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ORIGINAL ARTICLE

"*All the rivers we used to travel by*": Indigenous knowledge of hydrological change and its impacts in the Mackenzie Delta Region, Canada

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Abstract
Climate change is causing widespread impacts to hydrological systems and altering ecosystems across the circumpolar north. Indigenous peoples have a rich knowledge of environmental changes in their territories and the social-ecological impacts of shifting conditions, which can inform our understanding of how these systems are changing. In this study, we used a participatory, mixed methods approach (29 interviews, 32 questionnaires) to synthesize Gwich'in and Inuvialuit knowledge of hydrological changes observed in the Mackenzie Delta Region. There was a strong consensus among Indigenous knowledge holders that an observed reduction in water levels is linked to increases in permafrost mass wasting, riverbank erosion, and sandbar formation. Indigenous knowledge holders also noted that shifting hydrology has disrupted travel and fishing activities in ways that are likely to impact the health and well-being of Indigenous communities in the region. These findings demonstrate that collaborative partnerships with Indigenous knowledge holders are critical to effectively identify regional-scale environmental change, understand its socioecological impacts, and support local and regional decision-making. Interview participants also highlighted the importance of on-the-land education and intergenerational knowledge sharing to ensure youth can continue to care for the land in the face of rapid socio-ecological change.

Keywords Climate change · Western Arctic · Community-based research · Impacts · Indigenous-led research · Qualitative research

Introduction

Climate change is altering the global water cycle as warming temperatures drive increases in evaporation, surface drying, tropospheric water vapor, and intensified precipitation events (Huntington 2006; Rawlins et al. 2010; Trenberth 2011; Durack et al. 2012; IPCC 2014, 2019a; Caretta et al. 2022). Climate models suggest that ongoing change will increase the frequency of extreme events in wet and dry areas, exacerbating flood and drought risk (Pavelsky and Smith 2006; Trenberth 2011; Durack et al. 2012; IPCC 2019b). Hydrological systems in the Arctic and Subarctic are particularly vulnerable to climate change as temperatures are increasing at nearly four times the global average annual rate (Rantanen et al. 2022). As northern landscapes respond to warming temperatures and precipitation regimes shift from snow to rain dominated, many areas are likely to experience earlier snow melt, increased winter runoff, and decreased temporal and spatial snow cover (Barnett et al. 2005; Bring et al. 2016; Niittynen et al. 2018; IPCC 2019a; Bonsal et al. 2020). Across the Arctic and Subarctic, climate warming is also altering surface water dynamics in complex ways (Smol and Douglas 2007; Bouchard et al. 2013; Campbell et al. 2018; Higgens et al. 2019; Webb et al. 2022; Travers-Smith et al. 2022).

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Indigenous peoples whose livelihoods and culture are closely tied to lands and waterways are uniquely positioned to identify long-term environmental changes and their social-ecological impacts (Berkes 2009; Thompson et al. 2020; Parlee et al. 2021). In the past two decades, there has been growing interest in including Indigenous knowledge in environmental research to create a more holistic understanding of observed environmental changes, especially in Canada's north (Alessa et al. 2008; Gill et al. 2014; Wilson et al. 2015; Tyson et al. 2016; Turner et al. 2018; Proverbs et al. 2020a, b; Thompson et al. 2020; Parlee et al. 2021; Chila et al. 2022). 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). Indigenous ways of knowing provide different yet complementary information to western scientific approaches that enrich our collective understanding of observed environmental changes (Moller et al. 2004; Bohensky and Maru 2011). However, 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). This includes 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 a means to validate western scientific ways of knowing (Nadasdy 1999; UNDRIP 2007; Ignace et al. 2023). The overarching goal of the current study is to use an Indigenous-led approach to document Gwich'in and Inuvialuit knowledge of hydrological change occurring in the Mackenzie Delta Region, Canada, and its impacts on Gwich'in and Inuvialuit communities and livelihoods in this region.

Context

The Mackenzie Delta Region (referred to as "the Delta" throughout the manuscript) is located at the northern edge of the Mackenzie River Basin in Canada's western Arctic. This area lies within the Gwich'in Settlement Region and Inuvialuit Settlement Region (GSR and ISR, respectively) and is home to approximately 3590 Inuvialuit and Gwich'in residents in the four communities of Inuvik, Aklavik, Fort McPherson, and Tsiigehtchic (Government of Canada 2017). The Delta is centered on the alluvial terrain between Point Separation and the coast of the Beaufort Sea (Fig. 1). This region has a Subarctic climate characterized by long, cold winters and short, warm summers. Mean annual winter and summer temperatures at Fort McPherson are − 27 °C and 14 °C, respectively (Burn and Kokelj 2009). Total mean annual precipitation is 310 mm, approximately half of which falls as rain (Burn and Kokelj 2009). Snowmelt is an integral component of the hydrology of the Delta contributing to spring flooding, which is the principal annual hydrological event that typically occurs in the first few weeks following the onset of above 0 ℃ temperatures (Burn and Kokelj 2009). Water levels in the Delta are typically highest in May or June when melting occurs and ice jamming causes flooding (Burn and Kokelj 2009). Lake hydrology is strongly impacted by spring flood activity, which is the primary source of recharge. Waterways in the Delta are also sensitive to precipitation in the western mountains and the Peel River basin (Bigras 1990).

The low-lying terrain in the Delta supports highly productive ecosystems that provide important habitat to a diversity of fish, mammals, birds, and plants, many of which are critical to the local economy (Banfield 1951; Höhn 1962; Percy 1975; Martell and Pearson 1978; Marshal 1999; Wishart 2014; Turner et al. 2018; Proverbs et al. 2020b). The vegetation in the Delta is a mosaic of spruce forest, shrub thickets, and wetlands that is strongly influenced by the frequency and intensity of spring flooding (Gill 1971; Pearce et al. 1988; Burn and Kokelj 2009).

