State of Knowledge of Riverbank Erosion and Climate Change in the Northwest Territories

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

1. PLAIN LANGUAGE SUMMARY

Ecofish Research Ltd. completed a literature review and synthesized information on riverbank erosion and stability for the Department of Environment and Climate Change – Climate Change, Cumulative Impacts and Knowledge Division of the Government of the Northwest Territories (the Project) to support the Northwest Territories (NWT) Climate Change Risk and Opportunity Assessment.

The objectives of the Project are to:

- Present a comprehensive summary of riverbank erosion in the NWT, including information on climate linkages, causal mechanisms, regional variations, and differences between rivers;
- Determine which NWT communities are vulnerable to current and future riverbank erosion; and
- Identify data and research gaps concerning riverbank erosion across the NWT and provide recommendations to address these gaps.

Our approach for completing the Project was to summarize literature related to the character and behaviour of river systems, fundamentals of riverbank erosion, NWT riverbank erosion studies, and the predicted changes to riverbank erosion processes. We reviewed consultant reports for seven NWT communities and incorporated the outcomes of two community events, including the Riverbank Erosion Partnership Table Meeting and the NWT Climate Change and Riverbank Erosion Workshop, which involved multiple NWT communities and subject matter experts.

Climatic warming and permafrost thaw are predicted to increase Arctic riverbank erosion, threatening riverside communities and infrastructure (Douglas *et al.* 2023). Twenty of the 33 NWT communities are located on or adjacent to riverbanks that are susceptible to erosion in a warmer climate. However, there is a general lack of monitoring and research on riverbank erosion in the NWT. There are limited QA/QC'd climate, hydrology, permafrost, and streambed (bathymetry and cross-section) data, which are needed to develop hydraulic models and help fill information gaps such as the role of river ice versus open water discharge in driving riverbank erosion. No studies have focused on the socioeconomics of relocating communities and infrastructure away from riverbanks or local and traditional knowledge on erosion, hydrology, and other water processes.

Work in addition to the Climate Change Risk and Opportunity Assessment is needed to accurately and confidently assess the potential risks of riverbank erosion in the NWT. To fill the aforementioned information gaps, we recommend designing satellite- and aerial-based studies, completing site-specific geotechnical assessments and monitoring programs, implementing long-term solutions, expanding monitoring of climate conditions, hydrology, and terrestrial environments, ensuring leadership, collaboration, and consistency into the future, and sharing information through a centralized database to guide decision-making and inform future work.

2. INTRODUCTION

Ecofish Research Ltd. completed a literature review and synthesis on riverbank erosion and stability on behalf of the Department of Environment and Climate Change – Climate Change, Cumulative Impacts and Knowledge Division of the Government of the Northwest Territories (GNWT) (the Project) to support the Northwest Territories (NWT) Climate Change Risk and Opportunity Assessment (ROA). The ROA supports the development of the 2025-2029 NWT Climate Change Action Plan (Government of the Northwest Territories 2023). During the review and evaluation of the ROA, the GNWT determined that additional information on riverbank erosion was required to enhance and further inform the work completed to date. The Project will support future work on riverbank erosion.

Through a review of available research, the Project focused on three primary objectives:

- Provide a background or literature summary of riverbank erosion in the NWT, including climate linkages, causal mechanisms, regional differences, and differences between large and small rivers;
- Identify which NWT communities are susceptible to current and future riverbank erosion; and
- Identify data and research gaps related to riverbank erosion across the NWT and provide recommendations for addressing these gaps.

Following the initial draft of the Project, two events were held to hear from communities experiencing riverbank erosion and to gather subject matter experts to help inform and provide guidance on developing the ROA for riverbank erosion.

1. Riverbank Erosion Partnership Table Meeting, organized by the NWT Association of Communities, November 29, 2023. This meeting brought together community representatives, GNWT partners, researchers, and other stakeholders involved in this issue. This was the first meeting of an ongoing initiative to bring these partners together to share information, identify the gaps and needs of communities, and look for ways to work together.
2. The NWT Riverbank Erosion and Climate Change Workshop, organized by the GNWT-Climate Change Unit on March 6, 2024. This workshop brought together leading subject matter experts to help inform and provide risk scores for riverbank erosion in the NWT as part of the development of the ROA.

Results from these events have been incorporated into the Project. A summary of these events is included in Appendix A.

3. APPROACH

Using Google Scholar, literature searches were conducted to identify and locate peer-reviewed studies on riverbank erosion in the NWT. It became clear that literature on this topic is limited, so searches were expanded beyond the NWT using several search terms (e.g., riverbank erosion/stability, channel planform, channel stability, thermal erosion) to draw on circum-Arctic knowledge. Limiting search terms ensured that searches were targeted and repeatable and kept the resources requiring review manageable. Searches for reports that cite key information sources identified through this process were conducted where time allowed. We incorporated community-led studies and initiatives (where available from Ehrlich pers. comms. 2023) and assembled references to create a contemporary body of knowledge.

4. LITERATURE SUMMARY

Climatic warming and permafrost thaw are predicted to increase Arctic riverbank erosion, threatening riverside communities and infrastructure (Douglas *et al.* 2023). Twenty of the 33 NWT communities are located on or adjacent to riverbanks that are susceptible to erosion in a warmer climate (Table 1). In this section, we summarized the character and behaviour of river systems, the current knowledge of causal factors and processes controlling riverbank erosion, NWT studies, and the projection of change in riverbank erosion processes and rates in the future.

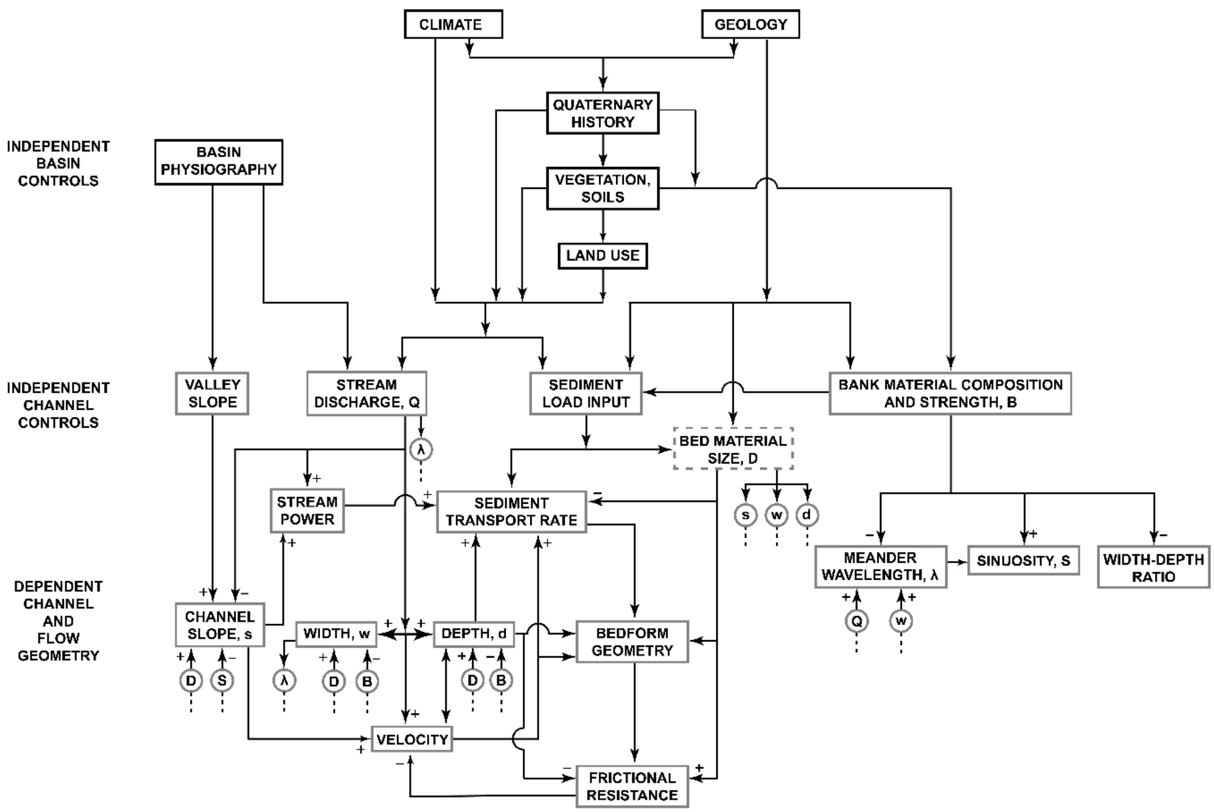
Table 1. NWT communities located on or adjacent to riverbanks.

Community	River
Aklavik	Mackenzie River (Peel Channel)
Enterprise	Hay River
Fort Good Hope	Mackenzie River
Fort Liard	Liard River
Fort McPherson	Peel River
Fort Providence	Mackenzie River
Fort Resolution	Slave River
Fort Simpson	Confluence of Liard and Mackenzie River
Fort Smith	Slave River
Hay River	Hay River
Inuvik	Mackenzie River (East Channel)
Jean Marie River	Confluence of Jean Marie and Mackenzie River
Kakisa	Kakisa River
Kátł'odeeche	Hay River
Norman Wells	Mackenzie River
Nahanni Butte	Confluence of Liard and South Nahanni River
Sambaa K'e	Island River
Tsiigehtchic	Confluence of Arctic Red and Mackenzie River
Tulita	Confluence of Great Bear and Mackenzie River
Wrigley	Mackenzie River

4.1. Character and Behaviour of River Systems

Rivers are dynamic systems whose character and behaviour at any location reflect the integrated effect of a set of upstream controls, notably climate, geology (including Quaternary history), basin physiography, and land use, which together determine the hydrologic regime, the quantity and type of sediment supplied, and the morphology of the river channel (Knighton, 1999; Church, 2006). Downstream controls, such as the base level, are also important. These controls have complex feedback relationships that operate across various spatiotemporal scales (King 1970), making it difficult to discern the importance of change in one system component over another. Figure 1 demonstrates this complexity among processes controlling river systems.

Figure 1. Interrelationships in river systems. Arrows indicate the direction of influence, and relationships are indicated as direct (+) or inverse (-). Modified from Knighton 1999.

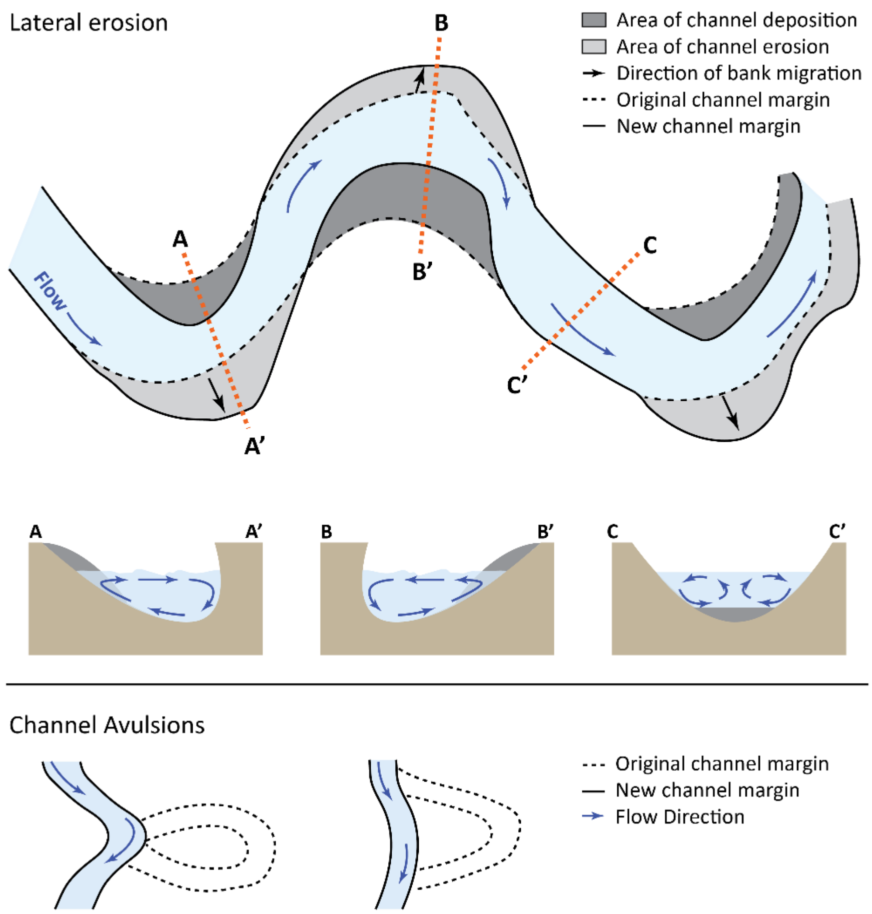


4.2. Fundamentals of Riverbank Erosion

There have been several recent literature reviews detailing the current understanding of riverbank erosion in northern watersheds (Lininger and Wohl 2019; Brown *et al.* 2020; Chassiot *et al.* 2020; Lotsari *et al.* 2020; Overeem *et al.* 2022; Tananaev and Lotsari 2022). These reviews describe the various causal factors, processes, and mechanisms and their associated landforms related to bank failure and those controlling bank stability. They distinguish ice-related phenomena from hydraulic mechanisms and discuss the relationships and possible feedback between processes and climate. In summarizing site-specific studies, the authors demonstrate that riverbanks are dynamic interfaces between atmospheric, terrestrial, and fluvial domains with complex feedback that prevail at different spatial and temporal scales. Here, descriptions of the causal factors, processes, and associated landforms controlling riverbank stability are intentionally brief and point the reader to resources for more detailed investigation.

