Canadian Journal of
Fisheries and
Aquatic Sciences

OPEN ACCESS | Research Article

A novel approach to assess the cumulative impacts of thawing permafrost on aquatic systems using both Indigenous knowledge and western scientific knowledge

Jackie A. Ziegler[a], **Trevor C. Lantz**[a], **Mike Newton**[a], **Steven V. Kokelj**[b], **Sarah Lord**[c], and **Gwich'in Tribal Council Department of Culture and Heritage**[d]

[a]School of Environmental Studies, University of Victoria, Victoria, BC, Canada; [b]Northwest Territories Geological Survey, Yellowknife, NT, Canada; [c]Gwich'in Renewable Resources Board, Inuvik, NT, Canada; [d]Fort McPherson, NT, Canada

Corresponding author: **Jackie A. Ziegler** (email: jziegler@uvic.ca)

Abstract

Increased temperatures and precipitation are intensifying mass wasting caused by the thawing of ice-rich permafrost in the western Canadian Arctic. Specifically, disturbances known as retrogressive thaw slumps deliver large quantities of sediment and dissolved materials into adjacent waterbodies, thereby negatively affecting culturally and ecologically important fish habitat. Very little information exists regarding the impacts of thaw slump expansion on fish habitat in northern Canada. To understand the risk of these potential impacts, we combined spatial data on cumulative thaw slump impacts in the Teetł'it Gwinjik (Peel River) Watershed, Gwich'in Settlement Region, with detailed information about fish habitat derived from Gwich'in knowledge and western scientific knowledge using a mixed methods approach. Areas at high risk of experiencing the cumulative impacts of slumping were found along the mainstem of the Peel River and its major tributaries. Gwich'in knowledge holders were concerned about the impacts of slumping on future access to fish. These findings raise concerns about the impact of permafrost thaw on Indigenous fishing livelihoods in the region and highlights the need for additional research.

Key words: cultural landscape, spatial overlay analysis, cumulative impacts, Indigenous knowledge, fishing livelihoods

Introduction

In the western Canadian Arctic, increased temperatures and precipitation are intensifying forms of permafrost degradation that significantly alter terrain conditions, vegetation, hydrology, and sedimentation (Lantz and Kokelj 2008; Kokelj et al. 2015, 2017, 2021; Vonk et al. 2015; Segal et al. 2016; Rudy et al. 2017; Lewkowicz and Way 2019). Permafrost landscape change is expected to intensify with ongoing changes in northern climate, which are occurring at rates nearly four times faster than the global average (Rantanen et al. 2022). Retrogressive thaw slumps are a form of permafrost disturbance that occurs when thawing permafrost exposes an ice-rich headwall in sloping terrain. As ground ice in the headwall melts, it mobilizes previously frozen sediment that moves downslope, creating a scar area that sometimes generates a debris flow (Kokelj et al. 2021; Fig. 1). Thaw slumps frequently occur along streams and coastlines, increasing sedimentation, altering water chemistry, turbidity, and macroinvertebrate community structure (Kokelj et al. 2009, 2013, 2021; Thienpont et al. 2013; Chin et al. 2016; Houben et al. 2016; Littlefair et al. 2017; Levenstein et al. 2018; Shakil et al. 2020). The widespread intensification of thaw slump activity (Segal et al. 2016; Lewkowicz and Way 2019) has the potential to impact important fish habitat, as well as Indigenous harvesting locations (Kokelj et al. 2013; Proverbs et al. 2020*b*; Kokelj et al. 2021; Ziegler et al. 2024). As an area that is rich in ground ice, the Peel River Watershed is especially vulnerable to the effects of thaw slumping and has experienced a significant increase in slump activity over the last 40 years (Kokelj et al. 2015, 2021). The Gwich'in, who have fished the Teetł'it Gwinjik (Peel River) for millennia, are concerned about the impact that thaw slumps are having on their fishing livelihoods (Gwich'in Renewable Resources Board 2018; Ziegler et al. 2024).

To understand the extent of these impacts, in this study we combined spatial data estimating the extent of thaw slump sedimentation to aquatic environments (Kokoszka and Kokelj 2021) with detailed information about culturally and ecologically important fish habitat based on Gwich'in knowledge and western scientific studies. We also interviewed Gwich'in knowledge holders to document actual and perceived impacts of permafrost thaw slumping on fish and fish habitat in the Peel River Watershed. This work builds on previous research that used a grid-based approach to map environmental impacts on culturally important landscapes in the Inuvialuit Settlement Region (Tyson et al. 2016) and Gwich'in Settlement Region (Proverbs et al. 2020*a*). In this study we focus specifically on the cumulative downstream impacts of

Fig. 1. Image of a debris flow from a permafrost thaw slump beside the Uudyit Njik (Miner River), NT, that has affected the water quality and habitat of the river (credit: Van der Sluijs et al. 2022).

retrogressive thaw slumps on the habitat of culturally important fish species for the Gwich'in in the Peel River Watershed (Greenland and Walker-Larsen 2001; Thompson and Millar 2007; Kuhnlein et al. 2013). In this paper, cumulative refers to the cumulative effects of multiple upstream slump events on downstream habitat.

Recently, there has been a call to find new, more equitable ways to bring together Indigenous and western ways of knowing in environmental research (Castleden et al. 2017; Reid et al. 2021). Indigenous ways of knowing provide different yet complementary information to western scientific approaches that enrich our collective understanding of observed environmental changes and their social and cultural impacts (Moller et al. 2004; Bohensky and Maru 2011). In this paper, we define Indigenous knowledge as "the collective term to represent the many place-based knowledges accumulated across generations within myriad specific cultural contexts" (Jessen et al. 2022, p. 93). We refer to Indigenous knowledge included in this manuscript as Gwich'in knowledge. Weaving Indigenous and western knowledge systems has been described as a form of knowledge co-production in which multiple ways of knowing are brought together in an equitable process that respects and maintains the integrity of the respective knowledge systems (Castleden et al. 2017; Alexander et al. 2019; Henri et al. 2021; Reid et al. 2021). Weaving multiple ways of knowing in environmental research can improve our understanding of social-ecological systems and build trust in decision-making and project results (Berkes 2009; Tengö et al. 2014; Mistry and Berardi 2016). However, recognizing and addressing existing power asymmetries between knowledge systems is critical to developing equitable approaches to environmental research (Townsend et al. 2020; Cousins 2021). In particular, it is important that research involving Indigenous knowledge be done in ways that uphold Indigenous rights rather than perpetuate colonial structures and histories (Nadasdy 1999; Smith 2021; Ignace et al. 2023), including prioritizing the research agendas of Indigenous Peoples as a means of reasserting their jurisdiction over their ancestral lands and ensuring that Indigenous knowledge is valued in its own right rather than as a means to validate western scientific ways of knowing (Ignace et al. 2023). In this study, we partnered with the Gwich'in Renewable Resources Board (GRRB) and the Gwich'in Tribal Council Department of Culture and Heritage (DCH) to address Gwich'in concerns regarding the impact of permafrost thaw slumping on the habitat of culturally and ecologically important fish in the Peel River Watershed of the Gwich'in Settlement Region using a novel approach that gave equal weighting to both western scientific and Gwich'in knowledges.

The study area

Fishing is vital to the Gwich'in way of life (McCartney and Gwich'in Tribal Council 2020). The Gwich'in call the Peel River Teetł'it Gwinjik, which means "head of the waters—along the course of" (Gwich'in Social and Cultural Institute n.d.), and have used it to travel, hunt, trap, and fish for millennia (McCartney and Gwich'in Tribal Council 2020). Over that time, Gwich'in land-users have developed a complex network of trails and camps that they continue to use today, with many families maintaining fish camps along the Peel River and its tributaries (Loovers 2010). Water and fish in particular play an important role in Gwich'in place names, origin stories, and artwork, as well as their livelihoods and culture (Collin 1973; Ritter and Sittichinli 1976; Kritsch and Andre 1997; Heine et al. 2001, 2007; Wishart 2014; McCartney and Gwich'in Tribal Council 2020; Gwich'in Social and Cultural Institute n.d.). Place names encode Indigenous knowledge reflecting land use, knowledge of place, habitat, history, and sacredness (Basso 1996). Fish is an important food for the Gwich'in and fishing practices are a vital component of livelihoods (Heine et al. 2001; Wishart 2014; McCartney and Gwich'in Tribal Council 2020; Proverbs et al. 2020*b*). Fishing practices are part of a complex social-ecological system that relies on reciprocal relationships between traditional foods, cultural practices, and the environment (Parlee et al. 2005; Andre 2006; Alexie 2015). Many Gwich'in community members grew up spending their summers and falls at fish camps in the Peel River Watershed, fishing, preparing, and storing traditional foods, and many continue to do so today.

This study focuses on the portion of the Peel River Watershed within the 90 379 km^2 Gwich'in Settlement Region (referred to as "the study area" throughout the manuscript; Fig. 2). Approximately 1300 Gwich'in live in the three Gwich'in communities who participated in this study, including the Ehdiitat Gwich'in of Aklavik, the Nihtat Gwich'in of Inuvik, and the Teetł'it Gwich'in of Teetł'it Zheh (Fort McPherson) (Government of Canada 2021).

The Peel River Watershed is a 73 600 km^2 sub-basin of the Nagwichoonjik (Mackenzie River) Watershed in the Yukon and Northwest Territories, which discharges into Ehdiitat (Mackenzie Delta), the world's second largest Arctic delta (Carson et al. 1998). The Peel River Watershed is an area of continuous permafrost, with many areas rich in ground ice, where the active layer is rarely thicker than 1 m (Hughes et al. 1981) making it particularly vulnerable to climate change (Kokelj et al. 2015, 2021). Since most of the Peel River Watershed within the study area was glaciated during the Pleistocene (80%–90%), it is particularly ice-rich compared to headwater reaches due to the widespread presence of relict ground ice (Kokelj et al. 2017) in a landscape steeply incised by the Peel River and its tributaries. The geology underlying the Peel River consists of sandstone, shale, limestone, and dolomite (Water Resources Division Indian and Northern Affairs Canada 2002; VanGerwen-Toyne et al. 2008). Gravel beds are also found in upstream areas that are important spawning areas for many species of fish (Water Resources Division Indian and Northern Affairs Canada 2002; VanGerwen-Toyne et al. 2008).

Author positionality

The authorship team is composed of both settler and Indigenous experts. JAZ, TCL, SVK, MN, and SL are white, settler scholars, all of whom except SL live outside of the Gwich'in Settlement Area. At the time this study was completed, SL was based in Inuvik, NT, and worked for our Gwich'in partner, the GRRB. TCL and SVK have a long-standing commitment to work with Gwich'in organizations with over 20 years' experience working in the region. The DCH, initially called the Gwich'in Social and Cultural Institute, was created in 1993 following the signing of the Gwich'in Comprehensive Land Claim Agreement with a mandate "to document, preserve, and promote Gwich'in culture, language, traditional knowledge and values" (Gwich'in Social and Cultural Institute 2005, p. 6). JAZ, TCL, SVK, MN, and SL have worked to address issues of positionality through self-reflection, ongoing relationship building, continuing reporting of results to the participating communities, and openly seeking community feedback on their contributions.

