Review of water quality research and datasets for the Gwich'in Settlement Area, Northwest Territories

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Introduction

In the Gwich'in Settlement Area (GSA) of the Northwest Territories, it has become exceedingly important to collect baseline data and conduct continuous monitoring to protect aquatic resources, as the Gwich'in people depend on those resources for food and livelihood and have reported concerning changes to their environment (Gill et al. 2014). Environmental datasets for the Northwest Territories have been generated by a mixture of stakeholders, including local communities, government agencies, and academic researchers. Many of the environmental datasets currently available were collected as part of projects funded by the Northwest Territories Cumulative Impacts Monitoring Program (NWT CIMP). CIMP is part of the Environmental Stewardship and Climate Change Division of Environment and Natural Resources (ENR) for the Government of the Northwest Territories. CIMP has aimed to partner with traditional knowledge holders and scientific researchers to monitor both anthropogenic and natural environmental changes through space and time. Its goal is to "support resource management decision-making and sustainable development by furthering our understanding of cumulative impacts." (GNWT 2021). Water and fish are key areas prioritized for research by CIMP, leading to many opportunities for researchers to collect baseline water quality data (GNWT 2021). Funding from CIMP represents key support for academic researchers, as well as for governmental and nongovernmental organizations.

In addition to research projects funded by CIMP, ENR also supports a large community-based monitoring program across the territory. ENR has partnered with 21 northern communities and has undertaken at least 24 water stewardship outreach activities across the land (Environment and Natural Resources, n.d). Many of the sites monitored are within the GSA,

including on the Mackenzie and Peel Rivers near Inuvik, Tsiigehtchic, Fort McPherson, and Aklavik.

In addition to the CIMP and community-based monitoring programs funded out of ENR, there are other important sources of environmental data for the GSA. The Gwich'in Renewable Resources Board (GRRB) has published many reports that include the collection and analysis of data. In addition, federal government agencies, such as the Department of Fisheries and Oceans and Indigenous and Northern Affairs Canada, periodically collect data relevant to the Gwich'in Settlement Area (e.g. DFO 2017).

Much of the existing water quality data available for the GSA can be accessed through various online portals or websites, including Mackenzie DataStream, the Gwich'in Tribal Council website, the Aurora Research Institute library, the NWT Discovery Portal, and online publications from the Departments of Fisheries and Oceans. However, it is difficult to get a full appreciation for the scope of water quality data and research that has been conducted in the GSA due to the fragmented nature of these resources.

For this review we had three objectives: (1) compile research or monitoring studies from all platforms; (2) search for studies and datasets that may not have been included on the most frequently used platforms (e.g. Mackenzie Datastream); and (3) to identify gaps in available data and research to better plan future work in the GSA. Having a synthesis of available data and research projects related to water quality should make it easier for researchers and the GRRB to address important research gaps and establish priorities for future study.

Methods

We performed a literature review to identify studies that investigated lakes and rivers in the GSA

using materials available from (1) NWT Discovery Portal (2) Departments of Fisheries and Oceans (3) Environment and Natural Resources, GNWT (4) Gwich'in Renewable Resources Board (5) Mackenzie DataStream (6) the Gwich'in Tribal Council (7) the Aurora Research Institute and (8) Google scholar. We considered data collected between 1970 and 2021 and used the following search terms in Google Scholar to identify studies: (i) fish in Gwich'in Settlement Area, (ii) water quality in Gwich'in Settlement Area, (iii) invertebrates in Gwich'in Settlement Area, (iv) phytoplankton in Gwich'in Settlement Area (v) traditional knowledge in Gwich'in Settlement Area. The start date of 1970 was chosen based on our inability to find many published datasets before that year. Stewart (1996) referenced many promising older studies in his literature review on harvest and fish stocks in the GSA, however most of the studies were unpublished and inaccessible, and therefore we could not evaluate if they contained water quality data. For each study we could access, we extracted information on the collected environmental variables, duration of the study, season of data collection, and summarized the purpose of each study and future research directions the researchers suggested.

Results

Our review of the literature found 51 studies that collected data about water quality in the GSA between 1970 and 2021. Of these studies, 25, 35, 18, and 14 collected data near the communities of Inuvik, Fort McPherson, Aklavik, and Tsiigehtchic, respectively (many studies visited multiple locations, so the numbers do not add to 51; Figure 1; Table 1). A wide variety of different sites were visited for data collection, but most of the available data were collected from just three locations: the Peel River, the Mackenzie River, and the Arctic Red River (Figure 2). The most common topics for the studies were water quality, fish, traditional knowledge of

environmental change, thaw slumping, benthic invertebrates, climate change, sedimentation, and metal contamination (Figure 3). In terms of habitat, rivers were studied more frequently than lakes (Figure 4).

Table 2 provides proposed recommendations or future directions for study extracted from each of the 51 studies we identified. Most of these recommendations were topic and site specific, but most of the authors suggested continuing monitoring and building on the existing data for a more through understanding of environmental changes (Table 2).

Table 1. The 51 studies found that collected water quality data or observations for the Gwich'in Settlement Area.

