, G., Smol, J.P. (2020). Contrasting the ecological effects of decreasing ice cover versus accelerated glacial melt on the High Arctic's largest lake. Proc. R. Soc. B 287: 20201185. http://dx.doi.org/10.1098/rspb.2020.1185

Milner, A. M., Khamis, K., Battin, T. J., Brittain, J. E., Barrand, N. E., Füreder, L., Cauvy-Fraunié, S., Gíslason, G. M., Jacobsen, D., Hannah, D. M., Hodson, A. J., Hood, E., Lencioni, V., Ólafsson, J. S., Robinson, C. T., Tranter, M., & Brown, L. E. (2017). Glacier shrinkage driving global changes in downstream systems. Proceedings of the National Academy of Sciences, 114(37), 9770–9778. https://doi.org/10.1073/pnas.1619807114

Norton, C. H., Cuerrier, A., & Hermanutz, L. (2021). People and Plants in Nunatsiavut (Labrador, Canada): Examining Plants as a Foundational Aspect of Culture in the Subarctic. Economic Botany, 75(3), 287–301. https://doi.org/10.1007/s12231-021-09530-7

Nunatsiavut Government. (2024). *Silavut Asianguvalliajuk Nunatsiavut Climate Change Workshop*. Nunatsiavut Government. https://nunatsiavut.com/research/climate-change/

Ohlanders, N., Rodriguez, M., & McPhee, J. (2013). Stable water isotope variation in a Central Andean watershed dominated by glacier and snowmelt. Hydrology and Earth System Sciences, 17(3), 1035–1050. https://doi.org/10.5194/hess-17-1035-2013

Parks Canada Agency. (2008). *Torngat Mountains National Park of Canada: State of Park Report* . https://parks.canada.ca/pn-np/nl/torngats/info/gestion-management

Ritcey, A., & Culp, J. (2008). *Environmental Drivers of Stream Ecosystem Structure and Function in Subarctic Labrador, Canada*. [Master's Thesis, University of New Brunswick].

Slemmons, K. E. H., Saros, J. E., & Simon, K. (2013). The influence of glacial meltwater on alpine aquatic ecosystems: A review. Environmental Science: Processes & Impacts, 15(10), 1794–1806. https://doi.org/10.1039/C3EM00243H

St. Pierre, K. A., St. Louis, V. L., Schiff, S. L., Lehnherr, I., Dainard, P. G., Gardner, A. S., Aukes, P. J. K., & Sharp, M. J. (2019). Proglacial freshwaters are significant and previously unrecognized sinks of atmospheric CO2. Proceedings of the National Academy of Sciences, 116(36), 17690–17695. https://doi.org/10.1073/pnas.1904241116

Thorne, R., Walker, B., Tutton, R., Fogal, A., Seto, J., Brocket, M., Dakin, B., Abumazan, N., Marsh, P. (2024). Predicting the future hydrology of western Canadian Arctic watersheds dominated by thermokarst lakes. International Permafrost Association (IPA). https://doi.org/10.52381/ICOP2024.199.1Wang, H., Liu, J., Klaar, M., Chen, A., Gudmundsson, L., & Holden, J. (2024). Anthropogenic climate change has influenced global river flow seasonality. Science, 383(6686), 1009–1014. https://doi.org/10.1126/science.adi9501

Way, R. G., Bell, T., & Barrand, N. E. (2014). An inventory and topographic analysis of glaciers in the Torngat Mountains, northern Labrador, Canada. Journal of Glaciology, 60(223), 945–956. https://doi.org/10.3189/2014JoG13J195

Wilkes, M. A., Carrivick, J. L., Castella, E., Ilg, C., Cauvy-Fraunié, S., Fell, S. C., Füreder, L., Huss, M., James, W., Lencioni, V., Robinson, C., & Brown, L. E. (2023). Glacier retreat reorganizes river habitats leaving refugia for Alpine invertebrate biodiversity poorly protected. Nature Ecology and Evolution, 7(6), 841–851. Scopus. https://doi.org/10.1038/s41559-023-02061-5

Wrona, F. J., Johansson, M., Culp, J. M., Jenkins, A., Mård, J., Myers-Smith, I. H., Prowse, T. D., Vincent, W. F., & Wookey, P. A. (2016). Transitions in Arctic ecosystems: Ecological implications of a changing hydrological regime. Journal of Geophysical Research: Biogeosciences, 121(3), 650–674. https://doi.org/10.1002/2015JG003133

Appendix A: Supplementary Material

Table A1: Stream water sample results and recorded field observations for each sample site.