Methods

This project explores the impacts of permafrost thaw on important fish habitat in the Peel River Watershed area. We build on the work of Proverbs et al. (2020*a*) and Tyson et al. (2016) but use new data (Kokoszka and Kokelj 2021) and a different analytical approach. Rather than using a grid-based analytical approach to understand the impacts of slumps to the aquatic environment, we used a stream network to overlay spatial estimates of sediment delivery from slumps in the Peel River Watershed (see Table 1) with a map layer representing important fish habitat (see Fig. S1 for an overview of the approach used). By engaging with both Gwich'in and western scientific knowledge, we draw on multiple perspectives that can contribute to a more complete understanding of these impacts.

Specifically, we explored the potential to use GIS to assess the risk of permafrost thaw slumping impacts on culturally and ecologically important fish habitat by completing a spatial overlay analysis using ArcGIS Pro 2.2 software (ESRI, USA). To complete the overlay analyses, we combined maps of (1) the density of important fish habitat (e.g., harvesting sites, spawning, feeding, overwintering and/or nursery areas) based on Gwich'in knowledge and the scientific literature, (2) the estimated cumulative downstream impacts of thaw slumps in the area (Kokoszka and Kokelj 2021), and (3) the direct impacts of thaw slumps in the area (Kokoszka and Kokelj 2021). We also interviewed Gwich'in Elders and knowledge holders who actively or previously fished the Peel River to understand how observed changes on the land are affecting fish and fish habitat in the study area.

This project is a collaboration among the University of Victoria, the GRRB, the DCH, the Northwest Territories Geological Survey, the Tetlit Renewable Resource Council, the Ehdiitat Renewable Resource Council, and the Nihtat Renewable Resource Council. The data in Kokoszka and Kokelj (2021) that were used in the current spatial overlay analyses were developed based on feedback from Gwich'in partners who wanted permafrost thaw slumping data in a format that would allow them to understand how slumping is affecting culturally and ecologically important fish habitat in the Peel River Watershed. This study was suggested as a next step during discussions of Proverbs et al.'s (2020*a*) project outcomes with Gwich'in partners in February 2018. Gwich'in fishers are concerned about the impact that high rates of permafrost slumping in the Peel River Watershed may have on culturally and ecologically important fish habitat downstream and the GRRB identified this as a research priority. Researchers from

Fig. 2. Map of the study area showing the portion of the Peel River Watershed within the Gwich'in Settlement Region (dark grey stream network), and the three Gwich'in communities who travel and harvest in the Teetł'it Gwinjik (Peel River) area (solid black circles). The stream network data are from NHN (2016). The late glacial limit is from Dyke and Prest (1987). The map was created using ArcGIS Pro with the "Light Gray Canvas" basemap from Esri and projected coordinate system NAD 1983/Canada Lambert Conformal Conic.

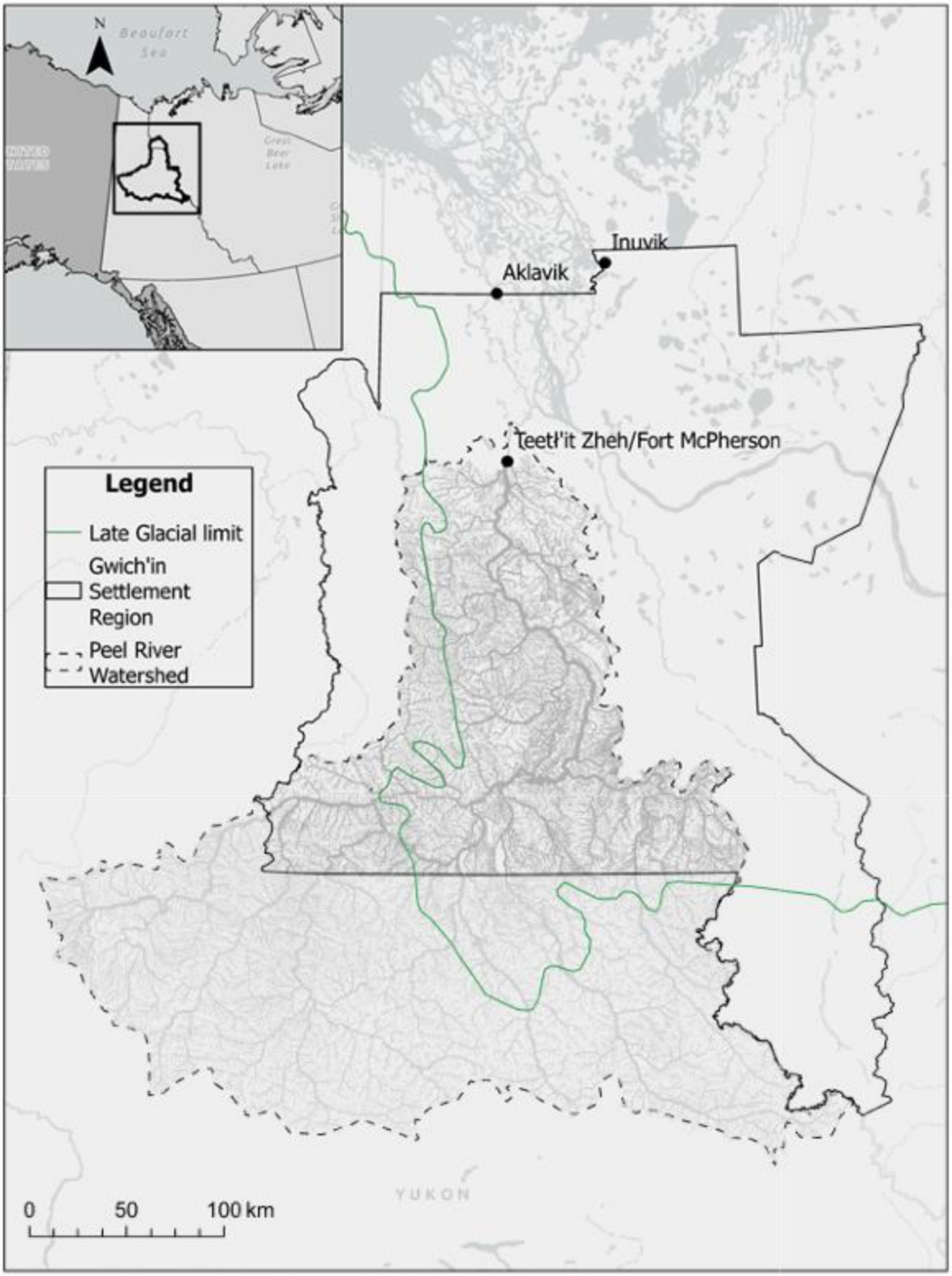


Table 1. Data, sources, and information about the contents of each data layer used in the spatial overlay analysis.

Data layer	Source layer(s)	Data type	Layer contents	Data source
Important fish habitat layer	Gwich'in knowledge of fish habitat	Point, polyline, polygon	Important harvesting locations, as well as fish spawning, overwintering, nursery, and summer feeding areas in the Peel River Watershed. Documented by the DCH, as well as interviews with Gwich'in knowledge holders as part of this project.	Gwich'in Tribal Council Department of Culture and Heritage (DCH) (DCH 2020*a*, 2020*b*, 2020*c*, 2020*d*), interviews completed during current project
	Knowledge of fish habitat from western scientific studies	Point, polygon	Important fish spawning, overwintering, nursery, and summer feeding habitat in the Peel River Watershed. Documented in a literature review.	Table S2
Thaw slump direct impact layer	Direct impacts of permafrost thaw slumps	Polyline	Binary presence/absence of active permafrost thaw slumps on a given stream segment as measure of direct impacts of slumping	NWT Geological Survey (Kokoszka and Kokelj 2021)
Thaw slump cumulative impact layer	Cumulative impacts of permafrost thaw slumps	Polyline	Number of slump-affected stream segments (based on binary presence/absence slump data above) upstream of a given location as a proxy of the amount of sediment affecting streams downstream from the slump	NWT Geological Survey (Kokoszka and Kokelj 2021)

the University of Victoria and the GRRB applied for funding together and our Gwich'in partners, GRRB and DCH, joined the project team that drafted this paper. All Gwich'in knowledge, including information from the DCH digital archive and interviews conducted during this project, were handled according to the Gwich'in Tribal Council's Gwich'in Traditional Knowledge Policy. As a part of this policy, our project had a Traditional Knowledge Research Agreement with the DCH. This research was conducted in accordance with the University of Victoria's Human Research Ethics Board (No. 22-0316). This work was completed under Northwest Territories Scientific Research Licence No. 16940.

Knowledge of fish habitat

Gwich'in knowledge of important fish habitat

In 2022 and 2023, we completed 43 semi-structured interviews with 54 Gwich'in Elders and active resource users to identify culturally important fishing locations and ecologically important fish habitat in the Peel River Watershed. Interviews were conducted in Aklavik ($n = 11$ interviews with 14 people), Inuvik ($n = 12$ interviews with 16 people), and Teetł'it Zheh (Fort McPherson) ($n = 20$ interviews with 24 people). Interview questions and focal fish species were developed with the GRRB and are based on Thompson and Millar (2007) who completed a similar study for the Tsiigehnjik (Arctic Red River) and Nagwichoonjik (Mackenzie River) in the Gwich'in Settlement Area. Fish species included in the interviews were: łuk dagaii (broad whitefish, *Coregonus nasus*), dalts'an (lake whitefish, *Coregonus clupeaformis*), sruh (inconnu, *Stenodus leucichthys*), sriijaa (Arctic grayling, *Thymallus arcticus*), treeluk (Arctic cisco (*Coregonus autumnalis*), least cisco (*Coregonus sardinella*)), chehluk (burbot, *Lota lota*), dhik'ii (Dolly Varden char, *Salvelinus malma*), vit (lake trout, *Salvelinus namaycush*), eltin (Northern pike, *Esox lucius*), walleye (*Stizostedion vitreum*), daats'at (longnose sucker, *Catostomus catostomus*), shii (chum salmon, *Oncorhynchus keta*), ninespine stickleback (*Pungitius pungitius*), and pink salmon (*Oncorhynchus gorbuscha*). Participants were identified through consultation with the Renewable Resource Councils (RRCs) in each community, as well as the DCH, and three community coordinators (one in each of Aklavik, Inuvik, and Teetł'it Zheh (Fort McPherson)). Participants received an honorarium for their participation, in accordance with current rates specified by the DCH. Interviews typically lasted 1–2 h and were semi-structured to allow participants to elaborate on the topics and observations most significant to them. Interview questions focused on important fishing locations, local knowledge of important habitat (e.g., nursery, overwintering, spawning, and feeding) in the Peel River Watershed, as well as how observed changes on the land are affecting fish or fish habitat in the area. Any spatial data discussed were digitised using Google Earth Pro during the interview to allow the participant to confirm location accuracy. These data were then included in the spatial overlay analysis. We reviewed all interview transcripts carefully to validate the completeness and accuracy of the spatial data. This analysis includes spatial data on fish habitat documented during the interviews.

We analysed interview transcripts using qualitative analysis software NViVO 12 Plus (QSR International, USA) to identify emergent themes related to the impacts (actual or potential) of permafrost thaw slumps on fish or fish habitat in the Peel River. Gwich'in knowledge documented during the interviews related to fish or fish habitat will be published as a Gwich'in Knowledge Report on fish in the Peel River through the GRRB.