Study	Topic	Water body	Summary
Babaluk et al. 2001	fish, migration	Mackenzie Delta, Arctic Red River, Ramparts Rapids	Results of radio-tagging and biological information (ex. age) on fish in the Lower Mackenzie conducted during 1992 and 1993.
Byers et al. 2019	traditional knowledge	-	Compilation and synopsis of literature on the traditional knowledge concerning Dolly Varden.
Canadian Science Advisory Secretariat 2017	fish	Rat River, fish Creek	Estimated abundance of Dolly Varden using population models, observed genetic mixed-stock fishery, reported fish tagging results and recorded biological information such as length, weight, sex/maturity, and otolith for age estimation.
Chin et al. 2016	benthic invertebrates, permafrost thaw, water quality, sedimentation	Unnamed	Investigated the correlation between physical and chemical variables and macroinvertebrates in disturbed and undisturbed streams.
Cohen et al. 2020	water quality, benthic invertebrates	Unnamed	Investigated differences in water quality and morphometric characteristics for 23 lakes in the GSA along the dempster highway. Evaluated differences in

			macroinvertebrate communities between lake types.
Czarnecki 2008	water quality, metals, contaminants, traditional knowledge	Peel River	Contributed more data about water quality to track changes over time. Also addressed community concerns about contaminants in water and suspended sediment (water and suspended sediment sampling program 2002-2007).
Czarnecki and Beavers 1999	water quality, metals	Peel River	Observed water quality changes through time, river discharge and associations to seasonality.
Droppo et al. 1997	bacteria, water quality, sedimentation	Arctic Red River, Mackenzie Delta	Investigated controlling factors of flocculation and flocculation playing a role in transporting sediment and associated contaminants in rivers.
Gill et al. 2014	traditional knowledge	Peel River	A community-based approach to mapping Gwich'in observations of environmental changes in the Lower Peel River Watershed.
Greenland and Larsen 2001	traditional knowledge	Mackenzie River	Community concerns and knowledge about Broad Whitefish (Coregonus nasus) in the Gwich'in Settlement Area.
Gunter 2017	water quality, thaw slumping, road dust, sediment coring	Unnamed	Investigated whether road rust from the Dempster Highway altered water quality in lakes closest to the highway compared to lakes further away. Investigated if the presence of metals and other elements in lake sediment cores changed after the construction of the Dempster Highway. Observed changes in Non-Pollen Palynomorphs in lake sediment cores related to construction of highway. Looked at climate warming as an influence to changing assemblages.
Harris 2005	fish, migration	Travaillant Lake, Andrew Lake, Travaillant River, Crossing Creek Lake	Tracked movements of a Lake-locked population of Broad Whitefish (Coregonus nasus) in the Travaillant Lake System. Identified spawning areas and overwintering areas and migration patterns.
Harwood 2001	fish	Mackenzie River, Rat River, fish Creek	Reviewed status of fish stocks, harvesting, timing of upstream migration, catch per unit effort, effectiveness of mesh size of gillnets, identifying biological information (i.e. age, sex and maturity, spawning

			frequency and mortality/lifespan of Dolly Varden from 1989-2000.
Harwood et al. 2009	fish	Mackenzie River, Rat River, fish Creek	Reviewed status of fish stocks, harvesting, timing of upstream migration, catch per unit effort, effectiveness of mesh size of gillnets, identifying biological information (i.e. age, sex and maturity, spawning frequency and mortality/lifespan of Dolly Varden from 1989-2000.
Haszard and Shaw 2000	traditional knowledge	Rat River	Documented traditional and historical use of the Rat River watershed and biodiversity of animals in the Rat River watershed (including fish and birds).
Hay and Smol 1997	diatoms, water quality, seasonality	Unnamed	Used statistical models (i.e., canonical variate analysis) to determine the key gradients separating lakes in the Mackenzie Delta (i.e., sediment diatom assemblages and water quality variables).
Hovel et al. 2020	traditional knowledge		Highlighted the process in which local management agencies set monitoring and research priorities in GSA.
Hynes 2018	fish, water quality	Big fish River	Gathered traditional knowledge and local knowledge about Dolly Varden for decision making and management strategies. Collected water quality variables relative to the “smoking hills” and slumping along big fish river.
Hynes 2018	metals, fish, traditional knowledge, thaw slumping	Big fish River, Smoking Hills	Collected water quality variables to investigate elevated metal concentrations in vicinity where a mudslide occurred (aluminum, cadmium, copper, iron, zinc). Used traditional knowledge to learn more about potential impacts to fish habitat.
Kokelj et al. 2013	thaw slumping, water quality, ground ice	Unnamed	(1) intensive thaw slump activity can significantly increase stream sediment and solute concentrations across a range of watershed scales and (2) diurnal ground-ice thaw influences the patterns of water, sediment, and solute flux in streams impacted by mega slumps.
Lea et al. 2021	fish, traditional knowledge	Rat River, Big fish River, Peel River, Babbage River, Mackenzie Delta	Described Dolly Varden fisheries and management from 2009–2014, including harvesting and harvesting rates, decisions, monitoring programs, reports, and communications about Dolly Varden.