Riverbank erosion is a natural geomorphic process integral to functioning river ecosystems (Florsheim *et al.* 2008). The fundamental processes of riverbank erosion are *lateral erosion* and *channel migration*. Lateral erosion is the process by which the flow of a river mobilizes riverbank material along the margins of the channel, causing the riverbanks to shift outwards (e.g., channel widening). Lateral erosion on both riverbanks can occur gradually over time or rapidly as mass failures (Rinaldi and Darby 2007). Lateral erosion allows a river to adjust its width and increase its sediment transport capacity in response to changes in hydrology, sediment supply, and channel morphology (Church, 2006). Channel migration is when a stream or river channel gradually migrates across its floodplain (e.g., the Mackenzie River Delta). Channel migration can occur progressively as meanders shift laterally or downstream due to flow around a sinuous channel bend, eroding its outer bank and depositing sediment along its inner bank (Leopold and Wolman, 1960). Similarly, it may occur as a rapid change in the channel alignment during an avulsion, a rapid abandonment of a river channel, or the formation of a new channel. Different types of river channels (meandering, braided, and straight reaches) have characteristically different bank erosion rates (Church, 1977; 2006; Walker *et al.* 1987; Walker and Hudson, 2003). These fundamental processes are demonstrated conceptually in Figure 2.

Figure 2. The fundamental concept of lateral channel migration at bends in the river as the flow of water erodes one bank and deposits sediment along the other (top), and examples of channel avulsions (bottom).



Riverbank stability is influenced by a suite of causal factors, processes, and mechanisms that can be grouped into three broad domains: atmospheric, terrestrial, and fluvial (Tananaev 2016; Tananaev and Lotsari 2022). The atmospheric domain includes the fundamental properties of climate, providing the energy for the most important processes shaping the terrestrial and fluvial domains (e.g., radiation, air temperature, precipitation, wind) (Knighton, 1998). The change in these processes has a cascading effect on all other domains. The terrestrial domain includes site-specific processes and mechanisms operating directly on the exposed riverbanks above water level, including the effects of human and wildlife action (Chassiot *et al.* 2020). They include slow-acting processes and mechanisms that affect riverbank stability (e.g., pore-water pressures, groundwater seepage, freeze-thaw cycles, vegetation) and more rapid, mass wasting processes (e.g., debris falls, slides, and slumps) (Chassiot *et al.* 2020; Beltaos and Burrell 2021). Riverbank stability also depends on the soil type and characteristics, bank geometry and in northern watersheds, permafrost, and active layer dynamics (Brown *et al.* 2020; Rowland *et al.* 2023). Fluvial processes are related to annual river ice dynamics, water temperature (thermo-erosion), and river flows that erode and convey material from the banks (Ettema 2002; Lotsari *et al*. 2020). Fluvial erosion occurs across all ranges of water levels, and water levels establish which sections of the riverbank are exposed to fluvial or terrestrial and atmospheric processes (Costard *et al*. 2014; Tananaev 2016). Given the multitude of causal factors and processes controlling riverbank erosion and their complex feedback relationships over varying spatiotemporal scales, it is impossible to discuss each in detail within this scope of work. Instead, we provide a conceptual diagram demonstrating the different components relevant to riverbank erosion in northern environments in Figure 3 and descriptions of each in Table 2. It should be noted that this list is not exhaustive and that other relevant mechanisms may have been unintentionally omitted.

Figure 3. **Summary of the domains and their causal factors, processes, and landforms that influence riverbank stability in northern rivers. These processes' nature, intensity, and timing are site-specific and controlled by local factors. Process descriptions are provided in Table 2. Modified from Lawson (1983) and Chassiot *et al.* (2020).**

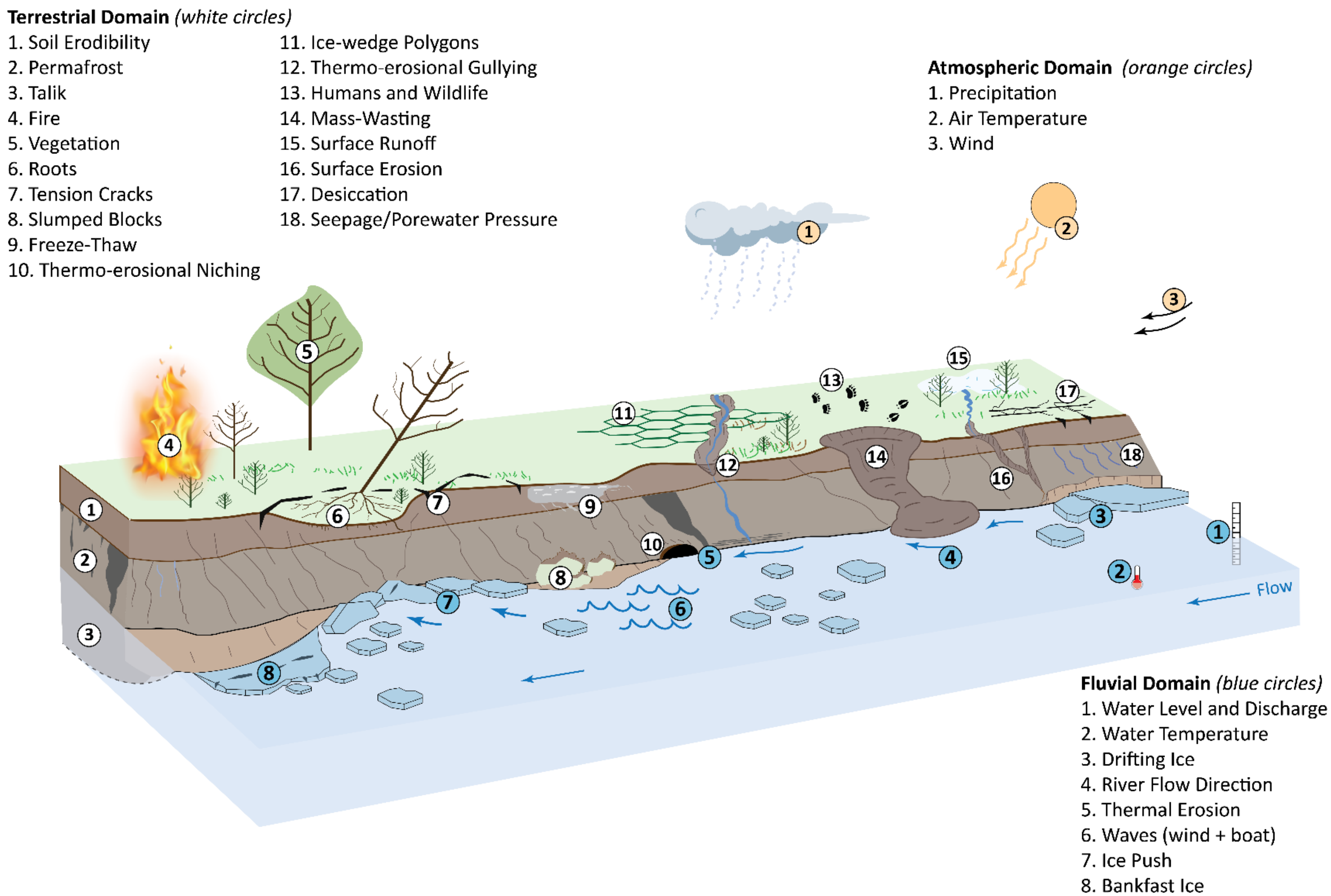


Table 2. Summary of the domains and their causal factors, processes, and mechanisms that influence riverbank stability in northern rivers.