We also obtained spatial data on fish camp locations, subsistence fishing routes, place names related to fishing, and historical fishing locations from our Gwich'in partners, DCH (DCH 2020*a*, 2020*b*, 2020*c*, 2020*d*). These spatial data were documented as part of interviews completed with Gwich'in Elders and knowledge holders in the 1970s through the 2000s (see Table S1).

Literature review of important fish habitat in the Peel River Watershed

We conducted a literature search of scientific publications to identify spatial data on important fish habitat (nursery, overwintering, summer feeding, spawning, harvesting). We focussed on culturally important fish species listed in the previous section. We included spatial data from the scientific literature that could be digitised, such as geographic coordinates, place names, and published maps showing the locations of fish camps used for sampling, important fish habitat, as well as important fishing locations based on interviews with Indigenous Peoples in the area. Many of the scientific reports we reviewed did not specify how they obtained information about culturally important fishing locations. We therefore did not include these spatial data in the cultural features layer, which specifically highlights the cultural value of fish for the Gwich'in, but rather in the scientific literature layer. Fishing locations represent important fish habitat because fish are typically targeted in areas where they are abundant, for example, in pre-spawning aggregation sites, spawning sites, and summer feeding locations.

We included the following types of publications in our search: peer-reviewed journal articles, government reports, gray literature, and unpublished data and reports. We did not limit our search to peer-reviewed literature because there was little information available on important fish habitat in the Peel River area and we did not want to exclude any potentially important information from our analysis. We searched the Government of Canada's Federal Science Libraries Network database (https://science-libraries.canada.ca) and Google Scholar (scholar.google.com) using key search terms that included the fish of interest (fish species listed in previous section, using both common and scientific names) and "Peel River". We also used the references from publications identified in our search to identify new publications not yet included in our database.

A total of 319 papers were identified through this search. We used the following exclusion criteria to remove publications from our database (1) publication was outside of our study area (the Peel River Watershed, Fig. 2), (2) publication did not include a fish species of interest, (3) publication did not include spatial data of important habitat, and/or (4) publication was a summary of previous work in the area (i.e., not original data) unless that data were not accessible anywhere else. We ended up with a total of 17 publications included in the analysis (Table S2). Once the relevant literature was identified, we digitised the spatial data included in ArcGIS to represent the data shown in the source publications. It is important to note that there may be ecologically important fish habitat in the study area that has not yet been studied in the scientific literature and is therefore not included in our analysis. We address this issue in the calculations section, as well as in the discussion.

Spatial overlay analysis

Preparing the hydrologic data

This analysis is based on the primary directed linear flow network in the National Hydrographic Network (NHN) Hydrologic Dataset (NHN 2016). This polyline file was processed using the RivEX 10.37 software package (Hornby 2021) for ArcMap 10.6.1 using the methods described in Kokelj et al. (2021) to determine the Strahler order of each stream segment in the study area. Since the NHN flow network contained only data on primary channels, we manually added secondary channels using the NHN linear flow polyline dataset and then assigned Strahler order. There were a total of 74 495 stream segments in the final dataset, ranging in length from 0.02 to 9171.9 m (mean: 236.4 ± 687.59 m, median: 237.2 m), included in our analysis. In the NHN dataset, the length of a stream segment depends on the location of tributaries and distributaries, with unique segments ending at branch points. We created a buffer around each stream segment to approximate the actual width of the streams using Downing et al. (2012)'s estimates of mean stream width based on stream Strahler order (Table S3).

Quantifying important fish habitat in the Peel River Watershed

We created an index of fish habitat intensity (FHI) to quantify the density and distribution of important fish habitat in the study area. Important fish habitat was mapped based on Gwich'in knowledge of important subsistence fishing locations and ecologically important habitat, as well as key habitat noted in the scientific literature (Table 1). This method is rooted in the assumption that the number and density of fishing-related features provide an indication of cultural use across landscapes (Proverbs et al. 2020*a*). The approach used to represent the cultural value of fish in a spatial overlay analysis in ArcGIS is based on Proverbs et al.'s (2020*a*) work. We modified the grid-based approach used by Proverbs et al. (2020*a*) to estimate FHI by calculating the number of features that overlapped with each buffered stream segment in the study area. To ensure that point, polyline and polygon data had a similar influence on FHI and remove any potential bias associated with stream segment size, we processed source data layers and calculated FHI as described below.

We buffered point data using a 1000 m buffer to ensure that they overlapped with water features in the vicinity. This was done to address any issues with mapping-related errors as many of these data were mapped using paper maps and later digitised. Point data were included in the FHI index by adding the number of points present per buffered stream segment and multiplying that number by the normalized stream segment length. Normalized stream segment length was calculated as $1 - (x_{\mathrm{i}} - x_{\min})/(x_{\max} - x_{\min})$, where x_{i} is the buffered stream segment length for a given stream segment, and $x_{\min}$ and $x_{\max}$ are the minimum and maximum buffered stream segment lengths for the study area, respectively. This approach ensured that larger stream segments did not overrepresent point data in the resulting FHI scores. Polygon data were included by dividing the total area of polygons in a given waterway by the total area of the buffered waterway in which the polygons were found. Polyline data were integrated by dividing the total length of all polylines in a given waterway by half the perimeter of the buffered waterway in which the polylines were found. We assigned each stream segment included in the analysis a baseline cultural value of 1 to reflect the fact that each waterway is of cultural importance to the

Gwich'in, regardless of whether fish habitat was recorded in our data compilation. We also assigned a baseline ecological value of 1 to all stream segments in the Peel River Watershed to reflect the fact that we do not know, conclusively, all important fish habitat in the area (see sample calculation in Fig. S2).

FHI per stream segment was calculated as

2 + (number of points per buffered stream segment * normalized buffered stream segment length) + (total area of polygons intersecting each stream segment/total area of the buffered stream segment) + (total length of polylines intersecting the stream segment/(0.5 * perimeter of the buffered stream segment)).

Estimating the impact of slumping on important fish habitat

We quantified and mapped areas of overlap, and therefore potential impact, between the cumulative permafrost thaw slump layer and important fish habitat data layer by multiplying the FHI score by the number of slump-affected streams present upstream from a given location (FHI*Cumulative slump impacts). The resulting risk map identifies areas of overlap where thaw slumps may be having negative impacts on important fish habitat. These risk scores were classified into six categories (none, low, moderately low, moderate, high, extreme) using a geometric interval approach in ArcGIS due to the skewed nature of the data.

The cumulative slump data layer estimated the cumulative upstream slump activity (i.e., number of slump-affected stream segments upstream of a given segment) as a proxy of the cumulative amount of slump-derived sediment and dissolved material delivery to a given stream segment (Kokelj et al. 2021; Table 1). This source layer was based on binary presence/absence of slumps on each stream segment. The upstream slump count will increase in a downstream direction, enabling the estimation of the relative amount of slump-derived sedimentary impacts. These values will vary across tributary stream networks depending on the watershed sensitivity to slumping and distribution of sensitive terrain.

We also identified areas directly impacted by slumps by mapping stream segments with one or more active permafrost thaw slumps present.

Community collaboration

Community consultation and participation was central to this project's success. We kept our Gwich'in partner organizations (GRRB, DCH, RRCs) and communities up to date on the project throughout the process by presenting at GRRB annual board meetings and organizing a variety of other meetings and events. Prior to starting interviews, we hosted a dinner to build relationships with Gwich'in Elders and knowledge holders with country foods provided by a local caterer in Teetł'it Zheh (Fort McPherson) in April 2022. We advertised the dinner on the local radio station and provided a brief overview of the project goals and next steps. Once the initial spatial overlay analysis was completed, we held a follow-up group meeting (n = 8 participants) to confirm the findings of the overlay analysis and get feedback on the maps generated. Participants were Gwich'in Elders and knowledge holders identified by our Gwich'in community coordinator and our partners at the Tetlit RRC in Teetł'it Zheh (Fort McPherson), many of whom were also interview participants. This verification meeting was held in Teetł'it Zheh (Fort McPherson) in February 2024 and lasted approximately 2 h. Participants were asked to look at the maps of individual fish habitat source layers (e.g., fish camps, fish habitat, traditional fishing locations) to see if the maps reflected their knowledge and if anything was missing from the maps. Feedback was that the maps of important fish habitat reflected their knowledge and were complete. We finalized the overlay analysis based on this feedback without any changes made. We also discussed the implications of the slumping risk map to identity key concerns and next steps in the research process. A project overview including this feedback was also provided to the GRRB during their 5-year research prioritization meeting held in October 2024.

Results

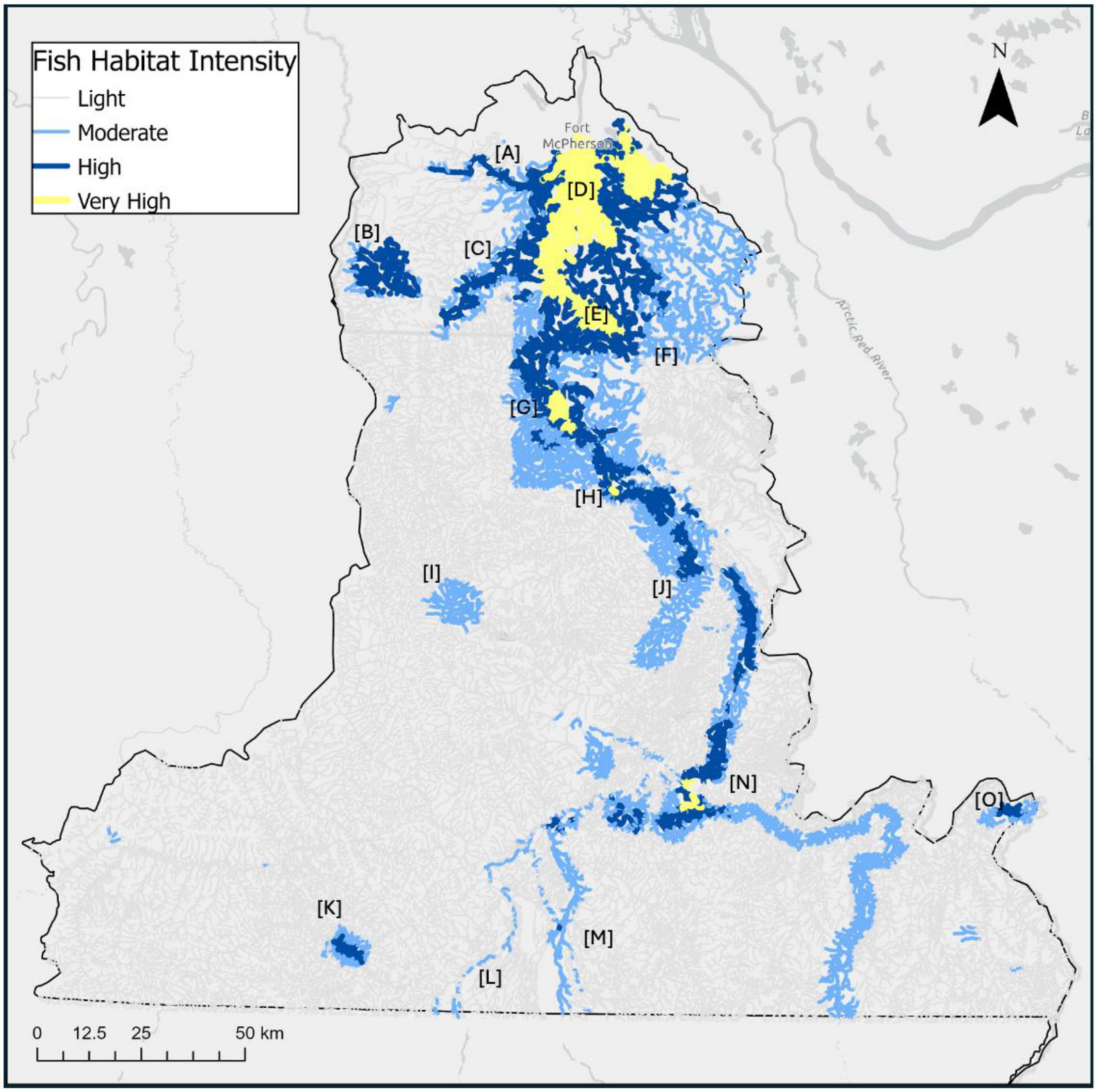
Important fish habitat in the Peel River Watershed