Sample	δ18O (‰)	δ2H (‰)	DOC (mg/L)	DIC (mg/l)	Elevation (m.a.s.l)	pH	EC (µS/cm)	Water Temp. (°C)
Torr Bay Brook								
TBB-1*	-7.89	-80.00	1.36	1.35	18	7.3	102.02	12.7
TBB-2	-13.04	-98.86	0.32	2.71	124	7.8	122.5	8.5
TBB-3	-11.91	-95.07	0.32	2.14	124	7.7	98.75	9.3
TBB-4	-11.62	-94.68	0.21	1.56	85	7.6	90.06	10.4
TBB-5	-11.29	-94.10	0.27	1.70	61	7.4	87.46	9.9
TBB-6	-13.10	-98.08	0.39	1.71	29	7.2	86.02	11
TBB-7	-11.96	-95.93	0.31	2.02	23	7	92.96	11.6
TBB-8	-13.52	-98.65	0.48	1.66	29	7.6	78.62	10.2
TBB-9	-12.67	-97.05	0.42	1.45	7	8.3	87.92	12.3
Nakvak Brook								
NVB-1*	-13.46	-107.77	1.55	0.34	427	6.4	2.13	4.1
NVB-2	-15.89	-114.76	0.41	1.08	418	7.5	41.38	6.3
NVB-3	-12.61	-100.92	0.28	1.31	414	7.1	47.65	6.9
NVB-4	-13.30	-104.12	0.21	1.21	411	7.3	56.64	8.9
NVB-5	-14.56	-107.18	0.26	1.41	366	6	30.51	9.3
NVB-6	-15.04	-109.64	0.32	0.74	76	7.4	71.24	9.9
NVB-7	-14.97	-114.88	0.73	1.55	76	7.1	56.54	10.3
NVB-8	-15.94	-118.30	0.59	1.59	76	6.9	53.13	11
NVB-9	-13.64	-106.48	0.54	1.47	343	7.1	69.88	10.4
Blow Me Down Mountains								
BMD-1*	-15.24	-109.74	7.08	0.95	400	6.7	17.4	0.7
BMD-2	-10.87	-88.14	0.38	0.50	400	6.7	4.15	0.5
BMD-3	-12.35	-93.80	0.48	0.28	509	6.2	3.3	6
BMD-4	-9.41	-86.67	0.34	1.23	245	6.9	1.15	10.2
BMD-5	-12.02	-93.14	0.34	1.11	186	6.2	10.3	10.8
BMD-6	-13.34	-95.31	0.67	1.25	175	7.1	1.07	14.1
BMD-7	-12.18	-93.64	0.37	1.09	144	6.8	2.29	11.1

** = endmember sample*

Figure A1: Photographs of each sample site in Torr Bay Brook (photographed by author).

