Lakeshore and Riverbank Erosion in the Yukon

Technical Guidance for Assessment and Risk Mitigation

Government of Yukon

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Plain Language Summary

This document explains how and why erosion happens along riverbanks and lakeshores in the Yukon, and what can be done to manage it. Erosion is a natural process that shapes the landscape over time, but it can also create challenges for roads, homes, infrastructure, and areas of cultural or environmental importance. In the Yukon, erosion is influenced by a combination of flowing water, wind-driven waves, river and lake ice, woody debris, permafrost, and changing climate conditions. These factors often interact in complex ways, making erosion more difficult to predict and manage than in many other parts of Canada.

The guide outlines a step-by-step approach to understanding erosion problems before taking action. It encourages users to consider the broader system—how a river or lakeshore has changed over time, what processes are driving those changes, and how conditions may continue to evolve in the future. It highlights the importance of using multiple sources of information, including local and Traditional Knowledge, historical data, and field observations. Monitoring over time is also emphasized as a way to improve understanding and support better decision-making.

A range of options for managing erosion is presented, recognizing that there is no single solution that works in all situations. These options include avoiding development in high-risk areas, relocating or redesigning infrastructure, and implementing erosion control measures. Both engineered approaches and nature-based solutions—using vegetation and natural materials—are discussed. The document emphasizes selecting approaches that are suited to the local environment, are sustainable over the long term, and do not create unintended impacts in nearby areas.

The guide also stresses the importance of early coordination and collaboration among governments, First Nations, landowners, regulators, and technical specialists. Working together early in the process helps improve project outcomes, reduce delays, and ensure that different perspectives and knowledge systems are considered. Overall, the goal of this document is to support more consistent, informed, and proactive management of erosion risks across the Yukon.

For a more detailed plain language summary of this guidance document, with the same organization as the technical guidance that follows, please refer to **Appendix A**.

Technical Executive Summary

Objectives and Strategic Context

The Government of Yukon (YG) commissioned this guidance document to guide territory-wide approaches for assessing and mitigating risks associated with erosion in fluvial (river) and lacustrine (lake) environments. Historically, the territory lacked a consistent framework, leading to reactive emergency measures rather than proactive, science-based planning. With a warming climate exacerbating erosional processes, this framework aims to mitigate rising construction costs and improve the resilience of public infrastructure and private property.

Critically, this document is designed to be paired with the YG (2019) guidance document *Preferred Practices for Works Affecting Yukon Waters.* While the 2019 document focuses on operational best practices and environmental protection during construction, this current guidance provides the technical engineering and geomorphic principles required for the assessment and design phases that precede implementation.

Unique Yukon Realities

Erosion management in the Yukon must address specific northern challenges that differ from those in southern jurisdictions, including:

- **Permafrost and ground ice:** Assessments of riverbanks and lakeshores must account for permafrost distribution and associated thermal regimes. Warming can transition ice-bonded banks into unstable masses, leading to "thaw-slumping" and accelerated retreat.
- **Dynamic ice processes:** Seasonal ice formation, thermal expansion (static ice push), and dynamic breakup may exert greater mechanical forces on riverbanks and lakeshores than typical open-water processes.
- **Logistical and environmental constraints:** The territory faces a short construction window and a limited growing season for site restoration. Furthermore, the scarcity of traditional materials, such as large-calibre riprap, necessitates outside-the-box thinking and the strategic use of local resources.

Assessment Framework

The guidance utilizes a diagnostic process to identify and characterize erosion issues across tiered levels:

- **Project scoping:** Establishes the administrative and spatial boundaries of the project. It involves defining the project budget, identifying applicable regulatory triggers, and setting the nested spatial scales (watershed, reach, and site) that will govern the subsequent technical investigations.
- **Preliminary assessment:** A high-level evaluation—supplemented by field reconnaissance and local and Traditional Knowledge—to establish a baseline understanding of dominant geomorphic processes. This phase identifies the primary physical drivers of erosion and evaluates the potential consequences to stakeholders, such as service disruptions or the loss of private property and cultural lands.
- **Detailed assessment:** A rigorous evaluation required when risks to critical infrastructure are determined to be unacceptable. It involves intensive field investigations, potentially including topographic/bathymetric surveys and geotechnical drilling or test pitting, and may utilize numerical modelling (e.g., hydraulic, wave, slope stability modelling) to inform the design of erosion mitigation.

Mitigation Strategies, Design and Construction

Erosion mitigation is categorized by the level of intervention and potential ecological impact:

- **Strategic approaches:** Strategies range from ‘Give Space’ (i.e. managed retreat), which is commonly the most sustainable long-term option, to Indirect Approaches (e.g., log spurs or rock vanes) and Direct Approaches (e.g., riprap revetments). Nature-based Solutions (NbS), or bioengineering, may be preferred over Direct and Indirect Approaches for their natural resilience and ecosystem benefits.
- **Design considerations:** Designs must move beyond southern practices to account for extreme ice forces, thermal instability in permafrost zones, and the regional scarcity of erosion mitigation materials (e.g., riprap). Designs must ensure the erosion protection is extended far enough upstream/updrift and downstream/downdrift to account for future watercourse/waterbody adjustments.
- **Construction and implementation:** Success relies on navigating the short Yukon construction season through careful sequencing and timing. Key execution requirements include proper isolation, robust erosion and sediment control (ESC) measures, and comprehensive site restoration. Effective implementation further requires a dedicated monitoring and inspection plan, with the design team remaining actively involved to manage inevitable field-fit adjustments.

Regulatory Review, Coordination and Collaboration

Proponents of riverbank and lakeshore erosion risk mitigation works must navigate a multi-layered regulatory environment involving the Yukon Environmental and Socio-economic Assessment Board (YESAB), the Yukon Water Board, Fisheries and Oceans Canada (DFO), and other regulatory bodies.

Effective projects prioritize early First Nations engagement to integrate local and Traditional Knowledge and mitigate impacts on settlement lands. Furthermore, the guidance advocates for proactive planning and "reach-scale" collaboration to prevent shifting erosion problems downstream or downdrift. Proactive investment in detailed assessments is emphasized as a key pathway to securing federal and territorial funding by demonstrating project readiness.

Table of Contents

Statement of Limitations i
Acknowledgements i
Plain Language Summary ii
Technical Executive Summary iii
Table of Contents v
Key Acronyms and Abbreviations xiii
1.0 Introduction 1
1.1 Document Purpose and Objectives 1
1.1.1 Target Audience 2
1.1.2 Scope and Terminology 3
1.2 Layout and Use of this Guide 5
2.0 Erosional Processes in the Yukon 7
2.1 Drivers of Riverbank Erosion 7
2.1.1 Water 7
2.1.2 Woody Debris 9
2.1.3 Ice 10
2.1.4 Permafrost and Ground Ice 13
2.2 Drivers of Lakeshore Erosion 14
2.2.1 Water 14
2.2.2 Woody Debris 17
2.2.3 Ice 18
2.2.4 Permafrost and Ground Ice 20
2.3 Interaction with Slopes 21
2.4 Anthropogenic Influences on Erosion 24
2.5 Climate Change 27
2.6 Challenges and Opportunities 28
3.0 Assessment of Riverbank and Lakeshore Erosion 31
3.1 Overview of Assessment Levels 31
3.2 Project Scoping 32
3.2.1 Spatial Scale 32
3.2.2 Temporal Scale 34
3.3 Important Data Sources 34
3.3.1 Approaches for Data-Poor Sites 38

3.4 Preliminary Assessment 40
3.4.1 Common Approaches for Lakes and Rivers 40
3.4.2 Prioritization of Erosion Challenges 45
3.4.3 Deliverable Expectations 46
3.5 Detailed Assessment 48
3.5.1 Detailed Field Investigations 48
3.5.2 Quantitative Analysis and Modelling 49
3.5.3 Deliverable Expectations 55
3.6 Integration with Flood Mapping and Hydrotechnical Studies 55
3.7 Monitoring 57
4.0 Mitigation of Erosion-related Risks 59
4.1 Key Considerations 59
4.1.1 Spatial Scale 59
4.1.2 Temporal Scale 60
4.1.3 River and Lake Ice Considerations 63
4.1.4 Permafrost and Ground Ice Considerations 64
4.2 Evaluating Risk Mitigation Approaches 65
4.2.1 ‘Give Space’ 65
4.2.2 Indirect Approaches 65
4.2.3 Direct Approaches 67
4.2.4 Nature-based Solutions (NbS) 69
4.3 Design Guidance 71
4.3.1 Options Analysis 71
4.3.2 Conceptual Design 72
4.3.3 Preliminary and Detailed Design 72
4.4 Planned Versus Emergency Work 76
4.5 Construction 79
4.5.1 Procurement and Contractor Selection 79
4.5.2 Erosion and Sediment Control (ESC) 81
4.5.3 Site Isolation and Dewatering 81
4.5.4 Site Restoration Requirements 82
4.5.5 Construction Oversight and Inspection 84
4.6 Post-construction Monitoring and Maintenance 86
4.7 Common Reasons for Failure 88

5.0 Regulatory Context, Approvals and Coordination 90
5.1 Regulatory Framework 90
5.2 Approval Pathways 91
5.3 Coordination and Collaboration 93
5.4 Funding Opportunities 94
6.0 Resources 96
6.1 References Cited 96
6.2 Technical Resources and Datasets 102
6.3 Relevant Agency Contact Information 103
7.0 Closure 104

Tables in Text

Table 4-1. Potential evaluation objectives and criteria when assessing various options for mitigating erosion-related risks 72

Figures in Text

Figure 1-1. A visual framework of the main content and flow of this guidance document. 6
Figure 2-1. Cross-sectional schematic of continuous and discontinuous permafrost, active layers, and taliks (source: Pidwirny, 2006). Areas near Yukon's southern border would be represented on the right (discontinuous permafrost) and northern areas would be represented on the left (continuous permafrost). 13
Figure 2-2. Lake ice break-up on Tagish Lake, May 20, 2022 (Imagery source: ESRI) 19
Figure 2-3. Schematic diagram illustrating the "erosion-landslide cycle," from Hugenholtz and Lacelle (2004) as adapted from Williams et al. (1979), which best explains long-term behaviour and eventual recession of hillslopes along lakeshores or riverbanks. 22
Figure 2-4. Old Crow is a remote community with no road access and is situated adjacent to dynamic watercourses. Other Yukon communities are connected by roads year-round but still have challenges accessing specialized equipment and materials for erosion mitigation. 30
Figure 3-1. Example of watershed (green shading), reach (black line), and site (orange dots) spatial scales. 33
Figure 3-2. A 1946 aerial photograph of Marsh Lake provides important information about erosional processes before widespread occupation of the shore (Source: YG) 35
Figure 3-3. An example of a LiDAR-derived hillshade of the Carmacks area available through NRCan's HRDEM database. 36

Figure 3-4. An example of discharge data recorded at the WSC station (09AH001) at Carmacks (accessed through the WSC website) that provides important current and historical flow records (1951-1994; 2014-2024). 38

Figure 3-5. An example of overlay analyses using historical and recent aerial imagery to better understand rates and trajectories of channel migration and to inform potential erosion hazard zones near Carmacks (source: Cronmiller et al., 2020). 41

Figure 3-6. An example of a longitudinal profile (bottom) and relative elevation model (top) for Porcupine River near Old Crow that helps demonstrate the distribution of energy and potential flow paths along a river (source: Northwest Hydraulic Consultants Ltd., 2025). 43

Figure 3-7. A schematic of key parameters that should be estimated during lakeshore assessments (figure courtesy of SJL). 45

Figure 3-8. Inventory and preliminary prioritization of erosion sites along a portion of the Dempster Highway (figure courtesy of SLR). Preliminary risk classifications were based on a site-level evaluation of current separation distance between the highway embankment and an encroaching watercourse and an interpretation of the relative rate at which the watercourse is migrating toward or alongside the highway. 47

Figure 3-9. An example of HEC-RAS hydraulic model outputs for both open water and ice-affected annual exceedance probability (AEP) flows for Porcupine River near Old Crow (flood mapping data provided by YG). 51

Figure 3-10. LiDAR change detection analysis using DEMs from 2006 and 2020 to highlight areas of elevation loss (~erosion) and gain (~deposition) as well as anthropogenic changes (figure courtesy of SLR). 52

Figure 3-11. For river and streams, practitioners could delineate the erosion hazard limits by establishing a meander belt (left) or a fluvial hazard zone (right). The variable width of the FHB reflects material erodibility and the height/condition of the confining slope. The irregular width of the ASC reflects the configuration of the floodplain and of confining terrace scarps. Conversely, a meander belt is defined by parallel lines. Figures courtesy of SLR. 54

Figure 3-12. Utilizing hydraulic model outputs, practitioners can spatially estimate the potential sediment sizes that can be entrained for a given flow event (Source: Northwest Hydraulic Consultants Ltd., 2025). 56

Figure 4-1. Aerial imagery from 2025 illustrates scour upstream of a riprap embankment, initiating outflanking of the revetment, and accelerated channel migration downstream along the Dempster Highway. The green line is the 2014 bank position. Riprap was installed in 2010 and again in 2015. 61

Figure 4-2. An example design drawing from a larger design package that provides sufficient detail for construction but is not overly complex or cluttered. The purpose of this design to construct naturalized slope-toe protection along the outer bank of a sharp meander approaching an existing pedestrian bridge that is at risk of being outflanked (design drawing credit: SLR). 74

Photos in Text

Photo 1-1. Bank erosion along the Yukon River near Whitehorse (photo credit: Yukon Geological Survey [YGS]) 1

Photo 1-2. Erosion and temporary erosion mitigation materials along the shoreline of Marsh Lake (photo credit: Benoit Turcotte) 3

Photo 1-3. Erosion of the Dempster Highway embankment following a high-intensity, mid-summer rain event in August 2016 (photo credit: YG Highways and Public Works – Transportation and Engineering Branch [HPW-TEB]) 4

Photo 1-4. Waves breaking along a lakeshore armoured with large riprap to help protect private properties on Lake Erie (photo credit: SJL Engineering Inc. [SJL]) 5

Photo 2-1. Examples of riverine erosion. Upper left: bank undercutting along the outer bend of Engineer Creek (photo credit: SLR Consulting (Canada) Ltd. [SLR]). Upper right: multiple channel cutoffs along Aishihik River (photo credit: SLR). Bottom left: bank erosion and slumping along Takhini River (photo credit: Benoit Turcotte). Bottom right: widespread channel adjustment downstream of a beaver-dam failure near Mud Lake (photo credit: SLR). 8

Photo 2-2. Woody debris jam adjacent to a recent wildfire along West Aishihik River (photo credit: SLR) 10

Photo 2-3. Examples of ice accumulations and processes. Upper left: damaged vegetation following an ice run in a secondary channel of the Montmorency River near Quebec City. Upper right: aufeis collapse and calving along the Blackstone River in central Yukon. Lower left: Residual anchor ice blanket in the Montmorency. Lower right: bank scour following an ice run along the Porcupine River. All photos courtesy of Benoit Turcotte. 12

Photo 2-4. A permafrost thaw flow (slump) along Takhini River partly triggered by toe erosion (source: Calmels et al., 2021) 14

Photo 2-5. Examples of lakeshore erosion. Top left: scarp erosion on Aishihik Lake (photo credit: SLR). Top right: an exposed and steep lakeshore on Canyon Lake (photo credit: SLR). Bottom left: lakeshore erosion on Marsh Lake following high waters in 2021 (photo credit: YG HPW-TEB). Bottom right: wind-generated waves crashing into an armoured lakeshore of Lake Erie during a storm event (photo credit: SJL). 16

Photo 2-6. Accumulation of wood along the lakeshore of Atlin Lake providing transient erosion protection (photo credit: SLR). 17

Photo 2-7. Ice ride-up along a gravel shore of Tagish Lake in May 2023 (photo credit: Benoit Turcotte). Note: human subjects have been digitally removed to protect privacy and accentuate the natural process. 19

Photo 2-8. Thermal-mechanical erosion contributing to permafrost thaw along a scarp in Aishihik Lake (photo credit: SLR) 21

Photo 2-9. Examples of slope failure along riverbanks and lakeshores. Top left: failure of a glaciolacustrine slope along Vermillion River (photo credit: SLR). Top right: recent failure within a larger, eroding scarp along Aishihik River (photo credit: SLR). Bottom left: scarp failure updrift and downdrift of lakeshore protection on Lake Huron (photo credit: SJL). Bottom right: ongoing ravelling of a sandy slope along Surprise Lake (photo credit: SLR). 23

Photo 2-10. Examples of anthropogenic influences. Top left: a hydro-electric flow control structure at Surprise Lake near Atlin, British Columbia (photo credit: SLR). Top right: gabion basket erosion mitigation structures on Marsh Lake (photo credit: Benoit Turcotte). Bottom left: anthropogenic berm protecting the village of Canyon (photo credit: SLR). Bottom right: historical placer mining tailings alongside Klondike River near Dawson (photo credit: SLR). 26

Photo 2-11. Channel widening, sediment deposition, and a woody debris jam following a wildfire in the Interior Region of British Columbia (photo credit: SLR). 28

Photo 3-1. UAV (i.e. drone), atop the all-terrain vehicle, along with survey equipment at a remote location (photo credit: SLR). 39

Photo 3-2. Examples of common field investigations to support detailed erosion assessments. Top left: topographic survey along a creek using an RTK GPS. Top right: shallow drilling to characterize permafrost and soil conditions. Bottom left: observation and measurements of surface and sub-surface sediments on the bed of a watercourse. Bottom right: measurement of channel hydraulics using a flow meter. All photos courtesy of SLR. 50

Photo 3-3. Examples of erosion monitoring. Top left: camera and staff gauge monitoring aufeis upstream of culverts (photo credit: Benoit Turcotte). Top right: monumented stakes incrementally track river migration (photo credit: Benoit Turcotte). Bottom left: UAV and RTK GPS surveys document geomorphic change (photo credit: SLR). Bottom right: meteorological thresholds (e.g., wind) can identify when lakeshore erosion may occur (photo credit: SLR). 58

Photo 4-1. Pronounced lakeshore erosion downdrift of localized erosion mitigation on Lake Ontario (photo credit: SJL). 61

Photo 4-2. Temporary erosion mitigation following a road washout along the Dempster Highway during the August 2016 flood (photo credit: YG HPW-TEB). The temporary measure does not negate the need to reconstruct the highway, but it minimizes the service disruption by allowing alternating traffic to pass until the highway is reconstructed. 62

Photo 4-3. River ice interacting with recently constructed erosion mitigation along the Dempster Highway (photo credit: YG HPW-TEB). 64

Photo 4-4. A small rock weir constructed to help dissipate energy and provide ecological benefit (photo credit: SLR). The weir was constructed as part of a larger channel realignment project in the Greater Toronto Area to reduce toe erosion along a failing slope near residential properties. 66

Photo 4-5. Constructed wood 'spurs' along Mayo River that deflect erosive energy away from the riverbank (photo credit: Ecological Logistics and Research Ltd.). 66

Photo 4-6. Examples of direct approaches to erosion mitigation. Top left: riprap embankment along the Dempster Highway (photo credit: YG HPW-TEB). Top right: gabion baskets along a lakeshore of Marsh Lake (photo credit: Benoit Turcotte). Bottom left: armourstone 'ribs' to protect buried sewers in Toronto, Ontario (photo credit: SLR). Bottom right: armourstone and riprap embankment in Kootenay National Park (photo credit: SLR). 68

Photo 4-7. Extensive incorporation of native willows into riverbank erosion mitigation (photo credit: Toronto and Region Conservation Authority). 70

Photo 4-8. Beach nourishment and plantings at Wasaga Beach, Ontario (photo credit: Zuzek Inc). 71

Photo 4-9. Following a high-intensity precipitation event in August 2016, a watercourse severed the Dempster Highway and necessitated emergency works to allow for safe passage of vehicles transporting critical supplies between communities (photo credit: YG HPW-TEB). 77

Photo 4-10. Emergency riprap installation utilizing end-dumping methods (photo credit: YG HPW-TEB). While expedient for rapid response, the lack of keyed placement and material segregation typically results in poor structural interlocking and limited long-term resilience. 80

Photo 4-11. Careful placement of riprap on an embankment using specialized equipment leads to better long-term results (photo credit: YG HPW-TEB). In this photo the riprap is being placed atop geotextile, which can form a slip-surface and contribute to revetment failure (see Section 4.6). 80

Photo 4-12. Example of site isolation along river using meter bags (photo credit: SLR). Note that the work area remains ‘wet’, but any sediments that become suspended within the work area cannot escape into the adjacent, flowing channel. 82

Photo 4-13. An example of site restoration including soil stabilization coir matting and riparian plantings (photo credit: SLR). 84

Photo 4-14. Inspection of completed erosion mitigation works by members of the design team, along an isolated (dry) section of watercourse, prior to advancing to the next phase of construction (photo credit: SLR). 85

Photo 4-15. A UAV inspection of recently completed erosion mitigation works (white area of cobble riffle between regraded banks), including site restoration and riparian plantings (dark brown areas of freshly placed topsoil, mulch, and plantings) (photo credit: Toronto and Region Conservation Authority). 86

Photo 4-16. Monitoring of erosion mitigation, site restoration, and riparian vegetation after construction (photo credit: SLR). 87

Photo 4-17. Examples of common reasons for erosion mitigation failure. Upper left: riprap embankment was not extended far enough upstream. Upper right: riprap was not adequately embedded, contributing to slope failure. Bottom left: geotextile created a slip plane for riprap. Bottom right: erosion protection was not extended far enough downstream. All photos courtesy of SLR. 89

Photo 5-1. An eroding bank of a watercourse is within a few metres of the road embankment (photo credit: SLR). Although not truly an emergency, this site may be classified as urgent as a large flow event may lead to a road washout. 92

Appendices

Appendix A **Section-based Plain Language Summary**

Appendix B **Glossary**

Appendix C **Erosion Mitigation Design 'Typicals'**

Key Acronyms and Abbreviations

CAD	computer-aided design
DEM	digital elevation model
DFO	Fisheries and Oceans Canada
ECCC	Environment and Climate Change Canada
GIS	geographic information system
GPS	global positioning system
HPW-TEB	Department of Highway and Public Works – Transportation Engineering Branch
LiDAR	light detection and ranging
LWD	large woody debris
NbS	nature-based solutions
NRCan	Natural Resources Canada
P.Eng.	Professional Engineer
P.Geo.	Professional Geoscientist
RTK	real-time kinematic
UAV	unmanned aerial vehicle
WSC	Water Survey of Canada
YG	Government of Yukon
YGS	Yukon Geological Survey
YESAB	Yukon Environmental and Socio-economic Assessment Board

1.0 Introduction

1.1 Document Purpose and Objectives

Historically, the Yukon has lacked a standardized framework for the assessment and mitigation of erosion along riverbanks (e.g., Photo 1-1) and lakeshores (e.g., Photo 1-2). This absence of formal guidance led to inconsistent technical applications, ambiguity regarding jurisdictional responsibilities, and a general lack of knowledge transfer among stakeholders and across projects. Furthermore, responses to erosional challenges in the territory have often been reactive, characterized by ad hoc emergency measures rather than proactive planning based on science and/or Traditional Knowledge.

Erosion problems are often addressed after damage occurs. This guide promotes proactive planning to reduce long-term costs, risks, and emergency responses.

The Government of Yukon (YG) commissioned this document to serve as a territory-wide resource for managing erosion in both fluvial (river) and lacustrine (lake) environments. As climate change continues to impact the North, the costs associated with erosion control are expected to rise (Schetselaar and Burn, 2024); this guidance aims to mitigate those costs through a proactive strategy. This document is intended to be paired with the *Preferred Practices for Works Affecting Yukon Waters* (YG, 2019) to provide a comprehensive suite of guidance for development and management near the territory's waterbodies.

Photo 1-1. Bank erosion along the Yukon River near Whitehorse (photo credit: Yukon Geological Survey [YGS])

The core objectives of this document are to:

- **Provide clarity and practicality:** The guide offers an accessible framework that supports both high-level regional planning and site-specific technical mitigation without being overly prescriptive.
- **Reflect Yukon realities:** These guidelines are specifically tailored to the unique environmental challenges of the North, including dynamic river ice processes, thawing permafrost, logistical challenges associated with remote sites, and the local scarcity of traditional construction materials such as large-calibre riprap.
- **Promote integration with hydrotechnical assessments:** Lakeshore and riverbank erosion studies are designed to inform—and be informed by—concurrent flood mapping and assessment efforts. This ensures a holistic understanding of hydrogeomorphic hazards and their interactions within the landscape.

1.1.1 Target Audience

Similar to the *Preferred Practices for Works Affecting Yukon Waters* (YG, 2019), the intent of this guide is to provide stakeholders with a comprehensive background in the principles of erosion risk management. It is intended to be a practical resource rather than a highly technical procedural document. In the Yukon, the overlap between flooding and erosion processes often complicates jurisdiction and funding. Additionally, overlapping assets—such as private property adjacent to territorial highways or First Nation Settlement Lands—can blur the lines of responsibility. This guide highlights the necessity of early coordination among the following primary roles:

- **Government of Yukon (YG):** Responsible for managing public infrastructure, overseeing territorial hazard mapping, providing historical and spatial data, and regulating land and water use.
- **Private developers and landowners:** Tasked with identifying risks to their own assets and initiating necessary assessments on their properties.
- **Consultants:** Technical specialists (typically *Professional Engineers* [P.Eng.] or *Professional Geoscientists*[1] [P.Geo.] designations) such as fluvial and coastal geomorphologists, water resources and geotechnical engineers, and permafrost scientists/engineers responsible for defining causes of instability and designing defensible mitigation.
- **First Nations:** Rights holders and land managers who own and govern Settlement Lands, contribute local and Traditional Knowledge, and collaborate on shared assessments.
- **Regulatory agencies:** Bodies such as Yukon Environmental and Socio-economic Assessment Board (YESAB), the Yukon Water Board, and Fisheries and Oceans Canada (DFO), which are responsible for reviewing project proposals and ensuring compliance with applicable legislation.
- **Contractors:** Construction professionals responsible for implementing designs, adhering to technical specifications, and managing the logistical realities of the Yukon's short construction season.

[1] As of the date of publication, the Yukon does not have its own professional geoscientist association; consequently, it recognizes P.Geo. designations from other Canadian jurisdictions.

Photo 1-2. Erosion and temporary erosion mitigation materials along the shoreline of Marsh Lake (photo credit: Benoit Turcotte)

1.1.2 Scope and Terminology

The scope of this document is specifically focused on the assessment and mitigation of risks associated with lakeshore and riverbank erosion within the Yukon. It is critical for practitioners to distinguish between the processes of inundation and erosion. While flooding and erosion are inextricably linked—for instance, high-flow events are the primary drivers of riverbank shear stress and failure—this document is strictly focused on the physical loss (retreat) of land.

To ensure the appropriate application of this resource, it is defined by the following technical and geographic parameters:

- **Geographic Scope:** This guidance applies to both watercourses (flowing water, such as rivers and streams) and inland waterbodies (still water, such as lakes and reservoirs) environments across the territory. While the guide addresses general lakeshore settings, it does not explicitly cover marine/coastal environments, nor the unique conditions of glacial lakes (e.g., ice calving) or steep mountain creeks prone to debris floods or flows. The primary focus remains on valley floor settings where infrastructure and development typically occur on terraces or other gentler terrain.
- **Focus on lateral erosion:** The document primarily addresses lateral bank erosion (Photo 1-3) and retreat, but it acknowledges that lateral and vertical erosion (channel or lake-bed scour) are highly interdependent and should be assessed in tandem.
- **Guidance vs. procedural status:** Following the precedent of the *Preferred Practices for Works Affecting Yukon Waters* (YG, 2019), this is a technical guidance resource rather than a rigid procedural manual. It outlines best practices and standardized principles but does not replace professional judgment or site-specific engineering requirements.
- **Risk assessment limitations:** Although this document discusses erosion-related risks, it does not outline or address a formal risk assessment framework. It is not intended to define "acceptable risk" levels for the territory or provide formal cost-benefit analyses for property protection.

Photo 1-3. Erosion of the Dempster Highway embankment following a high-intensity, mid-summer rain event in August 2016 (photo credit: YG Highways and Public Works – Transportation and Engineering Branch [HPW-TEB])

To ensure consistency across multi-disciplinary project teams, several core terms are defined below. For a comprehensive list of technical definitions, refer to the Glossary in **Appendix B.**

- **Lakeshore / Riverbank:** The physical interface between land and a waterbody. In this guide, "shoreline" refers to lacustrine (lake) environments, while "riverbank" refers to riverine (fluvial) systems.
- **Erosion:** The natural physical process by which land is worn away by the action of water, ice, wind, gravity and/or anthropogenic disturbance.
- **Assessment:** The diagnostic phase involving the gathering and analysis of data to understand the underlying causes, mechanisms, trajectories and rates of erosion. Assessment is required to inform the selection and design of effective mitigation measures.
- **Mitigation:** The implementation of strategies to manage or reduce erosion-related risks (e.g., Photo 1-4). A distinction is made between *mitigating erosion* (physically stopping bank retreat, e.g., structural armouring) and *mitigating risks associated with erosion* (e.g., managed retreat or relocating infrastructure), which addresses the threat from erosion without necessarily stopping erosion itself.
- **Hazard:** A potentially damaging physical event or phenomenon with the potential to compromise public infrastructure or safety, adversely affect private property, or cause environmental damage.
- **Risk:** The probability of harmful consequences or expected losses resulting from interactions between natural or human-induced hazards and vulnerable conditions.

Photo 1-4. Waves breaking along a lakeshore armoured with large riprap to help protect private properties on Lake Erie (photo credit: SJL Engineering Inc. [SJL])

1.2 Layout and Use of this Guide

This guide is structured to move progressively from foundational background principles governing erosion in the Yukon to specific technical assessment and mitigation practices. This organization ensures that users have a common understanding of the underlying geomorphic drivers of erosion before moving into the complexities of assessment, mitigation design and implementation. To assist users in navigating the document based on their specific project phase—whether in the early planning stages or during final engineering design—a visual guide to this document is included below (Figure 1-1).

Recognizing that the target audience for this document is diverse, ranging from regional planners and engineers to specialized technical consultants, the text is written for broad accessibility. A section-based plain-language summary document is also provided in Appendix A to help ensure that key concepts are easily understood by all readers and to help readers quickly navigate the main document.

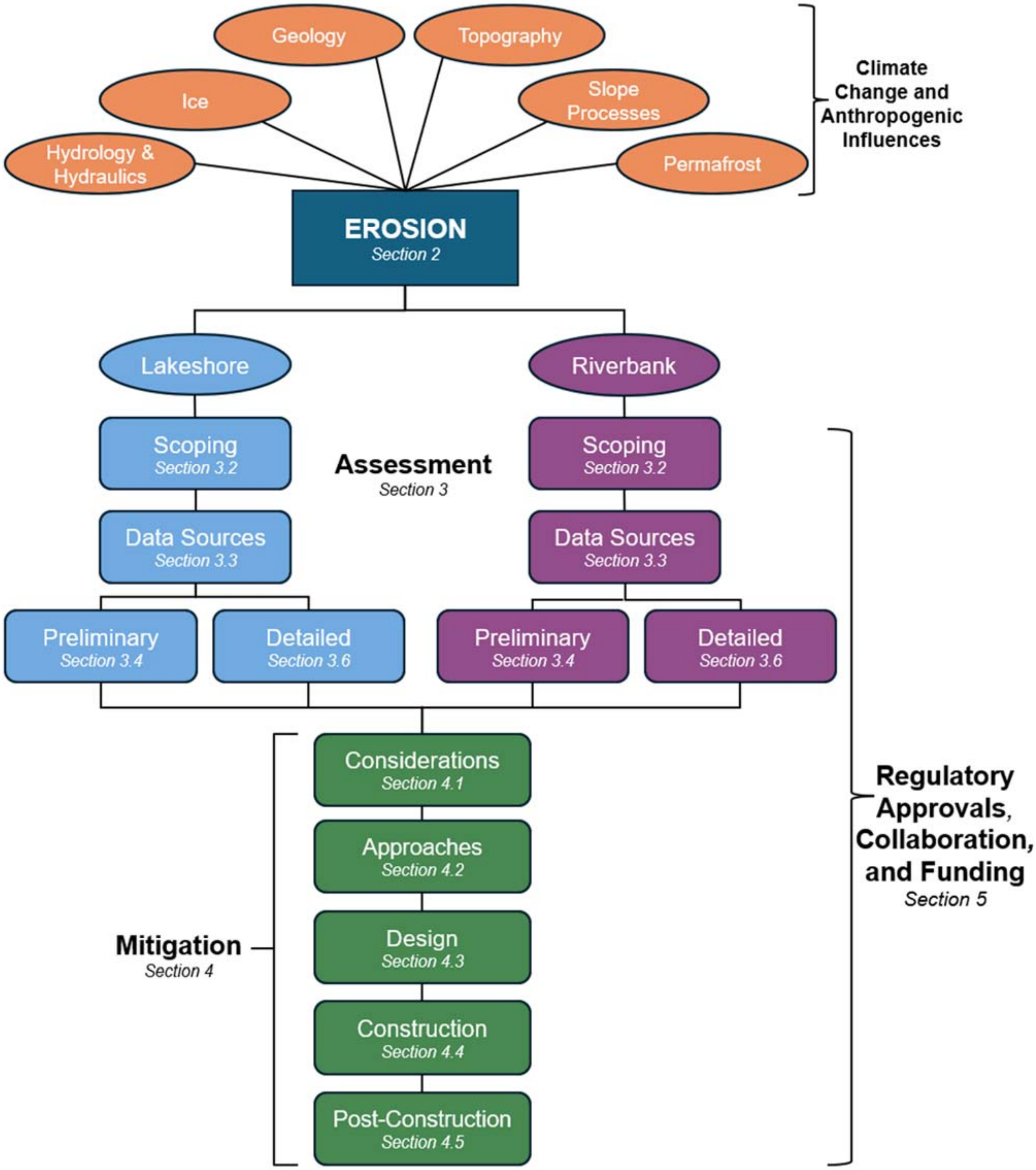

Figure 1-1. A visual framework of the main content and flow of this guidance document.