All 74 495 stream segments of the study area were delineated as fish habitat (Fig. 3). The majority (79.3%, n = 59 056) of those stream segments were in the light category (i.e., baseline value of 2), while 17.6% (n = 13 143) were in the moderate to high categories with mean (±standard deviation) FHI scores of 2.1 ± 0.31 and 4.3 ± 0.98, respectively. These stream segments were found along the mainstem of Teetł'it Gwinjik (Peel River), Gwatoh Taii Njik (Stony Creek), Vitreekwaa Viteetshìk (Vittrekwa River), Vihtł'òo Njik (Road River), Ndàk Nàdhàdlaii Njik (Three Cabin Creek), Edigii Njik (Caribou River), Gyuu Dazhoo Njik (Snake River), Tsaih Tł'ak Njik (Bonnet Plume River), and Tr'ineeditr'aii Njik (Wind River), as well as Dachan Dha'aii Njik (James Creek), the headwaters of Tr'atr'aataii Njik (Trail River), Van Choo (Hungry Lake), and Nihtavan Diniinlee (Fish Lake). It also included some of the lakes and creeks connected to Nataiinlaii (Eight Miles and Eight Mile Creek) and Tr'ineedadlaii and K'àii Tsik Njik (collectively known as Satah River) to the east of the Peel River mainstem. The remaining 3.1% of stream segments (n = 2296) were in the very high category, with a mean (±standard deviation) FHI score of 8.6 ± 1.52. These stream segments were located along the mainstem of the Peel River from Teetł'it Zheh (Fort McPherson) to the Satah River, as well as near Road River, Trail River, and at the mouth of Snake River. It also included some of the lakes and creeks connected to Eight Miles and Eight Mile Creek and the Satah River to the east of the Peel River mainstem.

Potential overlap between permafrost thaw slumps and important fish habitat

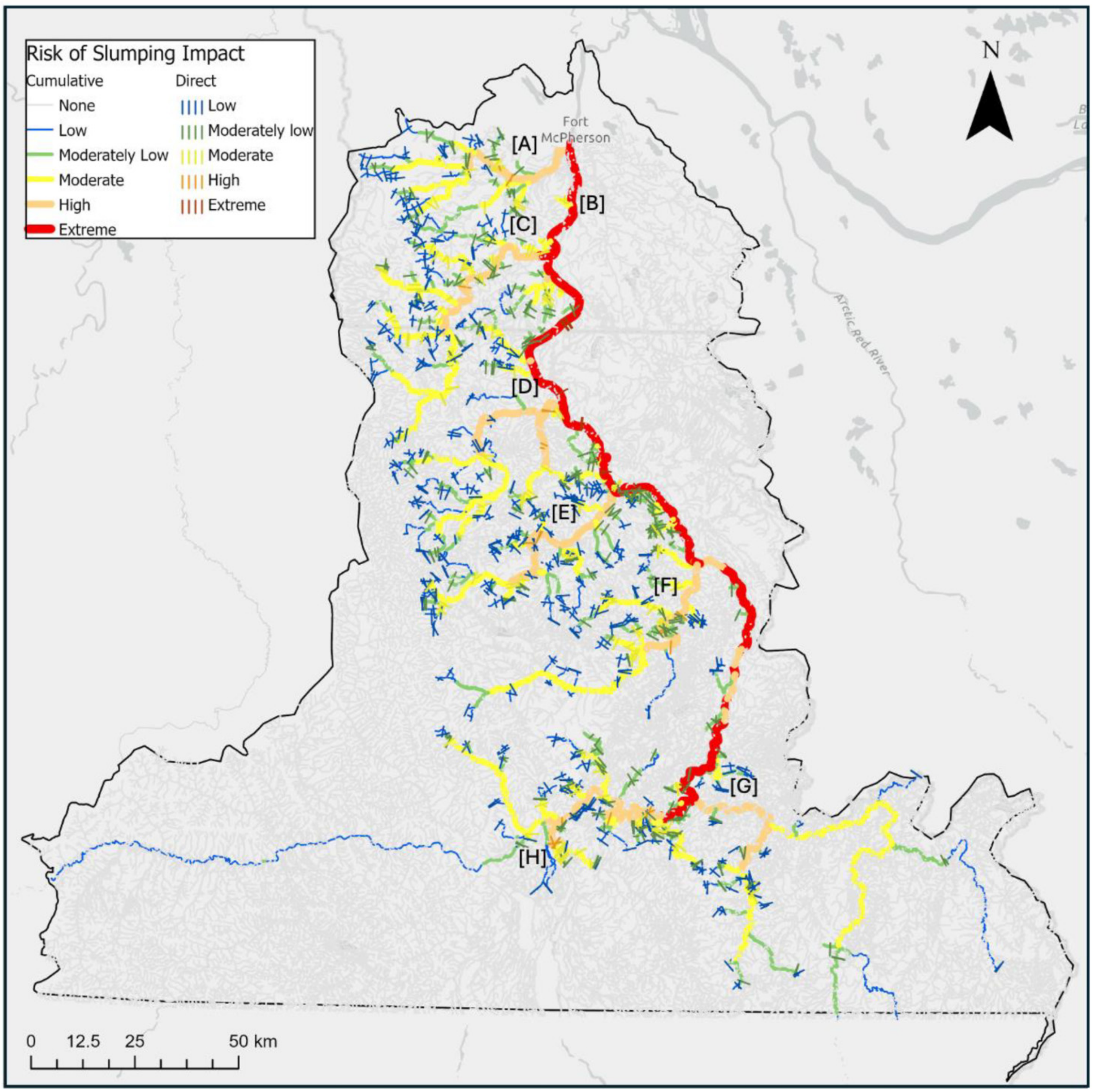
There is high potential risk to important fish habitat along the mainstem of the Peel River of experiencing the cumulative impacts of permafrost thaw slumping (Fig. 4). Overall, 8.9% of stream segments with documented fish habitat

Fig. 3. Map showing the density of important fish habitat per stream segment. Based on their fish habitat intensity (FHI) scores, stream segments were grouped into four categories reflecting the density of fish features they contained using a geometric interval approach: Light (FHI = 2.0), moderate (FHI = 2.1–3.0), high (FHI = 3.1–6.0), and very high (FHI = 6.1–14.9). Map key: [A] Gwatoh Taii Njik (Stony Creek), [B] Dachan Dha'aii Njik (James Creek), [C] Vitreekwaa Viteetshìk (Vittrekwa River), [D] Nataiinlaii (Eight Miles and Eight Mile Creek), [E] Tr'ineedadlaii and K'àii Tsik Njik (collectively known as Satah River), [F] Ndàk Nàdhàdlaii Njik (Three Cabin Creek), [G] Vihtł'òo Njik (Road River), [H] Tr'atr'aataii Njik (Trail River), [I] the headwaters of Tr'atr'aataii Njik (Trail River), [J] Edigii Njik (Caribou River), [K] Van Choo (Hungry Lake), [L] Tr'ineeditr'aii Njik (Wind River), [M] Tsaih Tł'ak Njik (Bonnet Plume River), [N] Gyuu Dazhoo Njik (Snake River), and [O] Nihtavan Diniinlee (Fish Lake). The map was created using ArcGIS Pro with the "Light Gray Canvas" basemap from Esri and projected coordinate system NAD 1983/Canada Lambert Conformal Conic. Gwich'in knowledge not documented during this study was provided by our Gwich'in partners, the Gwich'in Tribal Council Department of Culture and Heritage (DCH 2020*a*, 2020*b*, 2020*c*, 2020*d*). Stream segment data are from NHN (2016). Data mapped from western scientific literature are detailed in Table S2.



were identified as at risk of experiencing the cumulative impacts of permafrost thaw slumps ($n = 6594$; Table 2). Of these stream segments, most were in the low to moderately low risk categories (43.6%, $n = 2874$) with mean (±standard deviation) risk scores of 2.0 ± 0.021 and 4.2 ± 1.10, respectively. A further third were in the moderate risk category (33.1%, $n = 2180$) with a mean (±standard deviation) risk score of 20.9 ± 12.39, and nearly a quarter (23.4%, $n = 1540$) were in

Fig. 4. Cumulative and direct impacts of permafrost thaw slumps on important fish habitat in the Peel River Watershed within the Gwich'in Settlement Region (solid black line). Based on their overlap scores, stream segments were grouped into six risk categories reflecting the overlap between fish habitat features and the number of slump-affected stream segments present upstream from a given stream segment. Categories were created using a geometric interval approach: None (overlap score of 0), Low (overlap score = 2.0–2.3), Moderately Low (overlap score = 2.4–6.3), Moderate (overlap score = 6.4–55.7), High (overlap score = 55.8–669.3), and Extreme (overlap score = 669.4–8282.6). Stream segments directly impacted by thaw slumps are denoted with lines perpendicular to the stream (labelled as direct in the legend). Map key: [A] Gwatoh Taii Njik (Stony Creek), [B] Teetł'it Gwinjik (Peel River), [C] Vitreekwaa Viteetshìk (Vittrekwa River), [D] Vihtł'òo Njik (Road River), [E] Tr'atr'aataii Njik (Trail River), [F] Edigii Njik (Caribou River), [G] Gyuu Dazhoo Njik (Snake River), and [H] Tsaih Tł'ak Njik (Bonnet Plume River). The map was created using ArcGIS Pro with the "Light Gray Canvas" basemap from Esri and projected coordinate system NAD 1983/Canada Lambert Conformal Conic. Gwich'in knowledge not documented during this study was provided by our Gwich'in partners, the Gwich'in Tribal Council Department of Culture and Heritage (DCH 2020*a*, 2020*b*, 2020*c*, 2020*d*). Stream segment data are from NHN (2016). Data mapped from western scientific literature are detailed in Table S2. Slump data are from Kokoszka and Kokelj (2021).



the high to extreme risk categories with mean (±standard deviation) risk scores of 172.3 ± 133.55 and 2212.9 ± 1801.14, respectively. Those waterways in the high to extreme risk categories were largely located along the mainstem of the Peel River from Teetł'it Zheh (Fort McPherson) to the Bonnet Plume River and stretches of the main tributary rivers of

Table 2. Mean risk score of documented fish habitat potentially experiencing the cumulative impacts of permafrost thaw slumps per waterway and the number and percentage of waterways in each risk category.