For the Gwich'in and Inuvialuit who live in the Delta, water is vital to their way of life. Water, and the plants and animals that rely on it, plays an important role in Gwich'in and Inuvialuit place names, origin stories, and artwork, as well as their livelihoods and culture (Collin 1973; Ritter and Sittichinli 1976; Northwest Territories Education 1991; Kritsch and Andre 1997; Alunik 1998; Heine et al. 2001, 2007; Usher 2002; Alunik et al. 2003; Papik et al. 2003; Arnold et al. 2011; Inuvialuit Cultural Resource Centre 2011; McCartney and Gwich'in Tribal Council 2020; Gwich'in Social and Cultural Institute n.d.). The Gwich'in and Inuvialuit residents of the Delta depend on the many channels of the *Kuukpak* or *Nagwichoonjik* (Mackenzie River), *Teetł'it Gwinjik* (Peel River), and *Tsiigehnjik* (Arctic Red River) to maintain social and family networks and carry out cultural activities (Fig. 2a,d; Parlee 2016; Gwich'in Land Use Planning Board 2018; Turner et al. 2018). They use the network of interconnected lakes, streams, and channels in the Delta (Fig. 1) to hunt (caribou (*tuktu*, *vadzaih*), moose (*tuttuvak*, *dinjik*)), trap (muskrat (*kivigaluk*, *dzan*), mink (*itigiaqpak*, *chihthee*), marten (*qavviatchiaq*, *tsuk*), and fish (broad whitefish (*aanaaelirq*, *luk dagaii*), inconnu (*siigarq*, *shruh*), Dolly Varden char (*qaluhaq*, *dhik'ii*), burbot (*titaalirq*, *chehluk*), Arctic grayling (*suluqpauraaq*, *sriijaa*), as well as to collect plant foods and medicines (Condon et al. 1995; Marshal 1999; Johnson and Andre 2000; Morrison 2000; Heine et al. 2001; Papik et al. 2003; Murray et al. 2005; Parlee et al. 2005; Andre 2006; Wishart 2014; Andre and Kritsch 2015; Parlee and Caine 2018; Turner et al. 2018; Roburn 2019; McCartney and Gwich'in Tribal Council 2020; Ready 2021; Gwich'in Renewable Resources Board n.d.). These water bodies are therefore vital to their ability to be on the land and practice their culture (Heine