2.0 Erosional Processes in the Yukon

2.1 Drivers of Riverbank Erosion

2.1.1 Water

Fluvial erosion is driven primarily by flowing water exerting forces on materials forming the bed and banks of a river. In northern and cold-climate environments, the timing and intensity of these processes are largely governed by the hydrologic cycle. Spring snowmelt typically drives the annual peak flow, known as the freshet, in many Yukon rivers. This period results in prolonged intervals of elevated water levels and high-velocity flows, concentrating erosive energy against the banks for several weeks (Church, 1988).

Beyond the annual freshet, non-freshet flooding events also play a critical role in riverbank and lakeshore stability. These floods—including outburst floods from the failure of glaciers, moraines, landslides, ice jams, or beaver dams, as well as extreme late-summer convective rainstorms—can trigger sudden, highly erosive surges of water and sediment (Costa & Schuster, 1988). While these high-magnitude peak flows are significant, it is important to recognize that geomorphic change can also occur during moderate flow events and is not exclusively restricted to major floods (Wolman & Miller, 1960). Examples of riverbank erosion in the Yukon are illustrated in Photo 2-1.

Erosion is rarely caused by one factor. Water, ice, permafrost, and human activity often work together, making erosion more complex than it first appears.

Common mechanisms of water-related erosion include:

- **Entrainment of sediment:** As velocity and depth increase, the shear stress (tractive force) exerted on the channel bed and banks increases. When this force exceeds the critical resistance of the bank materials, individual sediment particles are plucked and entrained into the flow (Shields, 1936).
- **Toe erosion and undercutting:** Fluvial scour commonly concentrates at the base (toe) of the bank. This toe erosion undercuts the bank, removing foundational support and leading to the eventual mass failure or collapse of the overhanging material (Thorne, 1982).
- **Vertical erosion (degradation):** Down-cutting of the channel bed effectively increases the height and steepness of the adjacent riverbanks. This vertical instability commonly acts as a primary trigger for subsequent bank failure (Simon, 1989).
- **Sloughing as water levels drop:** High water levels saturate riverbanks and provide supporting hydrostatic pressure. When floodwaters rapidly recede (or during rapid anthropogenic drawdown), the water-logged bank loses this support and commonly sloughs into the channel (Simon et al., 2000).
- **Groundwater seepage, piping and sapping:** Subsurface water moving through the bank can wash away fine soil particles from within (piping), erode sediments where it seeps from a slope face (sapping), and compromise internal bank strength and cause the slope to collapse (Hagerty, 1991).
- **Surface runoff and rain splash:** Rainfall and snowmelt flowing over exposed bank faces cause various forms of erosion—including rain splash, sheet, rill, and gully—which wear down the slope from the top.

Photo 2-1. Examples of riverine erosion. Upper left: bank undercutting along the outer bend of Engineer Creek (photo credit: SLR Consulting (Canada) Ltd. [SLR]). Upper right: multiple channel cutoffs along Aishihik River (photo credit: SLR). Bottom left: bank erosion and slumping along Takhini River (photo credit: Benoit Turcotte). Bottom right: widespread channel adjustment downstream of a beaver-dam failure near Mud Lake (photo credit: SLR).

These combined mechanisms frequently manifest in channel migration, where flow moving through channel bends exerts higher velocities and shear stresses against the outer (concave) bank. This causes progressive lateral retreat and the evolution of the river's planform over time (Hickin & Nanson, 1984). Progressive meander evolution, channel migration, or rapid channel bed aggradation can trigger an avulsion—the sudden switching of a river's course to a new alignment. Avulsions frequently occur when eroding meander bends intersect (neck cut-offs), when floodwaters scour a new, steeper channel across a floodplain (chute cut-offs), or when an oversupply of sediment causes the existing channel to aggrade and force flow into secondary pathways (Slingerland & Smith, 2004).

The rate and nature of erosion are fundamentally linked to the balance of sediment. A river's erosive potential is often a function of its sediment load; for instance, "clearwater" or "hungry water" erosion occurs downstream of dams or lakes where the river has excess erosional energy and scours the bed and banks (Kondolf, 1997). Conversely, an oversupply of sediment can lead to channel aggradation, which raises the bed level and forces flow outward against adjacent banks, accelerating lateral migration or leading to avulsions.

2.1.2 Woody Debris

Woody debris, ranging from small branches to entire fallen trees, plays a significant role in the erosional dynamics of Yukon watercourses. The geomorphic influence of wood is highly dependent on the physical scale of the debris relative to the width of the watercourse (Keller & Swanson, 1979). A wide river can often accommodate significant tree fall with minimal impact on its overall planform, as the debris is easily transported downstream or remains confined to the channel margins. In contrast, in a narrow creek, a single fallen tree can span the entire channel, creating a "log jam" or "debris bridge." These obstructions can abruptly redirect flow directly into an adjacent bank, triggering localized and rapid lateral erosion (Abbe & Montgomery, 1996).

Primary mechanisms of wood-driven erosion include:

- **Flow redirection and scour:** Large woody debris (LWD) can act as a natural groyne, deflecting high-velocity flow toward the opposite bank or causing localized turbulence and scour "holes" around the debris itself.
- **Log jams:** The cumulative build-up of wood can partially or fully block a channel (Photo 2-2). This increases the upstream water level (backwater effect) and often forces the river to "outflank" the obstruction, cutting a new channel into the adjacent floodplain and accelerating channel migration (Brummer et al., 2006).
- **Mechanical abrasion:** During high-flow events or ice runs, floating logs can act as physical "battering rams," mechanically abrading and weakening the soil or permafrost at the bank face.
- **Root system stability:** While live root systems reinforce the soil, the weight of a leaning or fallen tree can act as a lever, physically prying large sections of the bank away as it topples into the water (Simon & Collison, 2002).

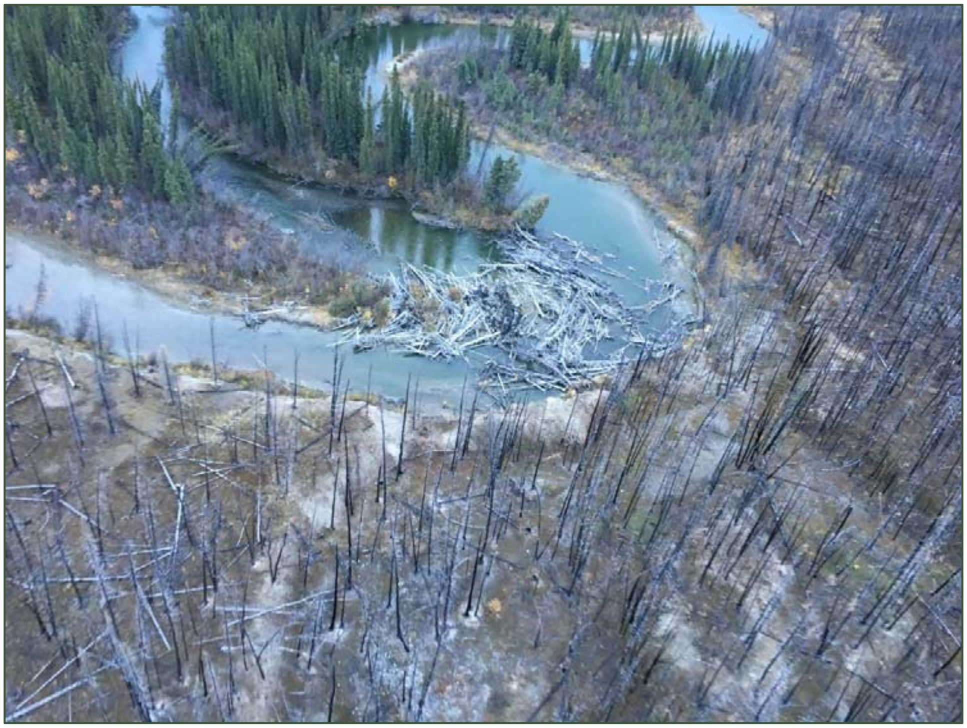

Photo 2-2. Woody debris jam adjacent to a recent wildfire along West Aishihik River (photo credit: SLR)

2.1.3 Ice

River ice is a primary geomorphic agent in cold-climate regions like the Yukon, commonly contributing to the physical structure and seasonal evolution of watercourses. The seasonal formation, presence, and breakup of ice heavily influence bank stability and channel morphology, often exerting more significant erosive forces and causing greater geomorphic change than typical open-water flood events (Ashton, 1986).

As ice accumulates and interacts with the channel boundaries, it modifies local hydraulics, altering velocity distributions and sediment transport capacities. These complex processes can drastically shift sediment dynamics at the watershed scale, triggering localized scour, widespread bank failure, and the sudden transport of coarse bed materials (Ettema, 1999, Turcotte and Morse, 2017). Example of ice accumulations and processes are illustrated in Photo 2-3.

In the Yukon, ice can exert greater forces than flowing water. Ice jams and breakup events can drive rapid, severe erosion in a short time.

Common types of river ice accumulations and processes include:

- **Frazil ice:** In turbulent, supercooled water, fine ice crystals (frazil) form and can generate slush runs down a river. When encountering a downstream ice cover, the frazil slush can deposit under the ice cover, resulting in massive "hanging dams" that restrict the channel cross-section and redirect high-velocity flow against the bed and banks (Ashton, 1986).
- **Anchor ice:** Frazil ice can also adhere to the riverbed, forming masses around and above gravel and boulders. When these accumulations or blankets become buoyant,

they can lift and carry significant sediment loads downstream, depositing them elsewhere as the ice melts in the spring (Kempema & Ettema, 2011).

- **Border ice:** Shore-attached "fast ice" narrows the active channel, increasing velocities near the thalweg. If border ice slabs are lifted by rising flows while still frozen to the bank, they can strip away protective sediment layers and armouring (Ettema, 1999).
- **Aufeis (icings or "glaciations"):** In shallow or braided rivers, winter flow can be forced to the surface, subsequently freezes in successive layers. These sheets block the main channel in spring, forcing freshet flows towards the banks and floodplain, causing erosion. Aufeis slabs can also collapse into the flowing water beneath, plucking large boulders (Ashton, 1986).
- **Ice runs:** During breakup, the transition from stationary to a mobile ice cover may result in severe abrasion against the banks. These runs combine mechanical scouring with high sediment transport capacity; turbidity levels often reach their annual peak during this phase (Zabilansky et al., 2002).
- **Ice jams:** Arrested ice runs cause significant "pushing and shoving" against banks and riparian vegetation. When an ice jam releases, the stored potential energy converts into a powerful kinetic surge that can travel for long distances, scouring the banks along the way (Beltaos, 2008).

Important mechanisms of ice-driven erosion include:

- **Flow deflection:** Ice accumulations (including dynamic breakup jams) create extreme localized scour by forcing high-velocity water underneath the ice or laterally into riverbanks and floodplains to bypass the blockage (Ettema, 1999). This process may be enhanced by the grounded (non-floating) nature of the ice cover (e.g., bed-fast or bank-fast ice).
- **Flow acceleration:** The sudden release of an ice jam unleashes a fast-moving hydrodynamic wave of water (a "jave"). This surging ice run exerts extreme shear stresses on the channel boundaries (Beltaos, 1983).
- **Ice gouging and abrasion:** During dynamic breakups, especially when a large ice jam releases, moving ice floes act as bulldozers. They physically gouge into the bank material, shear off riparian vegetation, and scrape away surface sediments (Zabilansky et al., 2002).
- **Ice rafting:** When buoyant anchor ice detaches, or when grounded border ice is affected by lifting forces, it plucks and rafts cobbles, gravel, and organic debris downstream (Kempema & Ettema, 2011).

Photo 2-3. Examples of ice accumulations and processes. Upper left: damaged vegetation following an ice run in a secondary channel of the Montmorency River near Quebec City. Upper right: aufeis collapse and calving along the Blackstone River in central Yukon. Lower left: Residual anchor ice blanket in the Montmorency. Lower right: bank scour following an ice run along the Porcupine River. All photos courtesy of Benoit Turcotte.

2.1.4 Permafrost and Ground Ice

The Yukon is situated entirely within a permafrost region (Figure 2-1), with distributions ranging from sporadic and discontinuous in the south to continuous in the northern half of the territory (Heginbottom et al., 1995). A fundamental requirement of this guide is that erosion assessments in any part of the Yukon must account for the potential presence and implications of permafrost, including its potential warming or degradation.

> Frozen ground can be strong—but once it thaws, it can quickly become unstable. Warming temperatures can dramatically increase erosion rates in permafrost areas.

When characterizing permafrost for riverbank and lakeshore assessments, the following key attributes should be considered (Bureau de normalisation du Québec, 2023; Canadian Standards Association, 2019):

- **Distribution:** The spatial extent and lateral continuity of permafrost across the project area.
- **Thickness and depth:** The vertical extent of the permafrost body and the thickness of the active layer (the near-surface zone subject to annual thawing and freezing).
- **Thermal regime:** The ground temperature profile, including the identification of any taliks (unfrozen zones) situated within or above the permafrost.
- **Ice content:** The volume and specific type of ground ice (e.g., pore ice, segregated ice, wedge ice, or massive ice) contained within the soil matrix.
- **Thaw sensitivity:** The potential for the soil—particularly ice-rich or fine-grained materials—to lose structural integrity or undergo significant volume change (thermokarst subsidence) upon thawing.

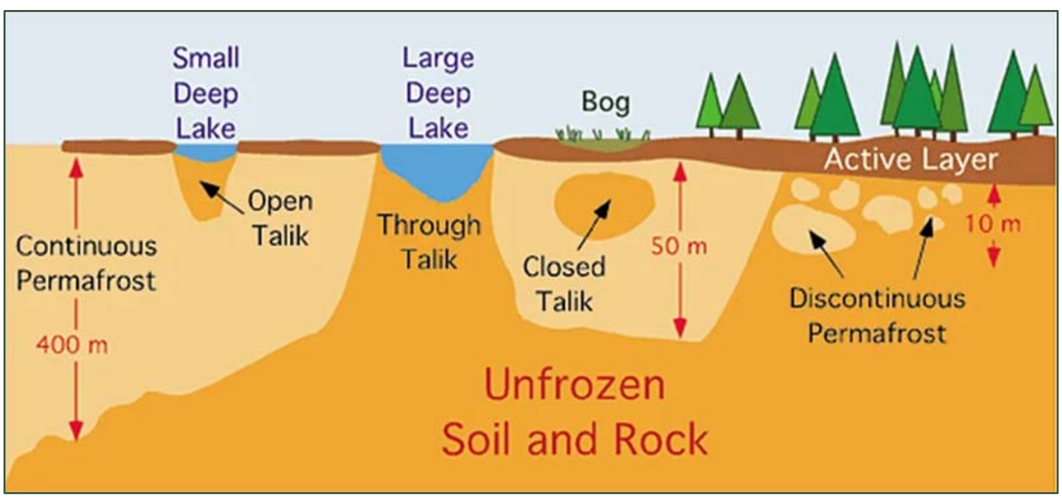

Figure 2-1. Cross-sectional schematic of continuous and discontinuous permafrost, active layers, and taliks (source: Pidwirny, 2006). Areas near Yukon's southern border would be represented on the right (discontinuous permafrost) and northern areas would be represented on the left (continuous permafrost).

Thermally stable, intact permafrost and ground ice can provide mechanical strength that resists fluvial erosion and lateral channel migration (Fields et al., 2025). As ground temperatures rise, especially above -2°C, the frozen soils lose strength. The eventual loss of ice-bonding as permafrost thaws transitions the bank from a competent mass into a highly erodible or unstable state. This transition promotes rapid destabilization and significantly accelerates fluvial erosion rates (Rowland et al., 2023). Retrogressive thaw flows (slumps) are a manifestation of thermokarst that occur along some riverbanks as toe erosion and active-layer detachments expose ice-rich permafrost to thaw (e.g., Photo 2-4).

Photo 2-4. A permafrost thaw flow (slump) along Takhini River partly triggered by toe erosion (source: Calmels et al., 2021)

2.2 Drivers of Lakeshore Erosion

2.2.1 Water

In the Yukon, lakeshore environments are the result of a dynamic interaction of erosional and depositional processes governed by local topography, bathymetry, water levels, and climate (Lawson, 1985; Newbury & McCullough, 1984). Larger waterbodies—such as Tagish and Bennett lakes—can develop significant wave energy capable of reshaping lakeshores and undermining infrastructure. Unlike river systems where flow is unidirectional, lake erosion is multi-directional and highly dependent on "fetch," which is the unobstructed open-water distance available for wind to build wave height (Herb et al., 2005). This energy, combined with the territory's unique sediment sources and regulated water levels in certain basins, creates a distinct erosional environment that requires site-specific consideration. Examples of lakeshore erosion are illustrated in Photo 2-5.

Primary mechanisms of water-related lakeshore erosion in the Yukon include:

> Large lakes can generate powerful waves. Long open-water distances (fetch) allow wind to build energy that can rapidly erode lakeshores.

- **Wind and waves:** Wind-generated wave action is the principal driver of lakeshore erosion during the open-water period. Wave energy is dictated by fetch, bathymetry, storm duration, and wind speed (Lawson, 1985). As waves propagate through shallow nearshore waters, they shoal and break, producing turbulence and large shear stresses that contribute to the vertical downcutting of the lakebed (Ontario Ministry of Natural Resources [OMNR], 1996).
- **Boat wake:** In highly trafficked areas, small harbours, or sheltered connecting channels, boat wakes can introduce unnatural, high-frequency wave energy. These localized surges can be a significant part of the total wave action, eroding lakeshores that are otherwise protected from natural wind-generated waves (OMNR, 1996).
- **High and low water levels:** Changes in water levels—whether natural or regulated—alter erosion patterns by determining the portion of the nearshore zone over which breaking waves expend their energy (OMNR, 1996). High water allows larger storm waves to bypass nearshore shoals and directly attack vulnerable upper banks and vegetation lines. Conversely, low water levels expose the bank toe to direct scour and the weakening effects of freeze-thaw action (Lawson, 1985).
- **Longshore currents:** Waves striking the shore at an oblique angle generate littoral currents that systematically transport mobilized sand and gravel along the lakeshore (Mangor et al., 2017). Bathymetric irregularities or changes in lakeshore alignment alter these transport rates, creating zones of erosion where transport accelerates and zones of deposition where it decelerates. The net impact is fundamentally linked to the local wave climate and sediment supply (Lawson, 1985).
- **Rapid drawdown:** In regulated reservoirs, a rapid drop in water levels can cause saturated, fine-grained lakeshores to slump due to pore-water pressure imbalances and an inability to drain at rates that keep pace with the lowering lake level (Lawson, 1985). This same destabilizing effect occurs naturally when a waterbody impounded by a beaver dam or landslide dam fails, causing a sudden loss of supporting hydrostatic pressure against the shore.
- **Tsunami:** Large landslides or detached glacial ice plunging into deep lakes can generate localized, catastrophic displacement waves (tsunamis) (Mulligan & Take, 2017). These events cause significant inland flooding and can heavily scour lakeshores far above the normal high-water mark, as was observed during the 2007 landslide-generated tsunami in Chehalis Lake (Roberts et al., 2013).

Photo 2-5. Examples of lakeshore erosion. Top left: scarp erosion on Aishihik Lake (photo credit: SLR). Top right: an exposed and steep lakeshore on Canyon Lake (photo credit: SLR). Bottom left: lakeshore erosion on Marsh Lake following high waters in 2021 (photo credit: YG HPW-TEB). Bottom right: wind-generated waves crashing into an armoured lakeshore of Lake Erie during a storm event (photo credit: SJL).

2.2.2 Woody Debris

In lake environments, the impact of woody debris is governed by its mobility, arrangement, and orientation relative to the lakeshore. Unlike in the unidirectional flow of rivers, woody debris along lakeshores is commonly redistributed by fluctuating water levels and multi-directional wind events, making its fate and transport highly dynamic (Murphy et al., 2021). Along lakeshores in the Yukon, where large-growth timber may be sparse but slow to decay, wood can act as either a natural defense against wave energy or a mechanical erosive agent (Falkenrich et al., 2021).

Primary mechanisms of wood-driven erosion include:

- **Mechanical impact (battering):** During high-wind events or storm surges, buoyant logs and debris can become mobilized. Driven by wave action, this mobile wood physically impacts the bank like a battering ram, weakening soil structure and shearing off riparian vegetation that would otherwise help maintain stability (Murphy et al., 2021).
- **Wave dissipation and protection:** Conversely, large, stable aggregations of wood that are embedded in or resting against the lakeshore can serve as natural breakwaters (Photo 2-6). These accumulations buffer the upper beach from wave attack, dissipate incoming wave energy, and trap sediment, effectively shielding the bank from direct hydraulic impacts and limiting storm-caused overwash (Kennedy & Woods, 2012).
- **Localized scour and channeling:** The presence of woody debris can also have adverse geomorphic effects depending on its orientation and the local wave climate. Significant accumulations or improperly placed logs may inadvertently channel wave runup, concentrating energy and causing localized beach scour or exacerbating erosion in specific sections of the bank (Falkenrich et al., 2021).

Photo 2-6. Accumulation of wood along the lakeshore of Atlin Lake providing transient erosion protection (photo credit: SLR).

2.2.3 Ice

In the Yukon, lake ice plays a dual role in lakeshore dynamics. While the formation of shorefast ice acts as a natural protective layer against wave action during the winter, the formation, thermal expansion, and wind-driven breakup of the ice cover are capable of causing severe erosion and infrastructure damage (OMNR, 1996). The duration of ice cover serves as a seasonal buffer that prevents wind-wave growth and physically shields the lakeshore from erosional energy. Consequently, a lengthening open-water season—driven by a warming climate—increases the duration of opportunity for wind-generated waves to impact the bank and drive lateral retreat (Bureau de normalisation du Québec, 2023; Lawson, 1985).

Mechanisms of ice-driven forces affecting lakeshores include:

- **Ice shove and ride-up (dynamic forces):** Driven by strong winds, waves, and surface currents—particularly during spring breakup—large pieces of floating ice are forcefully pushed onto the lakeshore (Figure 2-2). These dynamic events manifest as either ice ride-up (Photo 2-7), where intact sheets move landward over beaches, or ice pile-up, where ice buckles and fails upon contact with the shore (Natural Resources Canada [NRCan], 2024). This mechanical action gouges beach faces, shears riparian vegetation, redistributes sediment, and exerts large impact forces capable of damaging lakeshore infrastructure (OMNR, 1996).
- **Thermal expansion (static ice push):** Solid sheet ice expands and contracts as air temperatures fluctuate. In confined lake basins, water that freezes within ice cracks during cold periods causes the entire floating ice sheet to expand and push laterally during subsequent warming phases. This gradual but significant static pressure can buckle rigid bank-protection structures, erode banks, and physically displace beach sediments inland to create distinct ice-push ridges (U.S. Army Corps of Engineers, 2006).
- **Ice plucking and scour:** When shore ice forms, it commonly freezes around rocks, cobbles, and beach sediments. During water level fluctuations (e.g., reservoir drawdown) or spring breakup, the ice detaches and floats away, "plucking" and rafting these materials from nearshore areas and rock-based erosion control structures (Lawson, 1985; Vouk, et al., 2021). This process can weaken engineered structures and strip the lakeshore of its natural coarse armouring, leaving finer underlying sediments highly vulnerable to subsequent wave erosion during the open-water season (OMNR, 1996).

Figure 2-2. Lake ice break-up on Tagish Lake, May 20, 2022 (Imagery source: ESRI)

Photo 2-7. Ice ride-up along a gravel shore of Tagish Lake in May 2023 (photo credit: Benoit Turcotte). Note: human subjects have been digitally removed to protect privacy and accentuate the natural process.

2.2.4 Permafrost and Ground Ice

The interaction between lakes and permafrost is heavily influenced by the high heat storage capacity of standing water and the mechanical forces of wind-generated waves. Many Yukon lakes are bordered by, or situated entirely within, permafrost terrain (Figure 2-1). Factors that contribute to observed patterns and rates of erosion along lakeshores include ground ice content, thaw sensitivity, and the specific thermal dynamics of the water body (Grosse et al., 2013).

Key influences on lacustrine permafrost erosion include:

- **Sublacustrine taliks and heat storage:** Large or deep lakes store significant thermal energy, which alters the ground thermal regime beneath them by slowing the rate of seasonal freezing and increasing summer heat transfer (Bureau de normalisation du Québec, 2023). This commonly forms a talik—an unfrozen zone of ground surrounded by permafrost. If the lake water depth exceeds the maximum thickness of winter ice, bottom temperatures remain above freezing year-round, continually expanding the talik and contributing to lake-bottom settlement, sediment compaction, and lakeshore subsidence (Grosse et al., 2013; van Everdingen, 1998).
- **Thermal-mechanical erosion (thermal abrasion):** Wind-generated waves drive relatively warm surface waters directly against frozen lakeshores (Photo 2-8). This combined thermal and mechanical action—formally termed thermal abrasion—melts the ground ice while simultaneously washing the thawed sediment away into the littoral zone (Shiklomanov & Nelson, 2013). As waves continuously impact the base of ice-rich bluffs, they carve out deep thermo-erosional niches at the waterline. Once the overhanging frozen material loses its mechanical structural support, it shears off in massive block failures, leading to extreme, episodic retreat events (Bureau de normalisation du Québec, 2023).
- **Thermokarst expansion:** The thermal degradation of ice-rich permafrost along the lakeshore leads to significant ground subsidence, retrogressive thaw slumps, and lateral lake expansion, collectively known as thermokarst (Grosse et al., 2013). Gradual inundation of subsiding lakeshores tends to accelerate thermokarst and contribute to lakeshore retreat over time.
- **Loss of insulating cover:** The mechanical forces of lake ice shove and ride-up during spring break-up can physically strip away the insulating organic soil and vegetation layers from the lakeshore. This exposes the underlying permafrost to direct solar radiation and warmer air temperatures, upsetting the thermal balance and accelerating further thaw and long-term instability (Grosse et al., 2013).

Photo 2-8. Thermal-mechanical erosion contributing to permafrost thaw along a scarp in Aishihik Lake (photo credit: SLR)

2.3 Interaction with Slopes

Erosion and slope instability are distinct but intimately coupled processes. As a river or lake erodes the toe of a slope, it removes critical physical support for the material above, leading to undercutting and over-steepening that triggers mass wasting (OMNR, 2002). This dynamic frequently creates a continuous "erosion-landslide cycle," as first described by Williams et al. (1979) (Figure 2-3): toe scour leads to slope failure, and the resulting mass wasting debris is subsequently washed away by fluvial or wave energy, leaving the slope again over-steepened and primed for further retreat. Photographic examples of slopes failing along rivers and lakeshores are provided in Photo 2-9.

Erosion at the base of a slope can trigger landslides above. Efforts to stop erosion that focus only on the lakeshore or riverbank without considering the slope above, or vice versa, are commonly unsuccessful.

Some key considerations for slope interactions are summarized below:

- **Regional geological influences** – In the Yukon, river valleys and lakeshores commonly feature high, steep scarps formed at the margins of glaciolacustrine or glaciofluvial terraces. The specific soil composition of these terraces dictates the nature of slope failure. Cohesive slopes, such as those composed of clays and silts, are prone to mass movement and sudden, episodic failures that can cause the scarp edge to retreat significantly in a single event (OMNR, 2002). Conversely, cohesionless slopes composed of sands and gravels tend to experience gradual ravelling or sloughing, maintaining a relatively consistent slope angle through smaller, frequent adjustments rather than large-scale block collapses.
- **Hydraulic and thermal drivers** – Hydraulic factors and land use further complicate these slope-channel interactions. If a landslide mass reaches a watercourse, it alters the local bank configuration and composition. While this build-out of debris may temporarily counteract local erosion by protecting the slope toe, it can also deflect flow toward the

opposite bank, concentrating erosional forces and triggering new instabilities across the channel. Furthermore, internal water movement heavily influences slope stability. Overland flow or groundwater seepage exiting a slope face can internally weaken the soil, washing away fine particles (piping) and increasing porewater pressure until the slope collapses (OMNR, 2002). In northern environments, these failures can expose underlying ice-rich permafrost. The subsequent thermal degradation of this frozen core leads to retrogressive thaw flows (slumps), which can deliver large volumes of saturated sediment directly into the watercourse (McKillop et al., 2016).

- **Integrated assessment principle** – Erosion and slope stability should be assessed as an integrated system along riverbanks and lakeshores. A mitigation strategy that only protects the toe of a bank may prove ineffective if a landslide is already initiating from the upper slope due to groundwater seepage or permafrost degradation. Conversely, stabilizing an upper slope without protecting against hydraulic scour at the toe will ultimately lead to undermining and the failure of the stabilization works, as fluvial processes continually remove the supporting foundation.

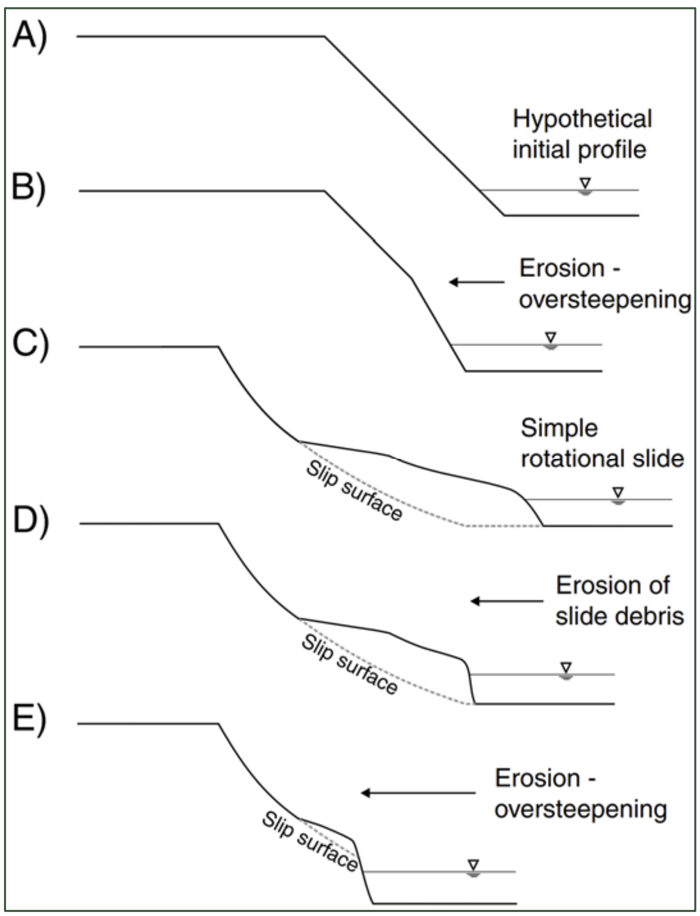

Figure 2-3. Schematic diagram illustrating the "erosion-landslide cycle," from Hugenholtz and Lacelle (2004) as adapted from Williams et al. (1979), which best explains long-term behaviour and eventual recession of hillslopes along lakeshores or riverbanks.