Risk category (overlap score range)	Mean overlap score (±sd)	Mean FHI (±sd)	Mean number of slump-affected streams upstream (±sd)	Number of waterways	Percentage of all waterways	Percentage of waterways with cumulative slump impacts	Percentage of affected waterways with direct slump impacts
None (0)	0	2.4 ± 1.30	–	67 901	91.2	–	–
Low (2.0–2.3)	2.0 ± 0.020	2.0 ± 0.021	1.0 ± 0.00	1667	2.2	25.3	4.3
Moderately low (2.4–6.3)	4.2 ± 1.10	2.6 ± 0.79	1.8 ± 0.67	1207	1.6	18.3	3.3
Moderate (6.4–55.7)	20.9 ± 12.39	2.6 ± 1.12	8.6 ± 5.28	2180	2.9	33.1	1.9
High (55.8–669.3)	172.3 ± 133.55	3.2 ± 1.52	52.8 ± 31.70	1167	1.6	17.7	0.30
Extreme (669.4–8282.5)	2212.9 ± 1801.14	6.1 ± 2.48	334.5 ± 161.25	373	0.5	5.7	0.11

Note: FHI = fish habitat intensity score.

the Peel River, including Stony Creek, Vittrekwa River, Road River, Trail River, Caribou River, and Snake River. Waterways in the moderately low and moderate risk categories were located along stretches of the major tributary rivers of the Peel River listed above. Across all risk categories, fish habitat based on Gwich'in knowledge contributed the most to the FHI score (from 53.1% to 56.3%), while Gwich'in place names contributed the least to the FHI score (0%–1.5%) (Table S4).

There were 659 stream segments experiencing the direct impacts of permafrost thaw slumps in the study area (Fig. 4). Most of the stream segments directly impacted by slumps were in the light FHI category (i.e., baseline value of 2; 41.7%, $n = 275$), followed by moderate (20.6%, n=136), high (10.9%, n=72), and very high (1.2%, $n = 8$). These waterways were located along Stony Creek, Vittrekwa River, Road River, Trail River, Caribou River, Sheih Tsoo Njik (Sheh Tsoo Creek), Iyeendak Gwichoo (Gwachoo Slough), Frying Pan Creek (Solo Creek), Nihtal Gyit Njik (Nihtal Git Creek), Aghòo Njik (Aghoo Creek), Snake River, and Bonnet Plume River, as well as along the mainstem of the Peel River near Shìłdii (Shiltee Rock), Tł'oondih, Old Robert's Island, Jim Harris Vidràa', Njuu Ghàlzrii (Zralrii Island), Ok Chì', Giddy's Island, Raspberry Island, Bullock's Camp, and near the mouth of Daats'at Chihvyah K'ìt Gwichoo (Sucker Creek) and the Satah, Road, Trail, Snake, Bonnet Plume, Wind and Edrìi Njik (Hart River) rivers (Fig. S3).

Gwich'in knowledge of slumping impacts

When Gwich'in knowledge holders were asked if there were any changes on the land that they were worried were affecting fish or fish habitat in the Peel River Watershed, one of their main concerns was the high rate of slumping in the region and its effect on fish health. Steven Tetlichi from Teetł'it Zheh (Fort McPherson) noted the impacts of slumping along Gwatoh Taii Njik (Stony Creek) and how it is already affecting fish in the area:

> *It's so full of sediment [that] fish won't be able to breathe if they go up there. It's thick, it's like chocolate milk in the summer. Never used to be. We used to go in there when we were kids, and used to be clear mountain water, and the grayling used to come down and we used to go in there and fish grayling. And now you won't see that because grayling only like clear, oxygenated water.*

Elizabeth Vittrekwa from Teetł'it Zheh (Fort McPherson), meanwhile, is worried about how the high rates of slumping in the Peel River Watershed is affecting fish health:

> *With all the mudslides and that, like what sort of minerals is going into the water? And will it affect the fish? Because as you go up the Peel further and further, you'll come across all different mudslides coming down. […] All the way up, you're going to see mudslides. [I'm] worried about that.*

James McDonald from Aklavik noted that the increased sedimentation from slumping is increasing the amount of silt in fish gills and changing their colour: "my sisters and me […] we put a net in one evening when this fish [looked] drowned, the gills are kind of greyish, but […] you pull it out and it's still alive, you could just see the silt in the gills." Gwich'in knowledge holders also noted that slumping in the Peel River has affected their ability to harvest fish. For example, a Gwich'in knowledge holder from Teetł'it Zheh (Fort McPherson) noted a slump at Tr'atr'aataii Njik (Trail River) destroyed his fishing eddy: "at Trail River, […] there's a big hill and when I used to stay there, I used to have a net. […] I drove by there, that whole hill, half of it, came down. There's no more eddy, can't set net there because it's just ruined."

Gwich'in knowledge holders are also worried about future access to fish. Gordon Koe from Teetł'it Zheh (Fort McPherson) has not yet experienced the impacts of slumping on his fishing but is worried about future potential impacts:

> *Say a creek got slumped in and the creek was cut off, it may affect me […] fishing-wise, where there'd be less fish. It's not enough […] to hurt [now], but if enough of it happened and [over] so many years, it's going to cause a decrease [in the amount of fish].*

A Gwich'in Elder from Teetł'it Zheh (Fort McPherson) explained: "only thing I'm worried about is the landslides, our eddies, and […] I'm worried about my fish. […] what's going to happen to our land after there's no more ice underneath. What's going to happen."

Gwich'in knowledge holders noted the need for research to understand how these slumps are affecting fish in the Peel River. A Gwich'in knowledge holder from Teetł'it Zheh (Fort McPherson) highlighted the importance of establishing benchmarks for water quality with expected increased slumping rates for the watershed:

> *[The slump] is draining into the Stony [Creek], but I'm not sure if anybody's taken [water] samples because at some point, you have to have a benchmark [because] there's [more] slumps coming up, there are some big ones going to come.*

Another Gwich'in knowledge holder from Teetł'it Zheh (Fort McPherson) would like more work done to track slumping and mapping of important fish habitat:

> *Just keep track on the slumps [and] mudslides. Report all mudslides, you know, some mudslide might not go right across the river, but eventually it will […] because they keep moving, right. […] And just to… mark out where all the fish holes are, start doing more surveys on finding fish holes.*

Discussion

Our analysis shows that culturally and ecologically important fish habitat in the study area is at high risk of experiencing the cumulative and direct impacts of permafrost thaw slumping. Of the 6594 stream segments experiencing the cumulative impacts of slumping, only 10.0% had one or more active slumps directly adjacent. However, of these, nearly a third were in the moderate to very high FHI categories. These findings suggest that slumps have the potential to affect Gwich'in fishing livelihoods and health and well-being in the region (Proverbs et al. 2020*b*; Ziegler et al. 2024). For example, the majority of the Gwich'in who fish the Peel River have a fish camp at Nataiinlaii (Eight Miles) on the mainstem of the Peel River where they fish łuk dagaii (broad whitefish) and sruh (inconnu) in the summer and fall. This section of the mainstem, near the community of Teetł'it Zheh (Fort McPherson), is also at high risk of experiencing the impacts of slumping. During interviews, Gwich'in knowledge holders who fish the Peel River noted that slumping is already affecting water quality, fish habitat, fish health and harvesting in the study area and are concerned how increased slumping rates will affect their access to fish in the future. These results highlight the need for more detailed analyses of the variability in slump impacts across scales within the Peel River Watershed.

Thaw slumping in the Peel Plateau has a variety of impacts on the aquatic environment. These impacts include the release of previously unavailable nutrients and pollutants (e.g., mercury, methylmercury, and lead), many of which are available for biotic uptake within the food chain, from thawing permafrost (Kokelj et al. 2009, 2013; Schuster et al. 2011; Chin et al. 2016; St. Pierre et al. 2018; Zolkos et al. 2020; Droppo et al. 2022; Staniszewska et al. 2022). Slumps have also been shown to increase stream productivity (Hayden et al. 2017) and alter invertebrate assemblages and sentinel fish populations (Thienpont et al. 2013; Chin et al. 2016; Hudelson et al. 2019; Sivarajah et al. 2019). The increase in fine sediments suspended in the system (Shakil et al. 2020) can also physically smother fish eggs (Mesquita et al. 2010).

It is important to note that the analysis presented in this paper identified important fish habitat that may be affected by slumping upstream. It did not assess the actual impacts of thaw slumps on fish habitat in the study area. The nature of the impacts that slumps have on aquatic ecosystems are likely strongly influenced by catchment area, discharge rates, and distance downstream from the location of the slump (Schuster et al. 2011; Chin et al. 2016; Zolkos et al. 2020). For example, St. Pierre et al. (2018) found high mercury concentrations in creeks draining slumps in the Peel River Watershed, with elevated levels persisting over a kilometre downstream. Staniszewska et al. (2022), on the other hand, found similar mercury, methylmercury and lead concentrations upstream and downstream from thaw slumps in the Old Crow River, despite higher total suspended solid concentrations post-slump. Additional research is needed to assess how slump impacts change with distance and across catchment scales to understand the cumulative impacts of slumping on fish habitat in higher order streams. Future analyses should also examine if slumping affects migratory fish species differently than non-migratory species. For example, Hodgson et al. (2020) found that migration routes of łuk dagaii (broad whitefish) in the Peel River Watershed are not obligate and that individual fish used the watershed differently potentially protecting broad whitefish from the effects of environmental change. Currently, there is not sufficient information regarding the distribution of key fish habitat types (gravel beds for spawning, deeper winter lakes for overwintering, etc.) in the Peel River Watershed to understand if migratory fish have access to alternative habitats not affected by slumping.

The results of our analysis can be used to prioritize areas of high cultural and ecological importance for additional monitoring. Future studies could assess water quality, changes in biogeochemistry, changes in macroinvertebrate communities, siltation of key spawning habitat, and fish health. As noted by a Gwich'in knowledge holder during interviews, it is essential to have benchmark values for water quality now to understand future impacts of increased permafrost slumping rates on fish health. During a follow-up workshop held in Teetł'it Zheh (Fort McPherson) in February 2024, Gwich'in Elders and knowledge holders identified several future research directions, including studies on fish health and water quality at Eight Miles and the mouth of Stony Creek, as well as fish tagging studies to confirm the location of key spawning habitat in the Wind, Bonnet Plume, and Snake rivers, and the impact of slumping on these areas.

Our analysis also shows that only the waterways in the upper, western portion of the Peel River Watershed are experiencing the negative impacts of slumping. This area is rich in ground ice and fine-grained tills associated with ice marginal environments of the late Wisconsin making it more vulnerable to changes in climate than the terrain to the east of the Peel River (Kokelj et al. 2017). This means that a significant portion of key cultural and ecological fish habitat in the eastern portion of the Peel River Watershed, which is less rich in ground ice, especially the rivers and lakes connected to Eight Miles and the Satah River, are not affected by slumping upstream. These areas are key harvesting sites for the Gwich'in and important nursery and overwintering places for culturally important fish species. The Bonnet Plume and Wind rivers were also in the lower risk category for slumping impacts despite being in the western portion of the watershed.