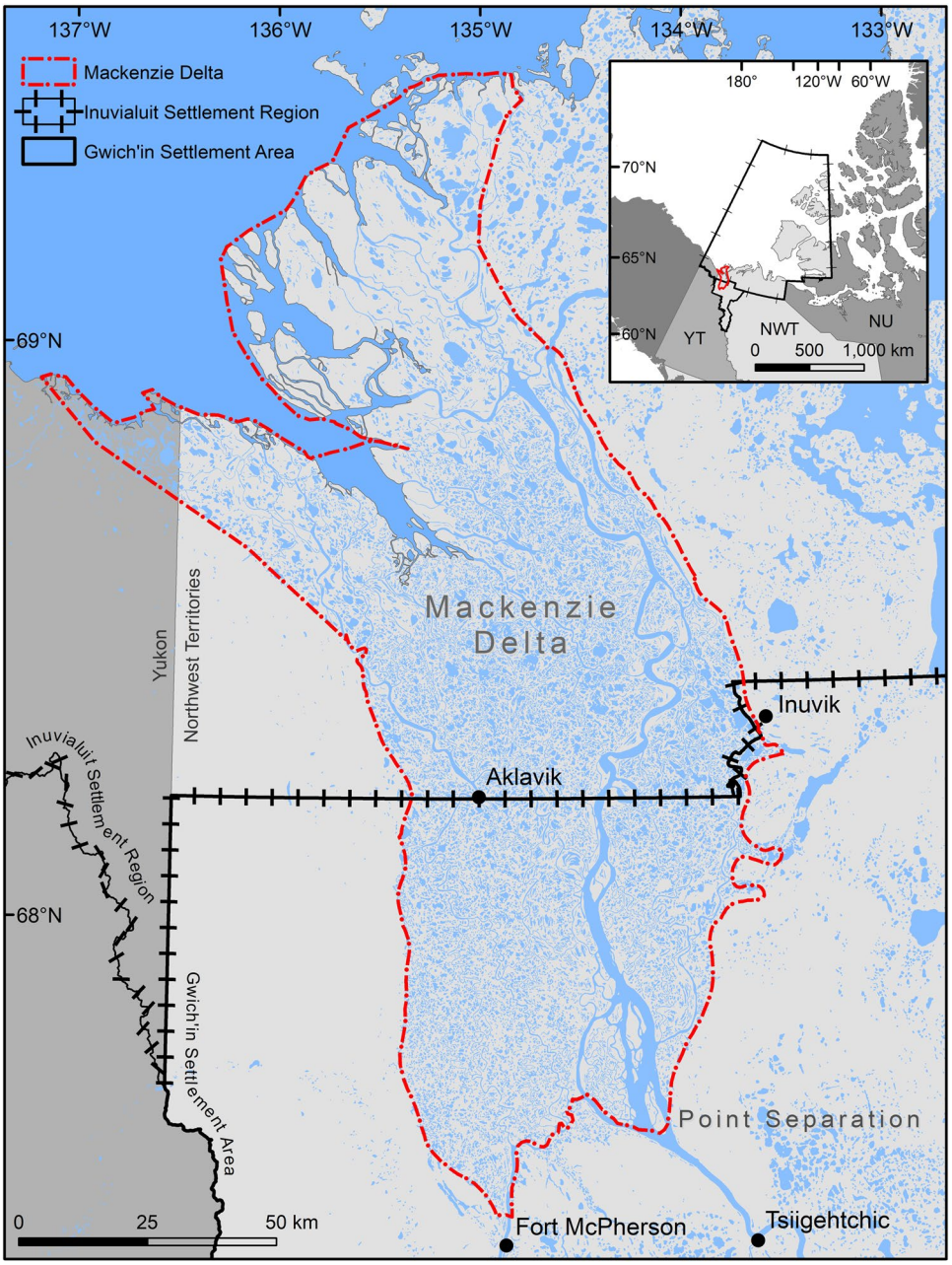

Fig. 1 Map of the study area showing the participating communities and the boundaries of the Mackenzie Delta Region, Inuvialuit Settlement Region, and Gwich'in Settlement Area. The inset in the upper right shows the location of the study area in western North America, as well as the borders of the Inuvialuit Settlement Region, the Gwich'in Settlement Area, and the Mackenzie Delta Region

et al. 2001; Papik et al. 2003; McCartney and Gwich'in Tribal Council 2020).

Gwich'in and Inuvialuit communities in the Delta are becoming increasingly concerned about the cumulative impact of climate-related changes on land-based livelihoods (Inuvialuit Regional Corporation 2016; Gwich'in Land Use Planning Board 2018; Turner et al. 2018; Heredia Vazquez 2019; Proverbs et al. 2020a, b, 2021). Rivers and lakes in the Delta are used as important travel corridors and have long facilitated the harvest of traditional country foods (GTC Department of Cultural Heritage Digital Archive 2016; Inuvialuit Regional Corporation 2016; Parlee 2016; Proverbs et al. 2020a, b). Residents of this region have indicated that impeded access to important waterways and traditional country foods are negatively impacting their livelihoods, health and well-being, and cultural identity (Inuvialuit Regional Corporation 2016; Turner et al. 2018; IPCC 2019a; Heredia Vazquez 2019; Proverbs et al. 2020a, b).

Recent research in the region shows evidence that hydrological systems are exhibiting widespread changes in response to climate warming, including changes in the extent of surface water, temporal shifts in break-up, freeze-up, and peak flow, and altered sediment transport linked to accelerated permafrost thaw (Prowse et al. 2006; Lesack et al. 2013, 2014; Bawden et al. 2015; Lantz and Turner 2015; Campbell et al. 2018; Ahmed et al. 2020; Bonsal et al. 2020; Kokelj

Fig. 2 **A** The many waterways of the Mackenzie Delta Region in the Gwich'in Settlement Area and Inuvialuit Settlement Region, Northwest Territories, Canada (credit: Jordan Seider). **B** A partially drained lake in the Mackenzie Delta Region (credit: Kiyo Campbell). **C** A permafrost thaw slump affecting a river in the Peel River watershed, a major tributary of the lower Mackenzie Delta Region (credit: Steve Kokelj). **D** Fish drying at a fish camp in the Mackenzie Delta Region (credit: Tracey Proverbs)

et al. 2021; Webb et al. 2022). Since increases in regional climate risks (ACIA 2004; Prowse et al. 2006; White et al. 2007; Bonsal and Kochtubajda 2009; IPCC 2019b) are likely to intensify these impacts (IPCC 2019a), it is imperative to document regional-scale changes in northern ecosystems using a community-based, collaborative research framework that prioritizes Gwich'in and Inuvialuit concerns and research interests (Wolfe et al. 2007; Pearce et al. 2008; Castleden et al. 2012; Brinkman et al. 2016). In regions experiencing rapid change, community-based research is vital to inform the development of locally appropriate and culturally relevant strategies to counter climate and ecological change (Hovel et al. 2020). In this study, we use a mixed-methods, community-based approach to synthesize Gwich'in and Inuvialuit knowledge of hydrological changes observed in the Delta and their impacts on livelihoods.

Author positionality

The authorship team is composed of both settler and Indigenous experts. J.Z., T.L., T.O., and S.L. are white, settler scholars, and T.P. is a scholar of Kaska-Dena, European, and Bajan descent, all of whom except S.L. live outside of the GSA and ISR. S.L. is based in Inuvik, NT. The community Hunters and Trappers Committees (HTCs) are composed of Inuvialuit harvesters elected by the community with a mandate that includes engaging in conservation, research, and management in their regions of the ISR (Government of Canada 1984). The Gwich'in Tribal Council Department of Culture and Heritage, 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 the practice of Gwich'in culture, language, traditional knowledge and values" (Gwich'in Social and Cultural Institute 2005 p.6). J.Z., T.L., T.O., T.P., and S.L. 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

Community-based research approaches are a means of preventing further harms related to past issues with the colonial history of Canadian research in Indigenous communities and using Indigenous knowledge (Castleden et al. 2012; Smith 2021). A community-based research approach centralizes Indigenous partners' ownership and power to ensure shared decision making, two-way flow of information between researchers and their Indigenous partners, as well as the co-production of knowledge that is mutually beneficial (Israel et al. 2003; Castleden et al. 2012). This section provides an overview of the community-based, Indigenous-led approach we used.

Research design

This project emerged from discussions initiated as a part of a research network that brought together Indigenous and university-based researchers to promote the contributions of Indigenous knowledge to environmental monitoring and governance in the Mackenzie River Basin (Parlee et al. 2021). Between 2016 and 2018, the Tracking Change network issued several calls for community-driven research to explore priorities identified by an Indigenous Steering Committee. In 2016 and 2017, the Gwich'in Renewable Resources Board and the Inuvialuit Fisheries Joint Management Committee worked with university partners to plan

and implement independent, but complementary, research exploring Indigenous knowledge of changes to aquatic environments. To develop these projects, the research team sought feedback from the Gwich'in Tribal Council Department of Culture and Heritage, the Renewable Resources Councils (RRCs) in Inuvik, Aklavik, Fort McPherson, and Tsiigehtchic, and the Hunters and Trappers Committees (HTCs) in Aklavik and Inuvik at meetings held in 2016 and 2017. Both initiatives built on a history of successful research collaboration on related topics (e.g., Bennett and Lantz 2014; Gill et al. 2014; Tyson et al. 2016; Turner et al. 2018; Proverbs et al. 2020a, b; Hovel et al. 2020).