Levenstein 2016	water quality, algae, thaw slumping, benthic invertebrates	Unnamed	Investigated the impacts of retrogressive thaw slumps on algal biomass, organic matter breakdown, water quality, primary production, and decomposition in streams. Assessed the impacts of thaw slumps on benthic macroinvertebrate communities.
Littlefair et al. 2017	water quality, thaw slumping	Unnamed	Examine the effect of retrogressive thaw slumps on DOC concentration and transport.
Malone 2013	water quality, thaw slumping	Unnamed	Examined the geochemistry of the slump runoff, and the factors that influence its composition. Determined how slump runoff is affecting pristine streams in the watershed.
Mesquita et al. 2010	macrophytes, thaw slumping, sediment chemistry, benthic invertebrates	Unnamed	Investigated changes in sediment chemistry and submerged macrophyte biomass in lakes disturbed and not disturbed by thermokarst slumping. water quality parameters, submerged macrophytes, benthic invertebrates, and sediment were collected.
Murdoch 2021	fish, water quality, thaw slumping, climate change	Unnamed	Drivers of fish community health in lower Mackenzie River basin lakes
Ogbebo et al 2009a	water quality, climate change, phytoplankton, nutrients	Bathing Lake, Deep Lake, Travaillant Lake, Sandy Lake, Crossing Creek Lake, Wood Bridge Lake, fish Trap Lake, Hill Lake, Caribou Lake, Noell Lake, Jimmy Lake, East Hans Lake, West Hans Lake, Parsons Lake, Wolf Lake, Pullen Lake, Mid Lake, Yaya Lake, Trench Lake, Old Trout Lake,	Limnological variables from 30 lakes situated along the proposed Mackenzie Gas Project pipeline route in the Canadian Northwest Territories. Collected phytoplankton from lakes.

		Kimialuk Lake, Denis Lagoon Lake, Big Lake	
Ogbebo et al. 2009b	water quality, climate change, phytoplankton, nutrients	Big Lake,Parsons Lake,Hill Lake,fish Trap Lake,Wood Bridge Lake,Travaillant Lake,Yaya Lake,Noell Lake,East Hans Lake	Water chemistry and the nutrients limiting phytoplankton growth were examined in lakes located in the Northwest Territories, Canada, along a transect from the Mackenzie River Delta south to Travaillant Lake.
Paquette 2015	water quality, thaw slumping, hydrology	Peel River, Big fish River, Willow River, Rat River, Stony Creek, Vittrekwa River, Road River, Caribou River	Generated a database of geochemical composition of streams in the Richardson Mountains, Peel Plateau. Investigated relationship between the distribution of thaw slumps and stream geochemistry at various hydrological scales. Observed size of slumps as factor influencing downstream geochemistry. Observed cumulative impact of thaw slumps on downstream geochemistry.
Parlee and Maloney 2016 (Editors)	traditional knowledge	Mackenzie River	Traditional knowledge on water quality, quantity, flow, groundwater, permafrost conditions, change in fish species (population, movements, diversity, invasive species) and other aquatic species (e.g., geese, beaver), sustainability of fishing livelihoods (e.g., harvesting levels and practices, diet, health, access issues, perceptions of change in the health of valued fish species) and management practices.
Parlee and Martin 2016	traditional knowledge	Peel River	Literature review of local and traditional knowledge in the peel river watershed including water quality and water levels, fish and fish habitat, ducks, and geese, disturbances of the watershed, climate change and governance and stewardship (and more).
Pienitz et al. 1997	water quality	Unnamed	Water chemistry and other limnological data gathered for lakes and interpreted using linear regression and principal components analysis.

Popper et al. 2005	fish, noise	Mackenzie River	Physiological evaluation of the effects of air gun uses on the hearing sensitivity of fish.
Proverbs 2014	traditional knowledge		Cumulative impacts in the cultural landscape, and determinants of access to fish.
Proverbs et al. 2020	traditional knowledge		Described multiple environmental changes occurring in the Gwich'in Settlement Area.
Reviewed by Andrea Czarnecki et al. 2012	water quality	Peel River	Collected baseline water quality for several water quality analytes of the Peel River. The effect of season and time on dissolved calcium concentrations was observed. The effect of season and flow rate on calcium concentration was also observed.
Ross 2003	fish, water quality, benthic invertebrate, traditional knowledge	Mackenzie River, Peel River	Collected information about habitat water quality upstream and downstream and near ferry crossing. Observed spawning and feeding habits of fish near ferry crossing. Observed hydrology changes such as current changes near ferry crossing.
Salokan 2005	traditional knowledge		Participants talked about their concern about run-offs, stream crossings, changes in water flow rates and fish migration. Most of the participants (74%) were very concerned about water. Infrastructure such as roads mentioned to cause pollution to lakes and caused the live hood in communities to go down. Run-off from sumps can cause contaminants potentially effecting fish.
Schwab et al. 2020	dissolved organic carbon	Arctic Red River, Mackenzie River, Peel River	Explored interannual variability in DOC export from a major Arctic fluvial system.
Stewart 1996	fish, harvesting	Unnamed	A literature review on stocks of fishes harvested for subsistence, commercial scale, and sport in the GSA. Management strategies are also discussed.
Tallman 2001	fish	Campbell Lake, Campbell Creek	Gathered baseline data about abundance, fork length, species composition and catch rates per season of various fish species.