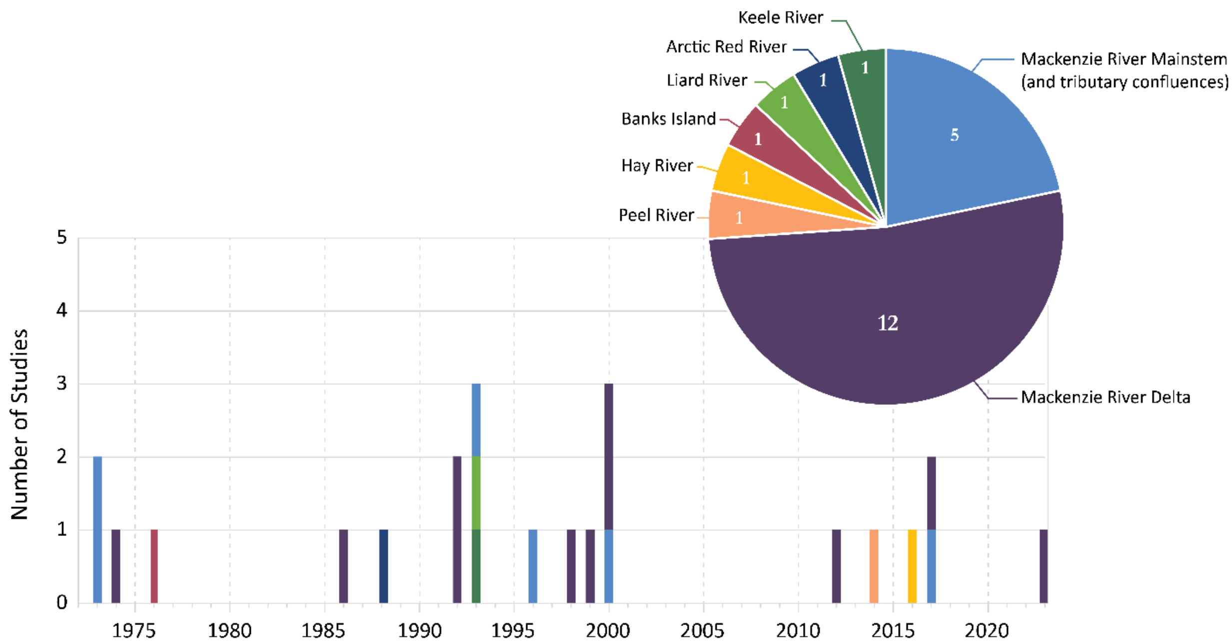
Domain	Causal	Influence on Riverbank Erosion	Source(s)
Atmospheric	Precipitation	Precipitation contributes to surface runoff; raindrops falling on the soil surface detaches soil particles. Snow can armour and protect channel banks from erosion.	Knighton (1999); Woo (2012)
	Air Temperature	Warmer temperatures are causing active layers to deepen and permafrost to thaw, destabilizing some riverbanks.	Chassiot *et al*. (2020); Dupeyrat *et al*. (2011)
	Wind	Wind is able to dry and erode sediments directly from riverbanks, create wave erosion, and push ice against riverbanks.	Walker *et al*. (1987); Turcotte *et al*. (2011); Chassiot *et al*. (2020)
Terrestrial	Soil Erodibility	Depends on soil type, texture, structure, soil moisture, infiltration capacity, organic matter content, vegetation cover.	Bryan *et al.* (1989)
	Permafrost	Permafrost limits riverbank erosion rates; erosion can be mechanical or thermal; Arctic warming and hydrologic changes are likely to increase bank erosion rates on large rivers. Melting of massive ice (ice formed in lenses, layers, and blocky structures) reduces riverbank stability.	Douglas *et al.* (2023); Rowland *et al.* (2023); Rowland *et al.* (2010); Ielpi *et al.* (2023)
	Talik	Large Arctic rivers have well-defined taliks beneath active channels or beneath substantial portions of the floodplain, such that outer banks do not, in most cases, directly expose ice susceptible to thermal erosion.	Ielpi *et al.* (2023)
	Fire	Removes vegetation; alters soil properties; increases runoff and erosion; promotes mass wasting; thaws and thermally alters permafrost.	Holloway *et al.* (2020); Li *et al.* (2021)
	Vegetation	Riparian vegetation cover increases riverbank stability through strengthening and binding by roots. The type of vegetation is important as the density of the root network is different between trees, shrubs, and grasses.	Chassiot *et al*. (2020); Ielpi *et al*. (2023)
	Roots	In permafrost environments, vegetation rooting is restricted to the active layer.	Lininger and Wohl (2019)
	Tension Cracks	Mass failure under gravity occurs when a slab of soil becomes detached by a tension crack.	Darby and Thorne (1994)
	Slumped Blocks	Slump blocks of soil/weed mats will temporarily protect the river bank against further erosion.	Woo (2012); Tananaev (2016); Douglas *et al*. (2023)
	Freeze-thaw	Freeze-thaw cycles contribute to reducing the internal strength and stability of riverbanks.	Gatto (1995); Turcotte *et al*. (2011)
	Thermo-erosional Niching	Thermo-erosional processes produce niches and subsequent large slumps of overhanging bank materials.	Costard *et al*. (2003)
	Ice-wedge Polygons	Melting and degradation of ice-wedge polygons along a riverbank may experience rapid erosion.	Woo (2012); Fortier *et al*. (2007)
	Thermo-erosional Gullying	Thermo-erosional processes develop a gully network in ice-wedge polygons.	Fortier *et al*. (2007)
	Humans and Wildlife	Humans and wildlife are direct and indirect agents of bank erosion.	Chassiot *et al*. (2020)
	Mass Wasting	The instantaneous transfer of sediments down the riverbank slope due to gravitational forces or turbulent flow (e.g., active layer detachments, retrogressive thaw slumps).	Dyke (2004); Chassiot *et al*. (2020); Tananaev and Lotsari (2022)
	Surface Runoff	Surface runoff from either snowmelt or rainfall can cause erosion.	Ashmore and Church (2001); Lininger and Wohl (2019); Chassiot *et al*. (2020)
	Surface Erosion	Runoff from precipitation can erode the surface of riverbanks, forming rills and gullies.	Chassiot *et al*. (2020)
	Desiccation	Desiccation cracks occur due to drying of the soil; reduces the strength of soils.	Chassiot *et al*. (2020)
	Seepage/Porewater Pressure	Changes in porewater pressures are a fundamental factor in determining conditions of instability and in triggering bank failures. Variations in pore pressures are complex, rapid, and difficult to predict.	Rinaldi and Darby (2004); Fox *et al.* (2007)
Fluvial	Water Level and Discharge	Fluvial erosion occurs in all ranges of water level. Higher water levels expose more of the riverbank to fluvial erosive processes and generally have more energy available to erode riverbanks.	Knighton (1998), Woo (2012)
	Water Temperature	Water temperature is a primary control on fluvial thermal erosion rates.	Costard et al. (2003; 20074; 2014); Tananaev (2016); Lotsari et al. (2020)
	Drifting Ice	During spring break-up, drifting ice can erode riverbanks by grinding the riverbank surface and undercutting bank materials.	Hicks (1993); Scrimgeour *et al*. (1994); McNamara and Kane (2009)
	River Flow Direction	The orientation of the riverbank in relation to the flow direction (or angle of attack) is an important control as this determines how much fluvial energy is available for erosion along a river reach.	Tananaev (2016); Vesakoski *et al*. (2017); Tananaev and Lotsari (2022)
	Thermal Erosion	The progressive thawing of riverbanks in contact with flowing water results in heat transfer between water and ice that produces easily removable sediments. Increased thermal erosion is correlated with increased water temperatures.	Costard *et al*. (2003, 2007, 2014); Kanevskiy *et al*. (2016); Tananaev (2016)
	Waves	Waves formed by wind and boats can cause erosion by directing fluvial energy toward the riverbank.	Chassiot *et al*. (2020)
	Ice-Push	During spring break-up, large ice pieces may be pushed into piles up on the riverbank.	Walker and Hudson (2003); Mackay and MacKay (1977)
	Bankfast Ice	Rotating or collapsing bankfast ice may wrench and dislodge riverbank material and vegetation. Its extent also creates a natural barrier to protect the lower riverbank from erosion.	Ettema (2002); Chassiot *et al*. (2020)

The nature, intensity, and timing of the processes controlling riverbank stability are highly localized and controlled by site-specific factors inherited from the climate, geological, geomorphological, and biological history (Figure 1), in addition to the cumulative effect of human activities and climate change (Brooks 2000; McNamara and Kane 2009; Lininger and Wohl 2019; Chassiot *et al.* 2020; Rowland *et al.* 2023). Erosion along any section of a riverbank is the result of complex, site-specific interactions between resisting and driving forces, with different processes acting on the bank at different times and magnitudes throughout the year (Lotsari *et al.* 2020; Ielpi *et al.* 2023.). As a result, the net effect of climate change will be spatially and temporally variable and be largely determined by a riverbank's sensitivity to the magnitude of change in processes and feedback that enhance and reduce riverbank stability (Lininger and Wohl 2019).

4.3. NWT Riverbank Erosion Studies

There is a lack of systematic observations of the spatial and temporal variability in riverbank erosion across the NWT (Figure 4). All studies were site-specific except one that focused on the entire Mackenzie River delta plain (Vesakoski *et al.* 2017), with no watershed-scale studies found during the literature searches. The primary focus of most of the available literature was not riverbank erosion (e.g., suspended sediment transfer, ice-jamming, and river-ice processes). Still, the authors did make secondary observations about processes. Given the complexity of the controls on riverbank stability (Figure 1, Figure 2), combined with a lack of observations across the NWT, it is currently impossible to draw conclusions on spatial and temporal trends and changes owing to climate change. Table 3 provides a summary of the NWT literature identified by the Project and the main observations or conclusions related to riverbank erosion. Here, we summarize the main findings from research in the Mackenzie River Delta, the middle reaches of the Mackenzie River (including tributaries), and other NWT rivers. Community-led studies and initiatives are discussed separately in Section 5.

Figure 4. Summary of NWT riverbank erosion and stability studies identified in this literature review.



Most NWT research on riverbank erosion and stability has concentrated on the Mackenzie River Delta due to the oil and gas industry conducting river crossing surveys to identify potential pipeline crossings in the 1960s through the 1980s (e.g., Outhet 1974; Lapointe 1984, 1986; Traynor and Dallimore 1992; Carson 1992; Carson *et al.* 1999; Fassnacht and Conly 2000). These early studies reported that riverbank erosion is ubiquitous along channel bends and straight reaches, being far more pronounced in Middle Channel (up to 10m/year), with smaller distributary channels migrating at a much slower rate (0.1 to 2.0 m/year) (Beltaos *et al.* 2012). Arnold (1986, 1988) described a small collection of artifacts obtained from an aboriginal Mackenzie Inuit grave eroded by the Mackenzie River. The author noted that the evidence obtained from the Bombardier Channel site was destroyed due to riverbank erosion. More recently, Vesakoski *et al.* (2017) used 1983-2013 Landsat data, coupled with hydrological time series, to investigate the spatial and temporal patterns of channel planform change of the entire Mackenzie River Delta plain. The authors found that the delta has experienced constant evolution at a highly varying rate over the 30 years of observation and estimated that channels migrate laterally at approximately 3 m/year on average across the entire delta plain. In an investigation of large sub-Arctic rivers, a recent study found statistically significant but marginal reductions in bank erosion rates over the last 50 years (including along a section of the Middle Channel). It concluded that the trend may be related to the observed expansion of shrubs increasing bank stability (Ielpi *et al.* 2023). However, the validity of these trends over a period as short as 50 years with intermittent observations is debatable (Carson *et al.* 1999), and more detailed analyses are needed.

There have been few studies and observations of riverbank erosion in the middle reaches of the Mackenzie River Basin (including tributaries) (Table 3). Between Fort Providence and Separation Point, multiple observations describe the riverbanks as unstable due to large-scale retrogressive failures, slope wash, gullying, and other mechanisms outlined in Figure 3 (e.g., Mackay and Mathews 1973; Code 1973; McRoberts and Morgenstern 1974; Brooks 1993). McRoberts and Morgenstern (1974) detail how these failures relate to bank sediment type and conclude that porewater pressures are an important control of slope stability. A detailed study in the middle reaches by Brooks (1996, 2000) described the channel characteristics, hydrology, and lateral channel change of 15 of the major tributaries of the Mackenzie River. The author highlighted that local factors control the specific type and relative magnitude of the processes of riverbank erosion, which vary from river to river and even between different reaches of the same river (Brooks 2000). Local knowledge from NWT communities has highlighted that the combination of warmer temperatures and heavy rainfall is causing permafrost to melt, increasing riverbank erosion in the Peel River watershed and the Mackenzie River (Gill and Lantz 2014; Parlee and Maloney 2017). Church (1988) described extensive flow over the floodplain and widespread destruction of floodplain forest in response to a summer rainfall event in the Arctic Red River. Still, it was noted that the morphological modification of the channel was minor, likely owing to the presence of permafrost. Multiple studies have concluded that the annual break-up of ice is an important geomorphic agent of riverbank erosion along the Mackenzie River (Brooks 1993; Hicks 1993), but systematic studies are absent. Studies from outside of the NWT have demonstrated that riverbank erosion rates are usually higher in the middle reaches of a watershed in ice-affected rivers, owing to the spatial zonation of river-ice processes and ice-jam occurrences (Lawler *et al.* 1999; Best *et al.* 2005). Since most NWT communities are situated along riverbanks in the middle reaches of watersheds, their susceptibility and concerns regarding contemporary and future riverbank erosion needs to be addressed.

Even fewer studies of riverbank erosion outside the Mackenzie River mainstem have been conducted. On Banks Island, NWT, Miles (1976) observed that spring break-up was relatively unimportant to riverbank erosion and bankline recession, with sufficient erosion occurring during summer rainfall events. In a recent evaluation of the state of aquatic knowledge in the Hay River Basin, Stantec (2016) compared aerial photographs from the 1950s with recent data from Google Earth and concluded that there has been no significant change in the morphology of the Hay River over the past 50 to 60 years, although there are localized examples of erosion and small landslides typical of large rivers (e.g., adjacent to the Hamlet of Enterprise).

Rates and processes of riverbank erosion across the NWT are strongly influenced by the south-to-north and east-west gradient in climate, hydrology, permafrost extent and ground ice distribution, topography, surficial materials, geology and Quaternary history, and other inherited environmental conditions. Furthermore, drainage basins of different sizes have varying sensitivities to changes in climate that make predictions across spatial scales inherently difficult. For example, a small watershed in the High Arctic (e.g., Banks Island, Melville Island) is unlikely to respond similarly to a small watershed in the Richardson Mountains, the Mackenzie River, or its tributaries. Likewise, riverbank erosion of bedrock and boulder channels common to areas of the Canadian Shield in the east of the Territory occur on longer time scales and is not directly comparable to watersheds where most change is likely to occur. Therefore, it is difficult to predict spatial or temporal changes in riverbank erosion across the NWT due to a lack of detailed studies, the localized nature of erosion processes, and the complexities of varying environmental controls. However, the predicted trends of key variables driving riverbank erosion in a warmer climate is summarized in the following section.