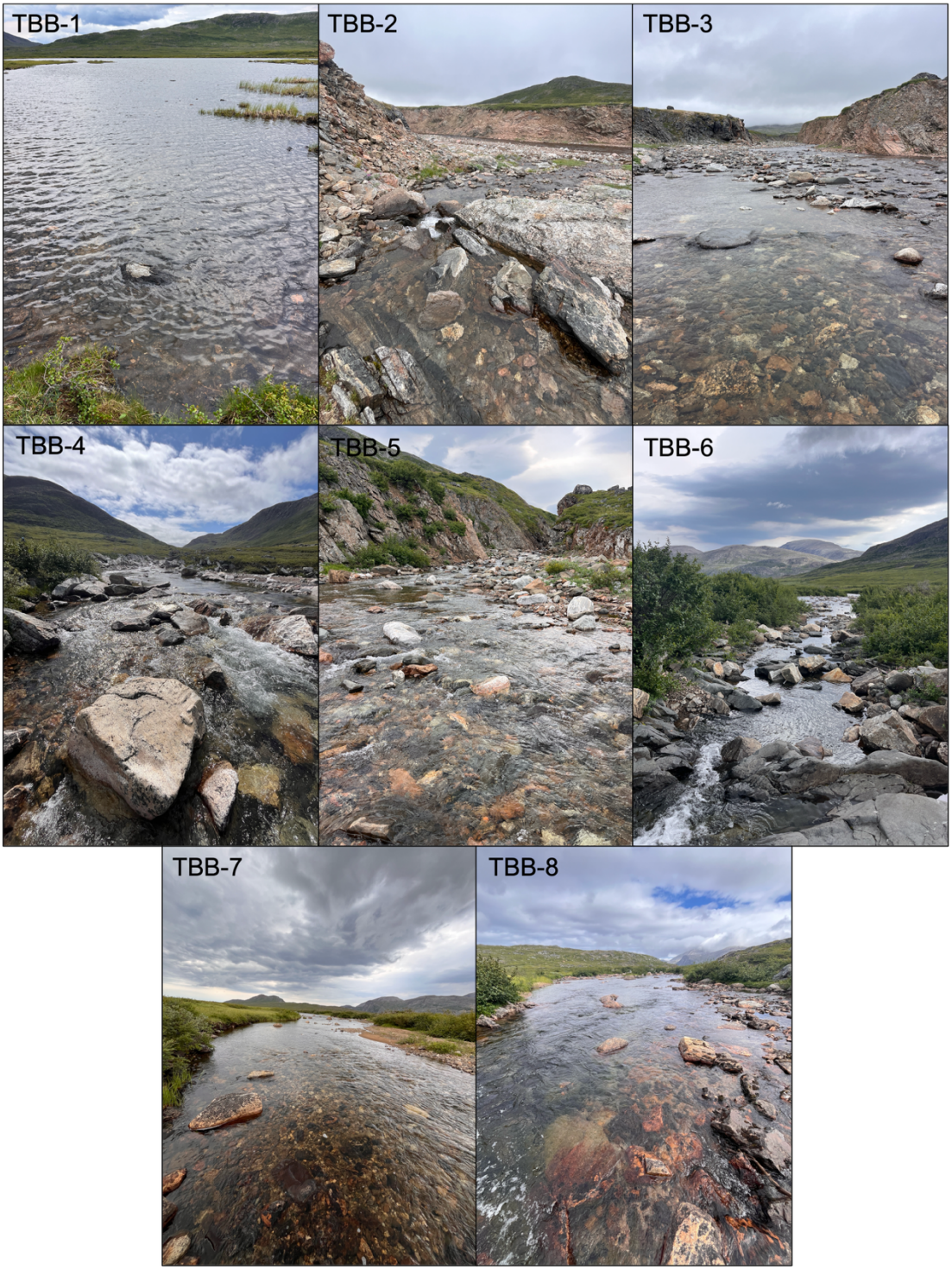


Figure A2: Photographs of each sample site in Nakvak Brook (photographed by author).



Figure A3: Photographs of each sample site in the Blow Me Down Mountains (photographed by author).



Table A2: Field protocol for collecting water samples for a stable isotope analysis of oxygen (δ18O) and hydrogen (δ2H) and aqueous carbon measurements of dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC).