Data collection

To document Indigenous knowledge of hydrological variability across the study area, we conducted 29 interviews involving 37 Gwich'in and Inuvialuit knowledge holders in the summer and winter of 2018 and spring of 2019. Interviews were conducted in Inuvik ($n=12$), Aklavik ($n=11$), Fort McPherson ($n=3$), and Tsiigehtchic ($n=3$). We spoke to 23 men and 14 women whose ages ranged from 31 to 82, with an average age of 58. Interview questions were developed, and participants were identified, through consultation with the RRCs and HTCs in each community. Interviews typically lasted about 1 h and were semi-structured to allow participants to elaborate on the topics and observations most significant to them. Interview questions focused on knowledge of waterways and the impact of hydrological variability on travel and subsistence harvesting (Appendix A). Interviews were conducted in English. We hired Gwich'in and Inuvialuit youth to assist with interviews, and Indigenous knowledge holders were compensated for their time based on the rates set by the Gwich'in Tribal Council Department of Culture and Heritage and the HTCs.

In 2016 and 2017, 32 Inuvialuit knowledge holders from Inuvik ($n=12$) and Aklavik ($n=20$) also completed questionnaires. Participant ages ranged from 18 to 73, with a mean of 43, and included 17 men and 15 women. Questionnaires included a series of open-ended questions regarding the impact of climate-driven changes on fish, fishing, access to fishing, and priority water management and monitoring concerns (Appendix B). For the purposes of this paper, only the questions related to environmental changes affecting access to fishing in the Delta, as well as priority concerns related to water and monitoring, were considered here. Questionnaire participants were compensated based on rates set by the HTCs.

All Gwich'in knowledge was handled according to the Gwich'in Tribal Council Department of Culture and Heritage's Gwich'in Traditional Knowledge Policy. As a part of this policy, our project had a Traditional Knowledge Research Agreement with the Gwich'in Tribal Council Department of Culture and Heritage. All Inuvialuit knowledge used in this study was archived with the Inuvialuit Joint Secretariat.

Data analysis

We analyzed interview transcripts using the qualitative analysis software NVivO 12 Plus (QSR International, USA) to identify emergent themes and areas of consensus. Thematic codes included large-scale environmental change influencing river and lake systems such as erosion, sandbar dynamics, river morphology, permafrost thaw, and water levels. Most coded sections of text were also assigned thematic sub-codes that linked observations to the perceived cause of change and the impacts experienced by individuals. Transcripts were also coded to document environmental obstacles to fishing and other concerns about environmental changes. We used a similar approach to code the questionnaires.

The project team presented initial project results to all four communities in 2019 and 2020. Once the COVID-19 travel restrictions were lifted in late 2021, we presented the updated findings of our analysis to each of the participating RRCs and HTCs in the four participating communities for feedback prior to publication. These presentations and associated discussions lasted approximately 30 min and occurred in 2022 and 2023.

Results

Observed changes in environmental conditions

> "… there's no more water left."—Abraham Stewart, Fort McPherson.

There was a clear consensus among interview participants (28 out of 29 interviews) that water levels in the channels of the Delta have become lower in recent decades. Allen Kogiak from Aklavik explained that he does not "recall [ever] seeing [water levels] this low." Eddy McLeod from Aklavik echoed this sentiment explaining that "the whole Delta is getting shallower, drier." Participant observations of shallower waters were linked to visible changes in frequently traveled waterways. Cheryl Arey from Aklavik explained that she recognizes that waters are lower because, when traveling, "stumps … are appearing … [that] weren't there before." Emma Kay from Fort McPherson explained that now "if you walk to the [river]bank, you see all these willows that weren't there when we were kids. That was river and [now] it's willows and shallow, shallow water."

Explanations for the cause of lower water levels varied among participants but were often attributed to the impacts of erosion caused by permafrost thaw or described as the result of temperature increases (Table 1). Most participants noted

Table 1 Observed environmental changes in the Mackenzie Delta Region described by interview participants in this study ($n=29$ interviews with 37 participants), and associated causes and impacts. Landscape changes include the caving in of banks, eroding cut banks, landslides, and permafrost slumping

Observation	*Cause and impact*	*Number of interviews (/29)*
Lower water		28
	Cause	
	Climate change and warming	16
	Erosion	11
	Increased beaver abundance	9
	Permafrost thaw	8
	Drained lakes	2
	Increased vegetation abundance	1
	Impact	
	Change in accessibility	25
	Change in subsistence harvesting practices	16
	More sandbars	15
	Change in fish and animal populations	3
Landscape change		28
	Cause	
	Permafrost thaw	13
	Climate change and warming	11
	Changes in river ice condition and flow	8
	Increased rainfall	8
	Impact	
	Change in accessibility	16
	Change in subsistence harvesting practices	9
	More sandbars	9
More sandbars		23
	Cause	
	Erosion	9
	Permafrost thaw	2
	Climate change and warming	2
	Precipitation	1
	Impact	
	Change in accessibility	21

that more frequent riverbank erosion is widening some channels and increasing sediment build-up resulting in shallower waters and an increase in the presence of sandbars along commonly used travel routes. William Storr from Aklavik explained that "a lot of the banks have eroded… [and] some of the rivers have gotten wider, but they're shallower." JD Storr from Aklavik shared his understanding of the changes, describing that "when the ice moves, it pulls the sediments out and [there is a] lot of erosion … filling the bottoms of the river and making sandbars." Dean Arey from Aklavik described the cumulative changes he has seen in the Delta over his lifetime and their contributions to changes in water depth as follows: "A lot of erosion. A lot of sluffs … water temperatures … global warming is a big thing now that I see and the rivers are really changing. They're getting shallower."