There is an urgent need for more inclusive methods to evaluate the cumulative impacts of disturbances on cultural and ecological landscapes using Indigenous knowledge. To date, cumulative impact assessments have largely used western scientific knowledge, while Indigenous knowledge has generally been overlooked (Mantyka-Pringle et al. 2017; Eckert et al. 2020; Adams et al. 2023). The omission of Indigenous knowledge means that these assessments may not reflect the full extent of the impacts of disturbances and can lead to conflict and ineffective assessment and management of cumulative impacts (Ehrlich 2010; McCormack 2017; Adams et al. 2023). More inclusive cumulative impacts research can also help address the moral and legal obligations set out in the Truth and Reconciliation Commission of Canada Calls to Action and the United Nations Declaration on the Rights of Indigenous Peoples that are critical for researchers to consider when doing research with Indigenous partners or on Indigenous lands (Wong et al. 2020; Ignace et al. 2023; Reid et al. 2024). One approach to building more inclusive cumulative impacts methods has been the use of Bayesian networks in combination with expert elicitation of both Indigenous and non-Indigenous knowledge holders to estimate the current and future cumulative impacts on a given focal species or ecosystem (Mantyka-Pringle et al. 2017; Kaikkonen et al. 2021; Moe et al. 2021; Adams et al. 2023). A key challenge to constructing a robust Bayesian network for complex cumulative impacts is that it requires significant expert knowledge to accurately define relationships and probabilities, which can be challenging to elicit and integrate (Uusitalo 2007). Validating the results of Bayesian networks for cumulative impact assessments can also be made difficult by a lack of appropriate data (Sperotto et al. 2017). Our spatial overlay approach avoids these challenges as it relies on existing knowledge, both Indigenous (culturally and ecologically important fish habitat) and western scientific (ecologically important fish habitat and cumulative slumping), to estimate how a given impact (slumping) will affect key species in a given region. Unlike Bayesian networks, however, our mapping approach does not include a predictive component and therefore cannot predict how slumping will affect culturally and ecologically important fish habitat in the future under different climate or development scenarios. Our approach also relies heavily on the extensive spatial data our Gwich'in partners provided, which is not commonly available. The approach we used in this paper gave equal weighting to each type of knowledge in a cumulative impact assessment of slumping across a watershed. This approach can be used for other types of disturbances in aquatic environments, such as industrial effluent, agricultural runoff, and sewage outfalls.

In the case of the Peel River Watershed, there was little information from fisheries science on important fish habitat in the region (i.e., only 17 sources with spatial data in the study area). Most of this work focused on the spawning of łuk dagaii (broad whitefish) along the mainstem of the Peel River, and most of these sources date back to the 1970s and 1980s (see Table S2). This type of knowledge also had minimal information about culturally important areas in the watershed. Gwich'in knowledge of important fish habitat was therefore essential in gaining a fuller understanding of the impacts of slumping on culturally and ecologically important fish habitat across the full watershed. It is important to note, however, that the approach we used relies on the spatial information available for both the cultural and ecological importance of fish habitat in the region. In the case of the ecological data derived from western scientific data, we were limited by the studies focused on fish habitat in the region. In the case of cultural and ecological data based on Gwich'in knowledge, some streams in the analysis are likely important to the Gwich'in people, but simply do not have cultural features recorded in the data we used. For example, some areas likely experienced greater use prior to European contact in the mid-1800s, which would not be captured in the spatial data included in the analysis (Andrews et al. 2016). We addressed this issue with the underlying data by assigning a baseline value of 2 to all stream segments to reflect the cultural importance of these streams in the analysis, as well as their potential ecological value.

We would also like to stress that our transdisciplinary, community-based project was made possible through the hard work and dedication of the DCH to document and map Gwich'in knowledge of fish in the Gwich'in Settlement Region (e.g., Aporta et al. 2014). Strong relationships with regional Indigenous organizations and territorial scientists also played a vital role in laying the groundwork for this project. For example, the spatial data on thaw slumping we used from the Northwest Territories Geological Survey were generated as a direct outcome of discussions with Gwich'in partners and their desire to understand ecosystem level impacts of slumping in the Peel Plateau and, specifically, for the scientific community to better link permafrost landscape change with questions surrounding water and fish. Our approach highlights the need for improved communication among those generating these kinds of datasets and the Indigenous communities who would like to use them to address environmental issues on their lands, as well as improved support for Indigenous nations to develop their own knowledge datasets over the medium- to long-term. In addition to taking the time to listen and build relationships with Indigenous partners, this approach also requires accepting that our (western scientists') modes of inquiry, including the questions we ask, the methods we use to collect data, and the ways of analyzing and sharing information, may need to change.

Acknowledgements

We would like to say Mahsi' choo (a big thank you) to the local organizations and community members who were essential in planning this project, helping with logistics, and assisting with participant selection. We would also like to say Mahsi' to the following people for their collaboration on this project: Sharon Snowshoe, Kristi Benson, Arlyn Charlie, Tracey Proverbs, Dolores Charlie, Laura Nerysoo, Cheryl Greenland, Steve Andersen, Stac-cee Francis, Crystal Koe, Velma Cardinal, Justin Kokoszka, Emma Street, Niek Speetjens, and Kiyo Campbell. We would like to thank Rachael Cadman and two anonymous reviewers for their insightful comments and suggestions on this manuscript. We would also like to thank the participating communities of Aklavik, Inuvik, and Teetł'it Zheh (Fort McPherson) for their warmth and generosity, as well as the RRCs in each community for their continued support throughout this project.

Article information

History dates

Received: 3 October 2024
Accepted: 23 May 2025
Accepted manuscript online: 13 June 2025
Version of record online: 26 August 2025

Copyright

Data availability

Data representing Gwich'in knowledge of fish habitat and important fishing places are not available publicly. Requests to access the data can be made to the Gwich'in Tribal Council Department of Culture and Heritage (contact email: info@gwichintribal.ca). Slump data can be accessed in Kokoszka and Kokelj (2021). The sources for the ecological data from the western scientific literature are detailed in the supplemental material.

Author information

Author ORCIDs

Jackie A. Ziegler https://orcid.org/0000-0003-3748-956X

Author contributions

Conceptualization: TCL, SL
Data curation: TCL, SVK, GTCDCH
Formal analysis: JAZ, TCL, MN
Funding acquisition: TCL, SL
Investigation: TCL
Methodology: JAZ, TCL, MN, SVK, SL, GTCDCH
Project administration: JAZ, TCL, SL
Resources: TCL, SVK, SL, GTCDCH
Software: JAZ, TCL, MN
Supervision: TCL, SL, GTCDCH
Validation: JAZ, TCL, GTCDCH
Visualization: JAZ, TCL, MN, GTCDCH
Writing – original draft: JAZ, TCL, MN
Writing – review & editing: JAZ, TCL, MN, SVK, SL, GTCDCH

Competing interests

The authors declare that they have no conflict of interest.

Funding information

This research was funded by the Northwest Territories Cumulative Impact Monitoring Program (#217), MITACS (Project #IT26892), Climate Change Preparedness in the North Program/Climate Change and Health Adaptation Program (CCPN-NT-166-2020), and the Natural Sciences and Engineering Research Council of Canada (RGPIN 06210-2018).

Supplementary material

Supplementary data are available with the article at https://doi.org/10.1139/cjfas-2024-0308.

References

Adams, M.S., Tulloch, V.J.D., Hemphill, J., Penn, B., Anderson, L.T., Davis, K., et al. 2023. Inclusive approaches for cumulative effects assessments. People Nat. **5**(2): 431–445. doi:10.1002/pan3.10447.

Alexander, S., Provencher, J.F., Henri, D.A., Taylor, J.J., Lloren, J.I., Nanayakkara, L., et al. 2019. Bridging indigenous and science-based knowledge in coastal and marine research, monitoring, and management in Canada. Environ. Evid. **8**(1): 36. doi:10.1186/s13750-019-0181-3.

Alexie, E.D. 2015. "Nakhwanh Gwich'in Khehłok Iidilii-We Are Our Own People": Teetł'it Gwich'in practices of indigeneity: connection to land, traditional self-governance, and elements of self determination. Doctoral dissertation. University of Victoria, Victoria, Canada. Available from https://dspace.library.uvic.ca/server/api/core/bitstreams/555dbaac-e927-4023-a8e6-ba375c507607/content.

Andre, A.M.T. 2006. Nan t'aih nakwits'inahtsìh (The Land Gives Us Strength): the medicinal plants used by Gwich'in people of Canada's western Arctic to maintain good health and well being. Master's thesis, University of Victoria, Victoria, Canada. Available from https://dspace.library.uvic.ca/bitstream/handle/1828/1258/Andre.pdf?sequence=1.

Andrews, T.D., Kokelj, S.V., MacKay, G., Buysse, J., Kritsch, I., Andre, A., and Lantz, T. 2016. Permafrost thaw and aboriginal cultural landscapes in the Gwich'in Region, Canada. APT Bulletin J. Preserv. Technol. **47**(1): 15–22.

Aporta, C., Kritsch, I., Andre, A., Benson, K., Snowshoe, S., Firth, W., and Carry, D. 2014. The Gwich'in Atlas: place names, maps, and narratives. *In* Modern cartography series. *Edited by* D.R.F. Taylor. Academic Press. pp. 229–244. doi:10.1016/B978-0-444-62713-1.00016-7.

Basso, K. 1996. Wisdom sits in place: landscape and language among the Western Apache. University of New Mexico Press, Albuquerque, NM.

Berkes, F. 2009. Indigenous ways of knowing and the study of environmental change. J. Royal Soc. New Zealand, **39**(4): 151–156. doi:10.1080/03014220909510568.

Bohensky, E.L., and Maru, Y. 2011. Indigenous knowledge, science, and resilience: what have we learned from a decade of international literature on "integration? Ecol. Soc. **16**(4): 6. doi:10.5751/ES-04342-160406.

Carson, M.A., Jasper, J.N., and Conly, F.M. 1998. Magnitude and sources of sediment input to the Mackenzie Delta, Northwest Territories, 1974–94. Arctic, **51**(2): 116–124. doi:10.14430/arctic1053.

Castleden, H.E., Hart, C., Harper, S.L., Martin, D., and Cunsolo, A. 2017. Implementing Indigenous and western knowledge systems in water research and management (part 1): a systematic realist review to inform water policy and governance in Canada. Int. Indig. Policy J. **8**(4): 1–34. doi:10.18584/iipj.2017.8.4.7533.

Chin, K.S., Lento, J., Culp, J.M., Lacelle, D., and Kokelj, S.V. 2016. Permafrost thaw and intense thermokarst activity decreases abundance of stream benthic macroinvertebrates. Global Change Biol. **22**(8): 2715–2728. doi:10.1111/gcb.13225.

Collin, C. 1973. A long time ago: a life story told by Mr. Christopher Collin of Fort McPherson. Available from https://www.capekrusenstern.org/docs/collin.pdf.