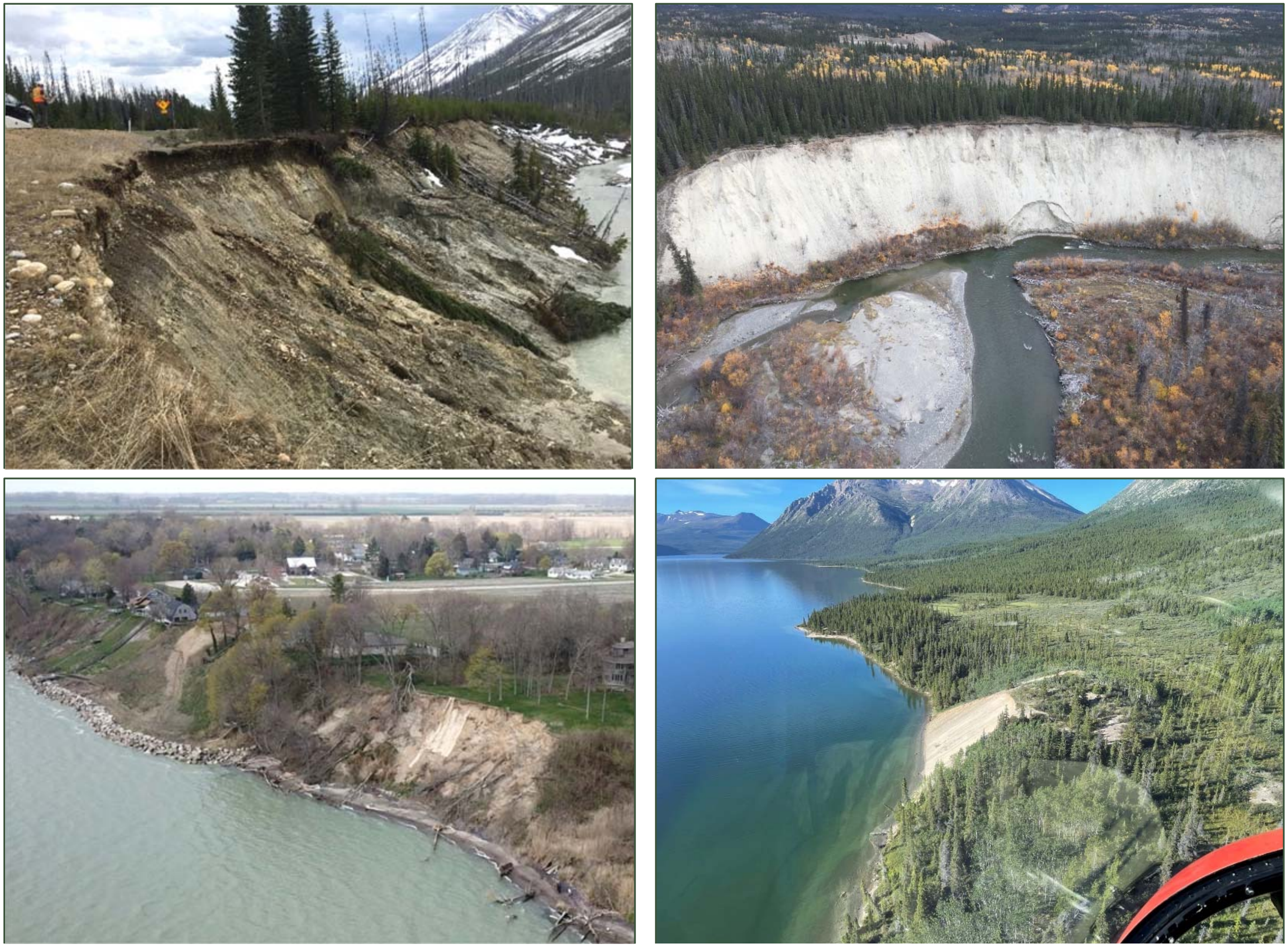

Photo 2-9. Examples of slope failure along riverbanks and lakeshores. Top left: failure of a glaciolacustrine slope along Vermillion River (photo credit: SLR). Top right: recent failure within a larger, eroding scarp along Aishihik River (photo credit: SLR). Bottom left: scarp failure updrift and downdrift of lakeshore protection on Lake Huron (photo credit: SJL). Bottom right: ongoing ravelling of a sandy slope along Surprise Lake (photo credit: SLR).

2.4 Anthropogenic Influences on Erosion

Although natural processes drive the majority of erosional changes in the Yukon, human activities frequently alter the rate, scale, and location of erosion. Understanding these influences is critical for distinguishing between hydrogeomorphic processes and human-induced instability. Notable anthropogenic activities or influences that impact erosion processes are listed below and illustrated in Photo 2-10:

- **Placer mining:** Extensive historical and ongoing placer mining, particularly in regions like the unglaciated Klondike Plateau, results in significant modifications to valley bottoms. These activities typically involve the removal of vegetation and organic soils, which can alter the thermal regime of the underlying permafrost. Additionally, the physical realignment of stream channels and the placement of unconsolidated tailings piles influence sediment transport dynamics and localized erosion patterns within the affected reaches.
- **Flow regulation:** Hydroelectric facilities and associated water storage fundamentally alter natural flow and water level regimes. While flow regulation may reduce peak flows downstream, winter releases can promote unnatural ice formation or exacerbate normal river ice processes (McParland et al., 2021). Furthermore, the trapping of sediment behind dams starves downstream reaches, leading to aggressive "clearwater erosion" as the river scours the bed and banks (Kondolf, 1997). On regulated lakes, unnatural drawdown or prolonged high water exposes vulnerable lakeshore elevations to concentrated wave action (Carmignani & Roy, 2017).
- **Linear infrastructure:** Yukon’s major transportation corridors frequently parallel lakes and rivers, artificially confining channels and restricting fluvial processes like meander migration. Highway embankments often face severe undercutting from redirected erosive energy. Additionally, culverts often initiate the formation of aufeis (icings) because the structure remains colder than the surrounding ground. Blocked culverts can result in water infiltrating the road embankment or overtopping the road, particularly during spring when snowmelt occurs much earlier than the ice within the culvert can thaw (Carey et al., 1975; Turcotte et al., 2024).
- **Downstream/downdrift energy transfer:** Uncoordinated hardening of riverbank and lakeshores by individual property owners often fails to address root geomorphic causes. These "ad-hoc" measures can exacerbate erosion on downstream or downdrift[2] properties by diverting flow and wave energy toward unprotected areas (Reid & Church, 2015).

> Efforts to “fix” erosion in one spot can make it worse somewhere else. Poorly planned protection can shift erosion downstream or along the lakeshore.

- **Impacts on sediment transport:** Armouring and infrastructure that obstruct the natural movement of sediment can significantly impact the supply of sediment to downstream/downdrift lakeshores, causing or accelerating erosion elsewhere in the system (NRCan, 2024).
- **Under-designed hardening:** Riverbank or lakeshore armouring that is under-designed for the range of conditions to which it is exposed can fail outright, resulting in the rapid

[2] The use of the terms ‘downdrift’ and ‘updrift’ in this document refers to the net direction of longshore currents and potential longshore sediment transport, and does not necessarily imply a volume or rate of actual sediment transport

exposure of native bank material and rapid erosion of the formerly armoured and adjacent riverbanks and lakeshores. These ad hoc measures can often aggravate the erosion problem or lead to unintended geomorphic consequences (U.S. Army Corps of Engineers, 2009).

- **Berming and channel straightening:** Constructing flood-protection embankments or berms restricts a river from accessing its natural floodplain, concentrating hydraulic energy within the main channel and increasing erosion potential. Similarly, artificially straightened channels increase stream gradients and velocities, prompting the river to aggressively erode its bed and banks as it readopts a natural meandering pattern (Church, 2015).
- **Clearing of riparian vegetation:** Removing vegetation for viewsheds or access significantly alters bank stability. Without root systems to bind soil and stems to dissipate energy, banks become susceptible to rilling, scour, and wave impacts. Vegetation loss also reduces water uptake, such that soil moisture remains higher and shear strength remains lower. In permafrost regions, the loss of the insulating organic layer can trigger thermal degradation and bank subsidence (Ecofish Research Ltd., 2024).
- **Localized hydromodification:** While the Yukon has a limited number of dense urban centres, the expansion of infrastructure in developing areas—particularly those near smaller watercourses—remains a notable consideration. In these settings, the increase in impervious surfaces like roads and roofs can unnaturally accelerate and concentrate runoff. While the scale of the Yukon's primary waterbodies generally buffers against significant hydromodification, localized storm runoff can trigger surface rilling and gullying, contributing to the degradation of adjacent bank slopes (YG, 2019).

Photo 2-10. Examples of anthropogenic influences. Top left: a hydro-electric flow control structure at Surprise Lake near Atlin, British Columbia (photo credit: SLR). Top right: gabion basket erosion mitigation structures on Marsh Lake (photo credit: Benoit Turcotte). Bottom left: anthropogenic berm protecting the village of Canyon (photo credit: SLR). Bottom right: historical placer mining tailings alongside Klondike River near Dawson (photo credit: SLR).

2.5 Climate Change

In the Yukon, where warming rates significantly exceed the global average, climate change can exacerbate natural drivers of erosion (Perrin & Jolkowski, 2022). Beyond simple warming, one of the most significant projected impacts is the increased variability in the future water supply, leading to a broader range of water levels in lakes and discharge magnitudes in rivers (Ecofish Research Ltd., 2024). These shifting extremes—encompassing more intense precipitation, higher wind speeds, and prolonged heatwaves—interact with a landscape already sensitive to change, often accelerating erosional processes beyond historical norms (Bush & Lemmen, 2019). Understanding these shifts is critical for the long-term design and maintenance of riverbank and lakeshore infrastructure.

> Climate change is increasing uncertainty. Future water levels, ice conditions, and erosion rates may differ from the past—designs must account for this.

The following are key considerations for climate change influences on erosion processes:

- **Regional relevance:** While the Yukon is experiencing rapid warming, the specific manifestations of climate change—such as changes in precipitation patterns or permafrost stability—vary significantly across the territory's diverse physiographic regions (Perrin & Jolkowski, 2022).
- **Flow, ice, and sediment regimes:** Shifts in the timing and magnitude of snowmelt, alongside rain-on-snow events and atmospheric rivers, directly influence peak river discharge. Dynamic river ice breakup events, including ice jams and runs, maybe become more common in some rivers and less common in others (Turcotte et al., 2020). Additionally, a trend toward shorter winters is extending the duration of open water conditions, increasing the "seasonal window" during which lakeshores are exposed to hydraulic currents and wind-generated wave action (Prowse & Beltaos, 2002; Turcotte et al., 2011).
- **Thermal dynamics of permafrost and water:** Rising air and water temperatures, coupled with elevated water levels, accelerate the thermal degradation of ice-rich riverbanks and lakeshores. In sensitive areas, the loss of ground ice reduces the structural integrity of the bank, leading to increased rates of slumping and bank retreat (Lininger & Wohl, 2019; Rowland et al., 2023).
- **Wildfire impacts:** An increase in wildfire frequency and intensity removes the insulating organic soil layer and riparian root networks. Wildfire also blackens the ground surface, in the short term. Beyond localized warming and degradation of permafrost, these changes significantly alter the hydrologic flow regime; burned catchments often experience much higher peak flows and increased sediment loading (Photo 2-11) for many years following a fire (Curran et al., 2006).
- **Vegetation patterns:** Changes in riparian species composition and density can alter natural bank reinforcement and the thermal stability of the near-shore environment (Ielpi et al., 2023).
- **Wind patterns:** Similarly, shifts in atmospheric patterns and long-term trends of increasing wind speeds—such as those documented in Yukon valleys—can significantly heighten the erosive energy of waves on lakes in the Yukon (Pinard, 2007). Furthermore, climatic warming extends the open-water season, leaving these shorelines

exposed and vulnerable to wave-induced erosion for longer periods each year (Lawson, 1985).

- **Data limitations and uncertainty:** Projecting future erosion rates remains a significant technical challenge. The Yukon faces a scarcity of long-term or continuous hydrometric and climate data. In many cases, existing datasets are either too brief or are influenced by anthropogenic flow regulation, making predictive modelling and trend analysis highly complex.

Photo 2-11. Channel widening, sediment deposition, and a woody debris jam following a wildfire in the Interior Region of British Columbia (photo credit: SLR).

2.6 Challenges and Opportunities

Successfully understanding and managing erosion in the Yukon requires a nuanced understanding of the territory's unique landscape. Most Yukon communities and linear infrastructure networks were historically established in close proximity to waterbodies for ease of travel, access to resources, and the availability of flatter terrain. However, because much of this development occurred in the absence of standardized territorial guidelines, a high concentration of assets now sits exposed to dynamic and shifting geomorphic risks. While the North presents extreme physical and logistical obstacles, it also offers a degree of flexibility—such as greater land availability—that is often absent in more developed southern jurisdictions.

The following are potential challenges for managing erosion challenges in the Yukon:

- **Diverse geomorphic setting:** The Yukon features a vast array of riverbank and lakeshore environments, from glacial lakes and steep creeks subject to debris flows to large hydro-regulated lakes and sensitive permafrost-affected banks. Because a "one size fits all" approach does not apply, mitigation designs that succeed in one setting may fail entirely in another.

- **Short construction and growing seasons:** The northern climate restricts most construction of erosion management works to a short window, which is often further restricted by environmental timing windows for fish and regulatory preferences for working in isolated, dry conditions. Additionally, the short growing season makes establishing vegetation and successfully implementing bioengineering efforts particularly difficult.
- **Scarcity of mitigation materials:** Adequate construction materials, specifically large-calibre riprap, are scarce in many areas of the territory. Transporting these heavy materials to remote communities is logistically complex and often prohibitively expensive (Ecofish Research Ltd., 2024).
- **Warming climate:** The Yukon is warming at a rate much faster than the global average. This may amplify existing hazards through acceleration of permafrost thaw, extension of open-water periods for wave generation, and creation of more volatile flow regimes (Perrin & Jolkowski, 2022).
- **Large, high-energy rivers:** The territory's primary rivers are often high-bedload, wandering systems typical of regions downstream from rugged mountain ranges. These systems exert strong hydraulic forces and are subject to complex ice dynamics that can rapidly compromise standard bank protection measures (Figure 2-4).
- **Population and funding eligibility:** With a small, distributed population, meeting the density-based eligibility requirements for certain federal funding programs is a challenge. Managing erosion risks requires highly strategic approaches to maximize limited resources for distributed infrastructure.

The following are potential opportunities for managing erosion challenges in the Yukon:

- **Availability of space:** Because the Yukon is less densely populated than southern Canada, there may be more physical room to implement sustainable, long-term strategies. This allows for managed retreat or the relocation of infrastructure, which can often be more cost-effective than the perpetual maintenance of structural protection (Ecofish Research Ltd., 2024).
- **Minimal buried infrastructure:** Relative to major urban centres, the Yukon has a comparative lack of complex underground utility networks (e.g., sewer mains or dense hydro corridors). This lack of fixed subterranean infrastructure simplifies the physical and economic process of relocating at-risk assets away from migrating riverbanks or lakeshores.

Figure 2-4. Old Crow is a remote community with no road access and is situated adjacent to dynamic watercourses. Other Yukon communities are connected by roads year-round but still have challenges accessing specialized equipment and materials for erosion mitigation.

3.0 Assessment of Riverbank and Lakeshore Erosion

3.1 Overview of Assessment Levels

Assessment represents the diagnostic phase of any project. They are usually initiated by landowners, asset managers, or First Nations in response to perceived erosion-related risks, and they are subsequently completed by technical specialists (typically P.Eng. or P.Geo. designations) such as fluvial and coastal geomorphologists, water resources and geotechnical engineers, and permafrost scientists/engineers.

The assessment provides the foundational understanding of the underlying causes, mechanisms, and rates of erosion required to eventually select and design an effective mitigation strategy. To be effective, every assessment should have a clear objective and actionable outcomes; the goal is never simply to "undertake additional assessment." These outcomes should focus on identifying specific drivers (such as wave action versus ice gouging), delineating hazard zones, prioritizing at-risk sites, and/or uncovering site-specific constraints that will dictate the success of future works. This document focuses on two types of assessment: Preliminary and Detailed.

> Good decisions rely on good understanding. Investing in proper assessment early can prevent costly mistakes and reduce the need for emergency repairs later.

Preliminary Assessment

- **Description:** A preliminary assessment is a high-level evaluation that relies primarily on desktop-based analysis and interpretation, supplemented by insights from initial field reconnaissance and any available local or Traditional Knowledge. The goal is to establish a baseline understanding of the site within its broader physiographic context and identify the dominant geomorphic processes at play. This phase generally precedes formal regulatory processes and culminates in recommendations for monitoring and/or high-level mitigative concepts.
- **Triggers:** A preliminary assessment is typically triggered during community-scale planning, route selection for linear infrastructure, or when a land manager needs to prioritize multiple at-risk sites to determine where limited funding should be allocated first. It serves as a necessary precursor to more intensive study.

Detailed Assessment

- **Description:** A detailed assessment is a rigorous, site-specific evaluation that builds upon the preliminary findings. It requires intensive, quantitative field investigations—often involving topographic/bathymetric surveys and geotechnical investigation (e.g., drilling, test pitting). This phase may utilize complex hydraulic, ice, permafrost, climate, or slope stability modelling to answer specific engineering questions and reduce design uncertainty.
- **Triggers:** A detailed assessment is initiated when a preliminary assessment confirms an erosional risk to critical infrastructure, property, or public safety, and when quantitative data are required to inform the detailed design of appropriate mitigation measures.

Although these two phases are typically distinct, project scales or compressed timelines may require that the Preliminary and Detailed phases be collapsed into a single, phased assessment. This approach allows for a continuous workflow—moving directly from desktop review into intensive field investigations—when the risks are already well-defined and the need for action is immediate. In rare scenarios where emergency works are required to protect life or critical infrastructure, the assessment process is necessarily compressed and simplified. In these urgent cases, the focus shifts to immediate, on-site advice from an experienced P.Eng. or P.Geo. to guide rapid, high-impact response measures.

3.2 Project Scoping

Proper scoping by the proponent and their technical team is a critical step before beginning any field work or desktop analysis. It ensures that the assessment addresses the right questions, utilizes the appropriate level of detail, and avoids wasting time and financial resources. A well-scoped project clearly defines the parameters that will guide the entire technical process.

- **Problem identification:** A clear statement of the specific issue being addressed. Scoping should distinguish between a perceived problem and the actual physical driver(s) of instability to ensure the assessment targets the root cause(es) rather than just the symptoms.
- **Objectives:** What is the primary goal of the assessment? Examples include determining the underlying cause of a recent bank failure, delineating a long-term erosion hazard setback for community zoning, or collecting quantitative data (e.g., depths of scour) required for structural design.
- **Temporal and spatial scales:** Defining the physical boundaries of the study area and the time horizons of interest. Erosion processes cannot be understood in isolation; they should be evaluated across appropriate scales (detailed further in Sections 3.2.1 and 3.2.2).
- **Project timeline:** The Yukon's short open-water and construction seasons often dictate project schedules. Assessments, environmental monitoring, and data collection usually need to begin a year or more in advance of any planned mitigation works. Furthermore, scoping should account for the intended design or service life of any future mitigation, as this dictates the time horizon for the supporting data analysis.
- **Budget:** Ensuring the level of analysis is commensurate with available funding and the value or criticality of the at-risk property and/or infrastructure. The remote nature and limited availability of materials in the North often result in costs that far exceed southern benchmarks, requiring regionally specific financial modeling."
- **Applicable regulations:** Identifying early which regulatory bodies (e.g., Yukon Water Board, YESAB, DFO, Transport Canada) will require assessment data for eventual permitting, as this will dictate specific data collection requirements (e.g., fish habitat mapping).
- **Expected outcomes:** Agreeing on the specific deliverables expected at the end of the assessment, such as a hazard susceptibility map, a risk prioritization matrix, a monitoring strategy, or a set of conceptual mitigation alternatives.

3.2.1 Spatial Scale

Erosion cannot be fully understood by looking only at the specific location where a bank is failing. River and lake systems are hierarchical (Figure 3-1); upstream and, in some cases, downstream conditions commonly dictate local behaviour. To capture these dependencies, assessments should explicitly define and consider the following nested spatial scales (Frissell et al., 1986):

- **Watershed and regional corridors:** This is the broadest scale, potentially covering hundreds to thousands of square kilometres. It includes the entire drainage basin, where large-scale changes—such as major forest fires, widespread permafrost thaw, or flow regulation—alter the volume of water, peak flows, ice regimes, and sediment volumes delivered downstream. This scale also applies to long linear infrastructure, such as the Alaska or Dempster Highways, where regional assessments across multiple watersheds are required for standardized geohazard identification and risk prioritization.
- **Reach:** A reach is a distinct length of a river or lakeshore (hundreds to thousands of metres) exhibiting similar geomorphic controls and physical characteristics, such as slope, topographic setting, sediment type, and hydrology (Montgomery & Buffington, 1997). In lacustrine environments, littoral cells are commonly the appropriate unit for reach-scale analysis, as sediment movement is generally contained within the cell boundaries.
- **Site/property:** This is the localized area of immediate concern (tens to hundreds of metres) where specific infrastructure or property is threatened. This is the scale where detailed geotechnical, bathymetric, or topographic data are collected to inform site-specific engineering designs.

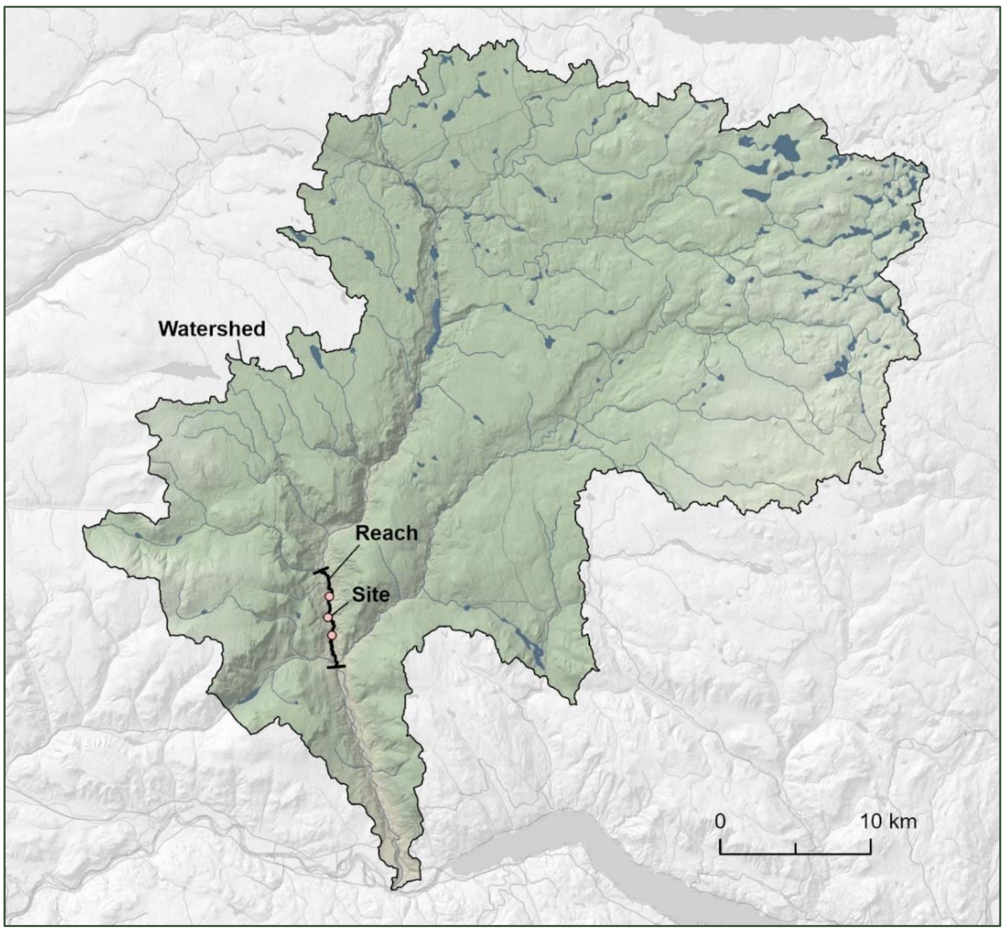

Figure 3-1. Example of watershed (green shading), reach (black line), and site (orange dots) spatial scales.

3.2.2 Temporal Scale

Erosion is a long-term process. Short-term observations can miss important trends. Looking at historical changes—and considering future conditions—is key to understanding hazards.

Erosional processes operate across vastly different timeframes. Defining temporal scales is essential to determining when risk mitigation actions can realistically be taken and defining the specific time horizon for projecting hazards or designing infrastructure (Wolman and Gerson, 1978). Because the Yukon's landscape is dynamic, assessments should not only look back at past erosion processes but should also account for a future influenced by climate change. For instance, assessment should seek to understand how warming temperatures and altered precipitation will accelerate permafrost thaw, shift ice-jam frequencies, and increase wave energy due to reduced winter ice cover.

The following temporal scales may be applicable to the assessment:

- **Historical (previous years to decades):** To predict the future, we must first understand the past. This involves analyzing previous decades of river channel migration, avulsions, historical wave climates, and shoreline recession. By using historical maps, aerial photography (Figure 3-2), satellite imagery, and LiDAR, professionals can establish a long-term average rate of change.
- **Emergency (instantaneous to days):** This scale involves rapid, immediate threats to life or critical infrastructure, often occurring during a major flood, an ice-jam formation or release, or a sudden landslide. In these urgent scenarios, there is typically no opportunity for formal, multi-stage assessments before action must be taken to protect public safety.
- **Short-term (1 to ~10 years):** This timeframe is most relevant for prioritizing routine maintenance, implementing temporary monitoring programs, or forecasting immediate hazard zones for "urgent but non-emergency" works.
- **Long-term (~10 to 100 years):** This is the standard planning horizon for defining regulatory flood hazard limits, designing structural mitigation (such as bridge abutments or riprap revetments), and planning long-term community subdivisions.

3.3 Important Data Sources

Assessments of erosion along riverbanks and lakeshores rely on a synthesis of spatial, hydrotechnical, and geotechnical data. However, given the Yukon's vast geography and sparse population, data availability is frequently a constraint. Professionals should identify existing data and potential gaps early in the scoping phase to determine if supplemental field data collection is required. Important data sources are highlighted in the bullets below. Web links to the applicable data sources are included in Section 6.2.

- **Records and previous reporting:** Local governments and territorial departments (e.g., HPW-TEB) often possess site photos and records of past maintenance or repairs to infrastructure that offer opportunistic insights into historical performance. Previous hydrotechnical reports, geotechnical investigations, and planning studies available online or from project partners can provide essential historical context and vital calibration data.

Figure 3-2. A 1946 aerial photograph of Marsh Lake provides important information about erosional processes before widespread occupation of the shore (Source: YG)

- **Local and Traditional Knowledge:** First Nations governments and citizens possess multi-generational, long-tenured knowledge of the land. This includes invaluable observational data regarding historical ice jam locations, past extreme flood extents, and long-term river behaviour that commonly fills critical gaps.
- **Imagery:**
  - **Historical and recent aerial photography:** Accessible via the National Air Photo Library or GeoYukon, these records are essential for tracking meander migration and lakeshore recession over several decades. Such photography (e.g. Figure 3-2) is available roughly every decade since the 1940s for many developed areas of the Yukon.
  - **Satellite imagery:** Platforms such as ESRI Wayback, Google Earth, Planet, Sentinel, and Landsat (offering various spatial and temporal resolutions) provide past and current conditions, even near-daily imagery in recent years, and can be used to monitor seasonal changes. Landsat imagery availability extends back to the 1980s, albeit at relatively low resolution (~30 m), and can be readily viewed and analyzed using platforms such as Google Earth Engine.

- **Elevation data:**
  - **LiDAR:** High-resolution LiDAR provides the "bare-earth" digital elevation models[3] (DEMs) required to delineate channels and observe subtle surface expressions of landforms otherwise virtually imperceptible in aerial/satellite imagery (Figure 3-3). At the time of publication, LiDAR is available for all territorial highway corridors, many Yukon communities, and various other areas of interest and typically has a resolution of 1 m or finer. Users can interactively view LiDAR hillshades through online portals, such as GeoYukon and NRCan's High Resolution DEM (HRDEM), and download high-resolution data tiles for specific project areas
  - **Alternative datasets:** Where LiDAR is absent, researchers can leverage satellite-derived topography like ArcticDEM (available through the HRDEM portal), which provides near-continuous coverage of the Yukon at 2 m resolution (note: this is a digital surface model and includes tree cover). Additionally, a 30-m medium resolution DEM (MRDEM) of the entire country is available through NRCan. Both the ArcticDEM and 30-m resolution DEM can be interactively viewed online.
  - **Bathymetry:** Data coverage within the Yukon is minimal and primarily limited to the Arctic coastline and local extents of rivers surveyed as part of recent flood hazard mapping studies for various communities. Inland waterbodies generally lack detailed hydrographic survey data from the Canadian Hydrographic Service. Bathymetry data may become outdated quickly due to morphological restructuring.

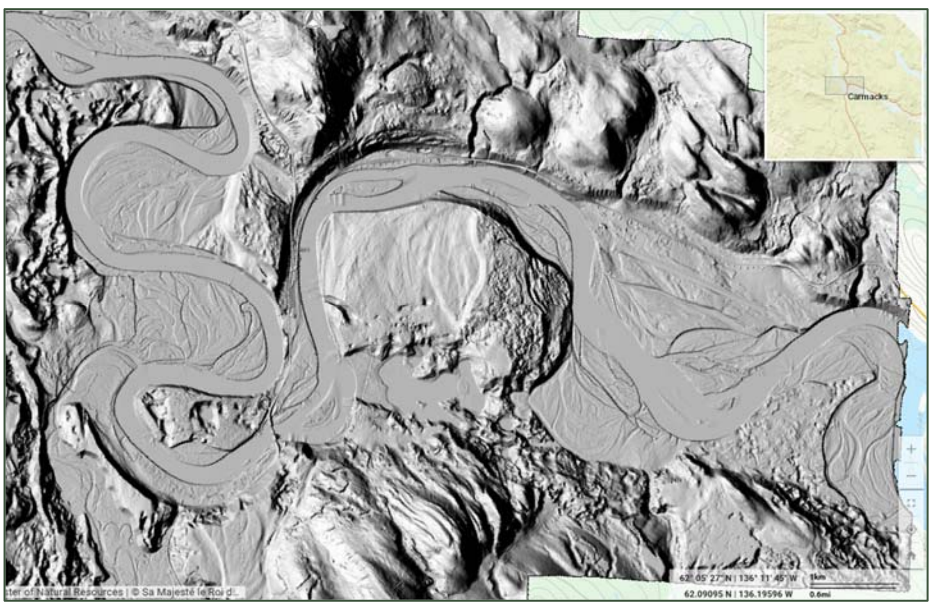

Figure 3-3. An example of a LiDAR-derived hillshade of the Carmacks area available through NRCan's HRDEM database.

[3] A Digital Surface Model (DSM) captures the highest elevations of a landscape, including all natural and human-built features like vegetation and buildings. In contrast, a Digital Terrain Model (DTM) provides a "bare-earth" representation where all overlying objects, such as plants and structures, have been filtered out.

- **Geotechnical and permafrost data:**
  - **Geotechnical:** Existing borehole logs, test pit records, and thermistor logs provide subsurface information on stratigraphy and ground temperature. Data are available through YG portals and previous reports. It is always wise to consult YGS about the availability of geotechnical data that may not yet be available publicly.
  - **Geological mapping:** Surficial and bedrock geology maps from the YGS provide baseline information on soil types, landforms, stratigraphy, and general erodibility, as well as various active or past geomorphic processes. Bedrock geology mapping is available for the entire territory at a scale of 1:1,000,000 surficial geology mapping coverage is incomplete but available at scales generally ranging from 1:20,000 to 1:250,000.
  - **Permafrost databases:** Resources include the Geological Survey of Canada's ground ice maps (O'Neil et al., 2020), regional permafrost probability models (Bonnaventure et al., 2012), territorial geohazard mapping via YGS, and the Yukon Permafrost Database (Lipovsky et al., 2022).
- **Hydrotechnical data (water and climate):**
  - **Streamflow and water levels:** Data from the Water Survey of Canada (WSC) and the Government of Yukon Water Science and Stewardship branch are fundamental for flood frequency analyses and peak discharge estimation (Figure 3-4). The Yukon Snow Survey Bulletin and Water Supply Forecast also offers insight into potential stream flows and water levels.
  - **Meteorological data:** Climate data—including precipitation, temperature, and wind speed/direction—are primarily sourced from Environment and Climate Change Canada (ECCC) and supplemental Yukon-specific networks (e.g., forest fire weather stations or aviation weather). However, because station density in the Yukon is commonly sparse, proponents may also utilize atmospheric reanalysis data (e.g., Canadian Surface Reanalysis or ERA5).
  - **Ice data:** Observational records and the Canadian River Ice Database (CRID) provide information on historical ice thickness and breakup timing at some sites in the Yukon. Ice thicknesses can be obtained for some WSC stations as this information is collected during winter streamflow measurements. Satellite imagery or aerial photos can be used to determine ice cover and ice jam presence, with the occasional coincidental capture of an ice run.
  - **Glacier databases:** Regional glacier inventories should be consulted to better understand hydrology and the potential for glacial lake outburst floods or changes in sediment supply from headwater regions.
  - **Climate projections:** While historical records are sourced from ECCC, projections from the Pacific Climate Impacts Consortium, Climate.ca, and Yukon University help assess changing hydrologic conditions and future climatic variability.