Teillet 2020	fish, benthic invertebrates, water quality, sedimentation, traditional knowledge	Mackenzie River,Peel River	Investigated influence of ferry landings on water quality and sediment loads in Mackenzie and Peel River. Used benthic macroinvertebrates as indictor species to assess the cumulative impacts of ferry landing activities. Used Traditional Knowledge to determine the impacts of ferry landing on study sites.
Thompson 2018	fish, contaminants	Bombadeer Creek, Sam Arey's Creek,Arctic Red River, Mackenzie River, Woody Elias Creek,Basook Creek, Nelson Creek,Husky River, Hudson Creek, Bay Creek, Rotten Eye Creek, Jackfish Creek	Compared the contamination content (organochlorines and metals) in fish livers from water that was characterized as "good or bad" by local Gwich'in fish monitors. Stable isotopes, age, length, weight, and sex were also investigated.
Thompson and Millar 2007	traditional knowledge	Arctic Red River,Mackenzie River	traditional knowledge of fish migration and spawning patterns in Tsiigehnjik (Arctic Red River) and Nagwichoonjik (Mackenzie River), Northwest Territories
Toyne and Tallman 2000	fish	Peel River	Recorded when fish species migrate up the Peel River to spawn, and collected biological information about fork length, weight, sex, maturity stage and fecundity (The Peel River fish Study, 1998 – 1999).
VanGerwen-Toyne 2002	fish	Peel River	Recorded when fish species migrate up the Peel River to spawn, and collected biological information about fork length, weight, sex, maturity stage and fecundity (The Peel River fish Study, 2001).
VanGerwen-Toyne 2008	fish	Peel River, Arctic Red River, Travaillant Lake	Compared life history traits between anadromous and lacustrine stocks of broad whitefish (Coregonus nasus).
Vucic et al. 2019	zooplankton, benthic invertebrates,	Unnamed	Compared gravel-pit and natural lakes by sampling lakes between Inuvik and Fort McPherson. Collected lake morphometry, water quality, and biological data

	water quality, fish		(zooplankton, macroinvertebrates, and fish presence) from six gravel-pit lakes and fifteen natural lakes.
Vucic et al. 2020	zooplankton, water quality, thaw slumping	Unnamed	Examined how changes in water quality associated with permafrost thaw might impact zooplankton, developed models linking variation in the abundance, diversity, and evenness of zooplankton communities to physicochemical, biological, and spatial variables.
Zhu et al. 2019	road dust, water quality, paleolimnology, diatoms, climate change	Unnamed	Investigated dust and its effects on water quality and diatom assemblages in lakes along the dempster highway. Explored the effect of accelerated regional warming on water quality and diatom assemblages.
Zolkos 2019	water quality, thaw slumping, carbon cycling, thermokarst	Unnamed	Explored the effects of thermokarst on mineral weathering, inorganic carbon cycling and DIC production in streams. Observed changes in CO2 and CH4 levels in streams affected from thermokarst. Determined the effect of permafrost mineral composition and thaw history on DIC production and speciation.

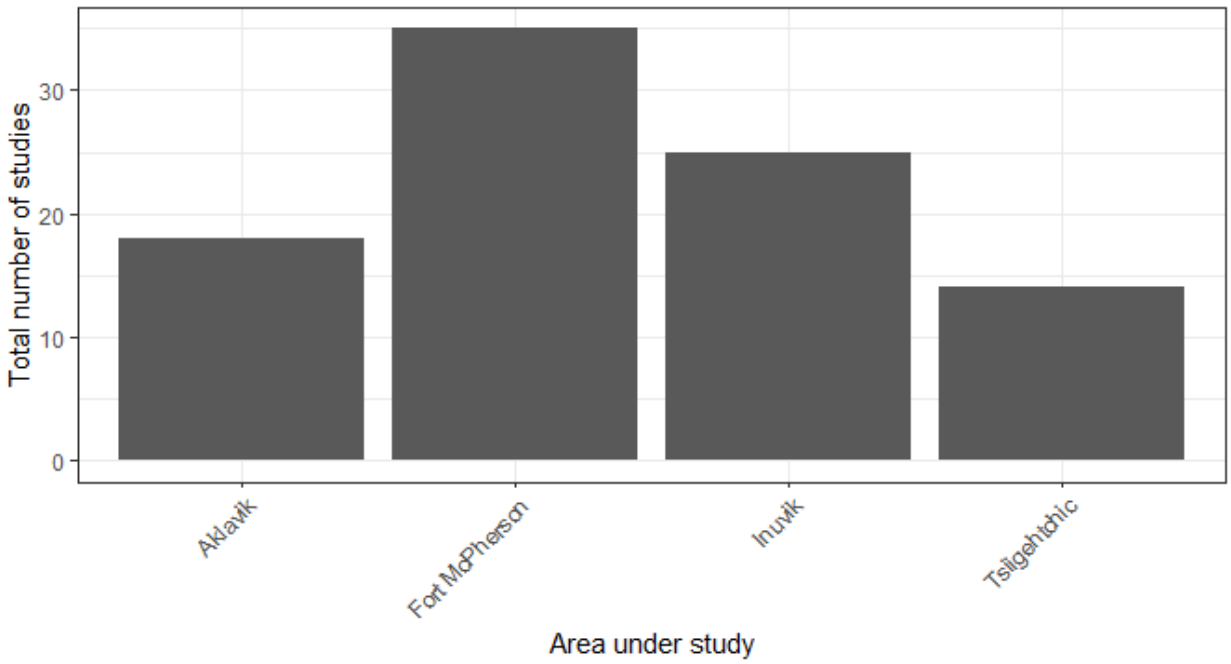

Figure 1. Total number of studies that collected data nearby or within the communities of Aklavik, Fort McPherson, Inuvik, and Tsiigehtchic.