Cousins, J.J. 2021. Justice in nature-based solutions: research and pathways. Ecol. Econ. **180**: 106874. doi:10.1016/j.ecolecon.2020.106874.

Downing, J.A., Cole, J.J., Duarte, C.M., Middelburg, J.J., Melack, J.M., Prairie, Y.T., et al. 2012. Global abundance and size distribution of streams and rivers. Inland Waters, **2**(4): 229–236. doi:10.5268/IW-2.4.502.

Droppo, I.G., di Cenzo, P., McFadyen, R., and Reid, T. 2022. Assessment of the sediment and associated nutrient/contaminant continuum, from permafrost thaw slump scars to tundra lakes in the western Canadian Arctic. Permafr. Periglac. Process. **33**(1): 32–45. doi:10.1002/ppp.2134.

Dyke, A., and Prest, V. 1987. Late wisconsinan and holocene history of the Laurentide Ice Sheet. Géog. Phys. Quatern. **41**(2): 237–263. Les Presses de l'Université de Montréal. doi:10.7202/032681ar.

Eckert, L.E., Claxton, N.X., Owens, C., Johnston, A., Ban, N.C., Moola, F., and Darimont, C.T. 2020. Indigenous knowledge and federal environmental assessments in Canada: applying past lessons to the 2019 impact assessment act. FACETS, **5**(1): 67–90. doi:10.1139/facets-2019-0039.

Ehrlich, A. 2010. Cumulative cultural effects and reasonably foreseeable future developments in the Upper Thelon Basin, Canada. Impact Assess. Proj. Apprais. **28**(4): 279–286. doi:10.3152/146155110X12838715793084.

Government of Canada. 2021. Statistics Canada census profile, 2021 Census. Available from: https://www12.statcan.gc.ca/census-recensement/index-eng.cfm [accessed 4 April 2025].

Greenland, B.J., and Walker-Larsen, J. 2001. Community concerns and knowledge about Broad whitefish (Coregonus nasus) in the Gwich'in settlement area. Gwich'in Renewable Resources Board, Inuvik, NT. Available from http://www.grrb.nt.ca/pdf/fisheries/BroadWhitefish.pdf.

Gwich'in Renewable Resources Board. 2018. Research and management interests for the GSA. Available from http://www.grrb.nt.ca/pdf/Public%20registry/research/Research%20Interests_2018.pdf [accessed 12 May 2021].

Gwich'in Social and Cultural Institute. 2005. Gwich'in traditional knowledge study of the Mackenzie Gas Project Area. Gwich'in Social and Cultural Institute, Inuvik, NT. Available from https://www.gwichin.ca/sites/default/files/gsci_2005_gwichintk_mgp_report.pdf.

Gwich'in Social and Cultural Institute. n.d. Gwich'in Place Names Atlas. Interactive resource. Available from https://atlas.gwichin.ca/index.html [accessed 5 October 2021].

GTC Department of Culture and Heritage (DCH). 2020a. Dene trails. DCH digital archive. Fort McPherson, NT, Canada.

GTC Department of Culture and Heritage (DCH). 2020b. Gwich'in Fish Camps. DCH digital archive. Fort McPherson, NT, Canada.

GTC Department of Culture and Heritage (DCH). 2020c. Gwich'in Place Names. DCH digital archive. Fort McPherson, NT, Canada.

GTC Department of Culture and Heritage (DCH). 2020d. Gwich'in traditional land use and traditional ecological knowledge. DCH digital archive. Fort McPherson, NT, Canada.

Hayden, B., Myllykangas, J.-P., Rolls, R.J., and Kahilainen, K.K. 2017. Climate and productivity shape fish and invertebrate community structure in subarctic lakes. Freshw. Biol. **62**(6): 990–1003. doi:10.1111/fwb.12919.

Heine, M., Andre, A., Kritsch, I., and Cardinal, A. 2007. Gwichya Gwich'in googwandak: the history and stories of the Gwichya Gwich'in, as told by the elders of Tsiigehtchic. *In* Gwich'in Social and Cultural Institute, Tsiigehtchic and Fort McPherson, NT. 2nd ed. Available from https://gwichin.ca/sites/default/files/gsci_heine_et_al_2007_gwichya_gwichin_googwandak.pdf.

Heine, M., Andre, A.M.T., Kritsch, I., and Cardinal, A., the Elders of Tsiigehtchic. 2001. Gwichya Gwich'in Googwandak" The history and stories of the Gwichya Gwich'in. Gwich'in Social and Cultural Institute, Tsiigehtchic and Yellowknife, NT.

Henri, D.A., Provencher, J.F., Bowles, E., Taylor, J.J., Steel, J., Chelick, C., et al. 2021. Weaving indigenous knowledge systems and Western sciences in terrestrial research, monitoring and management in Canada: A protocol for a systematic map. Ecol. Sol. Evid. **2**(2): e12057. doi:10.1002/2688-8319.12057.

Hodgson, E.E., Hovel, R.A., Ward, E.J., Lord, S., and Moore, J.W. 2020. Migratory diversity in an Arctic fish supporting subsistence harvest. Biol. Conserv. **248**: 108685. doi:10.1016/j.biocon.2020.108685.

Hornby, D.D. 2021. RivEX (Version 10.37). Available from http://www.rivex.co.uk.

Houben, A.J., French, T.D., Kokelj, S.V., XiaoWa, W., Smol, J.P., and Blais, J.M. 2016. The impacts of permafrost thaw slump events on limnological variables in upland tundra lakes, Mackenzie Delta region. Fundam. Appl. Limnol. **189**(1): 11–35. doi:10.1127/fal/2016/0921.

Hudelson, K.E., Muir, D.C.G., Drevnick, P.E., Köck, G., Iqaluk, D., Wang, X., et al. 2019. Temporal trends, lake-to-lake variation, and climate effects on Arctic char (*Salvelinus alpinus*) mercury concentrations from six High Arctic lakes in Nunavut. Sci. Total Environ. **678**: 801–812. doi:10.1016/j.scitotenv.2019.04.453.

Hughes, O.L., Harington, C.R., Janssens, J.A., Matthews, J.V., Morlan, R.E., Rutter, N.W., and Schweger, C.E. 1981. Upper pleistocene stratigraphy, paleoecology, and archaeology of the Northern Yukon Interior, Eastern Beringia 1. Bonnet Plume Basin. Arctic, **34**(4): 329–365.

Ignace, L., Burton, L., Mynott, S., Meehan, M., Olson, E., Steel, J., et al. 2023. Researchers' responsibility to uphold indigenous rights. Science, **381**(6654): 129–131. doi:10.1126/science.adh4470.

Jessen, T.D., Ban, N.C., Claxton, N.X., and Darimont, C.T. 2022. Contributions of indigenous knowledge to ecological and evolutionary understanding. Fron. Ecol. Environ. **20**(2): 93–101. doi:10.1002/fee.2435.

Kaikkonen, L., Parviainen, T., Rahikainen, M., Uusitalo, L., and Lehikoinen, A. 2021. Bayesian Networks in environmental risk assessment: a review. Integr. Environ. Assess. Manage. **17**(1): 62. doi:10.1002/ieam.4332.

Kokelj, S.V., Kokoszka, J., van der Sluijs, J., Rudy, A.C.A., Tunnicliffe, J., Shakil, S., et al. 2021. Thaw-driven mass wasting couples slopes with downstream systems, and effects propagate through Arctic drainage networks. Cryosphere, **15**(7): 3059–3081. doi:10.5194/tc-15-3059-2021.

Kokelj, S.V., Lacelle, D., Lantz, T.C., Tunnicliffe, J., Malone, L., Clark, I.D., and Chin, K.S. 2013. Thawing of massive ground ice in mega slumps drives increases in stream sediment and solute flux across a range of watershed scales. J. Geophys. Res. Earth Surf. **118**(2): 681–692. doi:10.1002/jgrf.20063.

Kokelj, S.V., Lantz, T.C., Tunnicliffe, J., Segal, R., and Lacelle, D. 2017. Climate-driven thaw of permafrost preserved glacial landscapes, northwestern Canada. Geology, **45**(4): 371–374. doi:10.1130/G38626.1.

Kokelj, S.V., Tunnicliffe, J., Lacelle, D., Lantz, T.C., Chin, K.S., and Fraser, R. 2015. Increased precipitation drives mega slump development and destabilization of ice-rich permafrost terrain, northwestern Canada. Global Planet. Change, **129**: 56–68. doi:10.1016/j.gloplacha.2015.02.008.

Kokelj, S.V., Zajdlik, B., and Thompson, M.S. 2009. The impacts of thawing permafrost on the chemistry of lakes across the subarctic borealtundra transition, Mackenzie Delta region, Permafr. Periglac. Process. **20**(2): 185–199. doi:10.1002/ppp.641.

Kokoszka, J.E., and Kokelj, S.V. 2021. Broad-scale mapping of hydrologic features affected by slope thermokarst from Arctic drainage, Northwestern Canada: methods and data. pp. 2020–2013. doi:10.46887/2020-013.

Kritsch, I., and Andre, A. 1997. Gwich'in Traditional Knowledge and heritage studies in the Gwich'in Settlement Area. *In* At a crossroads: Archaeology and First Peoples in Canada. *Edited by* G.P. Nicholas and T.D. Andrews. Archaeology Press, Simon Fraser University, Burnaby, BC. pp. 125–144.

Kuhnlein, H.V., Goodman, L., Receveur, O., Spigelski, D., Duran, N., Harrison, G.G., et al. 2013. Gwich'in traditional food and health in Tetlit Zheh, Northwest Territories, Canada: Phase II. *In* Indigenous Peoples' Food Systems & Well-being: Interventions & Policies for Healthy Communities. *Edited by* H.V. Kuhnlein, B. Erasmus, D. Spigelski and B. Burlingame. FAO, Rome.

Lantz, T.C., and Kokelj, S.V. 2008. Increasing rates of retrogressive thaw slump activity in the Mackenzie Delta region, N.W.T., Canada. Geophys. Res. Lett. **35**: L06502. doi:10.1029/2007GL032433.

Levenstein, B., Culp, J.M., and Lento, J. 2018. Sediment inputs from retrogressive thaw slumps drive algal biomass accumulation but not decomposition in Arctic streams, Freshw. Biol. **63**(10): 1300–1315. doi:10.1111/fwb.13158.

Lewkowicz, A.G., and Way, R.G. 2019. Extremes of summer climate trigger thousands of thermokarst landslides in a high Arctic environment. Nat. Commun. **10**(1): 1329. doi:10.1038/s41467-019-09314-7.

Littlefair, C.A., Tank, S.E., and Kokelj, S.V. 2017. Retrogressive thaw slumps temper dissolved organic carbon delivery to streams of the Peel Plateau, NWT, Canada. Biogeosciences, **14**(23): 5487–5505. doi:10.5194/bg-14-5487-2017.

Loovers, J.P.L. 2010. You have to live it: pedagogy and literacy with Teetl'it Gwich'in. Doctoral dissertation, University of Aberdeen.

Mantyka-Pringle, C.S., Jardine, T.D., Bradford, L., Bharadwaj, L., Kythreotis, A.P., Fresque-Baxter, J., et al. 2017. Bridging science and traditional knowledge to assess cumulative impacts of stressors on ecosystem health. Environ. Int. **102**: 125–137. doi:10.1016/j.envint.2017.02.008.