Table 3. Summary of available NWT literature on riverbank erosion.

Source	Area of Study	Findings Relevant to Riverbank Erosion/Stability
Mackay and Mathews (1973)	Mackenzie River	Rotational slumps in unconsolidated materials are present along numerous reaches of the Mackenzie River. Some stretches have been actively eroding for at least 150 years and river changes resulting from slumping have probably exceeded those due to lateral erosion.
Code (1973)	Mackenzie River	Mapped and described the banks of the Mackenzie River as unstable in sections between Fort Providence and Fort Good Hope. Mapped/described large-scale retrogressive failures, shallow earth flows, detachments slides, solifluction, gully erosion, and slope wash.
McRoberts and Morgenstern (1974)	Mackenzie River	Detailed inspection of aerial photographs and field investigation between Fort Simpson and Fort Good Hope. High pore water pressures appear to control the available shear strength in the unfrozen clay and that the long-term strength of the permafrost soils is governed by a frictional resistance.
Outhet (1974)	Mackenzie River Delta	Long-term erosion rates of the banks of the southern Mackenzie Delta varied from 1 to 11 m/year.
Miles (1976)	Banks Island	Spring break-up was relatively unimportant to erosion and bankline recession. Sufficient recession took place only during summer storms.
Arnold (1986)	Mackenzie River Delta	A small collection of artifacts obtained from an aboriginal Mackenzie Inuit grave eroded by the Mackenzie River. Some were found *in situ* in the erosional face of the riverbank, but most were obtained from slump blocks that had fallen from the bank. The site was destroyed by the Mackenzie River.
Lapointe (1986)	Mackenzie River Delta	Provides comprehensive map of channel bank scour rates in the Mackenzie River Delta based on comparison of aerial photographs.
Church (1988)	Arctic Red River	Despite extensive flow over the floodplain and widespread destruction of floodplain forest in response to a summer storm event (July 1970), morphological modification of Arctic Red River was minor, likely due to the presence of permafrost.
Traynor and Dallimore (1992)	Mackenzie River Delta	Cross-sectional changes (1975-1990) of the full delta. Unable to locate original paper, references to this work within other references.
Brooks (1993)	Keele River confluence	Annual break-up of ice is an important geomorphic process along the Mackenzie River. Described slope instabilities and gullying where small ephemeral streams and groundwater seeps flow downward into the river. Slopes have experienced creep as indicated by tilted trees.
Carson (1992)	Mackenzie River Delta	Review of 1990-91 channel stability cross-sections. Different methodologies result in different results of erosion rates. Difficult to restore original endpoints of transects for repeat surveys.
Hicks (1993)	Mackenzie River	Ice was the dominant geomorphological against near Fort Providence.
Prowse (1993)	Liard River	Elevated water levels due to ice resistance exposed considerable additional bank area to potential erosion.
Brooks (1996)	Mackenzie River Tributaries	Described valley characteristics, hydrology, channel characteristics, lateral channel change, and how tributaries interact with the Mackenzie River. Highlighted that morphology at the confluence could deflect the majority of Mackenzie River flows into opposite banks, increasing lateral erosion.
Droppo *et al*. (1998)	Mackenzie River Delta	The channels of the Mackenzie River Delta appear to have remained quite stable since their original mapping in 1826 by the Franklin Expedition. This stability likely reflects the influence of permafrost in armouring the riverbanks against significant erosion.
Carson *et al*. (1999)	Mackenzie River Delta	Between Point Separation and Raymond Channel, mean channel shifting was 5.2 ± 0.7 m/year.
Brooks (2000)	Mackenzie River Tributaries	The specific type and relative magnitude of the processes of lateral channel change are controlled by local factors and thus vary considerably from river to river and between different reaches of the same river.
Dyke (2000)	Mackenzie River Delta	Scouring on the outside of bends continually removes thawed sediment, thereby keeping permafrost at or close to the bed of the channel. Migrating rates are highly variable but average a few meters per year and can reach10 m/year where scouring is the strongest.
Fassnacht and Conly (2000)	Mackenzie River Delta	The scour hole in the East Channel of the Mackenzie Delta experienced 0.7-0.8 m/yr of lateral erosion.
Beltaos *et al*. (2012)	Mackenzie River Delta	It was not possible to find any controls points used in the 1985 and 1992 surveys.
Gill and Lantz (2014)	Peel River	Community-based approach; the combination of warmer air temperatures and heavy rainfall events was highlighted as a cause of permafrost melt and resultant riverbank erosion.
Stantec (2016)	Hay River mouth	Although ice jams and floods often generate riverbank erosion, no visible changes to the river flow path were identified when comparing 1955 aerial photographs with more recent imagery (2006 and 2012).
	Hay River at Enterprise	Comparison of 1950 aerial photographs with recent imagery (2014) showed the presence of unstable riverbank sections, mostly along the outer bank of river meanders where lateral erosion and progressive undercutting of the toe of the slope is causing them to fail.
Parlee and Maloney (2017)	Peel River; Mackenzie River	Community-based approach; Inuvialuit, Gwich'in and Decho First Nations all observed changes in riverbank erosion, with some participants noting more erosional features and impacts on hunting cabins and other infrastructure.
Vesakoski *et al*. (2017)	Mackenzie River Delta	Channels migrated laterally at 3.1 m/year over average (for the entire delta plain; 1983-2013).
Ielpi *et al*. (2023)	Mackenzie River Delta	Large sinuous rivers are slowing down in a warming Arctic. Expansion of shrubs may play a role in stabilizing channel banks and reducing channel bank erosion.

4.4. Predicted Changes to Riverbank Erosion Processes

Predicting the net effect of climate change on the rate of riverbank erosion is difficult due to a lack of long-term systematic monitoring (Rowland *et al.* 2023), the site-specific nature of riverbank erosion (Brooks 2000), and because multiple factors are changing simultaneously and interacting with each other, often with opposing effects (Ashmore and Church 2001; Rowland *et al.* 2010; Ielpi *et al.* 2023). Lininger and Wohl (2019) summarize the factors affecting erosive force and erosional resistance in permafrost settings and the predicted general direction of change in these factors associated with climate warming (shown in Table 4). For example, the magnitude and duration of peak river flow is predicted to increase in a warmer climate (↑), which not only increases the erosive force but also decreases (↓) the erosional resistance of riverbanks via a reduction in permafrost extent. Conversely, the expansion of shrubs and the treeline's northward progression could increase riverbanks' erosional resistance and decrease erosion rates (Ielpi *et al.* 2023). Similarly, a decrease in permafrost extent could increase the delivery of large woody debris to river channels via increased bank failure, resulting in decreased erosive force by armouring the banks. It is important to note that these directions of change do not consider interactions among variables (Lininger and Wohl 2019). Since each of these processes and their interactions operate on vastly different timescales, trajectories of change will depend on the sensitivity of systems to modifications in this balance between changes in erosive forces and erosional resistance, which will differ greatly within drainage basins and between drainage basins of different size.

Table 4. Summary of the factors affecting erosive force and erosional resistance, and the projected general direction of change associated with climate warming. Modified from Lininger and Wohl (2019). It is important to note that these directions of change do not consider interactions among variables.

Erosive force	**Change in erosive force with increase in factor**	**Direction of change in factor due to warming**	**Likely effect of warming on erosive force due to change in factor**
Discharge (magnitude, duration)	↑	↑	↑
Water temperature	↑	↑	↑
Sediment load	↓↑	↑	↓↑
Dispersed Large Wood			
Stationary	↓	↑	↓
In transport	↑	↑	↑
Large Wood Jams			
Upstream	↓	↑	↓
At	↓↑	↑	↓↑
Downstream	↓↑	↑	↓↑
Ice Jams			
Upstream	↓	↓	↑
At	↓↑	↓	↓
Downstream	↑	↓	↓
Erosional resistance	**Change in erosional resistance with increase in factor**	**Direction of change in factor due to warming**	**Likely effect of warming on erosional resistance due to change in factor**
Vegetation	↑	↑	Unknown
Buried logjams	↑	Unknown	Unknown
Permafrost	↑	↓	↓
Discharge (duration, magnitude, variation)	↓	↑	↓
Freeze/Thaw	↓	↑	↓
Grain Size	Site Specific/Variable	Site Specific/Variable	Site Specific/Variable

5. COMMUNITY-LED STUDIES AND INITIATIVES

Riverbank erosion is a primary issue with gaps in support, expertise, and capacity to help NWT communities address immediate and future concerns (Ehrlich pers. comms. 2023). Through climate change adaptation funds, NWT communities are addressing many climate-related risks, including riverbank stability and erosion.

Consultant reports from seven of the 20 NWT communities (i.e., Fort Smith, K'atl'odeeche, Norman Wells, Fort Good Hop, Tsiigehtchic, Fort McPherson, and Aklavik) have been reviewed at the time of writing. Of the available studies, recommendations vary from implementing extensive monitoring programs and short-term erosion mitigation to relocating homes, cemeteries, and churches. Consistent across most reports was the need to consider options to limit surface water runoff and infiltration by developing and implementing a comprehensive drainage plan. Multiple reports also highlight the need to develop long-term solutions and recommend further geotechnical site investigations to inform these decisions. More work should be done to identify and highlight the risks that riverbank erosion poses to community values, including ecosystems, connection to land and culture, and health and well-being, and to develop options to adapt to or mitigate these risks.

In this section, we include the broad recommendations from each of the seven NWT community reports to support GNWT decision-making for aiding communities with the implementation of recommendations. These excerpts are included here to illustrate riverbank erosion issues identified in communities and the urgency of this issue in many NWT communities. These issues and recommendations are similar across communities and highlight the challenges communities face. It is important to note that detailed site-specific options were also developed for areas of acute or significant instability. Stakeholders must review the full assessments to understand the extent of riverbank erosion in each community and the scope of work on which the recommendations were based. References within these reports that have not been assessed are included in Table 5. These unassessed reports should be located, reviewed, and added to a centralized library to improve accessibility, as outlined in Section 9 (Recommendations).

5.1. Fort Smith

Several geotechnical studies have been carried out and have identified possible causes of previous slope instability due to a weak clayey material at depth, shallow and deep aquifers, melting permafrost, steep slope configuration and river erosion (Wood 2019).

Wood (2019) made the following recommendations:

- "The additional reports should be reviewed. It is understood that there are borehole logs, field monitoring data and a seismic assessment which can be used for the subsequent phases of remediation on this slope. There also appears to exist a post-construction report on the installation of horizontal drains in 1988. This information may help identify the soil and permafrost conditions of the slope and reduce or refine the proposed borehole program. The information may also help determine an adequate slope flattening angle for remediation".

- "A site visit should be conducted of the slope (4.5 km reach of the Slave River). The site visit would focus on inspecting the known landslides and estimating their current level of activity. Where exposed, soil type and groundwater conditions could be identified. The groundwater regime may also be able to be determined based on surface seepage. Evidence of permafrost degradation may also be evident. The site visit could aid in determining where future boreholes might be drilled."
- "A history of landslide movement should be constructed if possible. It would be beneficial to correlate landslide movement to potential triggers such as high river flows, high precipitation, melting permafrost and earthquakes. Our current understanding has only two significant markers for catalogued slope movement: 09 August 1968 (unknown cause), 05 October 1985 (potentially earthquake related). Speaking with Elders within the community or reviewing town records may provide information on historical landslide activity."
- "Discuss with the Town of Fort Smith the potentially impacted structures. Some of these structures and areas may be acceptable to demolish as part of the regrading work. Some of them may not."
- "Alternative remediation options to slope re-grading should be considered. The costs of earthworks and in-river engineering is deemed to be significant. It might be challenging or impossible to secure an environmental work permit given the anticipated environmental impacts, such as tree clearing and earthworks near a water body. Soil cutting may also expose permafrost, which in turn will thaw and may lead to building settlement, erosion, or maintenance re-grading work on areas of this slope."
- "…a borehole drilling program should take place. The purpose of the borehole program would be to identify the soil, water, and permafrost conditions at the site, which are considered essential in developing a long-term solution for this slope. The borehole program would also include laboratory testing to quantify the soil properties. The findings of this program will aid in the design and preparation of construction drawings."