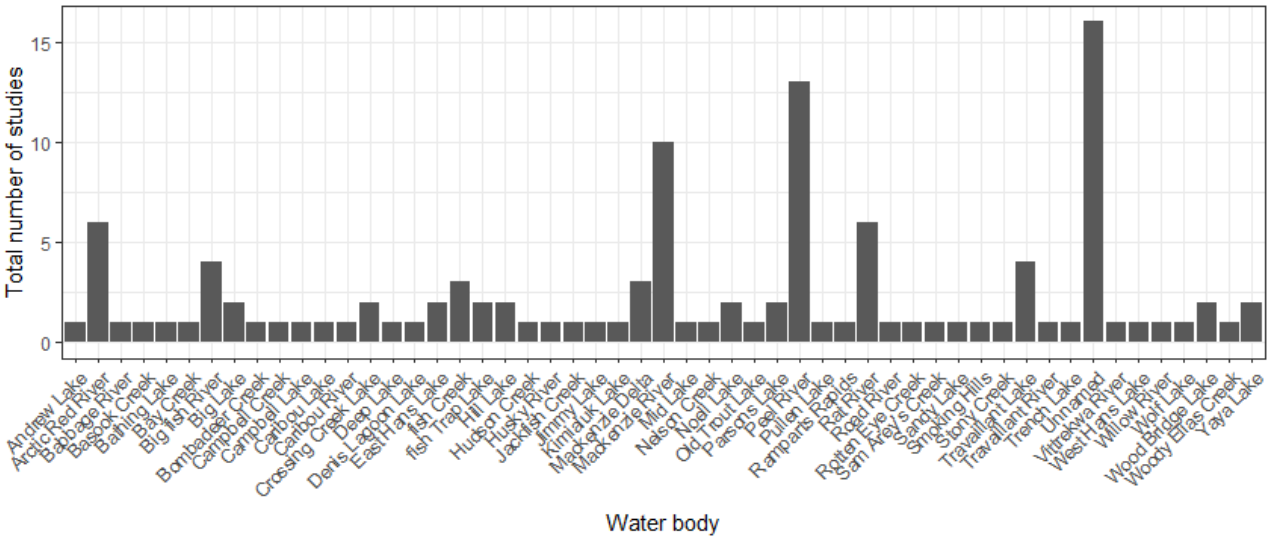

Figure 2. Locations visited for data collection in the 51 studies found during our review.

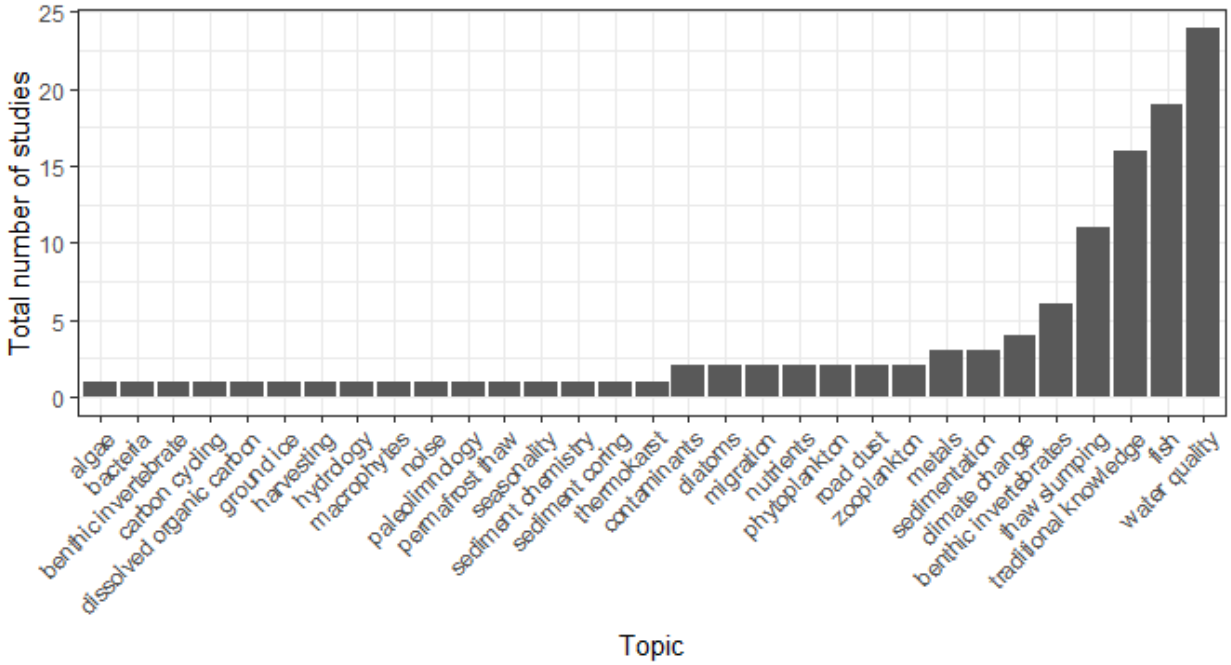

Figure 3. Number of studies that covered different research topics based on our review.