Stable Isotope Samples:
1. With clean nitrile gloves grab two 2ml filter vials and a 1ml syringe
2. Flush the syringe three times with stream water
3. Fill the syringe by plunging it into the center of the stream at ~60% stream depth from the surface if possible - otherwise the stream edge will work
4. Ensure you are standing downstream from sampling location
5. Fill the outer vial casings using the 1ml syringe until the water level reaches the marked "Fill Line" on the vial to reduce headspace
6. Place inner plunger back into the vial and slowly squeeze both ends together with your fingers until the vial is sealed (it will click)
7. Wrap a piece of lab tape with the sample number around the base of the vial
8. Make sure the tape does not overlap, as it won't fit into the autosampler
9. For snow or glacial samples: take a big sample from the center (if possible) in a clean bottle or bag and allow it to melt before transferring the water into a vial
10. Fill in the Stream Water Sampling Info Sheet
Aqueous Carbon Samples:
1. With clean nitrile gloves grab one 40ml vial, one syringe filter, and one 50ml syringe. Have zinc chloride solution and 1ml syringe ready on the stream bank
2. Flush both the 40ml vial and 50ml syringe three times with stream water
3. Sample from the center of the stream at ~60% stream depth from surface if possible - otherwise the stream edge will work
4. Ensure you are standing downstream from sampling location
5. Fill the 50ml syringe with ~30ml of stream water
6. Attach a new syringe filter to the end of the syringe and push a few drops of water through the filter before filling the sample vial with the rest
7. Be sure not to fill over ¾'s of the vial so there is enough atmospheric headspace for CO^2 sampling - a bit below is no issue
8. Once sample is collected use the 1ml syringe to add in 0.3 ml of zinc chloride solution
9. Seal the vial with the twist-on septum cap until it is finger-tight
10. Do not remove the cap once on as this will alter the headspace!
11. Wrap a piece of tape around the base of the lid so it does not come loose in transport
12. Fill in the Stream Water Sampling Info Sheet

Table A3: "Stream Water Sampling Info Sheet" used to record all sample information and field observations, with space for conducting a stream flow transect.

Stream Water Sampling Info Sheet - TMNP 2024

Please return all sheets to Katryna Barone - kbarone@uwaterloo.ca

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Collectors Name(s):_____

REQUIRED INFORMATION:

Sample Number(s): *(listed on the vial)*	
Sample Type: *(circle all samples taken)*	Isotope / Carbon / eDNA
Feature Sampled: *(circle one)*	Stream / Headwaters / River Mouth / Waterfall Rain / Confluence (above) / Confluence (below) Lake (inflow) / Lake (outflow) / Groundwater Spring Glacier / Glacial Outflow / Snow (old) / Snow (new) Other_____
Site Name: *(ex. Nakvak, Ivitak, etc.)*	
GPS Coordinates: *(to 4 decimal degrees)*	Latitude:__ __ . _ __ __ __ °N Longitude:__ __ . __ __ __ __ °W
Date & Time: *(in 24 hour format; hh:mm)*	Month:_____ Day: ___ ___ Time: ___ ___ : ___ ___
pH Level: *(to one decimal point)*	___ ___ . ___
EC Level: *(to two decimal points, µS/cm)*	___ ___ ___ ___ . ___ ___ µS/cm
Water Temperature: *(one decimal, ℃)*	___ ___ . ___ ℃
Elevation: *(in metres above sea level)*	___ ___ ___ ___ . ___ m . a. s. l.

ADDITIONAL INFORMATION:

Avg. Air Temperature: *(one decimal, ℃)*	___ ___ . ___ ℃
Average Humidity: *(one decimal, %)*	___ ___ . ___ %
Average Wind Speed: *(one decimal, m/s)*	___ ___ . ___ m/s
Soil Moisture: *(soil moisture in water fraction/volume to one decimal, distance from stream edge in metres)*	Moisture:___ ___ . ___ wf/v Distance:_____ m Side of stream *(when facing upstream)*: Left / Right
Site Photos: *(upstream and downstream)*	Device Used:_____ Device Owner:_____