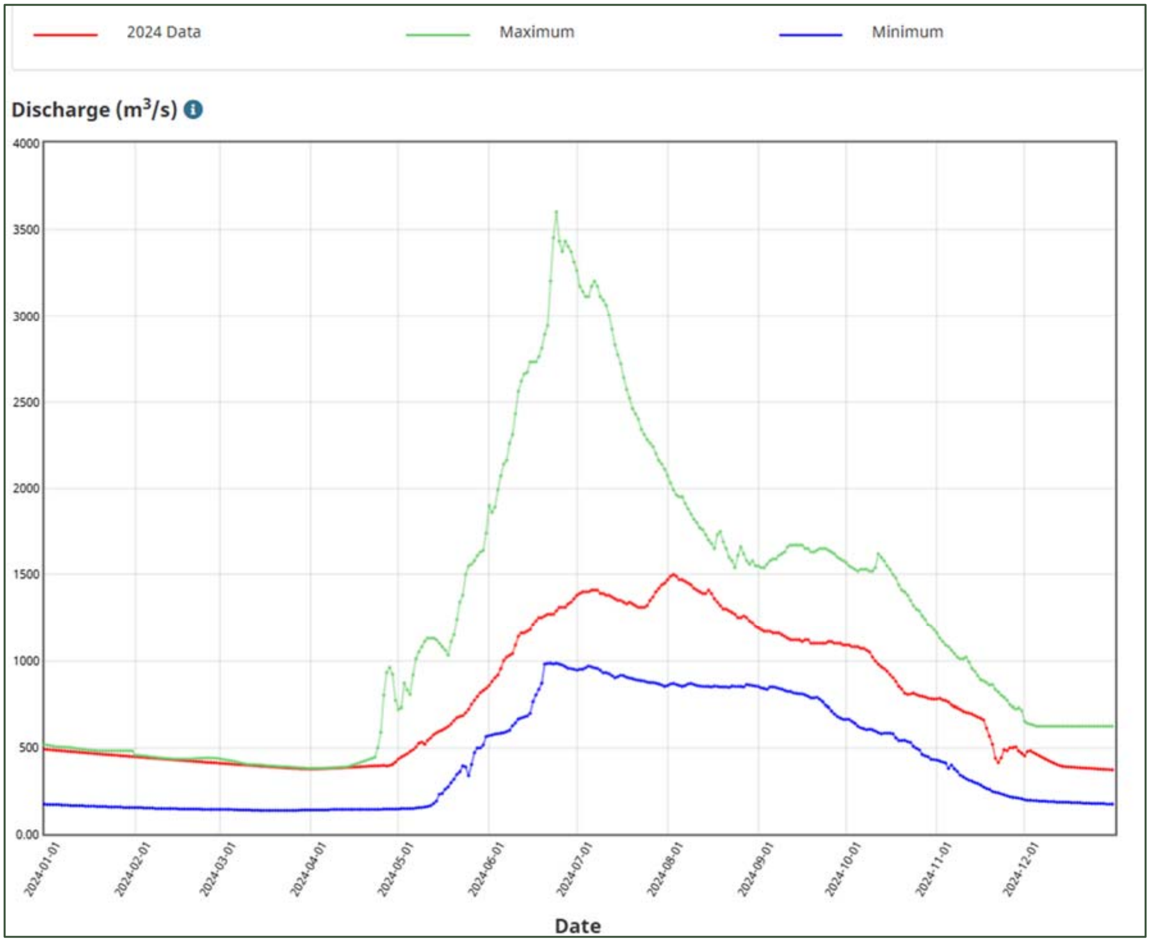

Figure 3-4. An example of discharge data recorded at the WSC station (09AH001) at Carmacks (accessed through the WSC website) that provides important current and historical flow records (1951-1994; 2014-2024).

3.3.1 Approaches for Data-Poor Sites

Many assessment sites in the Yukon lack long-term gauge records, detailed bathymetry, and/or high-resolution LiDAR. When an assessment is required in a data-poor environment, the methodology will rely on alternative tools, conservative assumptions, and considerable professional discretion. Some strategies for managing data-poor sites are highlighted below:

- **The role of integrated experience:** In the absence of dense datasets, the experience and regional repertoire of the professional (P.Eng. or P.Geo.) are critical. Interpreting Yukon sites under these conditions requires an integrated understanding of northern geomorphology to identify subtle indicators of instability—such as vegetation leaning or incipient tension cracks—that coarse numerical models might miss.
- **Regional analysis and data extension:** When site-specific streamflow data are missing or patchy, engineers and geoscientists can use regional analyses to estimate the flow regime at their sites of interest. This involves extrapolating or scaling flow data from nearby, hydrologically similar watersheds that have active gauges and/or using statistical data extension techniques to lengthen short periods of record. In the Yukon, practitioners should consult the Yukon Regional Flow Analysis report (Northwest

Hydraulic Consultants Ltd., 2023), which provides updated regional equations and tools specifically for flow statistics across the territory's diverse hydrologic regions. Proponents could utilize hydrologic modelling (e.g., Raven, HEC-HMS) or land-surface reanalysis products (such as ERA5-Land) to simulate runoff and streamflow based on regional climate inputs.

- **Remote sensing substitutes:** If high-resolution LiDAR or recent aerial photography is unavailable, project-specific data can be rapidly generated. For instance, drone-based (UAV) LiDAR acquisition and photogrammetry (Photo 3-1) can produce high-resolution DEMs and orthophotographs of the immediate site. Proponents can also leverage satellite archives (e.g., Landsat, Sentinel) paired with cloud-computing platforms to track long-term riverbank, lakeshore and ice movement.
- **Enhanced field investigations:** Robust field investigations become even more critical to compensate for gaps in desktop data. This may include detailed site mapping, soil sampling, and characterizing permafrost conditions through direct observation. It may also involve installing temporary instrumentation, such as water level transducers or wave buoys, to begin building a site-specific record.
- **Geomorphic interpretation alongside numerical modelling:** When complex quantitative hydraulic modelling is less reliable due to a lack of calibration data or bathymetry, the assessment should shift toward a process-based geomorphic interpretation. This approach relies on identifying landforms and erosional signatures—such as trimlines, scour marks, or point bar development—to infer historical behaviour and future risks.

Photo 3-1. UAV (i.e. drone), atop the all-terrain vehicle, along with survey equipment at a remote location (photo credit: SLR)

3.4 Preliminary Assessment

A preliminary assessment builds on the scoping phase by characterizing the hydrogeomorphic setting and identifying the dominant drivers of erosion. This level of assessment generally precedes formal regulatory processes and may be sufficient for community-scale planning, inventory of erosional issues, prioritizing sites for follow-up action, or informing conceptual mitigation options. Preliminary assessment approaches that are common to both lakes and rivers, as well as those unique to each environment, are introduced in the following subsections.

3.4.1 Common Approaches for Lakes and Rivers

Preliminary assessments for rivers and lakes rely heavily on desktop-based analysis and interpretation, supplemented by insights from basic field reconnaissance and local or Traditional Knowledge. Common approaches to both lake and river environment include:

- **Background data compilation and review:** Gathering existing bedrock and surficial geology maps, hydrology records, previous hydrotechnical or geotechnical reports, and historical infrastructure as-built drawings to establish a baseline understanding of the site (refer to Section 3.3). This approach helps determine if erosion is a localized issue or part of a broader watershed-scale adjustment, allowing practitioners to target and ultimately treat the root cause of instability rather than just the symptoms.
- **Aerial photography and overlay analysis:** Conducting comparative overlay analyses using historical aerial photography and recent satellite imagery (e.g., via GeoYukon) to calculate time-averaged rates and trajectories of channel migration (Figure 3-5) or lakeshore retreat. By projecting these historical trends into the future, practitioners can forecast when critical infrastructure or important lands may be impacted if no mitigative action is taken. However, it is important to recognize that historical rates serve as a baseline; in a changing climate, these projections should be viewed as conservative estimates.
- **Understanding sediment regime:** Reviewing historical imagery and LiDAR to locate primary sediment sources, such as tributaries, landslides, bluffs, or placer mining operations. Analyzing visible features like vegetation breaks or exposed scarps allows practitioners to deduce predominant sediment sizes (fine vs. coarse) and delivery timing (chronic vs. episodic pulses). This knowledge is vital for ensuring that proposed mitigation structures do not inadvertently starve downdrift areas of essential beach-building materials or become overwhelmed by large pulses of coarse-grained sediment.
- **Basic geotechnical review:** Utilizing available surficial geology mapping, borehole logs, and permafrost data to interpret bank materials, potentially slope stability issues, and glacial history. This includes distinguishing between highly erodible sands/silts, resistant bedrock, or cohesive clays, and identifying visual indicators of broader slope instability. Understanding subsurface conditions is critical to distinguishing between routine fluvial erosion and deep-seated mass wasting hazards, which ultimately dictates whether standard bank armouring or more complex geotechnical stabilization is required.
- **Riparian vegetation assessment:** Evaluating the density, age, and type of riparian vegetation. Robust root networks significantly increase the shear resistance of banks, while "drunken" (leaning) black spruce trees or exposed roots act as key geomorphic indicators of active erosion or permafrost thaw. The assessment should specifically note any evidence of recent or past wildfire; the loss of vegetative cover and organic insulation following a fire accelerates active-layer thickening and can trigger mass-wasting events. This evaluation helps inform whether natural bioengineering solutions

will be viable, or if the loss of root strength necessitates more robust structural reinforcement to stabilize the bank.

- **Documenting anthropogenic disturbance:** Noting any nearby infrastructure (e.g., culverts), upstream flow regulation (e.g., dams), historical channel straightening, ad hoc bank hardening, or placer mining that may be altering natural flow or sediment regimes. Identifying these artificial constraints helps explain sudden or unexpected changes in erosion processes and helps inform development of candidate mitigation approaches.
- **Understanding ice dynamics:** Documenting ice processes (e.g., shore-fast ice, anchor ice, freeze-up jams, aufeis) and ice cover types (e.g., smooth vs. grounded or jumble ice) through remote sensing, field reconnaissance, and instrumentation. Particular attention is paid to the historical timing and intensity of freeze-up and dynamic breakup events, as these events exert the most severe mechanical forces on banks.
- **Field reconnaissance:** When feasible, conducting a site visit (preferably by senior-level staff) to document current conditions with georeferenced photos, verify desktop interpretations, and record geomorphic indicators like bankfull elevations or tension cracks. Field reconnaissance is particularly important when geotechnical instability is suspected. On-the-ground validation prevents costly design errors resulting from misinterpreted remote sensing data and identifies subtle indicators that can greatly influence the feasibility of different mitigation options.

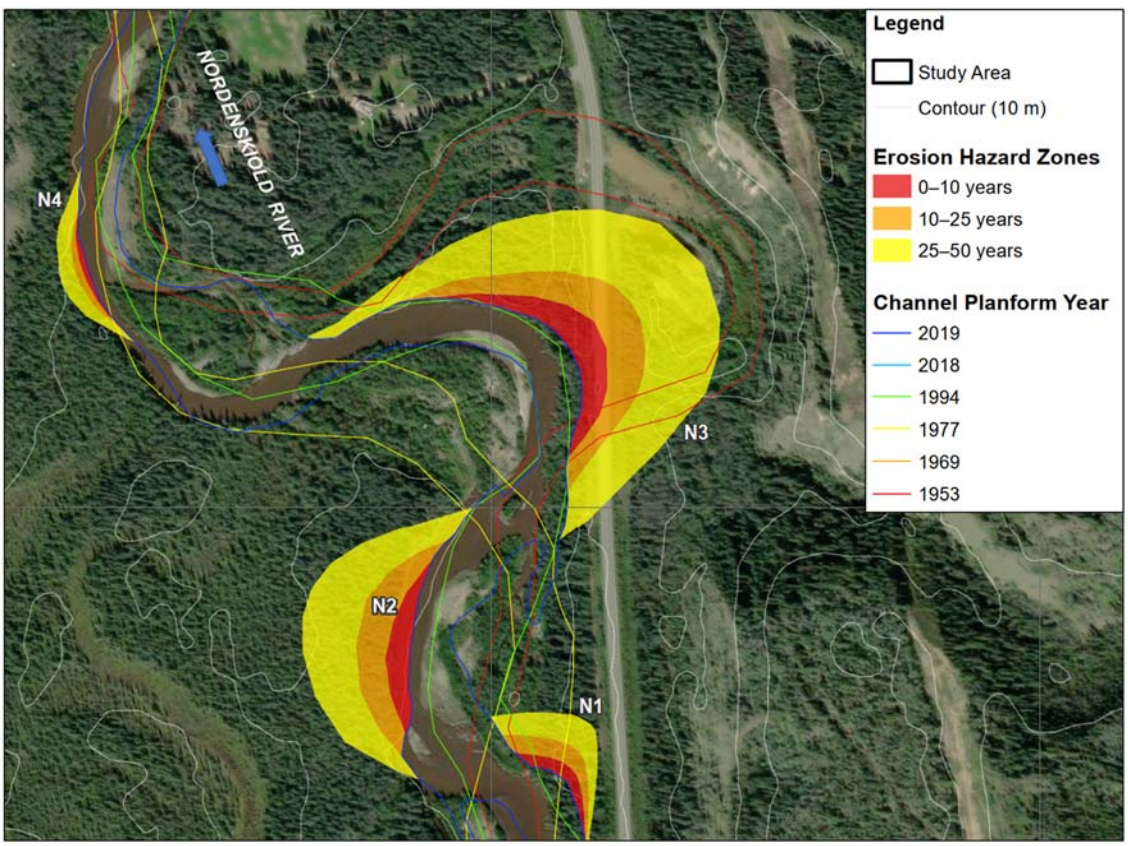

Figure 3-5. An example of overlay analyses using historical and recent aerial imagery to better understand rates and trajectories of channel migration and to inform potential erosion hazard zones near Carmacks (source: Cronmiller et al., 2020).

3.4.1.1 River-specific Analyses

For sites situated along watercourses, assessments should move beyond static observations to evaluate the dynamic relationship between flowing water and the channel boundary. These river-specific analyses provide the quantitative baseline necessary to understand how hydraulic energy is distributed and whether the existing boundary materials can withstand predicted flow forces. Below are river-specific analyses that build off common assessment approaches:

- **Longitudinal profiles:** Extracting water surface or channel bed profiles using bathymetry, LiDAR, or other topographic data to identify slope breaks, steep gradients, or knickpoints (Figure 3-6). These features commonly drive localized high velocities and concentrated scour, which are critical to identify before the design phase. Such features may also be diagnostic of histories of local instability.
- **Understanding flow regime:** Defining the timing, source (e.g., snowmelt freshet vs. rainfall-driven events), and magnitude of peak flows through hydrological analyses, such as flood frequency analysis, and interpretation of relevant hydrometeorological data (e.g., snow surveys). Estimating bankfull conditions is critical, as the bankfull flow (or "formative discharge") is typically associated with the greatest amount of geomorphic work and sediment transport.
- **Cursory sediment entrainment estimation:** Using basic hydraulic parameters—such as estimated water depth and slope—to calculate approximate shear stress. This analysis is used to corroborate the sediment mobility and geomorphic activity interpreted from aerial imagery by assessing whether the flow has the competence to mobilize observed bed and bank materials under various discharge scenarios.

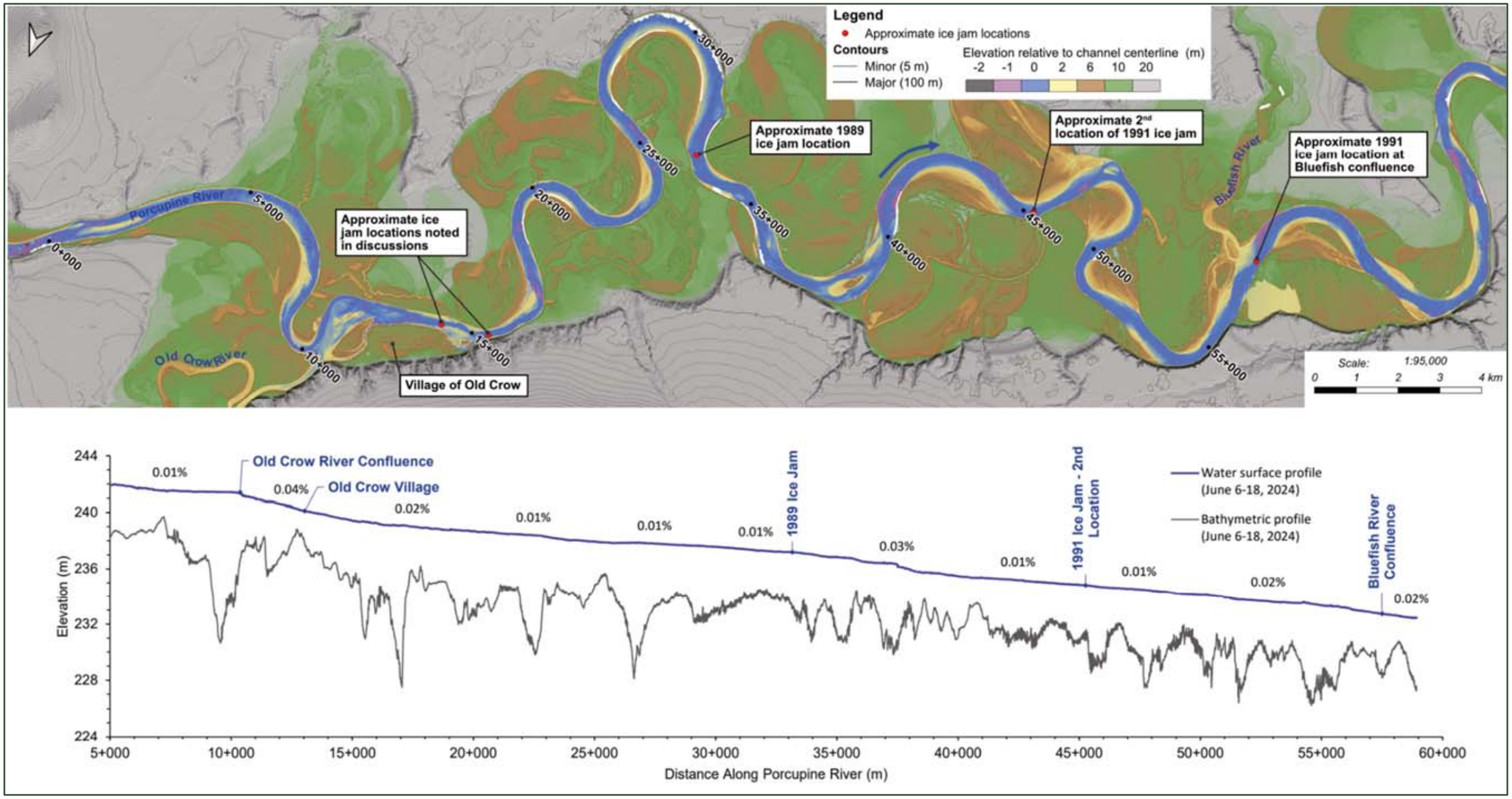

Figure 3-6. An example of a longitudinal profile (bottom) and relative elevation model (top) for Porcupine River near Old Crow that helps demonstrate the distribution of energy and potential flow paths along a river (source: Northwest Hydraulic Consultants Ltd., 2025).

3.4.1.2 Lake-specific Analyses

While river erosion is driven by gravity and the flow of water, lakeshores are primarily shaped by wind-generated waves. In the Yukon, these lake-specific processes are further complicated by seasonal ice cover and, in many cases, artificial water level management. Below are lake-specific analyses that build off common assessment approaches:

- **Water level analysis:** Evaluate the historical and seasonal variation of static lake levels, including extreme highs and lows. The water level dictates the available depths for wave propagation and determines where wave energy will be expended on the shoreline profile. For regulated systems, anthropogenic impacts should be accounted for, such as artificial winter drawdowns or prolonged periods of elevated storage in hydro-regulated lakes.
- **Wind climate analysis:** Wind is the primary mechanism for generating waves on lakes in the Yukon. Regional wind records are analysed, where available, to determine wind speeds and both the prevailing wind direction (which dictate long-term sediment transport and circulation) and the directions associated with large storms (which drive acute, extreme erosion events). Consideration should also be given to climate change, as shifting atmospheric patterns and reduced winter ice cover can expose shorelines to more frequent and severe wind events.
- **Wave climate and fetch analysis:** Calculate the fetch—the unobstructed, straight-line distance that wind travels over open water toward the site. By pairing fetch lengths with directional wind speeds and available water depths, practitioners can estimate the wave conditions (height and period) to which the shoreline will be exposed (Figure 3-7). This analysis is critical for determining the size of riprap or the height of protection measures required to prevent overtopping and erosion.
- **Lakeshore erosion hazard mapping:** To prioritize mitigation efforts at a broader scale, practitioners can systematically map the erosion potential around the perimeter of an entire lake. Following tailored protocols, this mapping approach integrates key variables—such as shoreline landforms, soil composition (erodibility), wind exposure, and shoreline profile criteria (e.g., backshore bank height)—to categorize and delineate the relative erosion hazard across different segments of the lakeshore (Guthrie & Law, 2005).

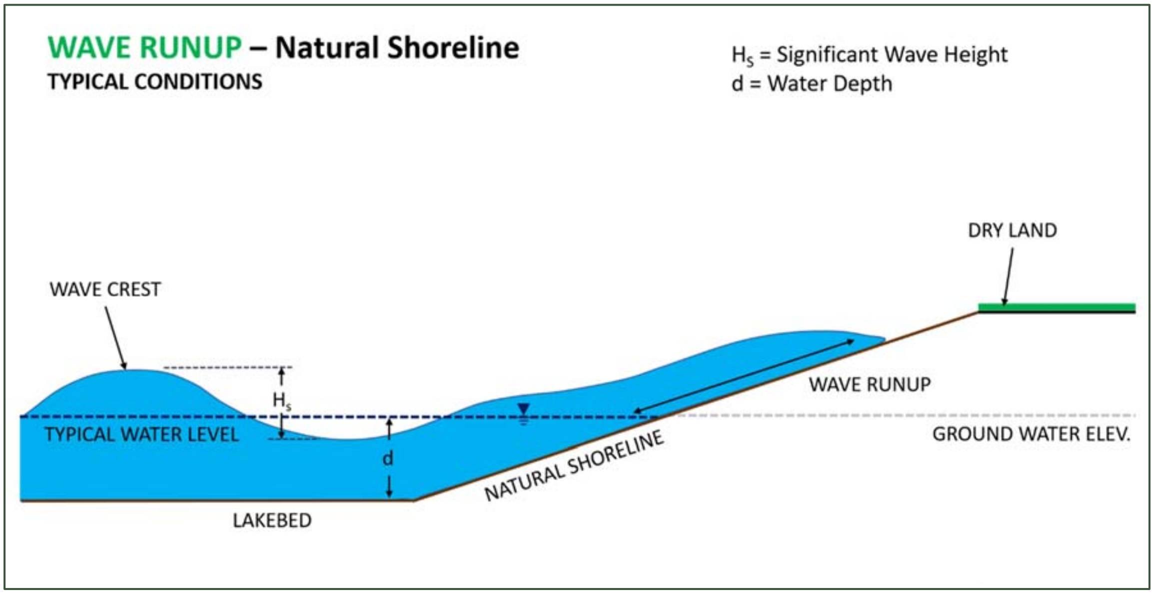

Figure 3-7. A schematic of key parameters that should be estimated during lakeshore assessments (figure courtesy of SJL).

3.4.2 Prioritization of Erosion Challenges

When assessing large watersheds or extensive regional corridors, such as territorial highways, practitioners commonly inventory dozens or even hundreds of locations where lakeshore or riverbank erosion is occurring. Because limited budgets, a scarcity of mitigation materials, and short northern construction windows make it impossible to address all sites simultaneously, a systematic prioritization process is essential (Guthrie & Cuervo, 2015).

While this guide focuses on identifying erosion-related risks, it does not prescribe a single, formal risk assessment methodology. Instead, it provides the principles necessary for practitioners and asset owners to define risk in a way that is tailored to their specific infrastructure, property, or cultural values. Drawing on recent regional-scale assessments—such as those conducted along the Dempster Highway (Figure 3-8)—the following principles offer guidance for systematic prioritization:

- **Risk matrices:** Prioritization is typically achieved using a qualitative or semi-quantitative matrix. This tool commonly evaluates the likelihood of an erosion event (or the site's physical vulnerability) against the potential consequence of that event occurring.
- **Evaluating likelihood and vulnerability:** To determine how likely a risk is to materialize, practitioners evaluate objective physical data. Key indicators include the separation distance (proximity) between the watercourse and the asset, historical rates and trajectories of meander migration, the erodibility and stability of bank materials, including consideration of the condition of any permafrost.
- **Evaluating consequences:** The consequence side of the matrix is defined by the values of the stakeholders involved. For highway corridors, consequences are commonly categorized by the expected duration extent of damage, operation and maintenance costs, or the severity of service disruption. In other contexts, consequences may be defined by the vulnerability of archaeological resources, the loss of cultural lands, or the failure of critical community infrastructure.

- **Assigning actionable outcomes:** The ultimate goal of prioritizing sites is to assign appropriate, scaled follow-up actions. For example, sites ranked as having a 'Very High' erosion-related risk may be prioritized for immediate field inspections, detailed geotechnical investigations, or quantitative channel overlay analyses to forecast exactly when and how much mitigation material is likely required. Conversely, sites ranked as 'Low' priority might simply be earmarked for routine monitoring (e.g., every five years) to track any future changes in separation distance.

3.4.3 Deliverable Expectations

The quality of a preliminary assessment is ultimately measured by its ability to translate technical observations into practical action items. To achieve this, the preliminary assessment report should include the following elements:

- **Clear findings and direction:** The report should outline what is happening at the site and provide practical next steps based on the available information. While additional study may be recommended, it should not be the only outcome of a preliminary assessment.
- **Key data gaps:** Important gaps in available information should be clearly identified, along with practical ways to manage them—such as targeted fieldwork, conservative assumptions, or monitoring.
- **Site-specific analysis:** Focus on the conditions at the site rather than general descriptions of erosion processes. The report should clearly identify the main drivers of erosion (e.g., river flow, waves, drainage, or thawing ground) and how they apply locally.
- **Use of visuals:** Maps, air photos, site photos, and simple annotated figures should be used to show key features, processes, and areas of concern. Visuals are often the clearest way to communicate how erosion is occurring.
- **Accessible summary:** Include a concise, plain-language summary of the key findings so that non-technical readers can understand the issue and the proposed direction.
- **Prioritization (where applicable):** For larger studies covering multiple sites (e.g. highway corridors), erosion issues should be ranked in a clear and consistent way to help focus effort and funding.
- **Constraints and opportunities:** Identify any key challenges (such as access, environmental sensitivities, or regulatory considerations) and outline practical options or erosion mitigation that could be explored in future detailed assessments or design stages.

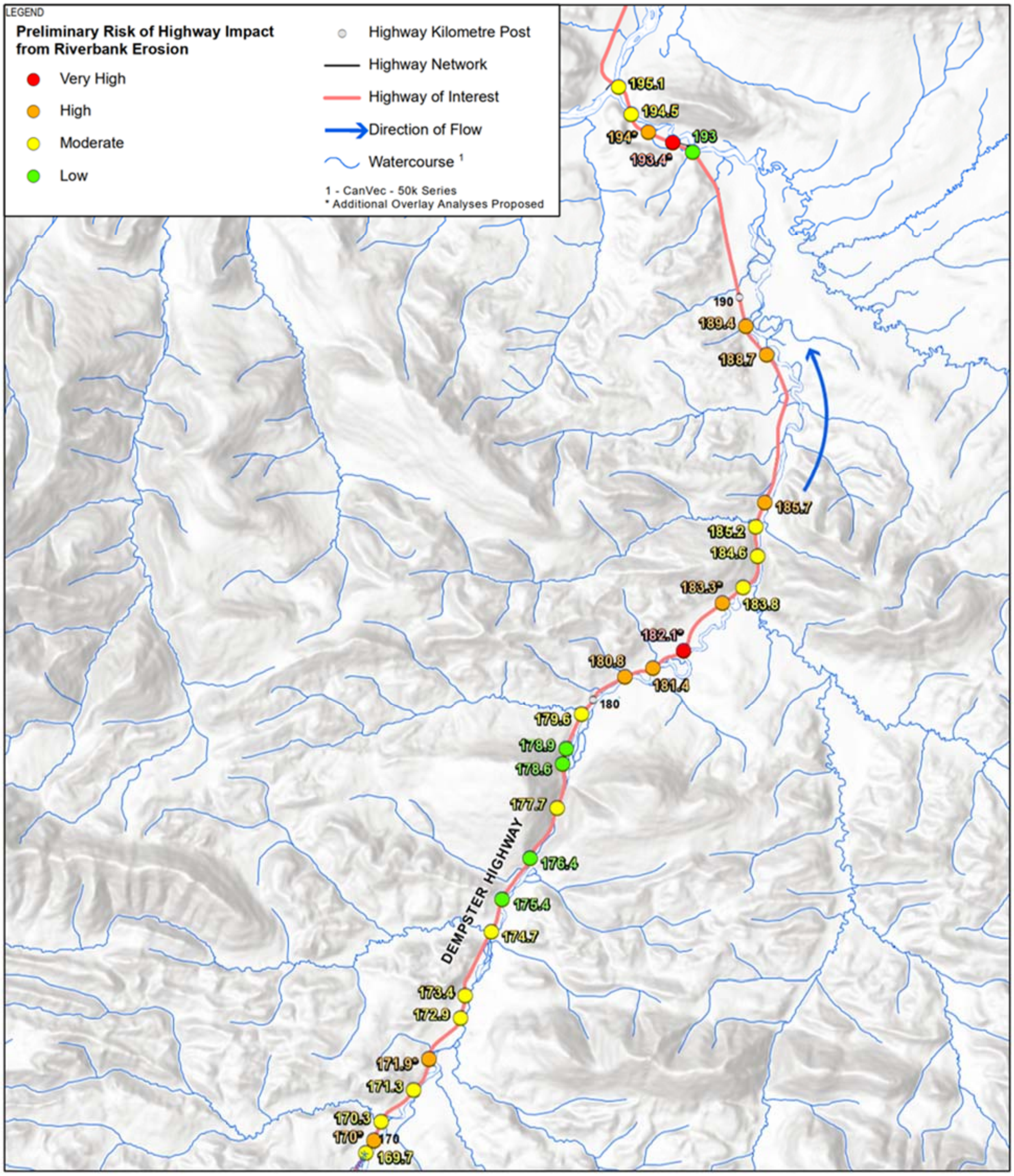

Figure 3-8. Inventory and preliminary prioritization of erosion sites along a portion of the Dempster Highway (figure courtesy of SLR). Preliminary risk classifications were based on a site-level evaluation of current separation distance between the highway embankment and an encroaching watercourse and an interpretation of the relative rate at which the watercourse is migrating toward or alongside the highway.

3.5 Detailed Assessment

A detailed assessment builds directly upon the findings of the preliminary assessment. It is required when an unacceptable risk to high-value infrastructure, public safety, or other valued components has been confirmed, and quantitative data are necessary to evaluate specific risks and potentially design mitigation measures. This phase shifts from observations, review of available data and professional judgement to intensive field investigations, scientific and engineering analysis, and potentially quantitative numerical modelling.

3.5.1 Detailed Field Investigations

This phase focuses on the precise characterization of the physical environment, providing the reliable data necessary to define design parameters, satisfy regulatory requirements, and reduce project uncertainty (Photo 3-2). By integrating geotechnical, hydrotechnical, and ecological data, practitioners can develop a comprehensive understanding of the site-specific interactions among soil, water, gravity, and ice that drive erosional processes.

The following field investigations are typically required to support a detailed mitigation design:

- **Topographic and bathymetric surveys:** High-resolution, georeferenced surveys—utilizing Real-time Kinematic (RTK) Global Positioning System (GPS), total stations, or UAV-based LiDAR—are used to capture the terrestrial bank profile. These are combined with bathymetric soundings to map the underwater riverbed or nearshore lakebed.
- **Geotechnical and permafrost investigations:** Drilling boreholes or excavating test pits allows for the collection of soil samples and the characterization of subsurface stratigraphy. In a northern context, this is critical for identifying the presence, depth, and type of permafrost and any associated ground ice. These investigations increasingly incorporate geophysics, such as Ground-Penetrating Radar or Electrical Resistivity Tomography, which are invaluable for mapping depth to bedrock and major stratigraphic contacts; they also aid interpretation of the lateral continuity of ground ice and identification of unfrozen zones (taliks) between borehole locations.
- **Hydrological and hydraulic characterization:** Collecting on-site measurements defines local conditions and validates hydraulic models. This includes measuring water surface elevations, wave heights, flow velocities, and discharge. In the Yukon, this also involves documenting ice-related features such as high-water or scour marks from previous ice jams and ice runs, aufeis (icing) extent, or evidence of thermal-mechanical scour. If investigations occur in late winter, ice thickness can be measured. Additionally, observing open-water leads in early winter can indicate highly turbulent locations or relatively warm groundwater sources that are commonly undetectable during summer months.
- **Instrumentation and monitoring:** Installing specialized equipment tracks site conditions over time. Examples include piezometers (to monitor pore-water pressure), wave buoys (track wave direction, height, and speed) and pressure gauges (for lake levels and wave dynamics), thermistors (to track ground temperatures and permafrost warming or thaw), inclinometers (to detect slope deformation or movement), and automated cameras to capture seasonal ice conditions and erosion progression.
- **Characterization of channel boundary materials:** Conducting field measurements, such as Wolman (1954) pebble counts or sediment sieving, quantifies the grain size distribution of bed and bank materials. Identifying the median (D_{50}) and coarse (e.g., D_{84})

grain sizes is usually a mathematical requirement for calculating sediment mobility and calibrating hydraulic models.

- **Ecological assessments:** Developing an inventory of riparian vegetation types and species helps determine their contribution to bank stabilization. Additionally, collecting fish species and habitat data is essential for supporting the regulatory permitting process with agencies like DFO.
- **Structural inspections:** Inspecting existing channel, bank, or lakeshore infrastructure—such as bridges, culverts, or old revetments—to evaluate their condition and influence on local hydraulics (may require the input of a structural engineer). These inspections help identify if existing structures are contributing to downstream or downdrift erosion.

3.5.2 Quantitative Analysis and Modelling

The data collected in the field serve as the essential input for detailed scientific and engineering analyses. These analyses move beyond empirical observations to build and calibrate numerical models that simulate different scenarios and extreme events, allowing practitioners to test the performance of various designs. By translating field measurements into engineering parameters, these models ensure that risk-mitigation measures are appropriately sized for the unique hydraulic, thermal, and geotechnical forces of the Yukon. Below are common modelling types and software used as part of erosion assessment.