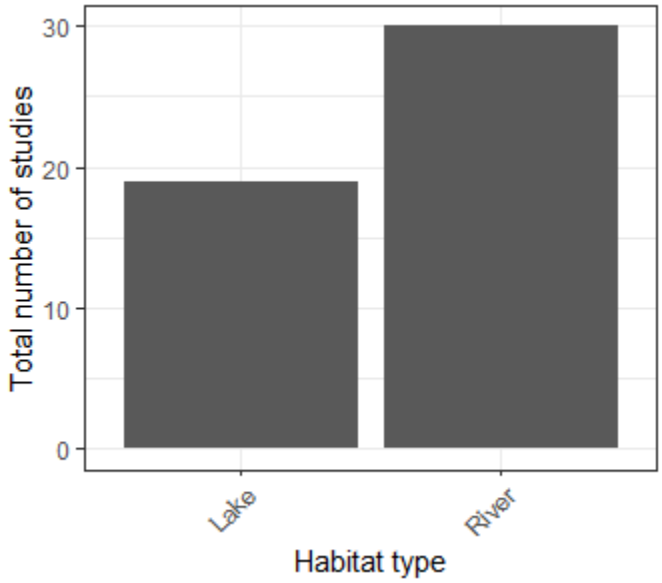

Figure 4. Habitat types covered by the 51 studies in our review.

Table 2. Future directions or research as suggested by authors of the studies found in our review.

Study (click for access where available)	Future directions/ gaps in research
Babaluk et al. 2001	- Suggested that conservation and management plans are needed for the studied fish populations.
Byers et al. 2019	- Continued studies of habitat change and Dolly Varden responses are needed to establish effective management of the species. Field observations are needed by Inuvialuit and Gwich'in land users.
Canadian Science Advisory Secretariat 2017	- Suggested to gather local knowledge in association with the harvest data to better understand how environmental conditions affected catches and effort in the fishery.
Chin et al. 2016	- Predict macroinvertebrate community response to TSS concentrations and distance to and intensity of thermokarst disturbance in streams - Better understanding of stream food web response to thermokarst disturbance is needed
Cohen et al. 2020	- Investigate if macrophytes can influence macroinvertebrate communities in lakes - Increase taxonomic resolution to a genus and species level to help understand responses to environmental gradients.
Czarnecki 2008	- Continue to monitor surface water samples from the Peel River upstream from Fort McPherson and perform follow-up water and suspended sediment sampling to monitor changes over time
Czarnecki and Beavers 1999	- Collect baseline information about polycyclic aromatic hydrocarbons (PAHs) organic compounds at Peel River above Fort McPherson - Collect sediment samples at Peel River above Fort McPherson to investigate the effect of sedimentation on water quality and to estimate sediment load - Sample during freshet and recession to better characterize the water-year in the basin
Droppo et al. 1997	- Examine particle size distribution of sediments on the Mackenzie River delta.
GeoNorth 2002-2003 *Ross 2003	- Community members suggested examining health of fishes near ferry crossing. - Community members suggested producing plan in case of oil or chemical spill near ferry crossing - Explore the potential connection between the pollution in caribou river and fish near ferry crossing. - Elders suggested ferry crossing study needs to be extended to observe long term impacts.

	- Community members suggested studies about changes in colour, taste, and parasitic presence in fish near ferry crossing. - Community members suggested studying river flow, sandbars and eddies affecting fish populations. - More benthos abundance studies are needed as they are believed to be declining therefore there is less food for fish.
Gill et al. 2014	- Continue dialogue with traditional knowledge holders to mapping Gwich'in observations of environmental changes in the Lower Peel River. - Researching topics such as dangers of infrastructure damage and climate change impacts should be explored
Greenland and Larsen 2001	- Traditional knowledge holders suggest conducting more studies on broad whitefish and commercial fishing and overharvesting by locals.
Gunter 2017	- Continue to investigate impacts of calcareous road dust on aquatic lakes near Dempster Highway. - Investigate the relationship between *Sphagnum* and algal palynomorphs (such as *Pediastrum*) found within the lakes close to the Dempster Highway. - Set dust traps along the Dempster Highway at various distances from the road to understand of how the dust travels and accumulates.
Harris 2005	- Continue to track movements of Broad Whitefish and other fish for exact locations in the Travaillant Lake System
Harwood 2001	- Continue to monitor status of fish stocks and collect relevant data to manage stocks and monitor compliance with the Rat River Dolly Varden fish plan.
Harwood et al. 2009	- Conduct genetic analyses on fin and other tissue samples from Dolly Varden
Haszard and Shaw 2000	- Use baseline information about Rat River status as a potential protected area for future decision making and management strategies about fish, birds and more.
Hay and Smol 1997	- Evaluate future warming impacts on the Mackenzie River discharge record.
Hovel et al. 2020	- External researchers in the GSA should collaborate with local community members more often. Use available data bases provided in study to build on past research.
Hynes 2018	- Community-wide surveys regarding observations related to Dolly Varden health and habitat are needed. - Suggested to encourage more youth to facilitate harvest. - Recommended that more training to monitors is needed to help avoid stress to Dolly Varden and potential incidental mortalities.
Hynes 2018	- Contribute to future decision-making processes and management recommendations of Dolly Varden using their study