A number of participants also described a reduction in the number of flooding events in the Delta in recent years ($n=8$). Late Gwich'in Elder John Jerome from Inuvik explained how it had been 5 years since he had seen a flood at his camp. Late Gwich'in Elder Abraham Stewart of Fort McPherson echoed this sentiment and elaborated by suggesting that large-scale floods are less likely to occur because when

> winter's warm, it won't flood because the ground stays soft. And when the snow and everything melts, it goes into the ground. When it's cold and the ground freezes, the snow and everything melts, the water stays on top of the ground, and it fills up everything.

Observations of low water levels were not confined to channels in the Delta. Nineteen interview participants also described lakes that had completely drained or were in the process of draining (Fig. 2b). As Ernest Vittrekwa from Fort McPherson observed, "Lots of lakes have drained out. Dried up …the lakes are just full of trees now in lots of places."

Some participants associated these changes with permafrost thaw, erosion, and the development of new outlet channels connecting lakes to adjacent lakes or nearby channels. Eddy McLeod stated that these changes are occurring because of climate change noting that "the permafrost is melting [because of] global warming." Harry Carmichael from Aklavik described how "there's a lot of [lakes that have] … washed out into the main channel" and others that have not "busted out yet but it's coming." Emma Kay described how the water in lakes had changed since she was a child, "most of the lakes are dried up and … look dark brown … [I] never used to see things like that." Some participants also indicated that vegetation change and lake drainage are contributing to changing water levels in the Delta.

Interviews with local experts made it clear that the long-term drying trend described by most participants is occurring in a system characterized by high variability. Many participants ($n=16$) noted that water levels were particularly high in 2018, and frequently linked this to increased summer precipitation in the Delta and areas of the Richardson Mountains that drain into the Mackenzie River ($n=7$). Other environmental factors such as climate change and changes in ice conditions were also noted as causes of variation in water levels. Many interview participants ($n=22$) also noted that beaver dams in the Delta cause both increases and decreases in water levels in adjacent lakes or rivers, and impact community access to clean drinking water and fish. Gwich'in Elder Ernest Vittrekwa explained that in "some place[s the] water is high because creeks are blocked up by beaver." The impacts of increasing beaver populations were typically described as an issue that requires management intervention.

Impact of changing environmental conditions on accessibility and fishing practices

> "Everything … just changed and … in order for me to do what I had to do, what I used to do, I had to change too. Change with it."—Abraham Stewart, Fort McPherson.

Environmental changes are affecting participants' ability to travel on the water and to fish (Table 1, Fig. 2c, Fig. 3). Most respondents ($n=17$) agreed that observed environmental changes are making it harder to travel on the rivers and lakes. For example, Nellie Arey from Aklavik notes that "You can't really do anything now … you want to go somewhere you can't go somewhere, you have to look for a way to go where you want to go." Many respondents ($n=17$) noted that they can no longer access certain areas or preferred traveling routes. For example, Michelle Gruben from Aklavik noted that erosion is affecting her ability to access fishing grounds:

> We thought oh let's go fishing at this one spot … we used to be able to drive in there with a boat? Now it's right closed. You can't get there but that lake is still there. You go down, you keep going down and it's, all you see is mudslides, mudslides, mudslides.

Melissa Rogers from Inuvik notes that low water levels and mudbars make important harvesting areas inaccessible, "There's some places [that] are just dried right up. Places where we used to go and fish or even pick berries and it just dried right out. Some of the lakes. We can't even access it anymore." Local experts explained that some commonly traveled channels in the Delta are completely inaccessible due to a build-up of sandbars. Hank Angasuk from Inuvik notes that the low water levels prevent him from accessing his fish camp: "Sometimes I can't get into Dennis lagoon because [the water] is too low. I have to wait until the water comes up and I can try … to get down to my cabin." Doug Esagok from Inuvik notes that:

> sandbars are getting bigger because of the amount of erosion that's going on in the riverbanks and … down on the west side [of the Delta], some rivers are absolutely plugged. You can't go through them anymore at normal summer water levels. The rivers are totally blocked with sandbars … So that's really altering where people travel.

These changes have also made travel on the water more dangerous and unpredictable regardless of season ($n=20$). During an interview at his fish camp, Louie Cardinal from Tsiigehtchic reported dangers with traveling by boat during the summer due to sandbars: "You have to be really careful of sandbars … because it's just like a widow maker, right? You could be going 90 miles an hour and you can't see [the] sandbar underneath and boom that's it… it's very dangerous."

Others noted that the lower water levels and shifting sandbars can damage their equipment ($n=4$). For example, Abraham Stewart warns:

> If you make a [skidoo] trip up Stony Creek or any one of those creeks—Rat River, Bear Creek or Vittrekwa Creek—you're going to wear your sleigh out right away … from all the rock … there used to be ice and you could travel on it because there was enough water. But there's no more water left.

Some respondents were also concerned their fish camps and homes would fall into the river due to the erosion of riverbanks and slumps ($n=6$). JD Storr explains "[people] used to build their [fish] camp way off in the trees and you have to walk to it [but] now a lot of camps on the rivers are falling over … into the water and [the river]banks are cut short here and there."

Environmental changes are also impeding land users' ability to fish and hunt. In some cases, fish eddies are disappearing due to increased erosion and associated landslides, as Allen Kogiak explains:

> Lots of places just slump right off … When that happens, I mean you know it'll affect your fishing if … there's a good eddy right there, right? … That's where you fish, you find the big eddies where … the fish congregate. So you know if you get slumping and sliding there it'll just take that away and you have to find a new spot [to fish].