- **Riverine hydraulic and ice modelling:** Utilizing 1D or 2D hydraulic models (such as HEC-RAS) to simulate design flood events (e.g., 1% or 1-in-100-year event) and calculate flow depths, velocities, and bed shear stresses (Figure 3-9). In the Yukon, this often requires the simulation of ice-covered and ice-jam conditions, including an assessment of the scour that occurs beneath or around grounded ice. While few models can fully capture the intensity of dynamic ice runs, specialized monitoring strategies can help obtain critical calibration data to better model the elevation, duration, and velocity of these events.
- **Lake wave and hydrodynamic modelling:** In lacustrine environments, practitioners apply wind-wave generation and propagation models (e.g., MIKE21 SW, SWAN) to simulate long-term wind and wave climates and nearshore wave transformations. From this analysis, design wave heights and periods can be determined, and wave run-up elevations and overtopping rates established for storm events.
- **Geotechnical slope stability modelling:** Slope stability modelling software (e.g., GeoStudio SLOPE/W or Slide2) is used to calculate the Factor of Safety for riverbanks, valley slopes, and coastal bluffs without permafrost. This modelling evaluates the potential for mass-wasting by incorporating slope geometry, soil shear strength, pore-water pressure, and potential seismic activity.
- **Permafrost thermal modelling:** Standard stability analyses do not typically account for the phase-change dynamics of frozen ground. In the Yukon, additional thermal modelling (e.g., TEMP/W) may be required to predict how changes in air temperature, snow cover, or surface vegetation will impact the thickness of the active layer and the temperature of underlying permafrost, considering ice content and latent heat effects. This helps quantify the resulting loss of soil strength as permafrost degrades over time.

Photo 3-2. Examples of common field investigations to support detailed erosion assessments. Top left: topographic survey along a creek using an RTK GPS. Top right: shallow drilling to characterize permafrost and soil conditions. Bottom left: observation and measurements of surface and sub-surface sediments on the bed of a watercourse. Bottom right: measurement of channel hydraulics using a flow meter. All photos courtesy of SLR.

- **Hydrogeology and groundwater analysis:** Dedicated groundwater analysis (e.g., SEEP/W) is required when pore-water pressure is a primary driver of instability. This is particularly relevant where naturally or artificially concentrated discharge contributes to "sapping" at the bank face. It is also critical in reservoir environments or following the rapid release of a large ice jam, where a "rapid drawdown" effect leaves the saturated bank unsupported.
- **Advanced geospatial analyses:** Advanced spatial analyses are commonly conducted using Geographic Information Systems (GIS) or Computer-aided Design (CAD) platforms to provide a 4D understanding of the site. These advanced analyses could include LiDAR change detection, which subtracts a historical elevation surface from a recent one to precisely quantify the volume and spatial distribution of loss (erosion) or gain (deposition) in elevation (Figure 3-10). Other analyses include calculating channel migration corridors, mapping "Relative Elevation Models" (REMs) to visualize floodplain features and performing viewshed or drainage-pathway modelling to assess overland flow risks.

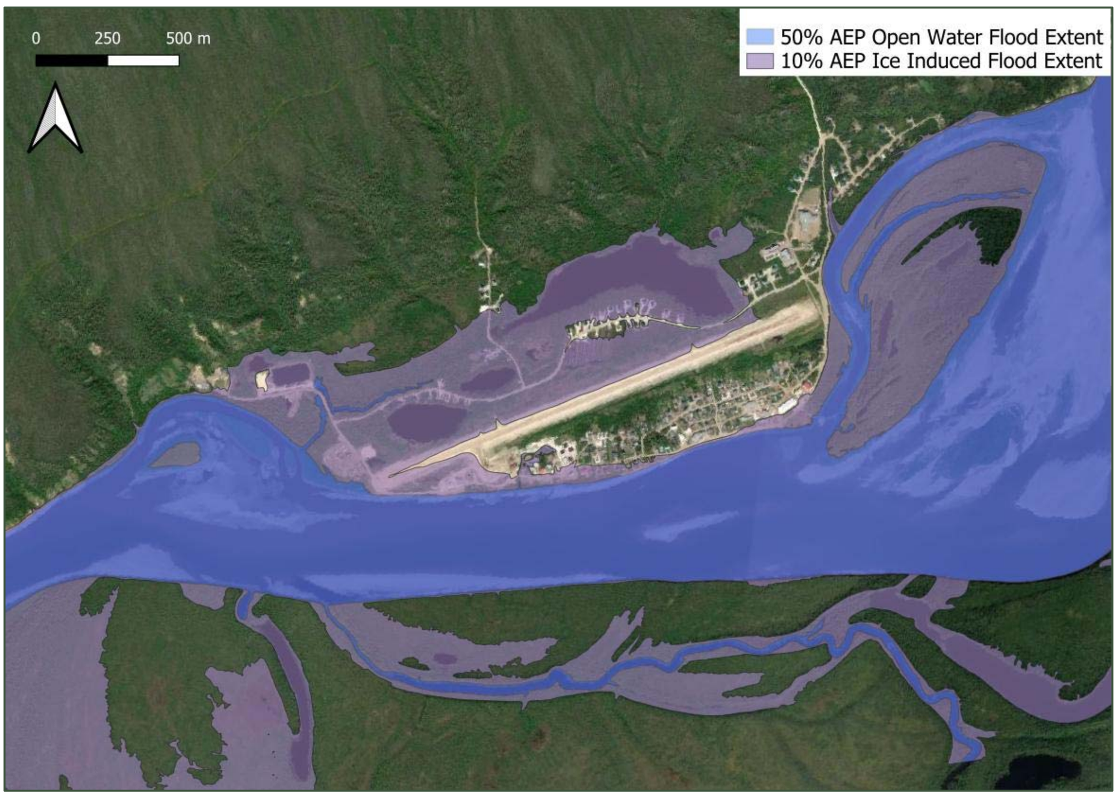

Figure 3-9. An example of HEC-RAS hydraulic model outputs for both open water and ice-affected annual exceedance probability (AEP) flows for Porcupine River near Old Crow (flood mapping data provided by YG).

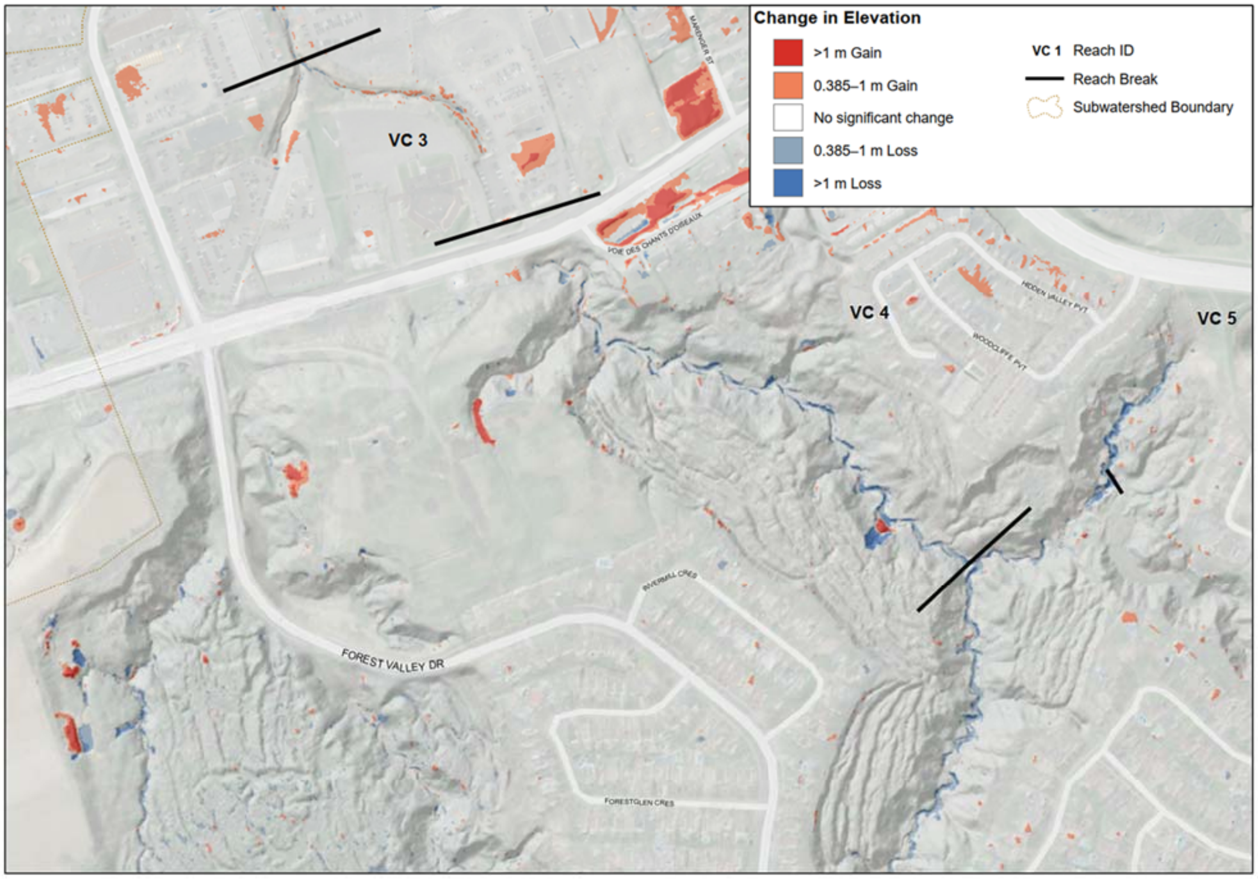

Figure 3-10. LiDAR change detection analysis using DEMs from 2006 and 2020 to highlight areas of elevation loss (~erosion) and gain (~deposition) as well as anthropogenic changes (figure courtesy of SLR).

3.5.2.1 Defining the Erosion Hazard Limit

A primary objective of many detailed assessments is to formally define the spatial extent of the erosion hazard. Depending on the project goals, the ultimate deliverable may be an erosion hazard map used to inform infrastructure setbacks, community zoning, or long-term asset management. The methodology used to delineate these limits is commonly dictated by the degree of valley confinement. **Unconfined systems** are those where the watercourse is free to migrate across a broad, flat floodplain, whereas **confined systems** are restricted by high banks, bluffs, or steep valley walls that limit lateral movement but introduce potential for slope failure (OMNR, 2002).

The following approaches are used to establish these technical hazard limits:

- **Meander belt delineation (unconfined river systems):** In broad, alluvial plains, lateral migration of the **river and streams** is the primary hazard. A hazard limit is established by identifying a meander belt axis and buffering it to encompass the outer banks of historical and current meander bends (Figure 3-11). A Factor of Safety is typically added to these outer limits to account for potential future widening driven by shifts in hydrology or sediment supply (Parish Geomorphic Ltd., 2004).

- **Confined system hazard limit:** For **watercourses and lake** environments restricted by high terrain, the hazard limit needs to account for both toe erosion and overall slope instability (OMNR, 2002). It is typically calculated as the sum of two distinct components:
    - **Toe erosion allowance:** A horizontal setback accounting for predicted erosion at the base (toe) of the slope over a specific timeframe (e.g., 50 or 100 years). This is determined using predictive modelling or historical migration rates. For lake settings with a low-relief lakeshore, the erosion allowance may be sufficient to establish the erosion hazard zone (OMNR, 1996).
    - **Stable slope allowance:** A horizontal setback applied from the projected future toe of the slope to account for the long-term stable angle of the slope based on sediment properties and groundwater levels. On slopes subject to groundwater sapping, additional consideration must be given to groundwater flow patterns and its effects on slope-face sediments. In permafrost environments, this calculation should explicitly account for permafrost conditions (e.g., temperature, salinity, ice content), as conventional limit equilibrium models may significantly underestimate the limits of slope adjustment and retrogression associated with thaw.
- **Fluvial hazard zone (FHZ) mapping:** This comprehensive approach delineates the area a **river or stream** has historically occupied, may occupy in the future, or may influence as it transports water, sediment, and debris within its valley (Blazewicz et al., 2020). It defines an Active Stream Corridor (ASC) and applies an outward Fluvial Hazard Buffer (FHB) to encompass adjacent terrain susceptible to progressive lateral erosion or slope failure (Figure 3-11). There is considerable subjectivity in the estimation of the limits of the FHB, at least in contrast to the stable slope allowance approach described above. FHZ mapping is effective in complex Yukon valleys for capturing dynamic processes such as avulsions and ice or debris jams.

Beyond the calculated physical hazard limits, a management buffer (or policy-type setback) is typically recommended. This ensures sufficient space remains for emergency equipment access, future maintenance activities, and a margin of safety for unforeseen geomorphic changes (OMNR, 2002). The appropriate width of this setback depends on the specific project context and the requirements of the local jurisdiction. An allowance of 6 m is often used in Ontario, for example, based on the space required for an excavator to manoeuvre along a slope crest.

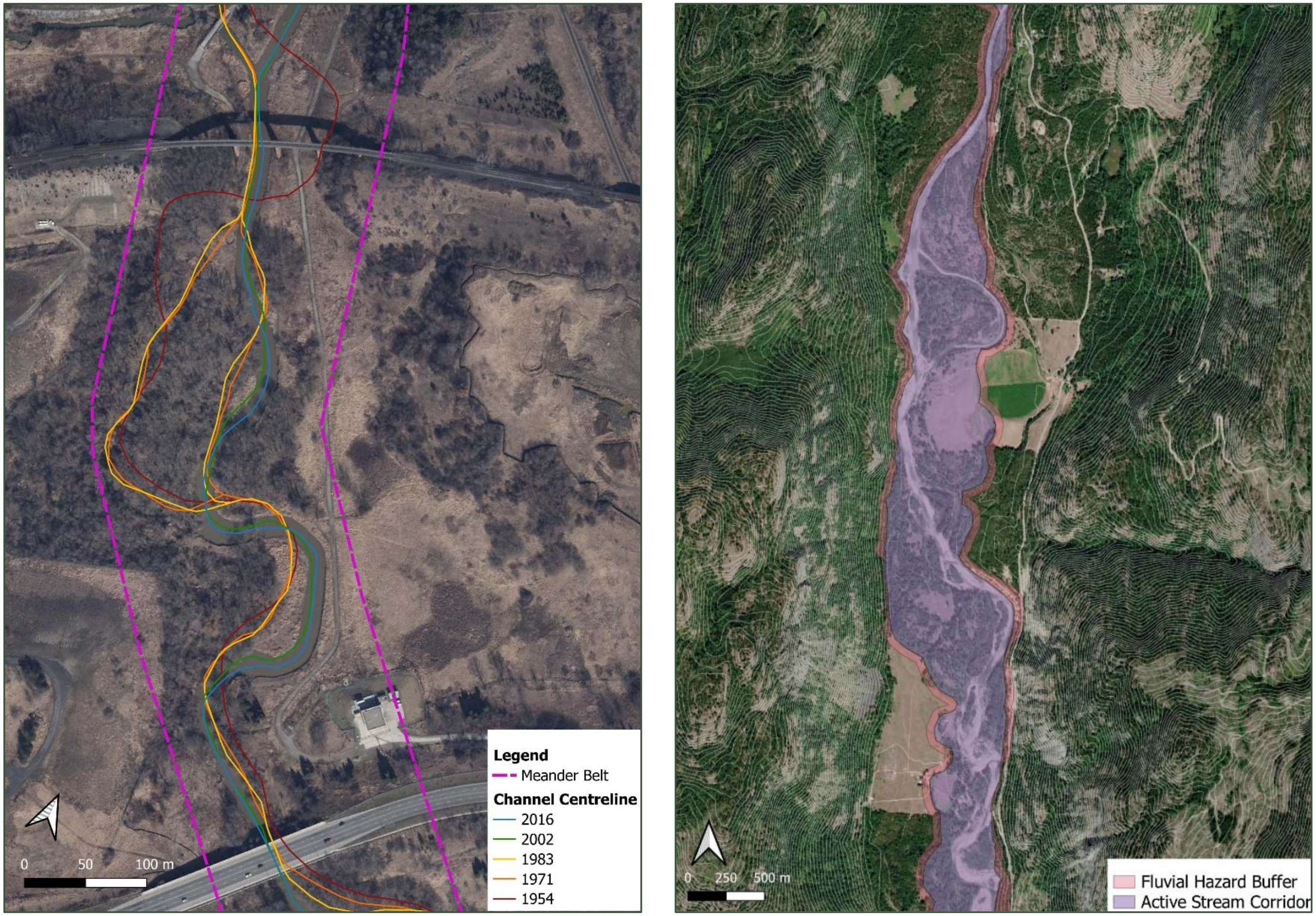

Figure 3-11. For river and streams, practitioners could delineate the erosion hazard limits by establishing a meander belt (left) or a fluvial hazard zone (right). The variable width of the FHB reflects material erodibility and the height/condition of the confining slope. The irregular width of the ASC reflects the configuration of the floodplain and of confining terrace scarps. Conversely, a meander belt is defined by parallel lines. Figures courtesy of SLR.

3.5.3 Deliverable Expectations

The final output of a detailed assessment provides the technical foundation required for the subsequent design of measures to mitigate associated erosion-related risks. Although the deliverable expectations share some similarities with those of a preliminary assessment—such as the need for clear communication and root cause identification—the detailed phase introduces highly-detailed quantitative nuances and rigorous model documentation. These deliverables should transform complex field data into the specific physical parameters necessary to ensure the structural integrity of any proposed works.

- **Design parameters:** Explicit quantification of the physical characteristics, processes, and forces that guide the development of a mitigation strategy. To accommodate a wide range of interventions—from structural armouring to channel realignment—design parameters encompass both the specific forces a measure must withstand and the intended morphological configuration of the site. This could broadly include specifying cross-sectional dimensions (e.g., bankfull width and depth), planform geometry (e.g., meander amplitude, and radius of curvature), and longitudinal profile characteristics (e.g., channel slope and pool-riffle spacing) for riverine settings. For lakes, it can include static and dynamic water levels and design wave heights
- **Model calibration and validation:** A detailed technical description of the numerical modelling process. This should include the parameter values utilized (e.g., Manning's 'n', ice thickness, or soil cohesion), the boundary conditions applied, and proof of calibration against historical high-water marks or observed events to ensure reliability of the model.
- **Uncertainty and limitations:** A transparent discussion regarding data gaps, model assumptions, and the sensitivity of the results. In the Yukon context, this should address the potential impacts of climate change, such as accelerating permafrost warming and thaw or shifting peak hydrology, and how these uncertainties influence the assessment's conclusions.
- **Hazard maps (if applicable):** High-resolution, georeferenced maps that clearly delineate the estimated physical hazard limits, existing infrastructure at risk, and the proposed footprints for any mitigative measures.
- **Refined mitigation opportunities, constraints, and recommendations:** A comprehensive evaluation of mitigation strategies that transitions project findings from problem identification into actionable engineering design. This should include an analysis of site constraints—such as seasonal access limitations or sensitive fish habitat—and a recommendation for viable solutions.

3.6 Integration with Flood Mapping and Hydrotechnical Studies

Historically, flood mapping and erosion assessments were treated as separate exercises, with standard flood mapping assuming a static, unchanging channel (NRCan, 2025). However, integrating these disciplines provides a comprehensive understanding of hydrogeomorphic hazards, ensuring that designs are resilient to both inundation and erosion. By viewing the river as a dynamic system rather than as a fixed corridor, practitioners can better predict how shifts in the landscape will influence future water levels and velocities.

Erosion and flooding are closely linked. Assessing them together provides a more complete understanding of riverine hazards and leads to better risk mitigation decisions.

- **Coupled hazards:** Flooding and erosion are intrinsically linked. Changes in channel form—such as sediment aggradation or bank retreat—can directly alter flood hazards by changing flow paths and how erosive energy impacts channel boundaries. Mapping only inundation can underestimate the true nature and extent of associated hazards; composite hazard mapping should be completed to unite inundation probabilities with geomorphic hazards like lateral bank erosion and avulsion zones.
- **Informing hydraulic models:** Geomorphic observations help refine 1D and 2D hydraulic models. Identifying active migration, avulsion potential, and appropriate roughness coefficients (e.g., Manning's 'n') allows modellers to adjust topographic inputs to reflect predicted future channel alignments. Conversely, hydraulic model outputs—such as velocity, depth, and shear stress—provide the quantitative data needed to calculate scour depths and size protection materials (Figure 3-12).
- **Infrastructure resilience:** For bridges and linear infrastructure, evaluating design flows along with erosion hazard limits (e.g., meander belts) ensures that structures are appropriately set back and sized to convey water, sediment, and debris without triggering localized scour or catastrophic failure.
- **Special considerations for mountainous terrain:** On steep creeks and alluvial fans, standard stage-discharge relationships are commonly unreliable due to highly mobile channels, aufeis development, and debris flows (NRCan, 2025). In these environments, detailed geomorphic fieldwork is essential to identify likely avulsion sites on the fan.
- **Adaptive management and mapping updates:** Observed geomorphic changes—such as reaching a specific threshold of bank retreat—should serve as formal triggers to update flood maps and hydrotechnical models. This iterative approach ensures that hazard documentation remains representative of current site conditions as the landscape evolves.

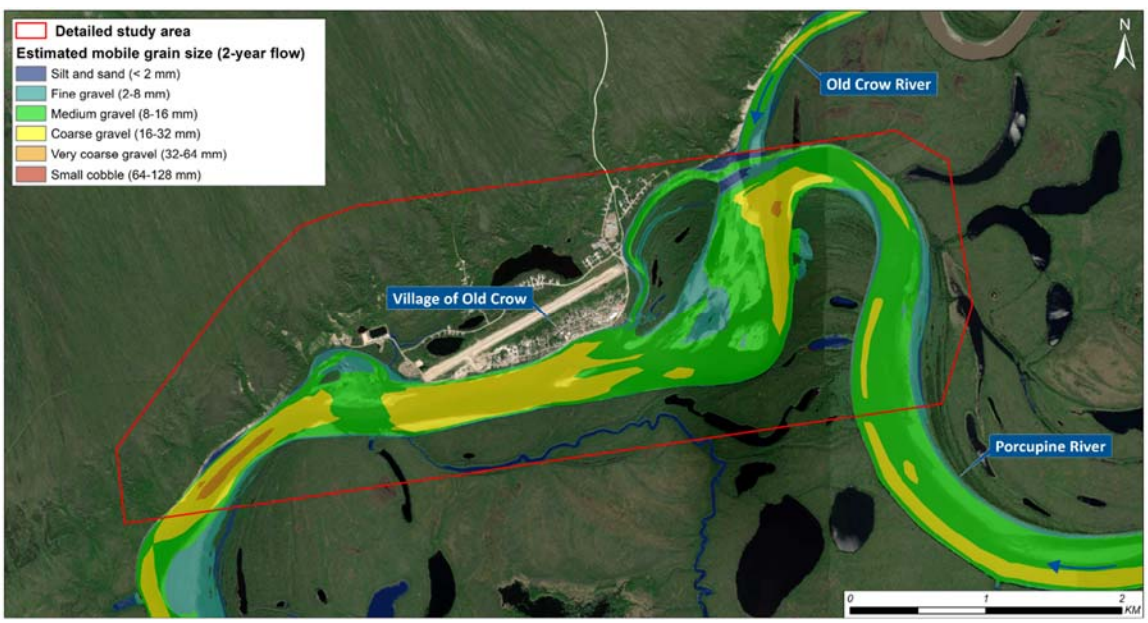

Figure 3-12. Utilizing hydraulic model outputs, practitioners can spatially estimate the potential sediment sizes that can be entrained for a given flow event (Source: Northwest Hydraulic Consultants Ltd., 2025).

3.7 Monitoring

Monitoring establishes a baseline to track geomorphic change over time, defining actual erosion rates and mechanisms. Monitoring data directly inform the urgency of design, identify or confirm the causes of erosion, help prioritize limited resources for imminent threats rather than perceived ones, and guide the selection of appropriate mitigation approaches (e.g., identifying when "giving the river space" is better than premature hard engineering). Photographic examples of a variety of applicable monitoring techniques are provided in Photo 3-3. The following grouping of methods can be deployed (alone or in combination) to monitor riverbank and lakeshore stability:

- **Remote sensing (satellite, UAV, LiDAR):** Used for broad-scale geomorphic tracking. Satellites monitor historical lakeshore or ice dynamics, airborne or handheld LiDAR captures highly accurate bare-earth DEMs, and UAVs provide flexible, high-resolution site topography and orthophotography.
- **Repeat topographic surveys:** Successive physical surveys (using RTK GPS or total stations) of monumented cross-sections or bank profiles. These are used to accurately quantify lateral channel migration, bed degradation, and volumetric sediment loss between survey intervals.
- **Movement detection (accelerometers, inclinometers):** Specialized instruments installed in boreholes or on the surface that provide early warning data regarding slope movements or the internal deformation of banks caused by permafrost degradation. Many of these sensors feature data loggers and satellite telemetry to transmit real-time site conditions, which reduces the need for frequent, high-cost maintenance visits to remote northern locations. However, practitioners must design these systems to withstand extreme cold, which can quickly drain batteries or exceed the operating limits of the instrumentation. Furthermore, robust protective housing is required for all exposed cables and equipment to prevent damage from wildlife, moving ice, or vandalism.
- **Visual Assessment (benchmark stakes, cameras):** Cost-effective methods including repeat photography from fixed monuments and benchmark stakes to manually measure the separation distance to infrastructure. Time-lapse cameras (including ‘game cameras’) are particularly useful for capturing episodic events like ice jams or rapid bank collapses during freshet.
- **Environmental threshold monitoring:** Rather than measuring erosion directly, this method establishes empirical triggers of other monitored processes associated with erosion events. This could involve monitoring for critical flow levels that mobilize bed material, precipitation intensity known to trigger slope failures, wind speeds that can create significant wave heights, increases in ground temperature that trigger thaw of permafrost, increases in active layer thickness that promote failure of water-logged soils on slopes, or abrupt changes in turbidity and electrical conductivity that act as proxies for high sediment concentrations or significant hydrologic shifts (e.g., increased groundwater discharge).

The appropriate frequency (continuous vs episodic) and duration (e.g. 3 years) of a monitoring program must be tailored to the specific project objectives, the remoteness and accessibility of the site, and the temporal scale of the dominant erosion processes. At a minimum, it is recommended that monitoring be conducted twice a year—specifically during or immediately following the spring freshet, and again during late summer or early fall baseflow conditions.

Photo 3-3. Examples of erosion monitoring. Top left: camera and staff gauge monitoring aufeis upstream of culverts (photo credit: Benoit Turcotte). Top right: monumented stakes incrementally track river migration (photo credit: Benoit Turcotte). Bottom left: UAV and RTK GPS surveys document geomorphic change (photo credit: SLR). Bottom right: meteorological thresholds (e.g., wind) can identify when lakeshore erosion may occur (photo credit: SLR).

4.0 Mitigation of Erosion-related Risks

4.1 Key Considerations

The selection of a preferred mitigation strategy by a proponent requires a multi-criteria evaluation that aligns technical requirements with site-specific logistical and regulatory realities. A design should not only be hydraulically, geomorphologically and geotechnically sound but also feasible within the constraints of the Yukon's unique land tenure systems, material availability, and environmental windows. Before advancing to detailed design, practitioners should screen potential alternatives against the following foundational criteria to ensure the selected approach is both viable and resilient:

- **Objectives:** Clearly defining the primary goal of the project (e.g., protecting a specific building, safeguarding a highway corridor, or enhancing habitat).
- **Timeline:** Determining how quickly the work needs to be completed based on the immediacy of the hazard. This should also include the intended design or service life of the mitigation.
- **Ownership of lands:** Identifying property boundaries and navigating land tenure for the site as well as adjacent lands that may be impacted.
- **Budget:** Evaluating the available funding for both upfront capital construction and long-term maintenance.
- **Applicable regulations:** Understanding the federal and territorial permitting requirements governing in-water works and shoreline alterations as detailed in YG's (2019) *Preferred Practices for Works Affecting Yukon Waters*.
- **Availability of materials:** Factoring in the scarcity or accessibility of local, suitably sized construction materials, such as large-calibre rock and root wads.
- **Contractor experience:** Recognizing that specialized skills are commonly required to successfully construct complex and eco-sensitive mitigations.

4.1.1 Spatial Scale

The spatial footprint of a mitigation project significantly influences its design requirements and its potential for unintended systemic impacts. Because rivers and lakes function as continuous transport systems for water, sediment, and wood, an intervention at one point necessarily affects conditions elsewhere. A professional assessment should move beyond the immediate property line to evaluate how a project integrates with existing infrastructure and how it alters the hydraulics of the natural reach.

- **Single or multi-site scope:** Confirm whether the project is an isolated fix for a single property, a community-scale approach protecting multiple assets, or part of a long linear infrastructure corridor (e.g., highways or pipelines). Linear projects commonly require standardized mitigation designs that can be replicated across varying terrain while maintaining consistent risk levels.
- **Upstream and updrift effects:** Consider how the mitigation might alter updrift lake water levels or upstream flow hydraulics (Figure 4-1). Structural interventions can create backwater effects or alter local flow velocities. It is critical to define the extent of these impacts, as changes in water surface elevations can propagate a significant distance upstream, potentially affecting property or habitats outside the immediate project area.

- **Downstream and downdrift effects:** Hardened structures can disrupt natural sediment transport. Along lakeshores, armouring can cut off sediment supply, leading to erosion of downdrift sections, especially beaches (Photo 4-1). Along rivers, channel narrowing or bank armouring can transfer erosive energy downstream (Figure 4-1), leading to lateral erosion or vertical adjustments (bed degradation/scour). The extent of these downstream or downdrift impacts should be assessed to ensure that solving an erosion problem at one site does not inadvertently initiate a new erosional failure or accelerate existing erosion rates farther down the reach.

> Erosion does not stop at property boundaries. Effective solutions consider upstream, downstream, and alongshore conditions to avoid unintended impacts.

- **Reach-scale vs. individual strategy:** Despite the higher upfront costs, reach-scale erosion mitigation strategies are typically preferred over individual private-property scales. Holistic evaluations make it significantly easier to mitigate and manage downdrift impacts across a larger portion of the lakeshore or riverbank.
- **Remoteness of site:** The geographic location dictates material availability, equipment access, mobilization costs, and logistical feasibility. In the Yukon, remoteness commonly necessitates creative use of local materials or designs that require minimal specialized heavy machinery.
- **Proximity to existing infrastructure:** New mitigation should be carefully integrated with existing infrastructure—such as bridges, culverts, or adjacent riprap revetments—to ensure compatibility and prevent "outflanking," where erosion bypasses the protection at the tie-ins to the natural bank.

4.1.2 Temporal Scale

The temporal scale of a project dictates both its urgency and its long-term performance expectations. Properly defining these parameters ensures that the selected mitigation is commensurate with the value of the asset and the evolving environmental conditions of the site. This requires an evaluation of the intended service life of the mitigation, the specific return periods used during engineering design, the total life-cycle economics of the installation, and the projected geomorphic evolution of the reach. Furthermore, the logistical reality of northern operational windows—including both construction seasons and the short window for vegetation growth—should be integrated into the project schedule from the outset. The following are key temporal considerations for erosion mitigation planning:

- **Emergency vs. proactive mitigation:** Emergency works address immediate threats to public safety or critical infrastructure but commonly require a "compressed" design process and rapid mobilization. Conversely, proactive mitigation, informed by rigorous assessments, allows for more sustainable, integrated, and cost-effective outcomes.
- **Temporary vs. long-term solutions:** It is essential to clearly define if the solution is a "stop-gap" (Band-Aid) measure meant to buy time for a larger relocation or protection project (Photo 4-2), or a long-term installation intended to function autonomously for decades.

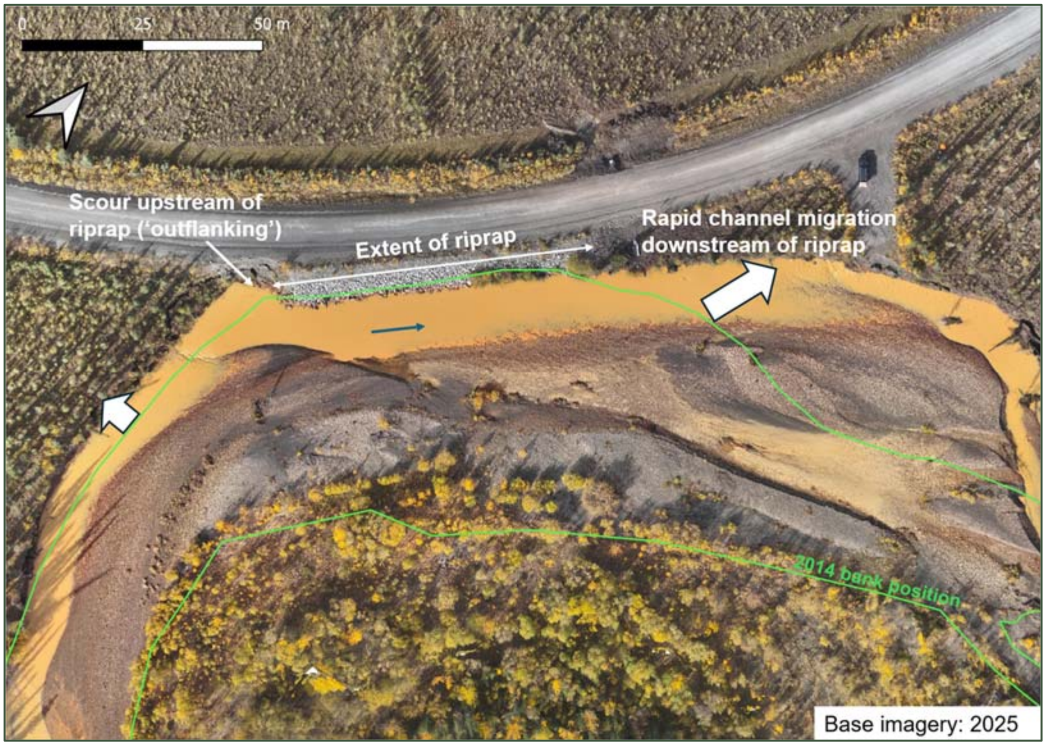

Figure 4-1. Aerial imagery from 2025 illustrates scour upstream of a riprap embankment, initiating outflanking of the revetment, and accelerated channel migration downstream along the Dempster Highway. The green line is the 2014 bank position. Riprap was installed in 2010 and again in 2015.