Stream Flow Rate: *(centimetres/second)* *One measurement taken where water samples were done and additional measurements taken at consistent intervals in a transect across the width of the stream.* *At sample location record the distance from stream bank and which stream bank distance was taken from (when facing upstream).* *Record total width of stream and distance between intervals in **metres**.* *Move from left to right (when facing upstream).* *At each point move the flow probe vertically up and down the entire height of the stream column for one minute and record the average in **centimetres** per second.* *Take total depth in **metres** at each measurement so discharge can be calculated later.*	At Sample Location: Flow:_____Depth:_____ Distance from bank:_____ Stream bank: Left / Right Stream Flow Transect: Total stream width:_____m Distance interval:_____ m **Measurement 1:** Flow:_____Depth:_____ **Measurement 2:** Flow:_____Depth:_____ **Measurement 3:** Flow:_____Depth:_____ **Measurement 4:** Flow:_____Depth:_____ **Measurement 5:** Flow:_____Depth:_____ **Measurement 6:** Flow:_____Depth:_____ **Measurement 7:** Flow:_____Depth:_____ **Measurement 8:** Flow:_____Depth:_____	**Measurement 9:** Flow:_____Depth:_____ **Measurement 10:** Flow:_____Depth:_____ **Measurement 11:** Flow:_____Depth:_____ **Measurement 12:** Flow:_____Depth:_____ **Measurement 13:** Flow:_____Depth:_____ **Measurement 14:** Flow:_____Depth:_____ **Measurement 15:** Flow:_____Depth:_____ **Measurement 16:** Flow:_____Depth:_____ **Measurement 17:** Flow:_____Depth:_____ **Measurement 18:** Flow:_____Depth:_____ **Measurement 19:** Flow:_____Depth:_____ **Measurement 20:** Flow:_____Depth:_____
Last Precipitation Event: *(circle all that apply)*	Past 12 hours / Past 24 hours Past 3 days / Past week Isolated Event / Continuous	Mist/Fog / Light Rain Moderate Rain / Heavy Rain Hail / Snow
Dominant Vegetation: *(circle most applicable - if more than one type is dominant circle multiple)*	Bare Ground / Lichen / Shrubs (below knee height) Moss / Grass / Shrubs (above knee height)	
Depositional Processes Present: *(circle any applicable)*	Glacial / Wind / River Lake / Ocean	Avalanche / Landslide Rockfall / Sinkhole / Slump
General Site Description: *Ex. nearby monitoring sites, notable geographical features or disturbances, archeological sites, signs of wildlife, etc.*		

Table A4: Summary of ANOVA results (degrees of freedom, sum of squares, mean squares, *f*-statistic, and *p*-value).

Variable	Degrees of Freedom	Sum of Squares	Mean Squares	*f*-statistic	*p*-value
Oxygen (δ18O)	2	31.03	15.515	12.21	0.00039
Hydrogen (δ2H)	2	1227.5	613.7	34.63	4.61e-07
Dissolved Organic Carbon (DOC)	2	0.0373	0.01867	0.932	0.411
Dissolved Inorganic Carbon (DIC)	2	3.286	1.6431	12.28	0.000378
pH	2	3.018	1.5089	8.661	0.00212
Electrical Conductivity (EC)	2	27367	13683	100.2	8.07e-11
Water Temperature	2	10.69	5.343	0.692	0.513

Figure A4: Isospace plot annotated with prominent physical features from the stream water sampling locations.