Hank Angasuk from Inuvik notes that lower water levels make hunting harder: "I've noticed in the last 10 years, maybe more, a lot of those shortcuts we used to take when we were hunting are no longer available to us, we can't use them. It just makes it harder for us to hunt now." Jerry Angasuk from Inuvik remarked that lower water levels are affecting his ability to ice fish: "you can't even set nets in those little creeks now they're so shallow." Furthermore, three interview participants noted that the lower water levels in the lakes and rivers are affecting the muskrats and fish, as Eddie McLeod explains:

> Some lakes that I used to trap muskrats on when I was younger, now you go there and it's just sad, sticks sticking out all over in the lake. There might be a few rats in it but we'll never get lots [of muskrats] again because there's no water for them.

Many interview participants noted that dangerous conditions, which limit days spent fishing, are becoming more frequent ($n = 17$). For example, Gail Raddi from Inuvik notes: "It's so rough out there … there are less days you can go set your net." The unpredictability of conditions is also an issue because setting net in waters that are too low or high is a problem, as Emma Kay points out: "The water comes up, [then] the water is going down so my godbrother set net for us again, next day the water was coming up. It's just like that all summer." Unpredictably high water levels in channels and excess sediment in the water can also create challenging conditions for net fishing. Cheryl Arey described the amount of debris brought by high waters and precipitation as deterrents to fishing, noting that "it's no use to even put your net in … it [is] just no use. It's going to get dirty so fast." Questionnaire respondents also noted that changing environmental conditions, including landslides associated with permafrost thaw, are affecting their ability to fish ($n = 15$; Appendix C).

Although most participants can still fish today, some expressed concerns about future accessibility ($n = 9$). Emma Kay said she "could still get fish and that but [I] don't know down the road, I don't know how it will be." Cheryl Arey also expressed concern about future accessibility based on her current observations of the impacts of bigger landslides on fishing in the Delta:

> Like I said the [fishing] eddies were there. Now [the eddies are] not as strong as [they] used to be, and if my [fish] camp is here and my fish net's already 5, 4 bends down [the river], how much further am I going to have to move it to look for that next eddy, right?

Communities in the Delta rely heavily on fish as an important source of food (Fig. 2d), yet many interview participants noted that they were catching less fish compared to previous years ($n = 16$). Some participants were concerned about future availability of country foods, including fish, due to the lower waters and increased severity of landslides along the riverbanks observed in the Delta ($n = 9$), as Cheryl Arey notes:

> You almost think, is this going to be the last time when we're able to come up here and do our fishing? … We've been doing it for 29 years. My kids grew up there … doing these things and then you wonder. Because we harvest our berries, our fish, our meat, you know? It's what gets us through the winter, right? Especially when you're used to that. It's how we were brought up.

The impact of environmental changes on the rivers and lakes extends well beyond access to food. A number of participants expressed sadness about the environmental changes occurring in the region because they no longer recognize the landscape they have lived on for decades ($n = 7$). As Nellie Arey states, "There is lots of erosion, lots. It's all different. It's not like long ago river anymore. Anywhere, any kinds of rivers, even in the Delta, everything is just dropping [into] the river. That's why I get so sad." Doug Esagok from Inuvik remarks:

> I don't think there's anywhere in the world that they're feeling climate change more than we are here in the Delta, you know? […] We're seeing so much change in such a short period of time and everything we do and we know is being impacted and altered and changed […] It's just like we don't live in the same place anymore.

Others still are concerned about what will be left for future generations if these environmental changes continue to occur in the Delta, with Michelle Gruben explaining, "You could see the future being in a worse state than it is now … that's what I think, will all these little delicate spots that we have, will they be there for our future generations?".

Despite these concerns, interview participants also noted a number of ways they are responding to the environmental changes in the Delta. Interview participants reported using different approaches to address reduced access caused by

regional environmental change. Most participants noted they use alternative routes if their preferred route is blocked by sandbars or shallow waters ($n = 20$). Boaters also help each other deal with these changing environmental conditions. Michelle Gruben points out "You'll hear your other fellow boaters they say 'oh you have to go this way' … because every year that channel will change so they're going to tell the next boater which way to go." Others still wait for better conditions before traveling on the land. For example, Nellie Arey notes, "Every year is different. You have to look for which way to travel or wait for high water." Many highlighted the importance of being careful when traveling on the rivers and lakes today due to the rapidly changing environmental conditions ($n = 10$). For example, Dean Arey points out: "People used to read [the weather] and they used to travel when they know it's good and now it's just, have to be really careful when you're traveling." Still other interview participants reported using proactive actions to ease access to key areas or prevent negative impacts. Eddie McLeod explains how

> We used to be able to just go and climb up the banks [on our skidoos], wherever we want. Now if you want to get up some banks, you have to fix them in the summertime. Shovel them and that because … they're pretty well all cut from falling in now. You have to fix your banks too. Where you want to travel with skidoo, like through our portages to get to our shortcuts to our camp.

When interview participants were asked what can be done to care for the land and water into the future, the majority of participants ($n = 18$) highlighted the need for ongoing monitoring, research, and environmental stewardship initiatives, including guardianship programs. Questionnaire respondents noted the importance of monitoring environmental changes like slumping and erosion and its impacts on fishing livelihoods in the Delta (Appendix C). Interview participants ($n = 11$) also noted the critical importance of on-the-land education and the benefit of youth engagement in land-based activities to ensure the land is well cared for into the future. Dean Arey described this as work that is already in progress and that "[i]t's the only way. Education and teaching our young." JD Storr echoed this by noting that on-the-land programs gained

> more interest just this past year, which is really nice, and it's a really good program …. Without my first year going there I still probably wouldn't know how to cut fish … so you do learn a lot on those trips.