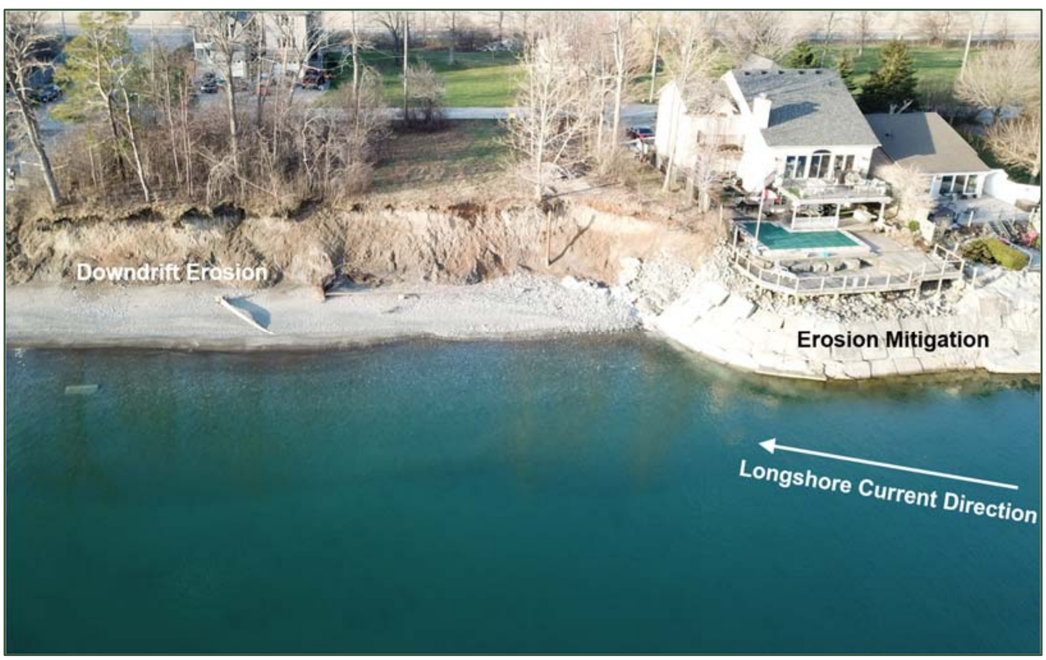

Photo 4-1. Pronounced lakeshore erosion downdrift of localized erosion mitigation on Lake Ontario (photo credit: SJL).

Photo 4-2. Temporary erosion mitigation following a road washout along the Dempster Highway during the August 2016 flood (photo credit: YG HPW-TEB). The temporary measure does not negate the need to reconstruct the highway, but it minimizes the service disruption by allowing alternating traffic to pass until the highway is reconstructed.

- **Service life:** The intended longevity of the project should align with the durability of the materials chosen. For example, untreated timber or biodegradable geotextiles have a significantly shorter service life than large-caliber rock or specialized synthetic armouring. Some lithologies of rock in the Yukon are predisposed to weathering, especially once exposed to wetting/drying and freeze/thaw cycles, so they are poor choices for riprap.
- **Design return periods:** Engineering parameters—including flow, velocity, waves, and water levels—should be based on specific return periods (e.g., Q_{50} vs Q_{200}) tailored to the criticality of the asset. While rural or resource roads may be designed to a higher frequency (lower return period) flow event standard (e.g., Q_{50}), primary Yukon highways may require designing to a low frequency, high magnitude event (e.g., Q_{200}) to ensure regional connectivity. Ice-induced flood levels are difficult to predict. While historical data (if available) provides some insight, most projects require complex modeling and force calculations. Alternatively, designers may opt for simpler, conservative adjustments like adding extra freeboard.
- **Capital vs. maintenance costs:** Initial construction costs should be weighed against long-term maintenance requirements. "Soft" or nature-based solutions (NbS) may offer lower upfront capital costs but often require more frequent monitoring and intervention in the early years compared to traditional "hard" infrastructure.
- **Evolving hazards:** Designs should account for how hazards may change over the structure's lifespan due to climate change. This includes anticipating shifting ice regimes, increasing peak flows, and the loss of soil shear strength due to accelerating permafrost degradation.

- **Construction and environmental windows:** The short northern construction season is further constrained by strict environmental timing windows designed to protect fish spawning or bird nesting. Winter construction options should be explored in coordination with regulatory agencies to take advantage of frozen ground access.
- **Growing season constraints:** For bioengineering or NbS, the exceptionally short growing season in the Yukon limits the window for successful vegetation establishment and root stabilization. This commonly necessitates multi-year planting phases, mulching, soil amendments, and supplemental watering to ensure the survival of live stakes and riparian transplants (YG, 2019).

4.1.3 River and Lake Ice Considerations

In northern environments, ice processes are commonly a key driver of erosion, frequently exerting forces that far exceed hydraulic shear stress alone. It is critical to evaluate the bi-directional relationship: how ice-induced backwater and physical ice forces will impact the structural integrity of the mitigation, and how the mitigation itself will alter the local ice regime. Failure to account for these dynamics can lead to premature structural failure or the unintended creation of ice jams and associated flooding that threaten local and upstream property.

Effect of ice on mitigation (structural integrity):

- **Ice characterization:** Designers should identify the specific ice processes at play, such as anchor ice, breakup ice jams, dynamic ice runs, or wind-driven lake ice shove. The seasonal timing and intensity of these processes are often driven by high-energy flows during spring breakup. Mid-winter breakup events may become more common in the Yukon in the context of climate change.
- **Material sizing and geometry:** Ice forces frequently dictate the design specifications. Mitigation materials must be sized to withstand the mechanical impact, abrasion, and "plucking" of moving ice floes (Photo 4-3). This commonly necessitates increasing stone size beyond what hydraulic models suggest, applying higher safety factors, and utilizing gentler bank slopes to allow ice to "ride up" the bank rather than impacting it head-on.

Effect of the mitigation on the ice (system impact):

- **Ice jam dynamics:** Mitigation structures should be designed so they do not inadvertently constrict the channel or create hydraulic "catch points"—such as protruding groynes or sharp transitions—that increase the probability or severity of ice jamming.
- **Hydraulic alterations:** Changes to bank roughness or channel narrowing can alter the thermal and mechanical nature of freeze-up and the timing and intensity of breakup. The design objective is to ensure the intervention does not cause a localized increase in ice-induced water levels or velocities that could destabilize adjacent reaches.

Photo 4-3. River ice interacting with recently constructed erosion mitigation along the Dempster Highway (photo credit: YG HPW-TEB).

4.1.4 Permafrost and Ground Ice Considerations

In the Yukon, permafrost is a dynamic thermal condition that dictates the long-term viability of any riverbank and lakeshore intervention. Successful design requires addressing the bi-directional relationship between the frozen ground and the mitigation structure to prevent unintended thermal degradation. Because water and air temperatures are shifting across the North, any physical change to the bank profile can disrupt the delicate thermal balance of the subsurface. Where banks or slopes are known to be underlain by permafrost—particularly if ice-rich—thermal modelling is essential to predict how the proposed infrastructure will interact with the ground and to ensure the design does not inadvertently accelerate thaw-driven failure.

Effect of permafrost on the mitigation (performance and stability):

- **Structural integrity:** Warming and thawing permafrost directly reduces soil shear strength. If a mitigation structure is designed without accounting for future warming and potentially thaw (depending on the expected service life), particularly if underlying permafrost is ice-rich, the loss of ground ice can lead to differential subsidence and structural damage or to the total collapse of the protection works as the competence of underlying support is lost.
- **Long-term evolution:** Mitigation designs must be resilient to the anticipated long-term warming of the ground. This may involve incorporating flexible designs—such as riprap—that can accommodate some degree of settlement and deformation without losing their primary functional purpose.

Effect of the mitigation on the permafrost (thermal impact):

- **Construction disturbance:** Construction commonly requires the compaction if not complete removal of the insulating organic mat and surface vegetation. This disturbance can alter the ground thermal regime and trigger rapid warming if not thermal erosion, leading to active-layer detachments or initiating retrogressive thaw flows (slumps) during the construction phase. However, practitioners must balance revegetation goals with thermal risks; inclusion of dense shrubs in the restoration can trap snow, providing winter insulation that inhibits ground cooling and potentially accelerates long-term thaw.

- **Thermal loading:** Hard structures, such as dark-coloured riprap, can act as heat sinks, potentially conducting heat deeper into the bank and accelerating the thaw of ice-rich permafrost. Similarly, the construction of lagoons or stormwater management ponds can introduce significant thermal energy into the surrounding ground. Conversely, smart design choices—such as incorporating shading, thick insulating layers of non-frost-susceptible fill, thermosyphons, or rapid revegetation—can help preserve or stabilize the thermal equilibrium of the bank.

4.2 Evaluating Risk Mitigation Approaches

Before defaulting to a specific engineering solution, practitioners should systematically assess the underlying drivers of the hazard to determine the most effective path forward. A fundamental distinction should be made between ***mitigating erosion*** (physically stopping bank retreat, e.g., structural armouring) and ***mitigating risks*** *associated with erosion* (e.g., managed retreat or relocating infrastructure), which addresses the threat from erosion without necessarily stopping erosion itself. In some instances, the most prudent strategy may be to "do nothing" and formally monitor the site, particularly when the rate of change is slow and the risk to critical infrastructure is low.

To ensure long-term performance, the chosen alternative must be precisely matched to the dominant geomorphic processes driving the erosion. For example, a design targeting overland drainage issues will not be effective if the primary driver is hydraulic scour at the base of the bank. Regardless of the chosen approach, designers should **prioritize toe protection**; the base of the bank is the most critical structural element. If the toe fails due to scour or ice action, the upper slope will inevitably collapse, rendering any surface-level treatments ineffective.

4.2.1 'Give Space'

This approach prioritizes mitigating erosion risk by **removing the vulnerable elements**—such as people, property, or infrastructure—from the hazard zone, rather than attempting to control the waterbody itself. By allowing the river or lake to naturally erode and reshape its banks, this strategy preserves the ecological and geomorphic integrity of the system. **"Giving the river space" is particularly relevant in the Yukon, where the high costs and logistical hurdles of transporting heavy materials to remote sites commonly make structural interventions prohibitive.** When undeveloped land is available, avoiding the hazard altogether through setbacks or infrastructure relocation is frequently the most sustainable and cost-effective long-term strategy, as it eliminates the need for ongoing structural maintenance and the risk of downdrift impacts.

4.2.2 Indirect Approaches

Indirect approaches focus on **moving or manipulating erosive forces** rather than reinforcing the bank itself. By targeting the causes of erosion—such as high-velocity flow impingement or concentrated hydraulic energy—rather than the symptoms, these methods aim to "train" the waterbody to redirect its energy away from vulnerable riverbanks and lakeshores. Common techniques include channel realignments, the installation of flow-training structures (such as groynes, spurs, or vanes), and the use of grade control to manage energy gradients (Photo 4-4). In many modern designs, these approaches strategically incorporate large woody debris and natural materials to help redirect and slow (increased roughness) flows while simultaneously enhancing aquatic habitat and providing complex cover for fish (Photo 4-5).

Photo 4-4. A small rock weir constructed to help dissipate energy and provide ecological benefit (photo credit: SLR). The weir was constructed as part of a larger channel realignment project in the Greater Toronto Area to reduce toe erosion along a failing slope near residential properties.

Photo 4-5. Constructed wood 'spurs' along Mayo River that deflect erosive energy away from the riverbank (photo credit: Ecological Logistics and Research Ltd.).

4.2.3 Direct Approaches

Direct approaches involve constructing hardened, engineered structures at the land-water interface to **combat erosive forces such as waves, currents, and ice 'head-on'**. While these methods are effective at halting bank retreat and protecting critical infrastructure in constrained spaces, they intentionally create a static riverbank or lakeshore that inhibits natural geomorphic processes. Because hardened banks re-direct rather than absorb energy, they can inadvertently transfer erosion problems downstream/downdrift or cause localized scour at the base of the structure. Furthermore, these interventions can disrupt natural longshore sediment transport, potentially starving downdrift beaches or lakeshores of material. Given the high logistical costs of importing heavy materials to remote sites in the Yukon, direct approaches are generally reserved for high-risk situations where relocating infrastructure or utilizing NbS is not technically feasible. Examples of direct approaches are illustrated in Photo 4-6 and highlighted below:

- **Riprap revetments:** Sloping structures built from layers of large, angular, interlocking rock. When designed correctly, the sloped face is highly effective at dissipating wave and flow energy, particularly when constructed at a lower angle to maximize local energy dissipation and reduce downstream transfer. The flexible nature of the structure allows it to withstand minor post-construction settlement or permafrost-related subsidence without failing completely. Furthermore, incorporating native plantings into the revetment further increases the shear resistance of the bank and locally improve terrestrial and aquatic habitat. River ice introduces significant complexity to these designs. On rivers prone to dynamic ice runs, revetments require a gentler slope and exceptionally large rocks—ideally matching or exceeding the thickness of the ice—to resist movement.
- **Vertical walls and bulkheads:** Vertical retaining walls constructed from interlocking steel sheet pile, pre-cast or cast-in-place concrete, mechanically stabilized earth (MSE) structures, or timber. These are useful where space is extremely restricted, but their vertical, impermeable faces strongly deflect energy. This deflection frequently causes severe scour at the toe, necessitating deep embedment and toe protection to prevent sudden, catastrophic failure.
- **Gabion baskets:** Wire-mesh baskets filled with smaller rocks. Gabions allow practitioners to "simulate" the mass and stability of very large stone using smaller rock sizes that are easier to access, transport and place by hand. However, they carry significant risks in the Yukon; the wire mesh is highly vulnerable to corrosion and can be easily sheared or torn open by dynamic ice break-ups and floating woody debris, leading to rapid structural failure.

The high cost of importing materials to remote sites in the Yukon requires asset managers, landowners, and practitioners to carefully evaluate the necessity of heavy armouring. In many cases, designers may need to reference low-cost, expedient methods for remote sites, such as soil-cement sack revetments, coir logs, or root wads. Even when utilizing direct hard-armouring, such as riprap revetments, designs should incorporate natural elements and reference the *Yukon Revegetation Manual* (Matheus and Omtzigt, 2013) for appropriate, climate-specific planting strategies.

Photo 4-6. Examples of direct approaches to erosion mitigation. Top left: riprap embankment along the Dempster Highway (photo credit: YG HPW-TEB). Top right: gabion baskets along a lakeshore of Marsh Lake (photo credit: Benoit Turcotte). Bottom left: armourstone 'ribs' to protect buried sewers in Toronto, Ontario (photo credit: SLR). Bottom right: armourstone and riprap embankment in Kootenay National Park (photo credit: SLR).

4.2.4 Nature-based Solutions (NbS)

NbS utilize natural materials—such as vegetation, soil, and wood—alongside natural physical and ecological processes to stabilize riverbanks and lakeshores, manage flood risk, and deliver environmental co-benefits like habitat creation. These approaches are increasingly being adopted across Canada to replace or complement traditional hard armouring. For instance, projects in British Columbia have successfully re-established natural floodplains to attenuate high flows, while municipalities in Quebec have rehabilitated kilometres of riverbanks using bioengineering (Eyquem, 2023). Similarly, hybrid approaches in Prince Edward Island have combined natural dune restoration with rock reefs to halt coastal erosion (Vouk et al., 2021).

Commonly effective ways to implement NbS in the Yukon include:

- **Riparian revegetation:** This involves utilizing locally adapted native species, such as native willows (*Salix*). Dormant cuttings can be harvested locally and planted as live stakes, which sprout quickly to develop dense, soil-binding root networks that increase bank cohesion. Preservation of existing vegetated riparian buffers as a means of managing erosion-related risks is also considered an effective NbS (Photo 4-7).
- **LWD and root wads:** These designs strategically embed salvaged logs or inverted root wads into the bank. This provides immediate physical resistance to deflect erosive flows and ice impacts away from vulnerable soils while simultaneously creating complex aquatic habitat, such as resting pools for fish. As project sites approach treeline in the Yukon, it may be necessary to bundle multiple trees together as part of wood placements to achieve the same diameter as what is possible using a single log in southern climates.
- **Beach nourishment:** Augmenting beach environments and gentle sloping lakeshores with sand, gravel, and cobble nourishment increases lakeshore stability (Photo 4-8). This reduces wave energy exposure and provides a critical influx of sediment for longshore transport. Furthermore, gravel augmentation of creeks and rivers is a practice used in some jurisdictions to help restore more natural sediment transport and moderate erosion downstream of dams.
- **Floodplain reconnection:** This method restores a river's access to its natural floodplain or relict side-channels to temporarily store overbank floodwaters. This disperses the water's energy and reduces the erosive shear stresses that would otherwise be concentrated within the main channel. This concept aligns with "Stage 0" restoration approaches being explored by DFO.
- **Biodegradable toe protection:** This technique uses natural, biodegradable materials like coir (coconut fibre) logs or sphagnum moss rolls at the base of a slope. These materials temporarily absorb wave and current energy, protecting the toe from scour long enough for planted vegetation to fully establish its permanent root system.

While regulators heavily favour these eco-friendly approaches, their application in the Yukon should be carefully adapted to handle short growing seasons, potentially severe ice scour, and permafrost interactions. It is important to recognize that NbS are not "simple" fixes; they commonly require more spatial area and a longer time horizon to become fully effective as vegetation matures. Success requires specialized expertise to ensure the design can withstand the specific hydraulic and ice stresses of the Yukon environment.

NbS can be more adaptable and resilient than hard structures. When designed properly, they work *with* natural processes rather than against them.

For practitioners seeking further guidance on the design and implementation of NbS, several comprehensive resources are available. The *Canadian Standards Association* provides a foundational overview of concepts, principles, and best practices for applying these solutions to manage coastal and riverine flood and erosion risks across Canada (Vouk et al., 2021). For northern-specific applications, the *Alaska Department of Fish and Game* offers a highly practical guide that details step-by-step instructions for using bioengineering and native vegetation to stabilize banks and restore riparian habitats in cold climates (Johnson et al., 2025). Additionally, for site-level planning, the *Green Shores* program provides resources that guide property owners and practitioners in implementing soft lakeshore protection and ecological enhancements along waterfronts (TransCoastal Adaptations & Stewardship Centre for British Columbia, 2023).

Photo 4-7. Extensive incorporation of native willows into riverbank erosion mitigation (photo credit: Toronto and Region Conservation Authority).

Photo 4-8. Beach nourishment and plantings at Wasaga Beach, Ontario (photo credit: Zuzek Inc).

4.3 Design Guidance

A thorough and rigorous site assessment serves as the technical prerequisite to the engineering design phase. The empirical data gathered during preliminary and detailed assessments—incorporating hydraulic shear stress, ice-loading parameters, and geotechnical stability—forms the technical foundation for selecting, sizing, and implementing the most appropriate mitigation strategies. Without this rigorous baseline, designs risk being under-engineered for the Yukon's extreme environmental stressors or over-engineered and unnecessarily costly due to excessive conservatism.

This section outlines the workflow required to transition from a multidisciplinary assessment to a constructible design. It details the progression from a conceptual options analysis to comprehensive detailed engineering packages, including site isolation protocols and Yukon-specific design "typicals." Furthermore, this section explores the technical nuances of stone sizing for northern waterbodies and differentiates the design rigour required for proactive, planned interventions versus the compressed timelines of emergency response works.

4.3.1 Options Analysis

Before proceeding to detailed engineering, practitioners should generally develop multiple conceptual options based on the identified opportunities and constraints of the site. Presenting a range of alternatives will better facilitate engagement with stakeholders and rights holders, commonly revealing localized constraints or new opportunities that a single, predetermined approach might overlook. This collaborative process can also attract diverse funding streams that may not be accessible for traditional engineering alone. Options should be evaluated through both subjective lenses, such as community preference and visual aesthetics, and objective metrics, including cost-benefit analysis and hydraulic performance, to systematically determine the most viable preferred alternative. Examples of potential evaluation criteria are listed in Table 4-1.

4.3.2 Conceptual Design

Advancing the preferred option to a conceptual design level allows for the initial "wrinkles" to be ironed out before significant capital is committed. This phase refines the engineering approach to confirm technical feasibility and improve the accuracy of rough order-of-magnitude (ROM) cost estimates for budgeting and preliminary permitting. By solidifying the design's footprint and material requirements at this stage, proponents can identify potential long-lead items—such as specialized rock gradations or bioengineering materials—and verify that the concept remains aligned with the project's primary objectives and site-specific geomorphic drivers.

4.3.3 Preliminary and Detailed Design

Once the conceptual design is approved, the project advances to detailed engineering. The level of detail should be carefully managed to strike a professional balance: the package should be sufficiently explicit for a contractor to execute the work accurately without being overly complex (Figure 4-2). In many cases, the level of prescriptive detail in a design package can be reduced if there is a committed plan for increased site supervision by the design engineer. Practitioners should ensure that all drawings are legible and clear, as most drawing sets in the field will be printed at 8.5 x 11 inches (22 x 28 cm) or 11 x 17 inches (28 x 43 cm).

Table 4-1. Potential evaluation objectives and criteria when assessing various options for mitigating erosion-related risks

Objective	Criteria
Physical Environment	Flooding Hazard
	Ice Processes
	Permafrost
	Erosion Hazards
	Slope Stability
Natural Environment	Terrestrial Habitat
	Aquatic Habitat
Social/Cultural Environment	Aesthetic Value
	Benefit to Public
	Archaeological Features
Environmental Approvals and Permitting	Regulatory Agency Acceptance
Financial Criteria	Design Costs
	Capital Costs
	Maintenance Costs
Constructability	Complexity of Construction
Risks	Potential Risks to Existing Infrastructure
	Potential Risks to Public
	Potential Risks to Private Property

A comprehensive detailed design package should generally include the following components:

- **Plan, profile, and cross-sections:** Standard engineering views defining the full three-dimensional geometry of the works. Survey control points and working points for layout should be provided.
- **Site isolation and fish protection:** Explicit details regarding the isolation of the work area from flowing water (e.g., cofferdams, turbidity curtains) to satisfy DFO requirements, including specific construction timing windows.
- **Logistics and access:** Demarcation of site access routes, equipment laydown areas, and known flood hazard extents for construction safety.
- **ESC and restoration:** Erosion and Sediment Control (ESC) details and comprehensive site restoration plans, including specific native planting lists, seed mixes, and quantities.
- **Construction specifications:** Detailed, written instructions defining material requirements (size, density, quality), installation methods, and quality standards.
- **Design brief:** A supplementary document providing background context, key design assumptions and limitations, monitoring objectives and expectations, and an explanation of the project's overall objectives.

During this phase, hydraulic models (if available) should be updated to incorporate the proposed works. This step quantifies how the mitigation structure will affect local water surface elevations and hydraulics, verifies that the selected materials can withstand the calculated shear stresses, and helps determine whether adverse upstream or downstream impacts are created. If the model indicates significant upstream or downstream hydraulic changes, the design should be iteratively adjusted to mitigate these effects.

For riprap embankments and other direct approaches, the design should account for spatial extent and embedment to ensure long-term stability. To prevent "outflanking" by the migrating channel, the mitigation must extend far enough upstream and downstream into stable sections of the bank (Figure 4-1). To protect against scour and undermining, materials should be adequately embedded below the anticipated scour depth of the channel bed. Where deep embedment is not technically feasible due to construction constraints, the design should extend the toe further into the channel to form a launching toe, with sufficient thickness to provide bed armouring as scour occurs.

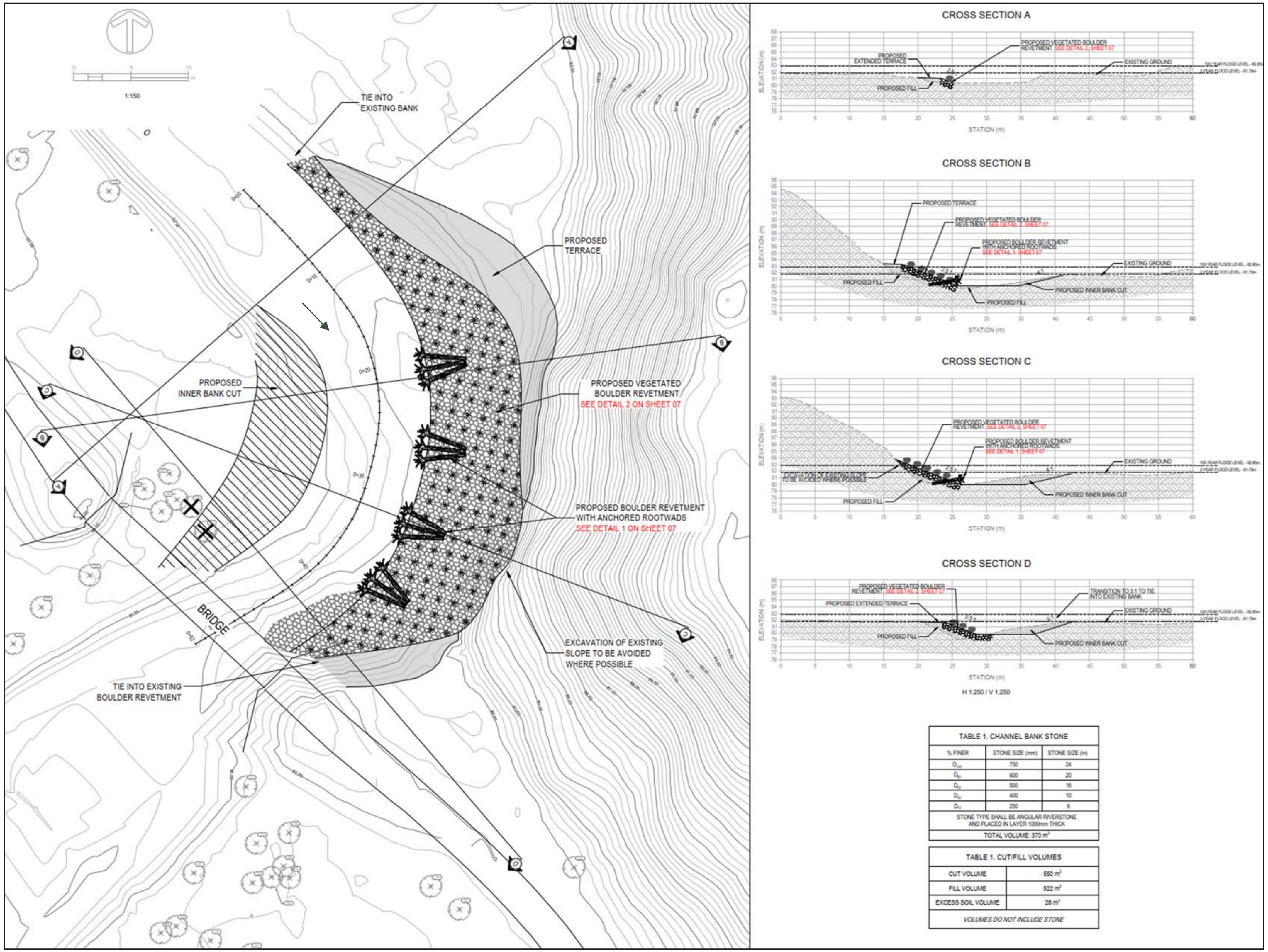

TABLE 1. CHANNEL BANK STONE		
% FINER	STONE SIZE (mm)	STONE SIZE (in)
D[illegible]	750	24
D[illegible]	600	20
D[illegible]	500	16
D[illegible]	400	10
D[illegible]	250	6
STONE TYPE SHALL BE ANGULAR RIVERSTONE AND PLACED IN LAYER 1000mm THICK		
TOTAL VOLUME: 370 m^3		

TABLE 1. CUT/FILL VOLUMES	
CUT VOLUME	550 m^3
FILL VOLUME	522 m^3
EXCESS SOIL VOLUME	28 m^3
VOLUMES DO NOT INCLUDE STONE	

Figure 4-2. An example design drawing from a larger design package that provides sufficient detail for construction but is not overly complex or cluttered. The purpose of this design to construct naturalized slope-toe protection along the outer bank of a sharp meander approaching an existing pedestrian bridge that is at risk of being outflanked (design drawing credit: SLR).

4.3.3.1 Design 'Typicals'

Design "typicals" serve as standardized cross-sections and plan views that provide contractors with a clear visual representation of the expected structural dimensions, material layering, and slope angles. These diagrams are critical components of a design package, as they translate complex engineering requirements into a format that is easily interpreted during construction. In the Yukon, typicals are especially valuable during emergency situations where rapid mobilization is required and time for bespoke drafting is limited. Practitioners are encouraged to refer to Appendix C of this guidance document for a suite of design typicals specifically tailored to northern environmental constraints and locally available materials of the Yukon. Site specific parameters such as design high water level, stone sizing, thickness and underlayment should be established by a qualified professional. The typicals included in **Appendix** C are listed below:

1. Vegetated cobble/boulder revetment with granular filter or non-woven geotextile filter fabric
2. Vegetated bank with rolled erosion control products
3. Vegetated (brush) layering
4. Wood spurs/deflectors
5. Site isolation for erosion mitigation projects
6. ESC details for erosion mitigation project

4.3.3.2 Stone Sizing

While standard design drawings and typicals provide a valuable starting point, exact stone gradations will be calculated and assessed by the designer on a site-specific basis. Stone sizing should account for open-channel hydraulics (e.g., velocity and shear stress), wave exposure, slope inclination, stone angularity, native substrate, positioning along a meander (outer bank vs inner bank), the potential for ice plucking, and the realistic availability of stone in remote Yukon locations. Factors of safety are often incorporated into the stone sizing gradation based on the complexity of the river or lake system, the number of unknowns (e.g., a lack of understanding of shear stresses during an ice run), and what is being protected.

Granular filter layers or geotextiles are commonly required beneath the armour layer to inhibit the loss of underlying fine-grained sediments. In northern environments, it is particularly critical to evaluate the specific types of ice interacting with the structure, such as aufeis, ice jams, and dynamic ice runs (U.S. Army Corps of Engineers, 2006). Stone should be extended vertically to the bankfull elevation if there is an accessible floodplain, but it may need to be extended even further (e.g., to a 5-year return water level) if the river is entrenched.

To effectively size stone, designers should incorporate specific hydraulic and riprap design guidance from the Transportation Association of Canada (2004) and British Columbia (Province of British Columbia, 2000). Furthermore, a guidance document prepared for Hydro-Québec provides foundational knowledge and practical calculation methods for stone sizing and mitigating erosion in various river-ice environments (Carter Consultants, 2003).

4.4 Planned Versus Emergency Work

The circumstances under which mitigation is constructed—whether as a rapid response to an active threat or as a planned project—heavily dictate the quality, regulatory compliance, and expected service life of the final structure.

Emergency works are typically triggered when culturally significant lands, private property, public safety, or critical infrastructure are actively compromised by a sudden erosional event. Under these time-sensitive scenarios, owners commonly have a limited choice of materials and must rely on temporary stabilization measures. Often, these emergency interventions proceed with little to no formal design, procurement, or engineering input. Instead, under intense pressure to maintain open transportation corridors and protect public safety, maintenance crews frequently must conduct immediate, unplanned repairs (Photo 4-9). These measures rarely offer long-term stability and typically require significant future upgrades or complete replacement once the immediate crisis has passed.

To ensure that emergency works are constructed as effectively as possible under duress—especially when advancing work without prior baseline data or technical specialist involvement—**owners of public infrastructure and maintenance crews** should adhere to several critical steps that span the emergency event (before, during, after):

- **Establish an emergency response plan:** Implement a clear chain of command, maintain a roster of pre-qualified contractors familiar with northern environmental constraints, and establish communication protocols for regulatory notification (e.g., Yukon Water Board, Fisheries and Oceans Canada) as soon as an emergency is identified.
- **Plan and stockpile ahead:** Whenever possible, calculate anticipated riprap gradations and stockpile suitable materials near historical maintenance hotspots before an emergency occurs. This enables a rapid response and eliminates the delay of mobilizing aggregate during a crisis.
- **Identify stable 'tie-in' locations:** Identify the start and end points of the repair carefully. Emergency works should ideally begin at a stable boundary upstream and downstream of the active erosion area. The works could also extend riprap down to the toe of the channel bank with sufficient thickness to maintain stability once toe-scour inevitably occurs.
- **Employ proper placement techniques:** Avoid direct dumping of aggregate from the crest of the slope, as this results in poor structural interlocking and material segregation. Instead, use an appropriately sized excavator to carefully place the rock (additional information is provided in Section 4.5).