5.2. K'atl'odeeche

Along the East Channel of Hay River, the primary cause of erosion is believed to be ice gouging and shearing action along the riverbank, especially during ice-jam events (Baird 2019), with erosion rates varying between 0.08 m/yr to 0.6 m/yr (AMEC unknown year in Baird 2019).

The recommendations provided by AMEC (unknown year) include:

- "Structural steel or reinforced concrete only alternatives for erosion protection. Very high cost to implement. Aesthetically undesirable."
- Recommended "allowing nature take its course."

Baird (2019) made the following additional recommendations and provided alternative solutions:

- "Do nothing/monitor. Erosion rate near the Arbour is relatively low. Would be helpful to repeat erosion measurements from 2001-2002 studies. Key to understanding risk to the Arbour. Delay implementing short-term solution and develop long-term solution for Arbour or entire shoreline."
- "Relocate Building. Move arbour building away from eroding shoreline. Could move approximately 30 m inland from current location (or further)."
- "Steel Sheet Pile Wall. Proven concept at Hay River, e.g., Coast Guard shoreline. Small footprint. Requires specialized equipment. Long-term maintenance cost. Requires geotechnical input."
- "Articulated Concrete Block Mattress. Mass, strength, and smooth surface resistant to ice damage. Flexible and forms to ground surface. Thin layer requires minimal excavation. Rapid modular placement (and removal). Could be removed and reused. Could possibly be pre-cast in Hay River."
- "Boulder Revetment. Less feasible at Arbour due to large footprint (gentle slope). Possible solution for 1 km reach."
- "Re-connect river channels in Hay River delta. Four channels in Hay River delta closed off between the 1940s and 1970s. Channel alterations may have exacerbated erosion along the KFN shoreline. Discussion with territorial and federal governments to restore function of the delta. Not a standalone solution to erosion. Options include reshape/excavate part of Island C to widen river, remove or lower Island C berm, or reconnect Poritts Landing channel."

5.3. Norman Wells

Stantec (2020) performed a geotechnical field investigation to evaluate existing soil conditions and conditions of the Mackenzie River banks within the Town of Norman Wells relating to erosion and bank stability.

Stantec (2020) made the following recommendations:

- "Mitigation measures to address slope stability include additional geotechnical investigations and monitoring, construction of stabilizing measures (rockfill buttress), and as a last resort potential relocation of impacted infrastructure."
- "Based on information gathered during the current November 2019 investigation, reaches of significant concern were identified; however geotechnical information is relatively limited given the size of the study area. Additional geotechnical investigations and monitoring will improve assessment of existing slope stability conditions and areas of future concern."

- "Future geotechnical investigation and monitoring programs will generally consist of testhole drilling throughout the reaches of greatest concern to slope stability. The geotechnical investigations will allow collection of additional samples for advanced testing of shear strength as they relate to riverbank stability. Given the importance of groundwater levels to riverbank stability in the study area, a focus will be to install groundwater monitoring piezometers. Slope inclinometer instrumentation should also be installed to monitor slope movements at locations of greatest concern (and could be used to confirm any slope stabilization construction measures are functioning as intended). The additional geotechnical investigation and monitoring will allow for detailed design of slope stabilization construction measures."
- "For the study area, an effective means of mitigating surface runoff erosion is by construction of armored channels at the culvert outlets, to direct surface runoff down the riverbank slope. The locations of the armored channels should be reviewed with the overall surface runoff management plans."

Since the Stantec (2020) report, the Norman Wells Town Council has supported developing and implementing a comprehensive drainage plan to reduce erosion and flooding risk along 7 km of the Mackenize River (Guilbault 2022). Several other considerations have been incorporated into the community plan, including restricting any future development that may adversely affect water quality and natural patterns of ground coverage, melting permafrost, and potential for erosion (Guilbault 2022).

5.4. Fort Good Hope

Several studies have reviewed the stability of the Mackenzie River bank at the north end of Fort Good Hope (Thurber 1991a; 1991b; 1997; EBA 2006; Tetra Tech 2023). Several mechanisms are considered to contribute to the riverbank instability: slope geometry, mass-wasting (retrogressive thaw slides and slumps), subsurface water seepage, and flows and slides are exacerbated by the erosive action of the river at the base of the slope (EBA 2006; Tetra Tech 2023).

Tetra Tech (2023) provided the following recommendations:

- "A topographic/LiDAR survey or a thermal analysis were not included in the present work scope. Associated with the slope stability and thermal analyses is the need for much better geotechnical and permafrost data than is currently available, because a detailed geotechnical site investigation has not been included in the work to date. Tetra Tech recommends that these items be incorporated into future phases of the project."
- "For proposed new housing development areas, a site-specific geotechnical engineering evaluation should be done. Such an evaluation should include a specific investigation of the site soils in the areas by proposed for development, by drilling or testpitting. Additional requirements such as a site-specific slope stability evaluation might also be necessary, depending on the proposed location."

- "A community drainage plan should also be commissioned to improve the surface water drainage conditions within the community. A drainage plan should also be incorporated in new development areas."

5.5. Tsiigehtchic

All the slopes on Church Hill (to the Northeast, West, and Southwest) are hazards; they are prone to slope instabilities that could affect the structures and other features on the hill, including the church and cemetery (EBA 2011). The likelihood of a landslide reaching either the churches or the cemetery is high, while the likelihood of a landslide reaching the new church is moderate. The overall risk is high to very high (EBA 2011).

To mitigate the assessed risk of failure, EBA (2011) provided the following recommendations:

- "Do nothing/monitor. However, it is very important that such a decision be made consciously, with the informed consent and consensus of community members. This is because it may cost nothing now to do nothing, but inevitably a slope will fail, and something will be lost that the community or community members feel is important, like the gravesites. Community dialogue and consensus is essential to come up with a good solution for the community while also accommodating the needs of individual members of the community. For example, some members of the community may be comfortable with having nature take its course and having their ancestors or family members end up in the Arctic Red River when a slope failure takes away part of the cemetery. Other members of the community may want to move their ancestors or family members to a safer place."
- "Avoid the unstable or landslide-prone terrain by moving elements at risk. Implement a minimum slope setback. Adjusting the slope setback to this extent would result in a major adjustment of the western and northern boundaries of the useable land area on Church Hill. In practice, implementing a minimum slope setback means having to move both churches and the cemetery. Further investigation could prove this measure to be appropriate, or it could show such a measure to be too conservative."
- "Reduce landslides. Consider options to limit surface water runoff and infiltration by keeping water from either flowing downslope or from infiltrating into the many frost-crack polygons and associated tension cracks. Consider alternatives to keep the ground frozen, thereby reducing the volume of soil that could fail. Consider soil retention options to keep the existing slope from failing, or even build up a buffer area between the crests of slopes and the elements at risk. Some of these options may be relatively inexpensive, but correspondingly ineffective over the long-term. Conversely, options that may be effective over the long-term are also likely to be very expensive. Note too, that only one very shallow corehole has been drilled at the subject site, and no detailed investigation has been carried out specific to slope stability at the site. Thus, there is a certain amount of risk involved in assuming that any of these options would be adequate to maintain slope stability at the site."

- "Protect elements at risk. For foundations at risk from thaw slides or thaw slumps, a remedial foundation could be designed such that slope failures would leave it relatively unaffected. For example, a landslide might have an immediate effect on a shallow foundation, but if the failure surface is not as deep as the foundation elevation, for example, as with piles, then site repairs might be easier and less expensive. Bedrock is estimated at about 8 m below ground surface in the vicinity of the churches, and about 11 m below ground surface at the cemetery, so conceivably the existing foundations could be underpinned and supported in bedrock. Another idea would be to construct a mat slab under the building so that it moves as a unit instead of breaking into pieces if soil falls away from under any one part of the foundation. However, such options will be expensive to install, and with the present lack of information, it is not known whether such protective measures would be cost effective, or even adequate to the intended purpose."
- "Because the cemetery and the graves nearest the west edge of the cemetery appear to be at the greatest immediate risk, we recommend that options related to the cemetery be considered first. Since low-cost options will not necessarily prevent slope failure, we further recommend that serious consideration be given to moving the gravesites most at risk."
- "A topographic/LIDAR survey, a slope stability analysis, or a thermal analysis were not included in the present workscope. Associated with the slope stability and thermal analyses is the need for much better geotechnical and permafrost data than is currently available, because a detailed geotechnical site investigation has not been included in the work to date. EBA recommends that these items be incorporated into future phases of the project."

5.6. Fort McPherson

NehTruh-EBA (2019) completed a slope stability review and evaluation of stabilization options for the slope along the western edge of the townsite at Fort McPherson.

NehTruh-EBA (2019) provided the following recommendations to reduce slope instability, similar to the recommendations for Tsiigehtchich provided by EBA (2011).

- "Avoid the unstable terrain. Implement a minimum 30-year slope setback or even a 50-year setback, as discussed above, to develop new areas of the townsite or redevelop existing built areas. Adjusting the slope setback to this extent would result in a significant adjustment of the western boundaries of the useable land area in the community. In practice, implementing a minimum 30-year slope setback means having to move the church and cemetery, several houses, and the health centre, a strategy that could be considered for the most urgent structures first. Further investigation could prove this measure to be appropriate, or it could show such a measure to be too conservative. If any of the structures are near the end of their service life, or already beyond their service life, the option to place a new building in a better location seems like a suitable one. However, if there is still plenty of life left in the structure, it might be more reasonable to consider moving the existing structure to a new location."

- "Reduce landslides. Consider options to limit surface water runoff and infiltration by keeping water from either flowing downslope or from infiltrating into the tension cracks. Consider alternatives to keep the ground frozen, thereby reducing the volume of soil that could fail. Consider soil retention options to keep the existing slope from failing, or even build up a buffer area between the crests of slopes and the elements at risk. For example, one possibility for the William Firth Health Centre and the Charles Koe Building would be to restore some of the material removed by the quarrying operations, effectively buttressing the slope. Some of these options may be relatively inexpensive, but correspondingly ineffective over the long-term. Conversely, options that may be effective over the long-term are also likely to be very expensive. Note too, that there are only a few boreholes or testpits along the slope in Fort McPherson, and no detailed investigation has been carried out specific to slope stability at the site. Thus, there would be a certain amount of risk involved in assuming that any of these options would be adequate to maintain slope stability at the site."

- "Protect the elements at risk. For foundations at risk from slides or slumps, a remedial foundation could be designed such that slope failures would leave it relatively unaffected. For example, a landslide might have an immediate effect on a shallow foundation, but if the failure surface is not as deep as the foundation elevation, for example, as with piles, then site repairs might be easier and less expensive. Bedrock is estimated at about 2.5 m to 4.0 m below grade at the church, so conceivably the existing foundations could be replaced, or underpinned and supported in bedrock. The William Firth Health Centre and the Charles Koe Building are already on piles, thus mitigating slope movements there, especially for the Charles Koe Building, which is further from the slope. Bedrock there is an estimated 3.0 m to 4.7 m below grade. Another idea would be to construct a mat slab under the church building so that it moves as a unit instead of breaking into pieces if soil falls away from under any one part of the foundation. However, such options would be expensive to install, and with the present lack of information, it is not known whether such protective measures would be cost-effective, or even adequate to the intended purpose."

- "Because there is very little site-specific geotechnical, permafrost or structural engineering information available along the slope, many of the options presented would require further investigation in order to develop appropriate recommendations for options to reduce risk, and to develop costing information for design and construction of those options."

- "A do-nothing or wait-and-see option is also a possibility. However, it is very important that such a decision be made consciously, with the informed consent and consensus of community members. This is because it may cost nothing now to do nothing, but inevitably a slope will fail, and something will be lost that the community or community members feel is important, like the gravesites. Community dialogue and consensus is essential to come up with a good solution for the community while also accommodating the needs of individual members of the community. For example, some members of the community may be comfortable with having nature take its course and having their ancestors or family members end up in the Peel River when a slope failure takes away part of the cemetery. Other members of the community may want to move their ancestors or family members to a safer place."