Overall, participants stressed the importance of local engagement in efforts to mitigate the impacts of a changing environment in the Delta and decision-making.

Discussion

Our analysis highlights the vital contribution of Indigenous knowledge to the effective monitoring of complex environmental systems. Gwich'in and Inuvialuit knowledge holders who participated in this research agreed that waterways in the Delta have become shallower over their lifetimes because of increased erosion and sedimentation. Similar observations made by Kátł'odeeche Dene observers in southern Northwest Territories (Stenekes et al. 2020) and Athabasca Chipewyan and Mikisew Cree observers in northeastern Alberta (Candler et al. 2010) suggest that lower water levels and riverbank erosion are occurring throughout the Mackenzie River Basin. Although considerable research has been conducted on trends in river discharge, few scientific studies employ metrics that measure the ways that water levels impact river travel—a socioecological factor of importance to the Indigenous communities living in the region (Candler et al. 2010; Carver and MacLean 2016; Peters et al. 2023). Temporal trends in northern streamflow data differ depending on the time-period, season, and spatial scale used. Some studies have shown an overall increase in streamflow into the Arctic Ocean (Whitfield and Cannon 2000; St. Jacques and Sauchyn 2009; Rood et al. 2017; Ahmed et al. 2020), while others have found that the observed trend depends on the geographic scale used (Déry and Wood 2005; Bawden et al. 2015). For example, Déry et al. (2005) found that there was an overall decrease in streamflow into the Arctic and North Atlantic oceans from 1964 to 2003, but an unchanged annual streamflow if only the rivers emptying into the Arctic Ocean were considered. Bawden et al. (2015), meanwhile, found that the Lower and Upper Mackenzie River basins showed a significant increase in annual runoff, especially during the cold season, while the Peel and Mid-Mackenzie River basins showed a slight decreasing trend in runoff that was not statistically significant for both the annual and warm-season runoff. The findings shared by Gwich'in and Inuvialuit knowledge holders in this study highlight that streamflow alone is not an ideal indicator of changes in water levels in northern basins and points to the need for a broader range of indicators to detect hydrological responses to a changing climate (Stevenson 1996; Berkes and Berkes 2009; Wilson et al. 2015; Parlee 2016). These indicators should be developed in partnership with Indigenous knowledge holders to ensure the selected indicators are based on land user needs and relevant to land-based livelihoods (Parlee 2016; Anderson et al. 2019; Parlee and D'Souza 2019).

Indigenous knowledge is also vital to environmental monitoring because it extends the temporal depth of observation, and provides detailed knowledge of key processes and feedbacks influencing environmental systems (Stevenson 1996; Berkes and Berkes 2009; Peletz et al. 2020; Skroblin

et al. 2021). Participants in this study noted that lower water levels were associated with increased sedimentation caused by thaw slumping and riverbank erosion. This observation parallels recent research showing the impact of thermokarst acceleration on sedimentation (Lamoureux and Lafrenière 2009; Rudy et al. 2017; Kokelj et al. 2021). Widespread intensification of thaw slumping is causing channel re-routing, rapid in-filling of lakes, and increased turbidity in downstream lakes by mobilizing slump-derived sediments across regional fluvial networks (Kokelj et al. 2021). Increased sedimentation from thaw slumping is especially concerning because it affects aquatic food webs, fish habitat, and water quality (Kokelj et al. 2013, 2021; Chin et al. 2016; Culp et al. 2019; Rudy et al. 2019; Spence et al. 2019, 2020).

Indigenous knowledge of water also provides critical information about how these observed environmental changes affect livelihoods. The disruption of travel and subsistence harvesting caused by shallow waterways, increased riverbank erosion and sandbars, is also impacting livelihoods in the Delta (Fig. 3). Fish are an important food source for Inuvialuit and Gwich'in in the Delta (Freeman 1997; Alunik et al. 2003; Wishart 2014; Proverbs et al. 2020b), and barriers to access are of critical concern because they negatively impact food security (Appendix C; Furgal et al. 2002; Parlee et al. 2005; Laidler et al. 2009; Ford et al. 2010; Harper et al. 2011; Kuhnlein et al. 2013; Cunsolo Willox et al. 2013; Inuit Circumpolar Council-Alaska 2015; Durkalec et al. 2015; Naylor et al. 2019; Proverbs et al. 2020b). Participant observations of reduced access to waterways and to fish in this study are also consistent with findings in many other Arctic regions (Fox 2002; Wesche and Armitage 2010; Ford et al. 2010; Moerlein and Carothers 2012; Dinero 2013; Wilson et al. 2015; Gérin-Lajoie et al. 2016; Brinkman et al. 2016; Baldwin et al. 2018; Cold et al. 2020; Stenekes et al. 2020), where the effects of environmental change on travel and fishing activities are influencing individual and community health and wellbeing (Fox 2002; Cunsolo Willox et al. 2012, 2013; Inuit Tapiriit Kanatami 2019). Waterways in the Delta are culturally important for travel and subsistence hunting and fishing (Hart 2011; GTC Department of Cultural Heritage Digital Archive 2016; Inuvialuit Cultural Resource Centre 2020; Proverbs et al. 2020b) and many participants noted feeling sadness in response to the observed landscape changes occurring in the Delta. Access to traditional foods is an integral part of Indigenous psychological and cultural security (Sakakibara 2017), since cultural identity and community wellbeing is directly linked to time spent on the land, harvesting, eating, and sharing traditional country foods (Northwest Territories Education 1991; Nuttall et al. 2005; Parlee et al. 2005; Ford et al. 2008; Dinero 2013; Inuit Circumpolar Council-Alaska 2015; Durkalec et al. 2015; Ready 2016; Naylor et al. 2019; Proverbs et al. 2020b; Gilbert et al. 2021). Hydrological changes in the Delta also have broader cultural implications because water, fish, and aquatic wildlife (e.g., muskrats, polar bears, whales, seals) feature prominently in Inuvialuit and Gwich'in origin stories, artwork, and in named places throughout the Delta (Schwarz 1970; Alunik et al. 2003; Arnold et al. 2011; Gwich'in Social and Cultural Institute n.d.).