Photo 4-9. Following a high-intensity precipitation event in August 2016, a watercourse severed the Dempster Highway and necessitated emergency works to allow for safe passage of vehicles transporting critical supplies between communities (photo credit: YG HPW-TEB).

Private landowners facing an active erosion emergency encounter distinct challenges, as they typically lack the pre-established chain of command, pre-qualified contractor rosters, and stockpiled materials available to public agencies. When a catastrophic bank failure or rapid erosion event threatens a private residence, landowners should prioritize life safety and site securement. Key actions for private landowners include:

- **Site securement and monitoring:** Immediately restrict access to the failing slope, relocate movable secondary structures (e.g., sheds) or assets away from the crest, and take repeated, time-stamped photographs to document the rate of failure. This documentation is critical for subsequent engineering assessments and emergency regulatory applications.
- **Surface water management:** Divert any surface runoff, such as roof downspouts or driveway drainage, away from the failing bank. Saturated soils significantly increase pore water pressure and decrease slope strength, making the diversion of water away from the failure a critical temporary measure.
- **Avoid ad-hoc dumping:** Landowners must resist the urge to dump yard waste, concrete rubble, or other unapproved debris over the bank in a panic. This practice often traps groundwater, adds unnecessary surcharge weight to the crest, and/or exacerbates slope instability.
- **Professional and regulatory consultation:** Landowners should contact territorial and local authorities immediately to report the emergency and arrange a consultation (additional information is provided in Section 5 and Section 6). Due to the complexities of

stone sizing, ice forces, and structural stability, landowners should engage qualified professionals and experienced contractors rather than attempting complex in- or near-water interventions independently.

- **Neighbour coordination:** Where possible, landowners should communicate with adjacent property owners to coordinate a response. Isolated, property-specific emergency works often transfer erosive energy to adjacent lots, accelerating erosion downdrift or downstream.

The **aftermath of any emergency works**—whether public or private—requires careful attention, follow-up assessment, and regulatory reporting. Because emergency installations are constructed under adverse conditions, they almost always fall short of standard design recommendations—rock sizes may be smaller than required, underlying filter layers are usually omitted, and toe protection is frequently insufficient. Consequently, best practice mandates a formal post-flood inspection and geomorphic assessment by a professional once the immediate crisis subsides. This follow-up assessment should evaluate the emergency structure's performance, document changes to the channel morphology, and establish formal design criteria for upgrading or reconstructing the works to a longer-term standard (including site restoration). In many cases, this involves removing temporary materials, installing appropriate filter fabrics, and fully reconstructing the bank using proper engineering guidelines.

Furthermore, while emergency activities can proceed without a prior environmental assessment to protect public safety or the environment, strict regulatory follow-up is required. Proponents must notify regulatory bodies immediately during the event. As soon as practicable after the emergency works are completed, a comprehensive written report must be submitted to the applicable agencies (such as the Yukon Environmental and Socio-economic Assessment Board, Yukon Water Board, and DFO). This report must justify the emergency status, detail the nature, extent, and duration of the activities, include photographic documentation, and outline any subsequent work required to restore or rehabilitate the affected area.

Whenever possible, **planned and proactive works** should be pursued, as they lead to superior engineering and environmental outcomes. Proactive timelines allow for thorough engagement with First Nations, stakeholders, and regulatory agencies, ensuring the project aligns with broader community values. This window also ensures that a comprehensive options assessment can be conducted and that the necessary materials—such as specific rock gradations or native plant stock—can be sourced and delivered before the site reaches a critical state of failure. Strategic planning ultimately reduces life-cycle costs by avoiding the "repair-fail-repair" cycle often associated with emergency interventions.

4.5 Construction

The successful transition from design to a functional, resilient structure depends on the quality of execution and the rigour of construction oversight. In the Yukon, project success is often determined by how effectively the construction phase manages environmental windows, specialized material handling, and the dynamic nature of northern watercourses. Implementation represents the start of a long-term process that includes adaptive construction management, environmental compliance, and post-construction monitoring to verify that the mitigation performs as intended over its design life.

4.5.1 Procurement and Contractor Selection

To ensure that both environmental requirements and long-term project objectives are met, procurement packages should leave as little to interpretation as possible. In the Yukon, vague specifications frequently lead to unauthorized corner-cutting or significant cost overruns when contractors encounter the realities of a short construction window. It is essential that the bid documents provide clarity to ensure all proponents are bidding on the same standard of care. A professional procurement package should include detailed contract line items for tasks that are traditionally under-budgeted or overlooked. To provide necessary clarity during the bidding process, the package should explicitly define:

- **Quantities and materials:** Precise cut-and-fill volumes and the specific stone size (gradation), rock type, and orientation.
- **Material placement:** Specifications for how material should be placed. The Province of British Columbia Ministry of Transportation Riprap Installation Guide (2013) provides useful guidance for material placement and construction monitoring.
- **Site isolation:** Dedicated payment items for the installation, maintenance, and removal of site isolation measures, such as cofferdams, bypass pumping, and turbidity curtains, as well as required fish salvage and relocation efforts. Weather events and other unforeseen changes to the construction plan may require multiple iterations of site isolation.
- **Restoration and ESC:** Dedicated items for site restoration and revegetation, along with the proactive maintenance of Erosion and Sediment Control (ESC) measures throughout the project duration.

The successful execution of complex natural channel designs and bioengineering requires far more than standard earthmoving skills; it demands a high degree of technical precision and experience operating specialized equipment. Proponents should prioritize contractors with a proven track record in northern riverbank/lakeshore works, specifically evaluating their ability to manage site isolation and maintain environmental compliance under a range of hydrologic conditions that may be expected.

This requirement for specialized skill is exemplified by restricting "end-dumping" stone from the top of the bank for riprap revetments (Figure 4-10). Because end-dumping leads to material segregation, poor structural interlocking, and habitat degradation, specifications should mandate the keyed placement of individual stones using equipment with a hydraulic thumb (Figure 4-11). Only by employing contractors with the experience to perform this level of precision work can the design's intended thickness, packing density, and long-term stability be guaranteed.

Photo 4-10. Emergency riprap installation utilizing end-dumping methods (photo credit: YG HPW-TEB). While expedient for rapid response, the lack of keyed placement and material segregation typically results in poor structural interlocking and limited long-term resilience.

Photo 4-11. Careful placement of riprap on an embankment using specialized equipment leads to better long-term results (photo credit: YG HPW-TEB). In this photo the riprap is being placed atop geotextile, which can form a slip-surface and contribute to revetment failure (see Section 4.6).

4.5.2 Erosion and Sediment Control (ESC)

Construction activity near or within a watercourse poses a high risk of mobilizing sediment, which can negatively affect downstream waterbodies and degrade sensitive aquatic habitats. Under the federal *Fisheries Act*, the "deposit of a deleterious substance"—which includes sediment-laden runoff—into fish-bearing waters is strictly prohibited. Non-compliance is not merely an environmental concern; it carries significant legal and financial risks, as failure to maintain adequate ESC measures can result in mandatory construction stoppages, substantial daily fines, and prosecution by DFO.

From an operational perspective, effective ESC is critical for maintaining project timelines. A single major sediment release event can trigger a regulatory investigation that halts work for weeks, potentially causing the project to miss the narrow Yukon construction window. To mitigate these risks, practitioners should adhere to several key ESC principles:

- **Minimize disturbance:** Limit the physical footprint of the disturbed area and the duration that soils remain exposed to the elements, especially within the riparian zone of a watercourse.
- **Adaptive scheduling:** Stage work appropriately and monitor weather forecasts to avoid high-risk activities during heavy rain or rapid snowmelt events. Avoid work during sensitive fisheries windows when the likelihood of harm to fish is greater.
- **Proactive monitoring and maintenance:** Inspect ESC measures—such as silt fences, check dams, and turbidity curtains—daily and immediately following any precipitation event to ensure they are functioning as intended. Be prepared to repair or replace ineffective measures by maintaining a supply of extras and qualified installers.

For comprehensive technical guidance and examples of proven methodologies tailored to northern conditions, practitioners should refer to YG's (2019) *Preferred Practices for Works Affecting Yukon Waters*.

4.5.3 Site Isolation and Dewatering

Conducting in-water works generally requires the work area to be isolated from open or flowing water to prevent sediment from being released from the work area. Detailed practices for isolating in-stream work areas are outlined in YG's (2019) *Preferred Practices for Works Affecting Yukon Waters*, which serves as the primary technical reference for these operations.

It is important for practitioners to recognize that isolation is fundamentally about containing sediment rather than achieving a perfectly dry workspace; it is <u>not</u> synonymous with working "in the dry." Equipment can still operate effectively in standing water within the isolated footprint, provided that the sediment generated by the construction activity cannot escape into the main watercourse. Furthermore, once isolation is complete, a fish salvage and rescue must be conducted within the isolated work area; all captured fish must be safely released into the active channel before any construction work commences. While isolation is the standard expectation, in rare circumstances—such as emergency works—in-water work without site isolation may be unavoidable.

The specific techniques utilized for isolation depend heavily on the site's environmental setting. Small streams characterized by low water levels and manageable velocities can commonly be bypassed entirely using high-capacity pumps or temporary diversion channels. In contrast, larger rivers or lakeshores typically require the construction of robust cofferdams—utilizing materials such as meter bags, clean gravel super-sacks, or steel sheet piles—to create a stable, isolated work zone (Photo 4-12).

When full isolation is not feasible due to deep water, extreme velocities, or the urgency of emergency works, strategies should be adapted to manage environmental risk. This may include the use of clean, self-launching angular rock placed carefully from the bank to avoid splashing or stirring up bottom sediments, minimizing the duration equipment spends in the water, and utilizing turbidity curtains to limit the dispersion of any suspended sediment.

Throughout the duration of the work, a qualified professional should conduct environmental monitoring. This process includes measuring turbidity levels upstream to establish a background baseline and monitoring downstream of the site to confirm that the works are not releasing sediment above allowable levels. These data points are critical for verifying that the isolation measures are performing effectively and for guiding any necessary corrective actions in real-time.

Photo 4-12. Example of site isolation along river using meter bags (photo credit: SLR). Note that the work area remains 'wet', but any sediments that become suspended within the work area cannot escape into the adjacent, flowing channel.

4.5.4 Site Restoration Requirements

Site restoration is not merely an aesthetic finishing touch; it is a critical engineering component (Photo 4-13). A properly vegetated slope and adjacent upland can provide considerable, self-sustaining stability that mitigates surface erosion and shallow mass movement (Johannessen et al., 2014). Vegetation provides flexible, self-perpetuating erosion control by increasing soil cohesion through root reinforcement, slowing surface runoff through increased roughness, and reducing pore-water pressure via evapotranspiration. The following are key considerations for site restoration in the Yukon:

- **Vegetation as engineered stability:** Plantings should be viewed as part of the structural design. Over time, as root systems mature, they provide "biological anchoring" that can greatly supplement mechanical stabilization. However, if restoration is poorly executed or under-budgeted, the long-term resilience of the entire structure may be compromised.
- **The active layer timeline:** Permafrost introduces a unique scheduling complication. The active layer remains frozen well into the spring, inhibiting early-season excavation or planting. Conversely, the active layer only reaches its maximum thaw thickness (and minimum stability) in late summer or early fall. This narrow window between "ground thaw" and "first frost" requires precise coordination to ensure plantings have enough time to establish before dormancy. Every effort should also be made to minimize disturbance to any organic cover of underlying permafrost, due to its insulating effects; if inadvertently stripped or compacted, organic cover should be re-established as part of site restoration.
- **Immediate soil protection***:* Exposed soils should be stabilized quickly to prevent seed washout. This requires 100% biodegradable coir matting (erosion control blankets), mulching, and proper slope grading to reduce runoff velocities. Native plantings and perennial seed mixes can provide long term stabilization but may be slow to establish in the Yukon climate. For rapid establishment of ground cover, annual grass (rye, or barley) can be seeded to stabilize the ground surface and provide short-term erosion and sediment control
- **Northern bioengineering:** Utilize locally adapted native species and techniques such as live willow stakes, rooted cuttings, and site-specific hydroseeding. While pioneer species like native willows (*Salix* spp.) are excellent for rapid establishment and providing dense, fibrous root networks near the waterline, incorporating deep-rooted deciduous trees farther up the slope is highly advantageous for achieving longer-term structural stability and deeper soil reinforcement (Matheus & Omtzigt, 2013; Johannessen et al., 2014).

To successfully implement these strategies, practitioners should adhere to regional best practices. For general site preparation, soil amendments, and appropriate seed mixes, designers should consult the *Yukon Revegetation Manual* (Matheus & Omtzigt, 2013) and the *Guidance Document: HPW Roadside Revegetation Seed Mixes* (Matheus & Omtzigt, 2021). Additionally, for specific bioengineering techniques and step-by-step installations, *Streambank Revegetation and Protection: A Guide for Alaska* provides excellent, climate-appropriate direction for northern riverine environments (Johnson et al., 2025).

Site restoration is not an afterthought—it is part of the design. Stabilizing soils and re-establishing vegetation are critical for long-term success.

Photo 4-13. An example of site restoration including soil stabilization coir matting and riparian plantings (photo credit: SLR).

4.5.5 Construction Oversight and Inspection

The **active involvement of the design team** or an owner's representative during the construction phase is critical to ensuring the project is built as designed, which leads to vastly superior long-term outcomes. Contracting out the oversight role to an individual or firm not involved in the original design is considered suboptimal, as it disconnects the field execution from the foundational engineering assumptions. To maintain this continuity, the designer should be on-site at critical milestones (Photo 4-14), such as the bidders' meeting, construction kick-off, initial site isolation and dewatering, and the commencement of material placement to verify sizing and positioning. Presence is also vital during the re-introduction of flow into the channel to monitor for scour and turbidity, as well as at the start of site restoration activities.

Because natural lakeshores and rivers are dynamic, site conditions frequently differ slightly from the topographic surveys used during the design phase. Consequently, **"field fits"**—on-the-fly modifications to the design—are an inevitable reality of water-based construction. Direct designer involvement ensures that these field adjustments do not jeopardize the overall function, stability, or environmental compliance of the mitigation strategy. These inspections serve to verify that the work is built precisely to specifications, that materials meet quality standards, and that environmental controls like ESC and site isolation are functioning effectively.

> Keeping the design team involved during construction improves outcomes. Real-time decisions on "field fits" help address unexpected conditions and reduce the risk of failure.

Photo 4-14. Inspection of completed erosion mitigation works by members of the design team, along an isolated (dry) section of watercourse, prior to advancing to the next phase of construction (photo credit: SLR).

Documentation is a core requirement of professional oversight. Inspections should be conducted daily for ESC measures and at all critical milestones by a qualified professional, such as the design engineer, fluvial geomorphologist, or an environmental monitor. This process includes maintaining daily construction logs that document the contractor's progress, equipment on-site, weather and flow conditions, and a formal log of any deficiencies and their corrective actions. Photographic records of each phase and documentation of any sediment releases are essential. UAVs can provide useful imagery of construction progress and the completed project (Photo 4-15). Furthermore, the contractor should have an appropriate and defined Quality Assurance/Quality Control (QA/QC) system in place for these inspections.

Following the completion of construction, a final topographic survey should be completed by the contractor to establish the baseline "as-built" conditions, including plan, profile, and cross-sections. This survey verifies that implementation tolerances were met and provides a benchmark for all future comparative monitoring.

Photo 4-15. A UAV inspection of recently completed erosion mitigation works (white area of cobble riffle between regraded banks), including site restoration and riparian plantings (dark brown areas of freshly placed topsoil, mulch, and plantings) (photo credit: Toronto and Region Conservation Authority).

4.6 Post-construction Monitoring and Maintenance

Post-construction monitoring is an essential technical requirement to verify that mitigation measures are performing as designed and to identify necessary repairs before localized instabilities escalate into systemic failures. Beyond ensuring structural integrity, a robust post-construction monitoring plan serves as a powerful tool during the permitting phase, as it provides regulators with the assurance that environmental and engineering outcomes will be verified and managed over time. Proactively including these plans can significantly streamline and support the regulatory approval process.

To ensure the long-term viability of the project, a formal monitoring plan should be established during the design phase by the proponent. This plan should include specific, quantifiable triggers for maintenance intervention—for example, the loss of 20% of riprap volume or 30% vegetation mortality, over particular time periods. Furthermore, for maintenance to be physically and legally viable, long-term access to the site should be secured by the proponent. This may involve establishing legal easements or rights-of-way across private, territorial, or Settlement Lands. Without guaranteed access for heavy equipment, the long-term success of the mitigation may be compromised.

The monitoring program systematically evaluates:

- **Structural performance:** Technical evaluations focused on identifying physical displacements, loss of materials, signs of overtopping, and/or the progressive undermining of the structure's toe (Photo 4-16).

- **Vegetation health:** Monitoring survival rates and vigour of plantings.
- **System adjustments:** Identifying unintended consequences or unforeseen changes to conditions, such as downstream scour or unexpected bank retreat at the project boundaries.

The monitoring plan should explicitly outline:

- **Monitoring methodologies:** Effective monitoring relies on standardized techniques, including repeat monumented photography—where photos are taken from the exact same GPS coordinates with the same fields of view over time—as well as physical cross-section surveys and UAV-based remote sensing. These methods allow for the tracking of subtle changes in bank geometry that may not be obvious based on observation alone. For further information on these specific monitoring techniques, practitioners should refer to Section 3.7 of this document.
- **Frequency and timing:** Inspections are scheduled at regular annual intervals and are also triggered by specific environmental events, such as freshet, major storm surges, or dynamic ice breakups, often coordinated with local observations from community members or maintenance staff.
- **Duration of oversight:** Monitoring periods are defined based on the stabilization target, typically requiring a shorter intensive window for biological establishment and potentially up to a decade for more structural mitigation works.

Photo 4-16. Monitoring of erosion mitigation, site restoration, and riparian vegetation after construction (photo credit: SLR).

4.7 Common Reasons for Failure

Even heavily engineered mitigation structures can fail if local site vulnerabilities and physical processes are ignored (Photo 4-17). All too often, protection works prove inadequate due to a lack of consideration for relevant lacustrine or fluvial mechanics, inadequate design procedures, and poorly executed construction (OMNR, 1996). Understanding these common pitfalls and implementing appropriate design solutions is essential for ensuring the long-term success of riverbank and lakeshore stabilization efforts.

Common reasons for failure include:

- **Geotextile slip planes:** The use of synthetic geotextile fabrics on steep slopes or beneath rock armour can create a smooth slip plane, causing the overlying materials to slide off into the watercourse. Instead, practitioners should utilize a properly graded and benched granular stone filter layer to prevent the piping of fine bank materials without creating a slip hazard.
- **Undersized stone:** Using rock that is too small for the calculated hydraulic shear stresses, ice impacts, or plucking forces results in the material being displaced if not washed downstream during floods.
- **Not extending far enough upstream or downstream:** Failing to tie the mitigation securely into adjacent stable banks allows the migrating channel to outflank the structure or rapidly erode downstream (Figure 4-1).
- **Not embedding material:** Failing to dig a proper toe trench and embed the base materials below the maximum predicted scour depth leads to the structure being undermined and collapsing into the channel.
- **Insufficient crest height:** Failing to protect the bank to an appropriate elevation for the conditions to which it may be exposed (e.g., water levels, waves, ice) can lead to overtopping and scour behind the crest, promoting ongoing erosion of the bank and settlement of the structure.
- **Failing to understand causes of erosion:** Applying a solution that does not match the primary driver of the problem (e.g., installing large-calibre riprap to stop wave erosion when the actual cause of failure is poor upland surface water drainage or groundwater seepage).
- **Failing to understand ice dynamics, permafrost conditions, or geotechnical situations:** Constructing heavy embankments on ice-rich permafrost can trigger thermal degradation, thaw-subsidence, and total structure failure. Similarly, failing to account for dynamic ice break-ups or deep-seated geotechnical slope instability will overwhelm standard surface-erosion treatments.
- **Improper construction sequencing:** Failing to plan the construction sequence can inadvertently trigger the very failures a project aims to prevent. Heavy equipment operating on or near a vulnerable bank can introduce temporary loads that exceed the slope's bearing capacity.

Photo 4-17. Examples of common reasons for erosion mitigation failure. Upper left: riprap embankment was not extended far enough upstream. Upper right: riprap was not adequately embedded, contributing to slope failure. Bottom left: geotextile created a slip plane for riprap. Bottom right: erosion protection was not extended far enough downstream. All photos courtesy of SLR.

5.0 Regulatory Context, Approvals and Coordination

5.1 Regulatory Framework

For general guidance, wording, and a comprehensive overview of the environmental regulations governing works within or near rivers and lakes in the Yukon, practitioners should refer to Section 4 of the YG's (2019) *Preferred Practices for Works Affecting Yukon Waters*. Navigating this complex regulatory environment is a critical component of riverbank or lakeshore erosion mitigation. Depending on the scale and location of the project, proponents will likely need to secure multiple approvals before construction can begin.

Potential Approvals Required for Erosion Mitigation in the Yukon:

- ***Yukon Environmental and Socio-economic Assessment Act*** **(YESAA) Evaluation:** An assessment under YESAA is generally required to identify and mitigate potential adverse environmental and socio-economic effects before development projects proceed.
- **Water Licence (*Waters Act*):** Issued by the Yukon Water Board, a licence is required for activities that alter a watercourse (e.g., bank alterations, placement of infill or erosion control materials), particularly for watercourses over 5 metres wide.
- ***Fisheries Act*** **Authorization / Request for Review:** Administered by DFO, this is required for works that might result in the harmful alteration, disruption, or destruction of fish habitat (HADD).
- ***Navigation Protection Act*** **Approval:** Administered by Transport Canada, this approval is required to protect the public's right to marine navigation when works are built or placed in, over, through, or across navigable waterways.
- **Land Use Permit (*Territorial Lands Act*):** Regulated by the YG's Land Management Branch, a permit is typically required for temporary use or work on public land, including site clearing, earthwork, or constructing new access trails.
- **First Nation government approvals:** Activities proposed on Settlement Land under a Yukon First Nation Final Agreement frequently require explicit permission or a permit from the respective First Nation government.
- **Municipal approvals:** Depending on the jurisdiction, local building or development permits may also be required.

The regulatory landscape is further defined by the location of the project **relative to the annual highwater mark**[4] and the logistical realities of the review process. Works situated within or below the annual highwater mark face a significantly more rigorous regulatory pathway, typically requiring a formal Request for Review by DFO to ensure the design avoids the HADD. In addition to federal oversight, these projects usually necessitate specific water licensing and authorizations from the Yukon Water Board.

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[4] The annual highwater mark (or ordinary highwater mark) is the highest water level reached by a waterbody during a typical year. It is defined as the elevation where water sits or flows long enough to leave visible evidence on the landscape, such as scour marks, debris deposits, changes in soil characteristics, or a distinct transition from aquatic to terrestrial vegetation. In riverine settings, the annual high watermark is sometime established by identifying the bankfull elevation or the elevation of the 2-year return flood event.

Proponents must also account for the significant time required to navigate these assessments. Because regulatory agencies may not always possess specialized in-house expertise in fluvial geomorphology or coastal engineering, the burden of proof rests with the proponent. It is essential to provide clear, technically-justified, and accessible assessment and design reports to facilitate an efficient review and minimize the risk of lengthy delays caused by requests for clarifications or more information.

5.2 Approval Pathways

The successful implementation of riverbank and lakeshore stabilization requires a regulatory strategy that aligns construction timelines with legal requirements. Projects often involve both territorial and federal approvals, and coordinating these processes is a common source of delay. Proponents should distinguish between different levels of urgency to apply the correct regulatory framework and utilize specific design and planning strategies to streamline agency reviews.

The distinction between planned, emergency, and urgent works dictates the legal flexibility available to the proponent:

- **Emergency vs. planned works:** While planned works follow standard regulatory timelines (often several months or longer), true emergency works—actions required immediately to protect public welfare, health, safety, or the environment—benefit from special legal provisions. Under the *Waters Act* and *YESAA*, certain emergency activities can proceed without a prior assessment. However, this is not a "free pass"; regulatory bodies must be notified immediately, and a comprehensive written report must be submitted as soon as practicable after the work is completed to justify the emergency status and document the actions taken (additional details are provided in Section 4.4).
- **Defining "urgent" works:** It is critical to distinguish "urgent" sites from legal emergencies. An urgent site is one where the bank has not yet failed or impacted infrastructure but is considered highly vulnerable—**likely to fail within the next one or two hydrological events** (e.g., Figure 5-1), such as the spring freshet or a major summer storm. While these sites generally fall outside the legal definition of an emergency and still require standard authorizations, proponents should explicitly flag the urgency within permit applications to trigger administrative prioritization. For instance, when submitting a Request for Review to DFO or a project proposal to YESAB, the application should clearly document the "imminent risk" to infrastructure or public safety, backed by a Qualified Professional's assessment (e.g., an engineer or geomorphologist) to provide technical weight to the claim of urgency. As well, to facilitate a smoother review, proponents should initiate a pre-submission meeting with regulators. By briefing agencies on the risk profile before the "official" clock starts, proponents can ensure the urgency is well understood by the assessors.

Photo 5-1. An eroding bank of a watercourse is within a few metres of the road embankment (photo credit: SLR). Although not truly an emergency, this site may be classified as urgent as a large flow event may lead to a road washout.

To optimize project timelines and reduce the risk of delays, proponents should leverage the following opportunities to fast-track the approval process:

- **Robust options analysis:** Submitting a transparent options analysis proves to regulators that the proponent has performed due diligence as well as helps alleviate concerns about potential biases. By demonstrating that alternative, potentially less impactful designs were considered, the selected approach is much easier for agencies to justify and approve. Submitting a *Design Brief*, if available, provides important context to the regulators during their review.
- **Eco-friendly mitigation:** Regulators are usually more supportive of projects that prioritize NbS or bioengineering. Integrating "green" elements into a design can reduce the actual or perceived environmental risk, leading to faster consensus during the review phase.
- **Comprehensive post-construction monitoring:** Proactively including a detailed monitoring plan—specifically addressing sediment control and fish habitat performance—provides regulators with the assurance that any unintended consequences will be caught and corrected.
- **Available fisheries data and on-site expertise:** Delays often occur due to data gaps. Proponents can speed up reviews by having current fish habitat data ready for submission and committing to having a qualified fish biologist on-site during critical construction phases (e.g., site isolation). This ensures real-time compliance and immediate resolution of environmental concerns.
- **Proactive multi-site and multi-year approvals:** For recurring work or work with similar geographic challenges, bundling multiple sites into a single application or applying for

long-term maintenance permits can eliminate the need for repetitive individual assessments, saving months of administrative time and uncertainty.

- **Strategic spatial design:** Designing mitigation to remain above the high watermark as much as possible can significantly reduce the regulatory burden by staying out of primary federal jurisdictions. However, this should be balanced against engineering requirements, as avoiding the "toe" of the bank can sometimes compromise the long-term stability and effectiveness of the structure.

5.3 Coordination and Collaboration

Effective riverbank and lakeshore management is a multi-jurisdictional challenge that requires a move away from site-specific interventions to integrated, system-wide strategies. Ad hoc, isolated mitigation commonly fails to address the root cause of instability and can inadvertently transfer erosion issues to other areas. Coordinating efforts across property lines and administrative boundaries, ensures that mitigation supports the natural continuity of the river or lake processes rather than providing temporary, localized fixes.

> Early coordination among governments, First Nations, regulators, and landowners leads to smoother approvals and better project outcomes.

A collaborative framework improves the technical and financial viability of stabilization projects and can be achieved through the following actions and strategies:

- **Pre-established communication channels:** Formal communication protocols should be established well before design finalization. This includes internal alignment across government departments and external engagement with First Nations, municipalities, and regulators. Early dialogue ensures that project objectives are transparent and that potential conflicts—such as impacts on traditional land use or municipal infrastructure—are identified and resolved in the planning phase.
- **Management of impacts to adjacent properties:** Coordination is critical when hard structural works, such as riprap revetments, are proposed. These structures can alter local hydraulics by deflecting erosive energy toward the opposite bank or cutting off the downstream sediment supply (sediment starvation). Collaborative modelling and design ensure that one landowner's protection does not become a neighbour's liability.
- **Cost and resource sharing:** Stabilization projects carry high fixed and operational costs. By collaborating with neighbouring stakeholders or agencies, proponents can achieve significant economies of scale. This allows for the sharing of financial burdens related to expensive technical assessments, specialized material procurement, and the high mobilization costs often associated with deploying heavy equipment and specialized labour to remote or logistically challenging locations.
- **Access to diverse funding streams:** Collaborative projects involving multiple partners—such as local municipalities, territorial departments, and First Nations—often qualify for a wider array of provincial and federal grants. These funding streams frequently prioritize multi-benefit, community-scale projects that a single entity acting alone cannot access.
- **Development of longer-term, large-scale solutions:** Coordinated efforts allow stakeholders to "step back" and evaluate the river or lakeshore at a reach-scale. This perspective facilitates comprehensive, long-term solutions—such as large-scale

managed retreat or continuous, reach-wide beach nourishment—which are more sustainable than temporary, lot-by-lot fixes that often require frequent repair.

- **Knowledge sharing and iterative design:** Collaboration ensures that "institutional memory" is preserved. By sharing data and lessons learned from previous local successes or failures, proponents can refine engineering designs to better suit specific regional conditions, such as unique permafrost interactions or specific ice-jam dynamics.

While this comprehensive level of coordination is rarely feasible during rapid-response emergency situations, proactive planning remains essential. Establishing emergency communication protocols in advance and thinking beyond property-scale mitigation—even when implementing expedient emergency measures—is a wise strategy to help minimize the unintended transfer of erosive energy to adjacent lands.

5.4 Funding Opportunities

Securing capital for erosion mitigation remains a primary challenge for erosion mitigation in the Yukon, as construction costs are high due to remote logistics, short seasonal windows, and specialized material requirements. Because these projects typically involve public safety, infrastructure protection, and environmental restoration, they often do not align with a single funding source. Consequently, proponents should consider inter-agency funding models, combining territorial and federal streams to finance their project. Proponents must navigate the Canadian policy landscape to align their erosion-related projects with the mandates of various funding agencies, ranging from disaster risk reduction to habitat restoration and climate adaptation.

Proponents should strategically explore the following funding pathways:

- **Disaster mitigation and climate adaptation funds:** Programs such as the federal Disaster Mitigation and Adaptation Fund (application intake windows are periodic) and the Federation of Canadian Municipalities' Green Municipal Fund are specifically geared toward large-scale infrastructure projects that protect against natural hazards. To be competitive, projects should demonstrate long-term community resilience. In the Yukon context, this means designs should explicitly account for climate change variables, such as increasing peak flows from glacial melt or the thermal degradation of permafrost underlying banks.
- **Habitat and environmental restoration streams:** Agencies like DFO and various environmental non-governmental organizations offer funding focused on the rehabilitation of aquatic ecosystems. By prioritizing NbS or bioengineering, proponents can frame an erosion risk mitigation project into a "habitat enhancement" initiative. This shift opens doors to funding that traditional riprap projects cannot access, provided the design offers measurable benefits to fish habitat and/or riparian biodiversity.
- **Hazard assessment and mapping grants:** Many capital funds require a high level of hazard assessment before construction dollars are released. Programs through Public Safety Canada or NRCan such as the Flood Hazard Identification and Mapping Program—frequently provide grants for the assessment phase. Securing these funds allows a community to complete the necessary hydraulic modelling investigations and fluvial geomorphology assessments required to build a defensible business case for large-scale construction.
- **Green infrastructure and natural asset programs:** Emerging federal priorities commonly focus on "Green Infrastructure." Funding through the Federation of Canadian

Municipalities or Infrastructure Canada increasingly recognizes natural assets (like stable riverbanks, lakeshores and wetlands) as equivalent to built assets. These programs commonly support innovative pilot projects that utilize bioengineering or hybrid techniques in northern environments.

- **Cost-sharing through multi-partner collaboration:** Cost-sharing through multi-partner collaboration can be a significant financial driver for northern infrastructure projects. When First Nations, municipalities, and territorial departments co-apply for funding, they can access more funding streams. This approach distributes the costs of mobilization and construction while aligning the project with the policy goals of multiple government levels, which often increases the competitiveness of the application. Furthermore, collaboration allows partners with limited available capital to participate by offering in-kind support—such as staff expertise, existing technical data, or the use of heavy equipment—in lieu of direct financial contributions.