Kokelj et al. 2013	- Continue to monitor thaw slumping and its effects to surrounding aquatic environments as climate projected to become warmer.
Lea et al. 2021	- Use their available data on Dolly Varden for management strategies and future decision making for preserving species.
Levenstein 2016	- Researchers should consider using a gradient design to observe thaw-slump stream disturbance intensity and magnitude as opposed to a control/impact design. - Investigate algal and microbial communities in streams affected by thaw slumping - Investigate chronic impacts of thaw slumping on primary production and organic matter breakdown in disturbed streams - Predict the long-term changes in streams that receive inputs from thaw slumps.
Littlefair et al. 2017	- Quantify mechanisms that enable DOC sequestration to occur
Malone 2013	- Increase sampling efforts (i.e., every hour) during mud flow event to obtain diurnal fluctuations - Determine solute flux emerging from thaw slumps
Mesquita et al. 2010	- Explore other environmental changes such as slump layer deepening, higher UV penetration in lakes, changes in biota composition/ metabolism, and changes in runoff input because of biogeochemical cycles at landscape level.
Murdoch 2021	- Author suggested that investigating the link between seasonal water quality and under ice-oxygen the winter season is needed. - Suggested that studying lakes and rivers on permafrost zone and near infrastructure has unknown impacts - Suggested that it would be beneficial to incorporate a broader range of permafrost thaw impacts on freshwater habitat into future studies.
Ogbebo et al 2009	- Create long term monitoring plan and track changes in for reference lakes (collected water quality in 30 lakes)
Ogbebo et al. 2009b	- Observe future effects (warming) on nutrient limitation of phytoplankton growth in Arctic lakes of the lower Mackenzie River Basin
Paquette 2015	- Investigate if unsuitable water could pose danger to fish spending months over-wintering in unfrozen water.
Parlee and Maloney 2016 (Editors)	Questions future researchers should consider while studying the Mackenzie River Basin for fish and river health, water quality and quantity, environmental and socioeconomic changes, access to fishing camps and equipment, knowledge transmission, and future project activities and goals: - *"What kinds of unusual events or patterns are visible and to what extent are these associated with the impacts of climate change and resource development?"* - *"What is the meaning and significance of observed trends and patterns of ecosystem change?"*

	- *"What are useful indicators for tracking aquatic ecosystem change in the Mackenzie River Basin?"* - *"How should we respectfully and meaningfully track these changes over time"*
Parlee and Martin 2016	Questions researchers should ask or address before conducting scientific aquatic ecosystem health studies: - *"Did the study involve documenting sources of Traditional Knowledge (i.e., documentation of the values, knowledge, practices, and institutions of a particular Aboriginal group?)"* - *"Was the study focus defined by Traditional Knowledge? (i.e., selection of issues or valued ecosystem components being studied)?"* - *"Was the study led or guided by an Aboriginal community?"* - *"Did the study have some other relevance to Aboriginal communities?"*
Pienitz et al. 1997	- Study deeper lakes for water quality in GSA - Explore the relationship between nutrient changes in lakes and their association with vegetational and climatic zones.
Popper et al. 2005	- Authors suggest that future studies should examine the time course of recovery of the effects of air gun uses on the hearing sensitivity of fish.
Proverbs 2014	- Future research could focus on documenting the relationship between social-ecological change, access to fish, and well-being. - Suggested that engaging local youth, organizations, and elders in studying disturbances and environmental changes is very important and needed.
Proverbs et al. 2020	- The need to bridge knowledge gap between science and local experiences and traditional knowledge to better examine environmental change.
Reviewed by Andrea Czarnecki et al. 2012	- Consider generating a risk-based site-specific protective guideline on all parameters (e.g., total metals) studied. - Consider studying nutrient limitations consistent the switch from oligotrophic to eutrophic, or from N-limitations in spring to P-limitations during winter in the GSA.
Salokan 2005	- More comprehensive studies should be conducted regarding flow rates and fish migration in the GSA. - Future studies should focus on having a broader and wider sampling plan in the GSA
Schwab et al. 2020	- Projections in climate warming show the urgent need to track the fate of aged carbon and the effects on the warming of permafrost thaw
Stewart 1996	- Use their available data and review of literature to manage Broad whitefish.