Our research also underscores the need to base regional responses to the changing environment on Indigenous knowledge. Gwich'in and Inuvialuit knowledge holders made it clear that they are using place-based knowledge of the Delta to respond to environmental changes not identified by conventional environmental monitoring programs (e.g., HYDAT; Bawden et al. 2015; Ahmed et al. 2020). Where lower water levels, increased sandbars, and landslides are blocking access to their preferred travel routes and/or fishing locations, participants are using alternative travel routes where possible. These observations are consistent with previous research describing changes to subsistence harvesting activities and travel on the land across the north (Berkes and Jolly 2002; Fox 2002; Jolly et al. 2002; Guyot et al. 2006; Pearce et al. 2008; Andrachuk and Pearce 2010; Hovelsrud and Smit 2010; Dinero 2013; Brinkman et al. 2016; Brown et al. 2018; Cold et al. 2020; Proverbs et al. 2020b, 2021).

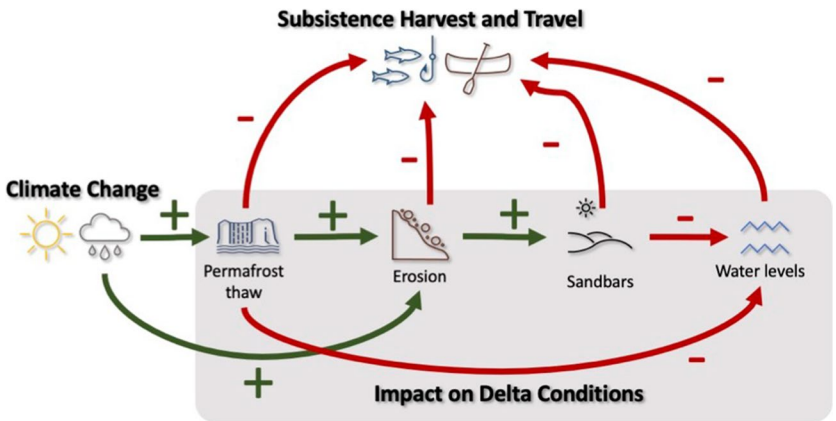

Fig. 3 Summary of observed environmental changes in the Mackenzie Delta Region and their impacts on Indigenous livelihoods according to Gwich'in and Inuvialuit knowledge holders from the Gwich'in Settlement Region and Inuvialuit Settlement Region, Canada

Interview participants also highlighted the need for Gwich'in and Inuvialuit leadership in water level monitoring in the Delta. Most interview participants stressed the importance of on-the-land education and intergenerational knowledge sharing to ensure youth are engaged in land stewardship activities (GTC Department of Cultural Heritage Digital Archive 2016). Previous studies focused on Indigenous-led environmental monitoring have highlighted the importance of teaching youth land-based skills and ensuring intergenerational transfer of knowledge (Pearce et al. 2008; Inuit Tapiriit Kanatami 2016, 2019; Stenekes et al. 2020; Proverbs et al. 2020b), with some programs prioritizing such knowledge transfer by including Indigenous youth in the data collection process itself (e.g., Bennett and Lantz 2014; Gill et al. 2014; Proverbs et al. 2020b; Hovel et al. 2020). Community-led initiatives also ensure that the outputs of research and monitoring activities benefit the Indigenous communities whose livelihoods and culture are affected by environmental change (Wilson et al. 2015; Inuit Tapiriit Kanatami 2016, 2019; Johnson et al. 2016).

Gwich'in and Inuvialuit knowledge holders noted the need for improved monitoring and research of environmental conditions in the Delta. There are many successful monitoring programs in the Gwich'in Settlement Area and Inuvialuit Settlement Region focused largely on wildlife (e.g., Eamer 2006; Ostertag et al. 2018; Hovel et al. 2020; Lea et al. 2021), which could be used as models to develop a water monitoring program for the Delta. Indigenous Guardian programs are among a growing number of environmental monitoring programs led by Indigenous organizations that center Indigenous knowledge as a means of understanding changing interactions between land, water, and wildlife. Indigenous Guardians, who are considered the eyes and ears of Indigenous communities on their territories (Wilson et al. 2018; Thompson et al. 2019; Popp et al. 2020; Reed et al. 2021), may be one means of addressing this need in the Delta. Such programs provide insights at spatial and temporal scales important to decision making (Bowie 2013; Johnson et al. 2016; Whyte et al. 2016; Baldwin et al. 2018; Ban et al. 2018; Thompson et al. 2019, 2020; Alexander et al. 2019; Stenekes et al. 2020; Hovel et al. 2020; Brunet et al. 2020; Reed et al. 2021). Furthermore, the growth of Indigenous Guardian programs in Canada (Thompson et al. 2020; Reed et al. 2021) provides a way for Indigenous groups to reassert their jurisdiction over their ancestral lands and for governments to work towards their moral and legal obligations arising from the Truth and Reconciliation Commission of Canada Calls to Action and the UN Declaration on the Rights of Indigenous Peoples (BC First Nations Energy and Mining Council and UVic Environmental Law Centre 2020; Reed et al. 2021; Parlee et al. 2021).

Conclusion

Overall, our findings demonstrate that collaborative partnerships with Indigenous knowledge holders are critical to effectively identify regional-scale environmental change, understand its socioecological impacts, and support local and regional decision-making. Community-based, participatory research approaches ensure that the research outcomes are meaningful for the participating communities and that Indigenous partners have ownership and power over the knowledge that is co-produced.

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