- "Because the cemetery at St. Matthew's Anglican Church and the graves nearest the west edge of the cemetery appear to be at the greatest immediate risk, we recommend that options related to the cemetery be considered first. Since low-cost options will not necessarily prevent slope failure, we further recommend that serious consideration be given to moving the gravesites most at risk. This task will begin with identifying such gravesites, their exact locations, and the people related to those buried there. Also, at very high risk are the St. Matthew's Anglican Church itself, several houses, and the William Firth Health Centre, due to their proximity to the slope. Options for long-term stability should be considered for these structures if they are to be preserved; otherwise options for moving them or demolishing and replacing them with new structures further from the slope should be considered."
- "A topographic/LiDAR survey, a slope stability analysis, or a thermal analysis were not included in the present workscope. Associated with the slope stability and thermal analyses is the need for much better geotechnical and permafrost data than is currently available, because a detailed geotechnical site investigation has not been included in the work to date."

5.7. Aklavik

The outer left bank along the Peel Channel upstream of the Hamlet of Aklavik has been experiencing erosion. NHC (2019), in discussion with Hamlet, identified riverbank erosion along Bickish Road, upstream of the Hamlet of Aklavik, as a priority for flood mitigation.

NHC (2019) provided the following recommendations relevant to riverbank erosion:

- "Structural flood mitigation measures include, riverbank erosion protection, airport improvements, road improvements, flood dikes, and culvert backflow prevention."
- "Non-structural flood mitigation measures include, development restrictions, installing flood forecasting and warning systems, and public education."
- "Based on evaluation of the proposed mitigation options, it is recommended that the following options are considered for implementation within the Hamlet: Option 1A – Riverbank erosion protection using rock riprap (Figure 4) carried out in stages, based on severity of current and anticipated erosion (Figure 3). In addition to mitigating a breach of the Peel Channel into adjacent lakes, erosion protection works will also protect the adjacent portion of Bickish Road. Rock riprap was selected based on the overall ease of construction and maintenance."

Table 5. Summary of reports referenced within community-led studies. These reports should be located, reviewed, and added to a centralized database.

Year	Location	Author	Report Title
1978	Fort Smith	Klohn Leonoff Consultant Limited	*Unknown*
1986	Fort Smith	Weyer Corp Incorporated	Engineering Reassessment of the Stability of the Slave River Bank and Alternative Remedial Measures, Volume 1.
1986	Fort Smith	Weyer Corp Incorporated	Effects of Recent Earthquakes on the Landslide Area in Fort Smith, NWT, Volume 2.
1988	Fort Smith	Thurber Engineering	Trail Installation of Horizontal Drains. Post Construction Report.
2004	Fort Smith	AMEC Earth and Environmental	Landslide Assessment, Slave River Slope - Task 1.
2004	Fort Smith	AMEC Earth and Environmental	Geotechnical Evaluation, Fort Smith Landslide, Geotechnical Design Guideline - Task 2.
2006	Fort Smith	AMEC Earth and Environmental	Slope Stability Assessment Raw Water Pipeline Location Fort Smith, NWT.
2008	Fort Smith	AMEC Earth and Environmental	Geotechnical Evaluation Recent Landslide Activity Slave River Slopes Fort Smith, NWT.
2012	Fort Smith	AMEC Earth and Environmental	Site Visit Report for Axe Handle Hill Slope.
Unknown	Hay River/K'atl'odeeche	AMEC Earth and Environmental	*Unknown*
2000	Norman Wells	Geological Survey of Canada	Climate Change, Permafrost Degradation anmd Infrastructure Adaptation: Preliminary Results from a Pilot Community Case Study in the Mackenzie Valley.
1978	Fort Good Hope	Thurber Consultants Ltd.	Fort Good Hope Water Reservoir Evaluation of Alternative Sub-Drainage Systems. Report submitted to the Government of the Northwest Territories, Department of Public Works and Services. November, 1978. Thurber File: 15-22-0.
1981	Fort Good Hope	Thurber Consultants Ltd. and W.L. Wardrop & Associates Ltd.	Assessment Study, Fort Good Hope Water Supply. Report submitted to the Government of the Northwest Territories, Department of Public Works and Services. November, 1981.
1991	Fort Good Hope	Thurber Engineering Ltd.	Fort Good Hope Riverbank Stability Geotechnical Investigation. Report submitted to Government of the Northwest Territories, Department of Municipal and Community Affairs, Inuvik, N.W.T. April, 1991. Thurber File: 15-23-45.
1991	Fort Good Hope	Thurber Engineering Ltd.	Riverbank Stability Fort Good Hope, N.W.T. Letter report submitted to Government of the Northwest Territories, Department of Municipal and Community Affairs, Inuvik, N.W.T. September 18, 1991. Thurber File: 15-23-45.
1997	Fort Good Hope	Thurber Engineering Ltd.	Riverbank Stability Fort Good Hope, NT. Letter report submitted to Government of the Northwest Territories, Department of Municipal and Community Affairs, Inuvik, N.W.T. September 10, 1997. Thurber File: 15-23-45.
1963	Tsiigehtchic	Bone, R.M., and R.T. Gajda	Arctic Red River, District of Mackenzie, Terrain and Site Analysis. File 406. Department of Mines and Technical Surveys, Geographical Branch, Ottawa.
1986	Tsiigehtchic	Thurber Consultants Ltd.	Geotechnical Investigation, Proposed Firehall, Arctic Red River, N.W.T., Detailed Geotechnical Evaluation. Submitted to GNWT, Yellowknife, NT, November 1986.
1986	Tsiigehtchic	Thurber Consultants Ltd.	Geotechnical Investigation, Proposed Gymnasium, Arctic Red River, N.W.T., Detailed Geotechnical Evaluation. Submitted to GNWT, Yellowknife, NT, November 1986.
1987	Tsiigehtchic	Thurber Consultants Ltd.	Tso Lake Water Intake / Pumphouse Facility, Arctic Red River, N.W.T., Detailed Geotechnical Evaluation. Submitted to Reid Crowther and Partners Ltd., March 1987.
2007	Tsiigehtchic	Johnson, R.	Slope Stability Investigation for Vik'ooyendik (Church Hill). Submitted to the Gwich'in Social & Cultural Institute, August, 2007.
2008	Tsiigehtchic	VFA Canada	Facility Condition Assessment, Community Church, Tsiigehtchic – Final Report. Submitted to the Government of the Northwest Territories, September, 2008.
2009	Tsiigehtchic	AMEC Earth and Environmental	Geotechnical Desk Study: Proposed Community Learning Center, Tsiigehtchic, NT. Submitted to Government of the Northwest Territories, Department of Public Works and Services, Facility Planning Sections (GNWT), Yellowknife, NT, December 2009.
2011	Tsiigehtchic	EBA, A Tetra Tech Company	Tsiigehtchic, NT, Community Permafrost Map. Submitted to Ecology North, January 2011.
2009	Aklavik	Dillon Consulting Limited	Hamlet of Aklavik Drainage Study - Final Report.

6. RESEARCH AND KNOWLEDGE GAPS

During the events (i.e., Riverbank Erosion Partnership Table Meeting and NWT Riverbank Erosion and Climate Change Workshop), multiple research, knowledge, and other gaps related to riverbank erosion were identified that are summarized here:

- The NWT is an understudied and under-monitored region in terms of climate, hydrology, ecology, and permafrost. There is a lack of QA/QC'd climate and hydrology records, and channel bathymetry and cross-section data are needed to develop hydraulic models. The role of river ice versus open water discharge in driving riverbank erosion has not been well established.
- Some communities have completed local erosion studies, but no large-scale studies across the NWT exist. There is a general lack of monitoring and research on riverbank erosion.
- No studies have focused on the socioeconomics of relocating communities and infrastructure away from riverbanks or local and traditional knowledge on erosion, hydrology, and other water processes.

6.1. Other Gaps

- Lack of support and expertise on riverbank erosion and slope stability within governance structures in the NWT is greatly impeding the progress of communities in addressing this risk. There is also an overall lack of recognition within the territorial and federal governments on the urgency of this issue for communities.
- There is no clear process or guidelines for communities with riverbank erosion concerns who want assistance. Communities face gaps in understanding who to talk to, what steps to take, how to find funding, and how to implement any recommendations. There is no established contact or support within the territorial government for communities facing this issue. Smaller communities (pop. < 500) are even more challenged to make progress and require even greater support.
- There is minimal information sharing between communities and between communities and the GNWT. There is no centralized storage of community river erosion projects, reports, and aerial/satellite imagery or other available data. There needs to be a more organized method for sharing successful funding proposals, community plans, and river erosion assessments/reports to improve accessibility and help inform communities, governments, and other stakeholders on the current knowledge of riverbank erosion impacts and solutions at the community level. The NWT Climate Change Library (released by the GNWT on March 1st, 2024) would be a good option for this centralized location (Government of Northwest Territories n.d.).

7. RESEARCH AND MONITORING NEEDS

The following research and monitoring needs identified during the events are summarized below:

- A strategic plan is needed to fill data gaps and ensure communities have the information they need to make decisions.
- Satellite-based monitoring to identify river reaches with the largest change (channel width and lateral migration) during recent decades and then prioritize more detailed monitoring of these reaches. This should include communication with communities to assess their perceived vulnerability to risk using a multi-disciplinary approach with engineers and geoscientists, social scientists, and community members.
- Geotechnical site investigations should be performed for all NWT communities. It is recommended that the assessment be standardized for spatial comparisons.
- Following geotechnical assessments, a ranked risk assessment can be used to inform the importance of different research needs for each community. This may include detailed hazard documentation, mitigation, design, and site-specific recommendations.
- Expanded hydrology, sediment transfer, water temperature, ground temperature, groundwater/porewater, permafrost, and climate monitoring. For example, NHC (2019) recommended reinstatement of WSC station 10MC005 – Mackenize River (Aklavik Channel) above Schooner Channel as it would benefit the Hamlet of Aklavik for flood warning. Reviewing the NWTs climate, permafrost, and hydrology monitoring networks (historical and current) would help to identify monitoring gaps and priorities.
- Community-based monitoring. For example, asking guardians or community members to produce a journal of events in each community to better understand when riverbank erosion occurs and the processes driving it. Implement ground pin surveys, visual inspections, photo points, and instrumentation/monitoring.
- Channel bathymetry and hydraulic modelling at key sites. Similarly, model and monitor ice jam events and how these relate to riverbank erosion.
- Need to understand how increased wildfire frequency and severity and increased extreme precipitation may impact the likelihood of riverbank erosion. Conversely, the effect of drought on riverbank erosion also needs to be better understood across the NWT.

8. CLIMATE CHANGE RISK AND OPPORTUNITY ASSESSMENT

Predicting the net effect of climate change on the rate of riverbank erosion is extremely difficult due to a lack of long-term systematic monitoring (Rowland *et al.* 2023), the site-specific nature of riverbank erosion (Brooks 2000), and because multiple factors are changing simultaneously and interacting with each other, often with opposing effects (Lininger and Wohl, 2019). Ranking the level of influence of temperature, precipitation, wind, permafrost, fire, or any other causal factor over another is not currently possible. Additional work beyond the ROA is needed to increase accuracy and confidence in assessing the risk of riverbank erosion. For example, the use of photogrammetry (e.g., aerial photography, satellite-based monitoring, light detection and ranging [LiDAR], and unmanned aerial vehicles [UAV]) to map and calculate average erosion rates is needed. This work coupled with geotechnical investigations to provide site-specific risk assessments can then be used to rank the risk of communities to riverbank erosion.

9. RECOMMENDATIONS

The research and monitoring needs section provides details to help inform future work across the NWT. Here, we provide further recommendations to guide the decision-making process.

- Designing satellite- and aerial-based studies.

Studies are used to calculate average erosion rates and map areas of high river erosion hazard for each community where imagery is available and of high enough quality. It would be worthwhile to collate the existing satellite- and aerial-based photogrammetry products and assess their usefulness in calculating average erosion rates. For example, Stantec (2020) notes that the air photo review undertaken around Norman Wells was inconclusive in terms of erosion rates. Future imagery needs should also be considered (e.g., repeat LiDAR of each community experiencing erosion).