McCartney, L., Gwich'in Tribal Council. 2020. Our whole Gwich'in way of life has changed /Gwich'in K'yuu Gwiidandài Tthak Ejuk Gòonlih: Stories from the people of the land. University of Alberta Press, Edmonton, Alberta.

McCormack, P.A. 2017. Walking the land: aboriginal trails, cultural landscapes, and archaeological studies for impact assessment. Archaeologies, **13**: 110–135. doi:10.1007/s11759-017-9309-7.

Mesquita, P.S., Wrona, F.J., and Prowse, T.D. 2010. Effects of retrogressive permafrost thaw slumping on sediment chemistry and submerged macrophytes in Arctic tundra lakes. Freshw. Biol. **55**(11): 2347–2358. doi:10.1111/j.1365-2427.2010.02450.x.

Mistry, J., and Berardi, A. 2016. Bridging indigenous and scientific knowledge. Science, **352**(6291): 1274–1275. doi:10.1126/science.aaf1160.

Moe, S.J., Carriger, J.F., and Glendell, M. 2021. Increased use of Bayesian Network Models has improved environmental risk assessments. Integr. Environ. Assess. Manage. **17**(1): 53–61. doi:10.1002/ieam.4369.

Moller, H., Berkes, F., Lyver, P.O., and Kislalioglu, M. 2004. Combining science and traditional ecological knowledge: monitoring populations for co-management. Ecol. Soc. **9**(3). doi:10.5751/ES-00675-090302.

Nadasdy, P. 1999. The politics of TEK: power and the "integration" of knowledge. Arctic Anthropol. **36**(1/2): 1–18.

National Hydro Network (NHN). 2016. National Hydro Network–NHN–GeoBase Series. Available from https://open.canada.ca/data/en/dataset/a4b190fe-e090-4e6d-881e-b87956c07977.

Parlee, B., and Berkes, F., Teetl'it Gwich'in. 2005. Health of the land, health of the people: a case study on Gwich'in berry harvesting in northern Canada. EcoHealth, **2**(2): 127–137. doi:10.1007/s10393-005-3870-z.

Proverbs, T.A., and Lantz, T.C., Gwich'in Tribal Council Department of Cultural Heritage. 2020a. Cumulative environmental impacts in the Gwich'in cultural landscape. Sustainability, **12**(11): 4667. doi:10.3390/su12114667.

Proverbs, T.A., Lantz, T.C., Lord, S.I., Amos, A., and Ban, N.C., Gwich'in Tribal Council Department of Cultural Heritage. 2020b. Social-ecological determinants of access to fish and well-being in four Gwich'in communities in Canada's Northwest Territories. Hum. Ecol. **48**(2): 155–171. doi:10.1007/s10745-020-00131-x.

Rantanen, M., Karpechko, A.Y., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., et al. 2022. The Arctic has warmed nearly four times faster than the globe since 1979. Commun. Earth Environ. **3**(1): 1–10. doi:10.1038/s43247-022-00498-3.

Reid, A.J., Eckert, L.E., Lane, J.-F., Young, N., Hinch, S.G., Darimont, C.T., et al. 2021. Two-Eyed Seeing": an indigenous framework to transform fisheries research and management. Fish Fish. **22**(2): 243–261. doi:10.1111/faf.12516.

Reid, A.J., McGregor, D.A., Menzies, A.K., Eckert, L.E., Febria, C.M., and Popp, J.N. 2024. Ecological research 'in a good way' means ethical and equitable relationships with indigenous Peoples and lands. Nat. Ecol. Evol. **8**(4): 595–598. doi:10.1038/s41559-023-02309-0.

Ritter, J.T., Sittichinli. 1976. Gwich'in history and toponymy. Presentation to Justice Berger–Mackenzie Valley Pipeline Inquiry. Available from https://www.capekrusenstern.org/docs/gwichinhistory.pdf.

Rudy, A.C.A., Lamoureux, S.F., Kokelj, S.V., Smith, I.R., and England, J.H. 2017. Accelerating thermokarst transforms ice-cored terrain triggering a downstream cascade to the ocean. Geophys. Res. Lett. **44**(21): 11,080–11,087. doi:10.1002/2017GL074912.

Schuster, P.F., Striegl, R.G., Aiken, G.R., Krabbenhoft, D.P., Dewild, J.F., Butler, K., et al. 2011. Mercury export from the Yukon River Basin and potential response to a changing climate. Environ. Sci. Technol. **45**(21): 9262–9267. doi:10.1021/es202068b.

Segal, R.A., Lantz, T.C., and Kokelj, S.V. 2016. Acceleration of thaw slump activity in glaciated landscapes of the Western Canadian Arctic. Environ. Res. Lett. **11**(3): 034025. doi:10.1088/1748-9326/11/3/034025.

Shakil, S., Tank, S.E., Kokelj, S.V., Vonk, J.E., and Zolkos, S. 2020. Particulate dominance of organic carbon mobilization from thaw slumps on the Peel Plateau, NT: quantification and implications for stream systems and permafrost carbon release. Environ. Res. Lett. **15**(11): 114019. doi:10.1088/1748-9326/abac36.

Sivarajah, B., Korosi, J.B., Blais, J.M., and Smol, J.P. 2019. Multiple environmental variables influence diatom assemblages across an arsenic gradient in 33 subarctic lakes near abandoned gold mines | Hydrobiologia. Hydrobiologia, **841**: 133–151. doi:10.1007/s10750-019-04014-1.

van der Sluijs, J., Kokelj, S.V., and Rudy, A.C.A. 2022. Geomatics field- and web-methodologies supporting a systematic aerial inventory and characterization of thaw-sensitive permafrost terrain in the Northwest Territories. Available from https://www.apps.geomatics.gov.nt.ca/arcgis/rest/services/GNWT_Operational/NTGS_ThermokarstCollective_Operational/MapServer.

Smith, L.T. 2021. Decolonizing methodologies: research and indigenous peoples. *In* Zed First Edition. Zed Books, London.

Sperotto, A., Molina, J.-L., Torresan, S., Critto, A., and Marcomini, A. 2017. Reviewing Bayesian Networks potentials for climate change impacts assessment and management: A multi-risk perspective. J. Environ. Manage. **202**: 320–331. doi:10.1016/j.jenvman.2017.07.044.

St. Pierre, K.A., Zolkos, S., Shakil, S., Tank, S.E., St. Louis, V.L., and Kokelj, S.V. 2018. Unprecedented increases in total and methyl mercury concentrations downstream of retrogressive thaw slumps in the western Canadian Arctic. Environ. Sci. Technol. **52**(24): 14099–14109. doi:10.1021/acs.est.8b05348.

Staniszewska, K.J., Reyes, A.V., Cooke, C.A., Miller, B.S., and Woywitka, R.J. 2022. Permafrost, geomorphic, and hydroclimatic controls on mercury, methylmercury, and lead concentrations and exports in Old Crow River, Arctic Western Canada. Chem. Geol. **596**: 120810. doi:10.1016/j.chemgeo.2022.120810.

Tengö, M., Brondizio, E.S., Elmqvist, T., Malmer, P., and Spierenburg, M. 2014. Connecting diverse knowledge systems for enhanced ecosystem governance: the multiple evidence base approach. Ambio, **43**(5): 579–591. doi:10.1007/s13280-014-0501-3.

Thienpont, J.R., Rühland, K.M., Pisaric, M.F.J., Kokelj, S.V., Kimpe, L.E., Blais, J.M., and Smol, J.P. 2013. Biological responses to permafrost thaw slumping in Canadian Arctic lakes. Freshw. Biol. **58**(2): 337–353. doi:10.1111/fwb.12061.

Thompson, A., and Millar, N.P. 2007. Traditional knowledge of fish migration and spawning pattern in Tsiigehnjik (Arctic Red River) and Nagwichoonjik (Mackenzie River), Northwest Territories. Gwich'in Renewable Resources Board, Inuvik, NT. Available from http://www.grrb.nt.ca/pdf/fisheries/Thompson%20and%20Millar%202007%20(GRRB%2007-01)%20-%20fish%20TK%20in%20the%20Arctic%20Red%20and%20Mackenzie%20rivers.pdf [accessed 9 June 2021].

Townsend, J., Moola, F., and Craig, M.-K. 2020. Indigenous Peoples are critical to the success of nature-based solutions to climate change. FACETS, **5**(1): 551–556. doi:10.1139/facets-2019-0058.

Tyson, W., Lantz, T.C., and Ban, N.C. 2016. Cumulative effects of environmental change on culturally significant ecosystems in the Inuvialuit Settlement Region. Arctic, **69**(4): 391–405. doi:10.14430/arctic4607.

Uusitalo, L. 2007. Advantages and challenges of Bayesian networks in environmental modelling. Ecol. Modell. **203**(3): 312–318. doi:10.1016/j.ecolmodel.2006.11.033.

VanGerwen-Toyne, M., Walker-Larsen, J., and Tallman, R.F. 2008. Monitoring spawning populations of migratory coregonids in the Peel River, NT: The Peel River Study 1998-2002. Fisheries and Oceans Canada, Winnipeg. Available from http://grrb.nt.ca/pdf/fisheries/Toyne_Larsen_Tallman%20MR%202851.pdf.

Vonk, J.E., Tank, S.E., Bowden, W.B., Laurion, I., Vincent, W.F., Alekseychik, P., et al. 2015. Reviews and syntheses: effects of permafrost thaw on Arctic aquatic ecosystems. Biogeosciences, **12**(23): 7129–7167. doi:10.5194/bg-12-7129-2015.

Water Resources Division Indian and Northern Affairs Canada. 2002. Peel River Basin water quality report. Indian and Northern Affairs, Yellowknife, NT. Available from https://publications.gc.ca/site/eng/468356/publication.html [accessed 29 May 2024].

Wishart, R.P. 2014. We ate lots of fish back then": the forgotten importance of fishing in Gwich'in country. Polar Rec. **50**(4): 343–353. doi:10.1017/S0032247413000715.

Wong, C., Ballegooyen, K., Ignace, L., Johnson, M.J. (Gùdia), and Swanson, H. 2020. Towards reconciliation: 10 calls to action to natural scientists working in Canada. FACETS, **5**(1): 769–783. doi:10.1139/facets-2020-0005.

Ziegler, J.A., Lantz, T.C., Overeem, T., Proverbs, T.A., and Lord, S., Aklavik Hunters and Trappers Committee, Gwich'in Tribal Council Department of Culture and Heritage, and Inuvik Hunters and Trappers Committee. 2024. All the rivers we used to travel by": indigenous knowledge of hydrological change and its impacts in the Mackenzie Delta Region, Canada. Region. Environmen. Change, **24**(2): 66. doi:10.1007/s10113-024-02209-4.

Zolkos, S., Tank, S.E., Striegl, R.G., Kokelj, S.V., Kokoszka, J., Estop-Aragonés, C., and Olefeldt, D. 2020. Thermokarst amplifies fluvial inorganic carbon cycling and export across watershed scales on the Peel Plateau, Biogeosciences, **17**(20): 5163–5182. doi:10.5194/bg-17-5163-2020.