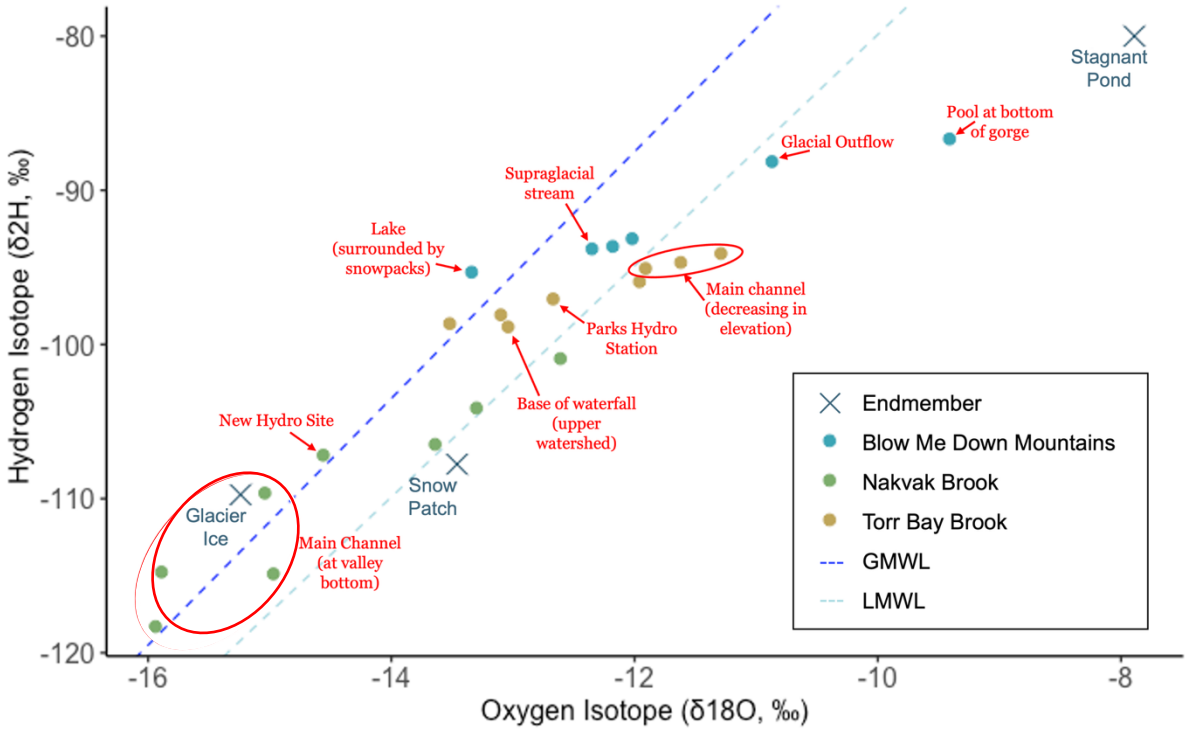


Figure A5: Average annual temperatures (°C) for the sampled watersheds from 2014-2024. Data derived from ERA5 atmospheric reanalysis data.

Torr Bay Brook		Nakvak Brook		Blow Me Down Mountains	
Year	Annual Average (°C)	Year	Annual Average (°C)	Year	Annual Average (°C)
2014	-6.2	2014	-8.2	2014	-6.4
2015	-7.9	2015	-9.8	2015	-7.9
2016	-6.4	2016	-8.6	2016	-6.5
2017	-5.7	2017	-7.6	2017	-6.0
2018	-6.6	2018	-9.2	2018	-6.8
2019	-5.4	2019	-7.3	2019	-5.5
2020	-5.5	2020	-7.7	2020	-5.7
2021	-2.9	2021	-4.9	2021	-3.3
2022	-4.9	2022	-7.0	2022	-5.2
2023	-4.0	2023	-5.6	2023	-4.3
2024	-3.0	2024	-5	2024	-4.0

Figure A6: Average annual rainfall (mm) for the sampled watersheds from 2014-2024. Data derived from ERA5 atmospheric reanalysis data.

Torr Bay Brook		Nakvak Brook		Blow Me Down Mountains	
Year	Annual Rainfall (mm)	Year	Annual Rainfall (mm)	Year	Annual Rainfall (mm)
2014	764	2014	731	2014	819
2015	756	2015	737	2015	853
2016	704	2016	710	2016	822
2017	939	2017	964	2017	1031
2018	719	2018	721	2018	779
2019	894	2019	853	2019	1053
2020	938	2020	923	2020	1084
2021	956	2021	958	2021	1053
2022	733	2022	734	2022	805
2023	567	2023	633	2023	669
2024	977	2024	986	2024	1040

Figure A7: Photos of vegetation (moss and leaves) found on the surface of the sampled Unnamed Glacier in the Blow Me Down Mountains (58.8°N, 62.9°W).