- Completing site-specific geotechnical assessments and monitoring programs.

Every consultant's report differs in scope, objective, and method. Still, they all conclude that further geotechnical assessments are required to assess slope stability due to a lack of information and data. It would be worth defining a set of standard scopes, objectives, and methods for geotechnical assessments moving forward for consistency and to enable direct comparison across locations. This should be developed with a long-term monitoring program (e.g., climate, ground temperatures, porewater, permafrost) that attempts to capture as much spatial variability as possible (e.g., from south to north and east to west across the NWT).

- Implementing long-term solutions.

In collaboration with the communities, it is necessary to review and support the development and implementation of comprehensive drainage plans to reduce erosion from surface runoff (e.g., Norman Wells). Similarly, communities should consider incorporating recommendations from other communities into their community plans, including restricting any future development that may adversely affect water quality and natural patterns of ground coverage, melting permafrost, and potential for erosion. The cost of in-river engineering is likely to be very high and costs more than the infrastructure it aims to protect. It would be worth performing a cost-benefit analysis to assess the differences between moving infrastructure, demolishing and rebuilding, or river engineering options. This should be done in conjunction with social scientists and the communities.

- Expanding monitoring of climate conditions, hydrology, and terrestrial environments.

Expanding monitoring programs related to climate, hydrology, and terrestrial domains (e.g., permafrost, slope stability) are essential to provide the baseline data needed to make informed decisions about processes such as riverbank erosion. The current monitoring networks should be reviewed to identify key monitoring gaps and priorities. This should be considered in parallel with geotechnical assessments.

- Ensuring leadership, collaboration, and consistency into the future.

Successfully implementing long-term solutions, future research projects, and recommendations will require clear leadership from the GWNT and a collaborative approach with communities, researchers, and industry to leverage funding and find expertise to address riverbank erosion. Governments need to recognize the urgency of the risk riverbank erosion poses to communities and develop a road map and capacity within the GNWT to help communities navigate what steps should be taken. This includes potential site investigations and mitigation options, a standardized protocol for accomplishing these steps, and assistance finding funding to complete any necessary adaptation or mitigation efforts. Utilizing environmental educators to disseminate complex information into plain language summaries may be helpful.

- Sharing information through a centralized database.

There is a disconnect in sharing of information between communities, and between communities and the GNWT. There is no centralized storage of community river erosion projects, reports, and aerial/satellite imagery. There needs to be a more organized method for sharing successful funding proposals, community plans, and river erosion assessments/reports to improve accessibility and help inform communities, governments, and other stakeholders on the current knowledge of river erosion impacts and solutions at the community level. The NWT Climate Change Library (released by the GNWT on March 1st, 2024) would be a good option for this centralized location (Government of Northwest Territories n.d.).

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PERSONAL COMMUNICATIONS

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APPENDICES

Appendix A. Events Summary

Riverbank Erosion Partnership Table

First meeting

Wednesday, May 15, 2024 from 10 am – 12 pm

MEETING SUMMARY

Attendees – a list is included on the last page.

Meeting goals

- Hear updates from communities experiencing riverbank erosion
- Hear updates from other partners working on this issue
- Share information and explore how to work together

Key messages:

- Partnerships are key to making progress to address this urgent risk.
- Communities want to know how to ensure that vegetation clearing for fire breaks does not weaken the ground near or at slopes and the riverbank.
- More information is needed on the options available to monitor riverbank erosion and slope stability, including community-based monitoring.
- More information is needed on erosion mitigation options.

Meeting notes

1. Update on activities of the riverbank erosion partnership table
   - Miki Ehrlich is the Partnership Facilitator at the NWTAC. She provided a brief overview of the partnership table approach and some of the things she is working on. A copy of the presentation is at this link: Meeting overview and update on partnership activities.

2. Updates from communities

   Community representatives discussed their experience with riverbank erosion, in response to these guiding questions:
   - Have you made progress since we last met in November? If so, what have you done and how has it helped? What do you want to do next?
   - What **barriers** do you face?
   - What are your **priorities**?
   - What **support and resources** do you need?

Summary of updates and needs shared by community partners

Community	Update	Needs
Tsiigehtchic	• We started the process to address riverbank erosion 5 years ago. • The partnership table has been a source of hope. • We made progress this past winter: we used seed funding from CCPN to engage PlanIt North (Jon Weller) to help us develop a plan for next steps. • We hired a geotechnical engineer to review previous work and analyze options to address and mitigate erosion. Here is a link to the report: Tsiigehtchic Slope Stability Review and Options Analysis. • We have submitted a funding proposal to proceed with further study of these options, including community engagement.	• More information on mitigation options – what has worked in other places? For example, protecting the slope by insulation, shading, retaining structures. • More information on monitoring, including what the different monitoring methods would tell us. • We want to make sure vegetation clearing being done for fire breaks is not negatively affecting the soil and slope stability.
Fort Good Hope (Kasho Gotine Housing Society)	• A lot is happening, it has been helpful to partner with other organizations on this work (e.g. Land Corp, Charter Community, consultants) • We held workshops and discussions with community members. They told us they do not want to wait for something bad to happen. While the likelihood is not very high, the consequences are very high. While a few members question it, the overwhelming majority want to act. • We developed a pamphlet for homeowners along the riverbank and went door-to-door to distribute it. The pamphlet has instructions in case residents want to move away from the slope during breakup and provides options if they feel they are at risk. • Homeowners want to explore their options and learn more about the risk due to erosion and what they could do about it. • We are looking into ways we could monitor and measure the slope movement in the community, with our own eyes. • The Canada Energy Regulator is holding a hearing for an Imperial Oil proposal. We told them we are concerned about contamination of our water from their development. • Our community has been contacted by the Standards Council of Canada to see if we want to participate in a pilot of a new standard for land development suitability maps. It would be	• Our water reservoir was identified as high risk in the slope stability assessment. We are especially concerned about an area below where the hoses go that is weakened. We need more information to support a decision on whether to relocate it or change how we store/manage our drinking water. • How can we ensure that the tree and vegetation clearing we are doing to build our fire break does not weaken the ground near or at slopes and the riverbank?

	very useful to have maps showing the good areas in the community for development and what areas to avoid (e.g. wetlands, slopes, etc).	
Katlodeeche	• We have experienced huge impacts due to last year's wildfires, including a loss of housing and staff turnover. This has hampered our ability to move forward on riverbank erosion. • Riverbank erosion is still a priority issue, however with the lower water level it is temporarily less pressing. • When we are ready, we will reach out to ask about funding and support to take the next steps.	• Lack of capacity and higher priorities slow our ability to take the next step: developing a terms of reference for the engineering study, preparing proposals for funding

3. Updates from other partners

NT Geological Survey – Tim Ensom

We are beginning a project to compile datasets from geotechnical investigations that have been conducted in communities, including community-led projects. We are pulling together this information to create a searchable resource for the public that will make these datasets accessible and help build a better understanding of the risk.

University of Alberta – Alexandre Chiasson and Jeffrey Campbell

- We are students working with Duane Froese, a University of Alberta professor who leads a permafrost research group. We will share a brief update on work we are doing in partnership with the NT Geological Survey (NTGS) and communities to develop surficial geology and permafrost conditions maps for Tulita and Fort Good Hope.
- It takes 1.5 to 2 years to develop surficial geology and permafrost conditions maps. Workshops and other engagement with the community happens at different stages of the project. Early on the community is engaged to identify priority areas for further investigation and mapping.
- In the past, surficial mapping was done at a 1:250,000 scale and was usually not ground-truthed. Ground truthing includes taking local soil samples to confirm the soil classification and presence/absence and extent of the permafrost. These older maps are not at an appropriate scale or level of accuracy for community planning. In our current project the surficial geology for many areas has been reclassified and corrected and ground-truthed.
- Update on work in Tulita:
    - A draft map of surficial geology was displayed and discussed.
    - A draft map showing permafrost conditions (stable/unstable) ground) was displayed – this map was derived from the surficial geology and other data layers.
    - Both maps are in draft format and need to undergo peer review. Once the maps are finalized, they will be shared publicly and circulated to this group.
    - Next steps include analysing different data sources such as historic airphotos to demonstrate how the shoreline has changed over the years.

    - We will present the reports to the Tulita Band, Mayor and Elders. Afterwards we hope to publish the report and the maps by October.
- Similar maps are being developed for Fort Good Hope. Slope stability studies were done for Fort Good Hope in 2006 and 2023. These studies included some surficial and geohazard mapping – this previous work helps shorten the timeline to develop maps.
- We began discussions with Deline in Sept. 2022. We plan to contact Deline soon to develop a relationship and make plans for a surficial mapping project in that community.
- Our research group will be in Sahtu communities this summer continuing to work with communities to ground truth and review these draft maps. They can deliver maps to the Hamlet of Tulita when they are there this summer.
- Can you comment on how the maps you are developing align with the land suitability map standard Risk-Based Approach for Community Planning in Northern Regions? This question was asked during the meeting and the following response was received in follow up emails after the meeting:
    - The surficial geology map is the foundation layer of a land suitability map. A surficial geology map will help us identify potential terrains prone to contain excess ice. For example, lacustrine sediments are frost-susceptible due to the water retention capacity of silt and clay. Glaciofluvial deposits, mostly composed of sands and gravel, are not prone to contain excess ice due to their low water retention capacity (versus clay and silt).
    - A fine-scale resolution (1:10,000) map with ground-truthing is crucial for each community to ensure accuracy. In Tulita, for instance, a large lacustrine deposit was identified within the community. However, there was no evidence of thermokarst features associated with excess ice prone deposits.
    - The permafrost conditions maps indicate the excess-ice contained within the different units (deposits). This map informs land-use planners and community members of the locations where it is more likely to have ground with high excess ice content.

GNWT-ECC Climate Change – Fritz Griffith

- The GNWT is conducting a literature review on riverbank erosion. It should be finished in around a month.
- We held a workshop to bring together river erosion experts as part of our work on the Climate Change Risk and Opportunities Assessment (ROA). Findings from the workshop include:
    - Riverbank erosion is a natural process and climate change intensifies it.
    - It is difficult to predict due to many local processes and factors such as sediment load, presence of permafrost, vegetation cover, precipitation, size of river, etc. We must avoid making generalizations as each situation and location is unique.
    - Increasing frequency and intensity of wildfires, more permafrost thaw, and changing hydrology can all contribute to erosion.
    - One of the largest gaps is monitoring of erosion and the processes contributing to erosion. There is a lack of capacity and expertise.
- The workshop outcomes will inform the ROA, to help define priorities and guide the Climate Change Strategic Framework update. We are hopeful a riverbank erosion monitoring plan will be included.
- We are interested in hosting copies of community-led slope stability and erosion assessment reports in the new NWT Climate Change Library. Please contact me if you can share your reports.

GNWT-ECE NWT Cultural Places Program – Mike O'Rourke

- Much of our work is away from communities, in places people used to live. I look for areas that may have heritage resources that are experiencing rapid change. So far, the sites I have worked on have been impacted mainly by coastal erosion. I work with the nearby community to determine the status of these sites and the risks they face. Then I discuss with the community what (if anything) should be done to protect the resources.
- These sites are places where we find objects used by humans or evidence of human activity that is more than 50 years old. The objects or sites have not been in continual use by one group of people and may have cultural, archaeological or historical features or values.
- I use remote sensing and other tools to detect long-term change in areas that may have heritage sites. This is a coarse grain search to see where change may have happened. Then we use air photos to develop a more defined and scoped model of change, especially for shoreline erosion along the Arctic coast.
- You can see examples of how remote sensing images are used to observe and monitor long-term landscape changes at this Landsat Long-Term Change Detection map viewer.
- We do not work on active cemeteries, but we may be able to assist with older cemeteries, or disused ones. There is no Act in the NWT that addresses cemeteries.
- Here is a link to a talk I gave that outlines the work I do as the Climate Change Archaeologist, with a focus on the mapping aspects of my work.