Tallman 2001	- Author suggested that a comprehensive assessment of the environmental condition of Campbell Lake is needed to understand the potential changes in fish and water quality.
Teillet 2020	- Sampling turbidity and total suspended solids throughout the water column in the Mackenzie and Peel river might be useful to show any missing trends. - Recommended to continue fish harvesting data in the Mackenzie and Peel River near ferry crossing. - Increase sample sizes of total sediment load in the peel and Mackenzie rivers to detect smaller changes in on going monitoring
Thompson 2018	- Future studies should increase the sample size of livers from fish to highlight any between metals and liver toxicity
Thompson and Millar 2007	- Future studies should consider including traditional knowledge as traditional knowledge holders could educate researchers about migration patterns and spawning seasons of fish in Arctic Red River and Mackenzie Rivers.
Toyne and Tallman 2000	- The authors recommended that providing more in-depth training for monitors and having more consistency with the monitors chosen for a study may be beneficial for monitoring programs. They also suggested that it may be beneficial to investigate if using smaller mesh sizes can catch younger whitefish and therefore increase catch-effort compared to using only larger nets.
VanGerwen-Toyne 2002	- Recommended building on information on fishes' biological characteristics, migration habits, spawning habits, and generate data that may be compared to future (e.g. post-disturbance) conditions in peel river.
VanGerwen-Toyne 2008	- Tagging or radio tracking on broad whitefish population dynamics needed in the lower Mackenzie River system.
Vucic et al. 2019	- Increase sample size of lakes studied (only able to get data from fifteen natural lakes and six gravel pit lakes). - Examine differences in profundal macroinvertebrate communities between gravel pits and natural lakes
Vucic et al. 2020	- Examine links between zooplankton and fish in arctic lakes - Incorporate long term data to study to observe how zooplankton have changed through time. - Observe changes in zooplankton in lakes affected by thaw slumps vs. lakes that are undisturbed.
Zhu et al. 2019	- Evaluate the distance at which dust ceases to lakes on along the dempster highway
Zolkos 2019	- Investigate the effects of thermokarst on carbon cycling in fluvial network headwaters in northern permafrost terrains

Discussion

Our review of the literature showed that more studies were conducted near Fort McPherson and Inuvik rather than Aklavik and Tsiigehtchic. The concentration of studies near these communities likely relates to Inuvik being the main hub for research with the Aurora Research Institute facilities and the difficulty of accessing Aklavik due to lack of road access. The locations for study were also driven by the water bodies that receive the most attention for study. The Mackenzie, Peel, and Arctic Red Rivers were overwhelmingly the focus of most past studies. Again, this may relate to their ease of access, but it also likely a function of their importance for the Gwich'in people as a source of fish, and a method for transportation to hunting or fishing camps (Thompson and Millar 2007; Wishart 2009; Wray and Parlee 2013). In recent years, researchers have recognized the importance of conducting research that is relevant to local communities and driven by community concerns (Parlee et al. 2014). Therefore, it is possible that the main rivers have been selected based on feedback from communities. Our presentation of research sites in Figure 2 demonstrates that a diversity of other sites have also been studied, including a variety of unnamed lakes and rivers. However, the lack of follow-up studies in many of these systems begs the question as to whether environmental monitoring data for many sites outside of the main rivers would allow for an assessment of cumulative impacts.

The topics most frequently studied included water quality, fish, traditional knowledge of environmental change, thaw slumping, benthic invertebrates, and climate change. The choice of research topics for environmental monitoring and research is likely influenced by both community concerns, funding availability, and the emergence of important environmental stressors. The preponderance of studies of water quality and fish may relate to the priorities and concerns expressed by Gwich'in communities (e.g. GeoNorth-Ross-AMEC 2003). The Gwich'in

have visited many of these water bodies for millennia, establishing fishing camps on both the Mackenzie and Peel Rivers (Nolin & Pilon 1994). The availability of funding is also likely a driver of the types of research that have been conducted in the GSA. The Cumulative Impacts Monitoring Program is perhaps the largest funder of environmental research in the area, and its stated goal is to "support resource management decision-making and sustainable development by furthering our understanding of cumulative impacts" (GNWT 2021). Funding projects that pursue this goal would tend to favour projects examining climate change, permafrost thaw, thaw slumping, and the collect of traditional knowledge on environmental change. No doubt the recognition of the rate of climate change within the last two decades, coupled with the recognition of important landscape changes by Gwich'in communities, has also made efforts to understand these topics desirable research areas.

We also found that more studies examined rivers rather than lakes. Again, this is likely driven by the importance of the three main river systems for Gwich'in communities. However, given the presence of thousands of lakes in the Mackenzie Delta, this raises the question as to whether lakes are understudied relative to rivers, and whether adequate baseline data exists for these systems. For example, the recent study by Murdoch et al. (2021) was one of few studies that have examined fish in the region's lakes. Tracking changes in fish in the region's lakes will be difficult without a conscious effort to support research and monitoring efforts outside of the three main river systems.

A synthesis of future research priorities based on our synopsis of future research suggestions in Table 2 is difficult due to the diversity of study locations and topics. Some of the most prominent themes identified for future research and monitoring include: (1) Continued monitoring of climate change effects on water quality, (2) Studies on how fish abundance and

distribution may be affected by environmental changes, (3) developing a better understanding of seasonal changes in water quality (4) conducting more community-based surveys and having continuous dialogue with traditional knowledge holders, (5) tracking the movement and effects of road dust along the dempster highway, (6) conducting more studies on lakes and ponds (7) investigating impacts of climate change on aquatic food webs (especially invertebrates) and birds, and (8) continuing to build baseline datasets that will allow for robust tracking of environmental change.

The themes we have identified for future research based on our assessment of the 51 studies in our review are likely biased by the research specializations of the authors of this review (Elmarsafy and Gray both study invertebrates in lakes and ponds). Therefore, we hope that others will consider the suggestions for future research summarized in Table 2 based on their own fields of study. Following up on research and monitoring gaps identified in past studies may be the best way to ensure that we are building up our knowledge of cumulative effects in the GSA rather than repeating studies or duplicating monitoring efforts already underway. Continuing dialogue with communities and Traditional Knowledge Holders should also be a significant goal to ensure that efforts to build on past research and monitoring projects will provide information relevant to those who make the GSA their home.

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