National Research Council (NRC) – Ivana Kubat and Ivana Vouk

- NRC has published a nature-based solutions guide to manage coastal erosion and flood risk. Nature-based solutions are systems that address or mitigate erosion and flood risks by mimicking natural systems. Pilot projects that use the guide are underway in southern Canada.
    - Link to the guide: Nature-based infrastructure for coastal flood and erosion risk management: a Canadian design guide
- We are interested in developing a guidance document for the North. We would like to find a northern community to work with us. We will follow up with Jon (PlanIt North) to learn more about projects in Fort Good Hope and Tsiigehtchic. There is an opportunity for a pilot study.
- NRC also has a research centre focused on permafrost and wildfire.

4. Next steps

- Miki will follow up on the ideas discussed and continue discussions and exploration with partners.
- A follow up meeting will be scheduled for October. We aim to hold partnership table meetings three times per year.
- Please contact Miki with any questions or comments (miki@nwtac.com or 867-873-8359).
- Stay tuned for more to come!

Meeting attendees

COMMUNITY REPRESENTATIVES		
Tsiigehtchic (Hamlet)	Grant Scott	sao@tsiigehtchic.ca
Fort Good Hope - Kasho Gotine Housing Society	Arthur Tobac	ndl_manager@yamoga.ca
Katlodeeche First Nation	Peter Redvers Victoria St. Jean	kfnnegotiations@katlodeeche.com kfnlands@katlodeeche.com
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Tulita (Hamlet)	Samantha Bayha	sao@hamletoftulita.ca
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Government of the Northwest Territories
Climate Change and Riverbank Erosion Workshop

Mural Board Link

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Workshop Objectives

- Discuss how climate-related drivers influence riverbank erosion across the territory.
- Assess the level of likelihood of riverbank erosion under recent baseline conditions.
- Explore how riverbank erosion is expected to change under future conditions (mid-century).
- Discuss research needs and knowledge gaps in the field of riverbank erosion.

Workshop Agenda

Time	Agenda Item
10 minutes	Welcoming and Introductions
15 minutes	Linking to GNWT's CROA
20 minutes	Understanding Riverbank Erosion
5 minutes	Activity and Mural Demonstration
20 minutes	Activity 1: Regional Considerations
10 minutes	Break
20 minutes	Activity 2: Climate-related variables
25 minutes	Activity 3: Likelihood Scoring
15 minutes	Activity 4: Research Needs and Knowledge Gaps
10 minutes	Concluding Remarks

Workshop Attendance

Name	Organization	Attendance
Ellen Wohl	Colorado State University	Yes
Philip Owens	University of British Columbia	No
Michael Church	University of British Columbia	Yes
Alessandro Ielpi	University of British Columbia	Yes
Sean Ferguson	National Research Council Canada	Yes
Ivana Kubat	National Research Council Canada	No
Michael Rawlins	University of Massachusetts	Yes
Bernard Bauer	University of British Columbia	Yes
Duane Froese	University of Alberta	Yes
Katherine Liniger	University of Colorado	No
Leif Burge	Ecofish	Yes

Name	Organization	Attendance
Casey Beel	Ecofish	Yes
Miki Ehrlich	NWTAC	Yes
Christa Domchek	NWTAC	Yes
Tim Ensom	GNWT	Yes
Brian Sieben	GNWT (Project Team)	Yes
Fritz Griffith	GNWT (Project Team)	Yes
Alli Myles	CRI (Project Team)	Yes
Sam Page	CRI (Project Team)	Yes

Workshop Notes

Activity 1: Regional Considerations

Objective: Identify how climate-related processes influence riverbank erosion vary across regions of NWT, noting highly vulnerable areas.

Notes:

- Notes on regional vulnerability
    - Wrigley and Fort Good Hope express concerns about erosion, including the need to move houses and protect cemeteries.
    - Willow River, buried glacial ice, RTS, and channel avulsions exemplify erosion dynamics in the region.
    - Bridges and other infrastructure connecting communities are at risk from erosion.
    - NWT exhibits differences in erosion rates and dynamics from north to south and west to east.
- General erosion processes
    - Erosion can be event-based or progressive over time, driven by storm events or spring freshet. Lag time was also noted as an important consideration: watersheds require time to respond to external stressors, which may propagate downstream.
- Bank material composition
    - Understanding bank material composition is crucial for assessing erodibility. Vegetation strength affects bank stability and varies regionally.
    - Changes to vegetation - increasing vegetation/shrubification and plant coverage to stabilize banks may impact erosion mechanics. Shrub growth affects erosion, riverbank stabilization, hydrology, and snow cover thermal regime.
- Permafrost influence
    - Presence or absence of permafrost affects runoff volumes, groundwater storage, and river flows, influencing erosion. Permafrost's role in erosion varies based on sediment distribution and hydrologic vs. thermal drivers.
- Winter flow and aufeis
    - Winter flow increase can lead to aufeis formation, causing erosion similar to spring ice jams.
- Ice dynamics

    - Understanding ice dynamics is crucial, especially regarding flooding and divergence between main stem and tributaries.
- Watershed size
    - Small watersheds change at different rates than large ones, with more direct interaction with permafrost.
- Community practices and conditions:
    - Snow clearing and vegetation management practices influence erosion.
    - Intense boat traffic areas should consider the impact of boat wakes on erosion.
    - Will be influenced by climate change (e.g. more snow, vegetation growth, lengthened open-water season).

Activity 2: Climate-related Variables

Objective: Discuss and rank climate-related variables based on their level of influence on riverbank erosion in NWT, considering the most vulnerable areas.

Notes:

- Freeze-thaw cycles
    - Daily temperature fluctuations impacting soil stability.
- Seasonal minimum temperature
    - Average minimum temperature across seasons affects soil freeze-thaw dynamics.
- Fire
    - Frequency and severity of wildfires affecting permafrost stability, particularly in smaller watersheds.
- Flow dynamics:
    - Timing, magnitude, and regime shifts of river flows influence erosion rates.
- Ice jam magnitude
    - Ice jam occurrences driven by temperature fluctuations drive erosion.
- Biota and vegetation changes
    - Influence of flora and fauna on bank stability through root reinforcement and hydraulic roughness.
- Permafrost degradation
    - Directly impacted by temperature changes, leading to changes in riverbank stability.
    - Active layer reflects water storage dynamics in the landscape.
    - Influence of soil ice dynamics on bank stability.
- Rain on snow events
    - Driving spring freshet events and influencing erosion rates.
- Storm Surge Impact
    - Consideration of storm surges in delta regions affecting erosion.
- Two major processes and related variables:
    - Flow-related variables influencing erosion
    - Resistance forces

        - Flow and resistance forces are influenced by precipitation, temperature, rain on snow influencing flow, while non-climatic factors such as bank materials and permafrost resistance also play a role.
- Summary of key variables:
    - Precipitation: Amount and intensity of rainfall or snowfall directly impact water flow in rivers.
    - Rain on Snow Events: Driving spring freshet events and influencing erosion rates.
    - Temperature: Fluctuations in temperature influence freeze-thaw cycles, permafrost stability, and soil moisture content.
    - Permafrost Degradation: Directly impacted by temperature changes, leading to changes in riverbank stability.
    - Seasonality and Biota: Changes in seasons alter precipitation patterns, temperature regimes, and vegetation growth, impacting erosion dynamics.
    - Humidity: Moisture levels in the air and soil contribute to soil stability and erosion susceptibility.
    - Solar radiation: Sunlight affects evaporation rates, snowmelt, and overall hydrological processes.
- Overall, the discussion wrapped up with explaining that riverbank erosion is complex and influenced by a combination of climatic, hydrological, biotic and regional factors, making it challenging to pinpoint the highest influencers definitively.

Actions for CCROA:

- Identify available climate variables (from Elvis' spreadsheet) that influence 'Flow' or 'Resistance'. For example:
    - Seasonal average, maximum and minimum temperature
    - Monthly maximum surface snow amount
    - Annual total snow amount
    - Maximum 5-day precipitation total
    - Amount of rainfall from extremely wet days
    - Active layer thickness
    - Mean annual ground temperature
    - Wildfire - Changes in lightning and ignition
    - Mean of daily relative humidity - annual
    - Mean daily incoming shortwave radiation
- Analyze likelihood scores for all climate variables related to flow and resistance forces.
- Apply the highest likelihood score to the riverbank erosion scenario (listing all those considered in the report, along with an explanation of why the index with the highest likelihood score was chosen as a precautionary measure.)

Activity 3: Likelihood Ranking

Objective: Assess the likelihood of riverbank erosion under baseline conditions and explore how riverbank erosion is expected to change under future conditions (mid-century).

Notes:

- Consideration for spatial assessment in next GNWT CCROA
    - Spatial Assessment:
        - Evaluating relative risk spatially, initially focusing on scales relevant to communities would be useful
        - Applying GIS and climate data analysis
    - Consideration of erosion rate changes versus mere occurrence.
    - Systems Approach
        - Recognizing the interconnectedness of erosion with watershed dynamics and broader ecosystem changes.
    - Community Perspectives
        - Importance of engaging with communities to understand erosion impacts, local practices, and historical perspectives.
- Multiple factors influence the likelihood of this scenario
    - Bank erosion is influenced by climate change, community development, and broader dynamics like sedimentation.
- Consideration for socio-economic and development changes
    - Community development impacts erosion risks, necessitating planning mechanisms to mitigate increased risk
- Past Drivers
    - Understanding whether erosion was historically driven by ice or discharge.
- Baseline
    - Baseline erosion frequency informed by the persistence of erosion issues in communities.
    - Three participants ranked the baseline for this scenario as "probable"
- Future Likelihood
    - Expectation of increasing bank erosion challenges due to climate change impacts, including permafrost degradation, increased fire frequency, and hydrological regime shifts.
    - Anticipated increase in runoff and river flow in northern regions due to climate change.
    - Five participants ranked future likelihood (2050s) as remaining within "probable", mainly due to lack of evidence to support an increase. Three participants ranked future likelihood (2050s) as increasing to "very likely".
- Planning for Resilience
    - Communities addressing erosion also consider resilience to other climate-related risks, such as wildfires and sedimentation.
    - Advocating for a holistic systems approach integrating community knowledge and practices into erosion management strategies.
- Overall, the discussion emphasizes the complexity of riverbank erosion dynamics, the need for spatially informed assessments, and the importance of community engagement and focusing more on resilience-building measures in addressing future challenges.

Actions for CCROA:

- Based on feedback from the workshop participants, the baseline conditions should be ranked as "probable." This ranking is informed by the persistence of erosion issues in some communities and the acknowledgment that erosion is currently an issue in certain locations. Therefore, the likelihood of the riverbank erosion scenario as ‘probable’ is appropriate for baseline conditions.
- For the future mid-century period, based on feedback from the workshop participants, the likelihood of the riverbank erosion scenario should be ranked as "very likely" (applying precautionary approach). This ranking reflects the expectation of changing conditions driven by climate change including factors such as permafrost degradation, increased fire frequency, and shifts in hydrological regimes. Therefore, it is considered very likely that this riverbank erosion will be "very likely" in the future mid-century period.

Activity 4: Moving Forward

Objective: Identify and discuss research needs and knowledge gaps in the field of riverbank erosion in the NWT

Notes:

- Utilize historical observational data from communities to understand erosion patterns.
- Implement community-led initiatives such as River Watch and local geotechnical assessments.
- Utilization of available GIS and climate data to assess erosion risks and identify gaps.
- Compile data on erosion rates, mitigation options, and impacts across communities.
- Conduct comprehensive studies on community needs regarding erosion.
- Utilize long-term aerial imagery to document historical erosion and understand meteorological and hydrological associations.
- Incorporate local and Indigenous knowledge into erosion research.
- Assess socio-economic impacts and options for relocating communities and infrastructure.
- Develop predictive models and hydraulic simulations to assess erosion dynamics and bank strength.
- Expand monitoring efforts, including bathymetry, sediment, and satellite-based techniques.
- Prioritize community-based risk assessments and vulnerability assessments.
- Engage in multidisciplinary approaches to understand vulnerability and community impacts.
- More funding towards communities preparing for the impacts of erosion that we already know is going to increase.
    - Need to make space to accommodate the natural dynamics of the fluvial systems.
- Conduct surficial geological mapping to inform hazard mapping and erosion research.