6.0 Resources

6.1 References Cited

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6.2 Technical Resources and Datasets

Aerial Imagery

- **GeoYukon**: mapservices.gov.yk.ca/GeoYukon/
- **National Air Photo Library**: eodms-sgdot.nrcan-rncan.gc.ca
- **ESRI Wayback:** livingatlas.arcgis.com/wayback/
- **Google Earth:** earth.google.com/web/
- **Google Earth Engine:** earthengine.google.com/

Topographic Data

- **Canadian High-resolution DEM (HRDEM):** app.geo.ca/en-ca/map-browser/record/957782bf-847c-4644-a757-e383c0057995
- **Canadian Medium-resolution DEM (MRDEM)**: app.geo.ca/en-ca/map-browser/record/18752265-bda3-498c-a4ba-9dfe68cb98da
- **ArcticDEM**: https://livingatlas2.arcgis.com/arcticdemexplorer/
- **Canadian Hydrographic Service:** dfo-mpo.gc.ca/science/hydrography-hydrographie/index-eng.html

Geotechnical, Geological, and Permafrost Data

- **YG Geotechnical Borehole:** open.yukon.ca/data/geotechnical-borehole-point
- **YG Permafrost:** service.yukon.ca/permafrost/
- **YGS Geological Mapping:** data.geology.gov.yk.ca/data-compilations

Hydrometeorological Data

- **Water Survey of Canada:** wateroffice.ec.gc.ca/search/real_time_e.html
- **Yukon Water Data Explorer:** service.yukon.ca/water-data/shiny/?page=home&lang=en
- **Yukon Weather:** weather.service.yukon.ca/weather/
- **Yukon Snow Survey and Water Supply:** yukon.ca/en/science-and-natural-resources/water/snow-surveys-and-water-supply-forecasts
- **ECCC Meteorological Data:** weather.gc.ca/mainmenu/weather_menu_e.html
- **Canadian River Ice Database:** data-donnees.az.ec.gc.ca/data/water/scientificknowledge/canadian-river-ice-database/
- **Canadian Climate Projections:** climatedata.ca
- **International Glacier database:** glims.org/glacierdata/

Yukon Administrative, Land Planning, Transportation, etc.

- **GeoYukon**: mapservices.gov.yk.ca/GeoYukon/

Regulatory

- **DFO Projects Near water:** dfo-mpo.gc.ca/pnw-ppe/index-eng.html

6.3 Relevant Agency Contact Information

Fisheries and Oceans Canada (DFO)
Yukon/Trans-boundary Main Office
100 – 419 Range Road
Whitehorse, Yukon Y1A 3V1
Phone: 867-393-6722 or 1-866-676-6722 (toll-free)
Email: Admin.Whitehorse@dfo-mpo.gc.ca
http://www.pac.dfo-mpo.gc.ca/yukon/default_e.htm

Transport Canada – Navigation Protection Program (Prairie and Northern Region)
1100-9700 Jasper Avenue
Edmonton, AB T5J 4E6
Phone: 780-495-8215
E-mail: NPPPNR-PPNRPN@tc.gc.ca
https://www.tc.gc.ca

Yukon Environmental and Socio-economic Assessment Board Head Office
200-309 Strickland Street
Whitehorse, YT Y1A 2J9
Phone: 867-668-6420 or 1-866-322-4040 (toll-free)
Email: yesab@yesab.ca
http://www.yesab.ca

Yukon Water Board
Suite 106, 419 Range Road
Whitehorse, Yukon Y1A 3V1
Phone: 867-456-3980
Email: ywb@yukonwaterboard.ca
http://www.yukonwaterboard.ca/index.htm

Government of Yukon – Environment, Water Science and Stewardship Branch
Box 2730 (V-310)
Whitehorse, Yukon Y1A 2C6
Phone: 867-667-3171 or Toll Free (in Yukon) 1-800-661-0408 ext. 3171
https://yukon.ca/en/science-and-natural-resources/water

Government of Yukon – Land Management Branch
Box 2703 (K-320)
Whitehorse, Yukon Y1A 2C6
Phone: 867-667-5215
Email: land.use@gov.yk.ca
https://yukon.ca/en/housing-and-property/land-and-property

Government of Yukon – Yukon Geological Survey
300 Main Street
Whitehorse, Yukon Y1A 2B5
Phone: 867-667-8508
Email: geology@yukon.ca
https://yukon.ca/en/places/yukon-geological-survey

7.0 Closure

This guidance document represents a significant step toward establishing a more consistent, practical, and technically informed approach to the assessment and mitigation of riverbank and lakeshore erosion across the Yukon. SLR is grateful for the opportunity to support YG in the development of this resource and to collaborate with the many contributors who provided technical expertise, local knowledge, and review throughout the process.

Given the dynamic nature of Yukon landscapes, evolving climate conditions, and continued advancement in technical understanding and monitoring approaches, this document is intended to serve as a living guidance resource rather than a static reference. Future updates and refinements are anticipated as new information, lessons learned, and emerging practices become available. It is our hope that this guidance will support more proactive, coordinated, and resilient approaches to erosion risk management across the territory.

Regards,

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Appendix A Section-based Plain Language Summary

Lakeshore and Riverbank Erosion in the Yukon

Technical Guidance for Assessment and Risk Mitigation

Government of Yukon

SLR Project No.: 216.030123.00001

May 1, 2026

Section-based Plain Language Summary

How to Use This Summary

This summary report provides a **plain language overview of the guidance document**, following the same general structure as the main report. It is intended to help readers understand the key ideas without needing technical expertise. For readers interested in learning more about any of the topics, this summary report identifies section numbers and figures in the main report where more information is available on each topic.

The guidance is organized as a step-by-step process: first understanding erosion processes, then assessing the problem, and finally selecting and implementing solutions. This overall approach is shown in *Figure 1-1*, which acts as a roadmap for the document. Each step builds on the previous one, and the process is meant to be followed in sequence where possible.

1.0 Introduction – Purpose and Scope

The opening section explains why this guidance was developed and how it is intended to be used. Across the Yukon, erosion has often been addressed after damage occurs, and approaches have not always been consistent. This document supports a more **planned and coordinated approach** to managing erosion risks.

The guide is written for a broad audience, as described in *Section 1.1*, including government staff, First Nations, landowners, and technical professionals. It is not a strict set of rules, but a useful resource that brings together science, experience, and local knowledge.

The scope of the document, outlined in *Section 1.2*, focuses on erosion along riverbanks and lakeshores. Flooding is closely related, but is not the main topic. One of the key ideas introduced early is that erosion problems should not be rushed into solutions—**understanding the cause is an important first step**.

2.0 Erosional Processes in the Yukon – Understanding the Causes

This section provides an overview of the processes that drive erosion in the Yukon and explains why conditions can be complex.

Rivers and lakes are discussed separately in *Sections 2.1 and 2.2*. Along rivers, flowing water is the main cause of erosion, especially during spring melt and major rainstorms. Along lakeshores, wind-driven waves and changes in water levels play a larger role. In both settings,

erosion often begins at the bottom of a bank, removing support and causing the ground above to fall away.

Understanding the role played by ice in erosion in the Yukon is so important that it is described in *Sections 2.1 and 2.2*. During ice breakup, moving ice can push and erode riverbanks and lakeshores. Ice jams can also lead to sudden and severe erosion. **In many cases, ice has a stronger effect than open water alone.**

Permafrost also plays an important role in erosion in the Yukon. Frozen ground can help hold soil in place, but once it thaws, it can weaken quickly. This can lead to more rapid erosion and larger slope failures, particularly where the ground contains a lot of ice. As noted in *Section 2.5*, climate change is expected to warm temperatures and change water conditions. These effects will likely speed up the loss of permafrost from some riverbanks and lakeshores, making it easier for them to erode.

The connection between erosion and slope stability is explained further in *Section 2.3*. When erosion removes material from the base of a slope, the slope above may collapse. This creates a repeating cycle that can gradually move the lakeshore or riverbank over time.

Human activities, described in *Section 2.4*, can also influence erosion. Land clearing, home building, road construction, and erosion protection may increase erosion or shift it to other locations if not carefully planned.

Overall, this section highlights that **erosion is usually caused by several processes acting together**, and these need to be understood as a system.

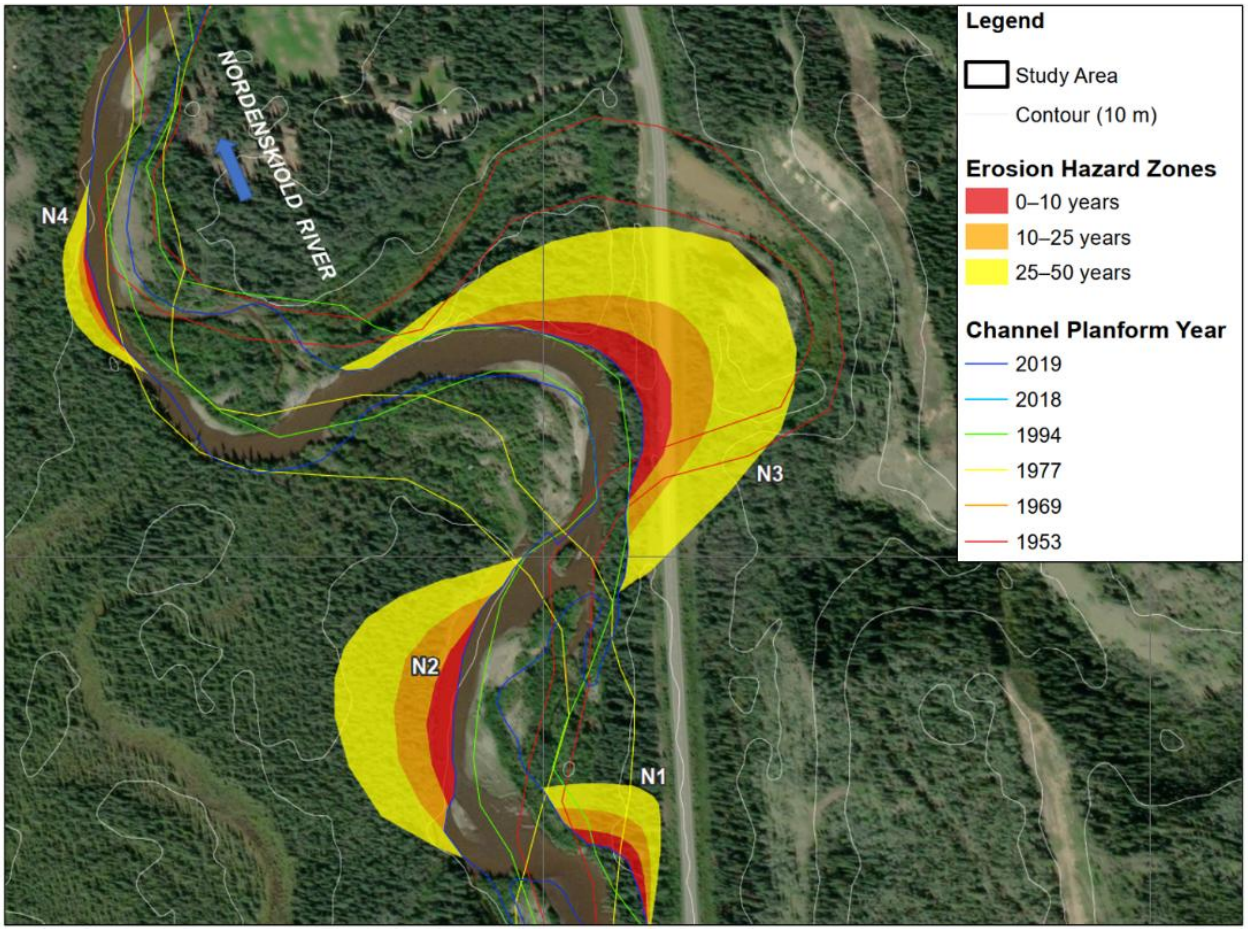
3.0 Assessment of Erosion – Improving Understanding

The next part of the guidance focuses on how to understand an erosion problem before deciding what to do. **Section 3.0** outlines a step-by-step approach addresses the main topics of assessment.

The process begins with project scoping. This involves defining the problem, identifying the area of interest, and sorting out how to learn more about it. This includes considering the broader river or lakeshore system, not just the eroding site, because upstream and downstream conditions may be making conditions worse.

From there, an initial study is typically carried out, as described in *Section 3.4*. This study involves reviewing background information, visiting the site, and drawing on local and Traditional Knowledge. **The goal is to identify the main causes of erosion and understand what is at risk.** The map below shows an example of the movement of the meanders (bends) of a river, based on what is visible from a bird's eye view in air photos from 1953 to 2019, and how this information can help predict the position of the river bends up to 50 years into the future.

Where risks are higher or conditions are more complex, a more detailed level of study may be needed. *Section 3.5* describes this stage, which can include field investigations, surveys, and more computer modelling. This helps predict how erosion may continue in the future and supports the design of measures to reduce risk.



Monitoring, discussed in *Section 3.7*, is an important part of the overall process. Observing how a site changes over time improves understanding and helps confirm whether mitigation measures are working as intended.

A key message from this part of the guidance is that **effective solutions depend on a solid understanding of the problem**. Skipping initial and detailed studies can lead to solutions that are short-lived or that create new problems elsewhere.

4.0 Addressing Erosion-Related Risks – Approaches and Construction

Once the problem is understood, the guidance turns to how erosion risks can be managed. *Section 4.0* describes a range of possible approaches and how to choose the right one for a site.

As outlined in *Section 4.2*, one of the best strategies is to avoid high-risk areas where possible. Moving infrastructure away eroding riverbanks or lakeshores can reduce the need for ongoing protection. Where this is not possible, other approaches may be used to direct water or wave energy elsewhere, harden and stabilize the bank, or protect the bank using vegetation and other natural materials.

Topics to consider when designing erosion control solutions are discussed in *Section 4.3*. Common challenges in the Yukon—such as ice, thawing ground, and limited access to materials—can affect how well a solution performs. It is also important to think about how the riverbank or lakeshore may change over time and to avoid creating new problems in nearby areas.

Emergency Works

Emergency situations are addressed in more detail in *Sections 4.3.4 and 4.4*. These situations arise when there is an **immediate threat to infrastructure, public safety, or access**, such as during floods, ice breakup, or sudden slope failures.

In these cases, action is required quickly to stabilize the area and keep people and structures safe. This may involve placing rock, building temporary barriers, or redirecting flow. These works are often carried out urgently with little to no information on site conditions.

For this reason, emergency works are **generally temporary measures**. While they help in the short term, they are not usually designed to last. If left in place without follow-up, they may fail or cause erosion to shift to other areas.

The guidance makes it clear that emergency works should be followed by a proper study and a longer-term solution. Even during urgent situations, it is important to consider environmental impacts and how the temporary work will connect to future improvements. Ultimately, emergency stabilization is a stopgap measure toward long-term resilience, not a substitute for a final engineered design

Construction and Long-Term Performance

The success of any mitigation measure depends not only on its design, but also on how it is built. *Section 4.4* describes important topics to be addressed before construction, including the challenges of working in remote areas and within short construction seasons.

After construction, monitoring and maintenance are needed to ensure that the work continues to perform as intended. *Section 4.5* highlights the importance of follow-up actions. *Section 4.6* outlines common reasons for failure, such as not extending the mitigation measure far enough upstream and downstream, not installing it properly, or not accounting for key processes like ice impact or thawing ground.

This part of the guidance emphasizes that **long-term performance depends on good design, careful construction, and ongoing attention**.

5.0 Regulatory Context and Coordination

Erosion mitigation projects often involve multiple organizations and approval processes. *Section 5.0* provides an overview of this regulatory context.

Coordination is especially important. As described in *Section 5.3*, engaging with regulators, First Nations, and stakeholders early in the process can provide opportunities to gain local and Traditional Knowledge, reduce delays, and help improve project outcomes.

This section highlights that erosion management is not only a technical task, but also one that requires **clear communication and working together**.

6.0 Resources

The final section of the guidance document provides supporting resources, including full report references, data sources, and contact information for key groups. These materials can help users build on the approaches described in the document and support future work.

Appendix B Glossary

Lakeshore and Riverbank Erosion in the Yukon

Technical Guidance for Assessment and Risk Mitigation

Government of Yukon

SLR Project No.: 216.030123.00001

May 1, 2026

Glossary

Active layer: The top layer of ground above permafrost that is subject to annual freezing and thawing. Its thickness and stability strongly influence the susceptibility of northern riverbanks and lake shorelines to seasonal erosion and mass movement.

Aggradation: The geologic process by which streambeds or floodplains are raised in elevation due to the deposition of sediment. This process can alter hydraulic capacity and direct erosive flows toward adjacent banks or induce an avulsion.

Alluvial fan: A fan-shaped landform created by the deposition of sediment where a tributary stream's gradient or confinement decreases, commonly at a valley bottom.

Anchor ice: Ice that forms and attaches directly to the bed of a watercourse in supercooled, turbulent water. Its formation and sudden release can significantly alter channel hydraulics and pluck sediment from the riverbed.

Annual exceedance probability (AEP): The probability that a flow or flood event will exceed a particular magnitude at a specific location in any given year. This metric is frequently used by hydrotechnical engineers to determine the design flood for sizing erosion mitigation structures.

Annual high watermark: The annual highwater mark (or ordinary highwater mark) is the highest water level reached by a waterbody during a typical year. It is defined as the elevation where water sits or flows long enough to leave visible evidence on the landscape, such as scour marks, debris deposits, changes in soil characteristics, or a distinct transition from aquatic to terrestrial vegetation. In the Yukon, this mark serves as a critical regulatory threshold, as works situated within or below the annual high watermark face significantly more rigorous permitting pathways.

Assessment: The diagnostic phase involving the gathering and analysis of data to understand the underlying causes, mechanisms, trajectories and rates of erosion. Assessment is required to inform the selection and design of effective mitigation measures.

Aufeis (icings): The incremental surface accumulation of ice formed by successive freezing of overflow layers, commonly at sites of braided channels, groundwater discharge, or culverts. Aufeis can obstruct natural drainage, forcing water over banks or roads and causing severe localized erosion.

Avulsion: An abrupt change in the planform of a river or creek where the watercourse breaks through its banks to form a new channel, commonly cutting across a meander loop.

Bankfull discharge: The flow rate at which a stream first overflows its natural banks and spills onto the adjacent floodplain. This flow, sometimes termed ‘formative flow’, represents the channel-forming discharge that frequently exerts the highest geomorphic work. Along channels that have become entrenched (deepened relative to their floodplain), bankfull stage may be considerably lower than the physical tops of bank.

Bathymetry: The underwater topographic mapping of a waterbody's floor or bed. Accurate bathymetry is crucial for modeling nearshore wave dynamics and designing the embedded toe of a riverbank or lake shoreline structure.

Bedload transport: Sediment such as sand, gravel, or cobbles that moves along the streambed by jumping, rolling, or sliding. Understanding bedload transport is vital for evaluating channel scour and long-term channel stability.

Bioengineering: The use of live plants and biodegradable materials to provide structural support and erosion control.

Border ice: Ice that forms and remains attached along the bank of a river or shore of a lake. Although it can temporarily protect banks from winter flows, its breakup can mechanically scour the shoreline.

Channel migration: The lateral and/or down-valley shifting of a river channel across its floodplain over time. Predicting migration rates based on documented historical trends is a core component of delineating erosion hazard limits and designing setbacks.

Computer-aided design (CAD): Software used by engineers to create precision drawings, plans, and cross-sections for construction projects. CAD is routinely used to map surveyed hazard limits and detail the structural components of erosion mitigation works.

Confined setting: A stream system located in a corridor where high valley walls or terraces restrict lateral channel movement. In confined systems, erosion assessments must heavily account for toe scour leading to geotechnical slope failure.

Debris flow: A fast-moving, channelized landslide comprising a saturated, slurry-like mixture of water, sediment, and organic debris. Debris flows exert extreme impact forces and can rapidly destabilize rivers or lakeshores they enter.

Degradation: A progressive lowering or downcutting of the channel bed and floodplain over time. It typically occurs when the river's sediment transport capacity exceeds its sediment supply.

Deposition: The process by which previously eroded sediments are dropped or settled out of moving water due to a decrease in hydraulic energy.

Design: The engineering phase where assessment data are used to develop specific plans, material sizing, and cross-sections for mitigating an identified erosion hazard. Proper design ensures structures withstand predicted wave, ice, and hydraulic forces over their intended service life.

Dewatering: The process of pumping or removing water from an isolated work area to allow for construction "in the dry." It is a common practice for environmental protection during the installation of in-stream erosion mitigation works.

Digital elevation model (DEM): A high-resolution, 3D digital raster representing the topography of a landscape. DEMs are widely used in geographic information systems to analyze slope gradients, watershed boundaries, and erosion susceptibility.

Direct mitigation: Structural engineering interventions applied directly to an eroding riverbank or lake shoreline, such as rock revetments or bioengineering works. These measures are designed to immediately halt active scour.

Downdrift: Located in the direction of the net longshore transport of sediment along a lake shoreline. Armouring a shoreline can often transfer erosional energy or starve sediment supply to unprotected downdrift properties.

Drawdown: The natural or artificial lowering of water levels in a lake or reservoir. Prolonged drawdown can expose vulnerable, fine-grained lower shoreline elevations to concentrated wave action and erosion.

Embedment: The depth to which the base (toe) of an erosion protection structure is buried below the channel bed or lake shoreline. Proper embedment below the maximum predicted scour depth is crucial to prevent the structure from being undermined and collapsing.

Entrainment: The initial lifting and mobilization of sediment particles by the shear stress of flowing water or wave action. Calculating the threshold for entrainment helps engineers appropriately size rock armouring for a specific site.

Erosion: The physical process by which land is worn away by the action of water, ice, wind, gravity and/or anthropogenic disturbance.

Fetch: The unobstructed open water distance over which wind can blow to generate waves. Fetch length is a primary variable used to calculate wave heights and determine the required robustness of lakeshore protection.

Fluvial: Pertaining to the processes, flows, and landforms associated with rivers and streams. Practically, fluvial is synonymous with alluvial. Fluvial geomorphology studies how these flowing waters erode, transport, and deposit sediment, along with their load of ice and/or woody debris, to shape the landscape.

Floodplain: The relatively flat land adjacent to a watercourse or waterbody that is naturally subject to periodic inundation during high flows/levels. Allowing high flows/levels to safely access the floodplains dissipates hydraulic energy and reduces erosive stress on riverbanks and lake shorelines.

Flow: The volume of water passing a specific point in a watercourse over a given time, typically measured in cubic metres per second. High flows during storms or freshet drive the hydraulic shear stresses responsible for bank erosion.

Flow regulation: The artificial alteration of natural water levels and discharge regimes, typically via hydroelectric dams or storage reservoirs. Regulated flows can exacerbate erosion by starving downstream reaches of sediment, artificially extending high-water periods, or releasing high flows more frequently (e.g. hydro-peaking).

Frazil ice: Fine, needle-like ice crystals suspended in turbulent, supercooled water. Frazil ice can agglomerate to form blockages or hanging dams that dramatically alter local hydraulics and promote severe bank scour.

Freshet: The period of high river flow resulting from widespread snow and ice melt in the spring. Freshet is a critical period for riverbank erosion due to the combination of peak discharges and dynamic river ice movement.

Gabion: A rectangular wire mesh basket filled with small rocks to simulate the effect of larger rock, used modularly to construct retaining walls and erosion protection structures. While cost-effective, gabions can be vulnerable to severe damage from ice forces in northern environments.

Geotextile: A permeable synthetic fabric placed beneath rock armouring to inhibit the loss of underlying fine native soils by water movement (piping). If used improperly on steep banks, geotextiles can create a smooth slip plane that causes the overlying rock to slide.

Geographic information system (GIS): A computer-based framework used for mapping, managing, and analyzing spatial data. GIS is essential for delineating erosion hazard limits by overlaying historical imagery, topography, and infrastructure locations.

Geomorphology: The scientific study of landforms and the physical processes—such as water, wind, gravity, and ice—that shape them. Understanding fluvial and coastal geomorphology is fundamental to diagnosing the root causes of shoreline erosion.

Geotechnical: A branch of civil engineering concerned with the engineering behaviour of earth materials, including soil and rock mechanics. Geotechnical assessments are required to evaluate slope stability and design the foundations of heavy erosion control or slope-stabilization structures.

Ground Ice: A general term for all types of ice contained within freezing or frozen ground, including pore ice and massive ice wedges. The thawing of ground ice drastically reduces soil strength and accelerates riverbank and lake shoreline subsidence and erosion.

Hazard: A potentially damaging physical event or phenomenon with the potential to adversely affect private or territorial holdings, compromise public infrastructure or safety, or cause environmental damage.

Hazard maps: Spatial representations that delineate areas susceptible to a hydrogeomorphic (e.g., flooding or erosion) over a specified timeframe. These maps are critical planning tools used to establish safe development setbacks from dynamic water bodies.

Hydraulics: The study of the mechanical properties and behaviour of moving water, focusing on variables like velocity, depth, and shear stress. Hydraulic analysis dictates the size and type of materials needed to withstand erosive forces.

Hydrodynamic: Pertaining to the forces exerted by moving water, particularly the complex interactions of waves, currents, and water levels in rivers, lakes and estuaries.

Hydrogeology: The study of the distribution, flow, and quality of groundwater beneath the surface. Hydrogeological conditions, such as groundwater seepage from a bank, can internally weaken soils and trigger slope failures independent of surface water erosion.

Hydrogeomorphic: An integrated term describing the interacting hydrological and geomorphological processes that modify landforms. Typical hydrogeomorphic hazards include clearwater floods, debris floods, and channel-altering debris flows.

Hydrology: The science dealing with the occurrence, circulation, distribution, and properties of Earth's waters. Hydrological assessments determine the frequency and magnitude of peak discharges and peak water levels that drive erosion.

Ice breakup: The seasonal period when solid river or lake ice fractures and begins to move. Dynamic breakup events can produce severe mechanical gouging and shoving forces that rapidly erode shorelines and dismantle erosion mitigation structures.

Ice jam: A stationary accumulation of fragmented ice that partially or fully blocks a river channel or lake outlet. Ice jams cause rapid upstream backwatering and force highly erosive, high-velocity flows into adjacent floodplains and banks.

Ice ride-up: The process where an intact sheet of lake ice is pushed by wind or currents up onto a sloping shoreline. This mechanical force can physically strip away protective vegetation and damage shoreline infrastructure.

Ice run: The downstream flow of fragmented ice, slush, or frazil following river breakup. Heavy ice runs act as an abrasive slurry, scouring riverbanks and testing the durability of shoreline protection works.

Ice shove: The onshore buckling and pushing of fragmented ice driven by wind, currents, or thermal expansion. Ice shoves exert immense mechanical pressure against shorelines, easily displacing undersized riprap or natural bank materials.

Ice-rich permafrost: Permanently frozen ground containing a volume of ice that at least exceeds the natural pore space of the soil ("excess ice"). When exposed to warming air or water, ice-rich terrain is highly susceptible to rapid thermal degradation, thaw flows (slumping), and erosion.

Indirect mitigation: Management strategies that address erosion risks without building hard structures at the site of impact. Examples of indirect mitigation include flow deflectors, channel realignments, or energy dissipation weirs. These approaches commonly prioritize working with natural processes rather than fighting them.

Inspection: The systematic, often periodic, visual and physical evaluation of a riverbank or lake shoreline or an associated erosion mitigation structure to assess its condition and performance. Post-flood inspections are critical to identify undermined toe protection or displaced rocks before total failure occurs.

Inundation: The temporary covering of normally dry land by water, typically due to high river flows, storm surges, or ice jams. While inundation causes flooding, it is the associated velocity and shear stress of the moving water that drives erosion.

Isolation: A construction technique used to separate an in-water work zone from the flowing watercourse, typically using cofferdams or bypass pumps. This practice minimizes the release of suspended sediments and protects aquatic habitat during the installation of erosion works.

Knickpoint: An abrupt, steep drop in the longitudinal profile of a stream bed, such as a waterfall or active headcut. Knickpoints often migrate upstream, leading to rapid bed degradation and subsequent bank destabilization.

Lacustrine: Pertaining to the environment, sediments, processes, or landforms associated with lakes. Lacustrine shoreline erosion is primarily driven by wind-generated waves and fluctuating water levels rather than unidirectional flow.

Lakeshore: The dynamic physical boundary where land meets a lake. Lakeshores are subject to unique erosional forces, including wave uprush, littoral sediment transport, and ice ride-up. In this guide, the term "lakeshore" is used more or less synonymously with "lake shoreline" to describe these lacustrine environments

Light detection and ranging (LiDAR): A remote sensing technology that uses pulsed laser light from aircraft or drones to generate highly accurate, 3D bare-earth elevation models. LiDAR is invaluable for mapping complex topography, identifying old landslide scars, and quantifying bank retreat.

Littoral processes: The combined physical interactions of waves, currents, wind, and sediment supply within the nearshore zone of a lake. These processes dictate whether a shoreline will experience net erosion, stability, or deposition.

Longshore transport: The movement of sand and gravel parallel to the shoreline, driven by waves approaching at an angle. Interrupting longshore transport with poorly designed structures can starve downdrift beaches and accelerate their erosion.

Mitigation: The implementation of strategies to manage or reduce erosion-related risks. A distinction is made between *mitigating erosion* (physically stopping bank retreat, e.g., structural armouring) and *mitigating risks associated with erosion* (e.g., managed retreat or relocating infrastructure), which addresses the threat from erosion without necessarily stopping erosion itself.

Meander: A distinct, sinuous curve or loop in a river's course that usually naturally migrates across the valley floor over time. Erosion is typically concentrated on the outer bank of a meander due to higher flow velocities and secondary currents.

Meander belt: The lateral corridor across a valley floor that a meandering stream currently occupies or is expected to shift into over time. Delineating a meander belt allowance is a key planning tool to keep infrastructure safely set back from migrating channels.

Monitoring: The systematic, repeated measurement and observation of a site to track geomorphic changes or environmental thresholds, such as bank retreat rates or the functional integrity of a mitigation structure. Reliable monitoring data are essential for practicing adaptive management and timing maintenance efforts.

Nature-based solutions (NbS): Engineering and management approaches that use natural materials—like vegetation, wood, and soil—to stabilize lake shorelines and riverbanks and manage water. NbS aim to mimic natural processes, providing effective erosion control while enhancing local aquatic and riparian habitats.

Orthophoto: An aerial photograph or satellite image that has been geometrically corrected to remove distortion, creating a uniform scale. Orthophotos or georeferenced imagery are essential GIS base layers used to accurately measure historical shoreline positions and calculate erosion rates.

Outflank: An erosional failure mode where a migrating channel or wave action erodes the unprotected native bank immediately behind or beside the ends of a hard structure. To prevent outflanking, mitigation works must be securely keyed into adjacent, stable shoreline reaches.

Peak discharge: The maximum instantaneous volume of water passing a given point on a watercourse during a flood event. Determining the peak discharge is critical for calculating the maximum hydraulic shear stresses that an erosion protection structure must withstand.

Permafrost: Ground consisting of soil or rock that remains at or below 0°C for at least two consecutive years. Permafrost provides structural cohesion to northern riverbanks, but its thaw can trigger rapid and severe geomorphic instability.

Piping: An internal erosion process whereby groundwater flow physically removes fine soil particles from the subsurface, forming hollow, pipe-like conduits along preferential flow paths. Piping undermines a slope from within, commonly leading to collapse even in the absence of high water levels.

Photogrammetry: The science of extracting precise 3D measurements and topographic data from overlapping photographs. It is frequently applied using drone imagery to create detailed surface models for tracking volumetric bank loss over time.

Reach: A defined continuous segment of a river or lakeshore that exhibits relatively homogenous physical characteristics, such as gradient, channel pattern, and bank materials. Reach-scale assessments ensure that localized erosion mitigation does not ignore broader upstream (updrift) or downstream (downdrift) processes.

Real-time kinematic (RTK): A highly precise GPS surveying technique to collect centimeter-precision elevation data. RTK rovers are standard tools for capturing detailed bank profiles, property boundaries, laying out new structures, and as-built dimensions of erosion structures.

Remote sensing: The collection of environmental data from a distance, typically using satellites, aircraft, or drones. Remote sensing techniques are essential for tracking broad-scale geomorphic changes, ice dynamics, and historical riverbank or lake shoreline migration without intensive fieldwork.

Thaw flow (Slump): A retrogressive mass-wasting feature common in permafrost regions, triggered when ice-rich ground is exposed and thaws (thermokarst). The saturated, thawed slurry flows downslope, commonly into a waterbody, causing the steep headwall to incrementally retreat.

Revetment: A protective covering, typically made of angular riprap or boulders, placed directly against a sloping bank to armour it against hydraulic and wave forces. Revetments are designed to absorb energy and halt the lateral retreat of a riverbank or lake shoreline.

Riprap: Graded, angular rock strategically placed along a bank or shoreline to prevent erosion and scour. It is one of the most common materials used in structural erosion mitigation.

Risk: The probability of harmful consequences or expected losses resulting from interactions between natural or human-induced hazards and vulnerable conditions.

Riverbank: The defined, sloping terrain alongside the bed of a flowing watercourse that contains the water during normal levels. The stability of a riverbank is dictated by the balance between the resisting strength of its soils and the erosive forces of the river.

Scour: The localized, aggressive removal of underwater sediment by the hydrodynamic forces of flowing water or waves. Scour frequently targets the outside of river bends and the base of protective structures, making deep embedment of toe materials critical to prevent failure.

Sediment transport: The process by which water, wind, gravity, or ice entrains and moves solid particles from one location to another. Interruptions to natural sediment transport, such as dams or extensive bank armoring, can starve downstream or downdrift areas and induce aggressive clearwater erosion.

Shoreline: The dynamic boundary where land interfaces with a lake lake. Shorelines are constantly reshaped by the interacting forces of water-level fluctuations, wind-driven waves, and ice dynamics. In this guide, the term “shoreline” is used more or less synonymously with “lake lakeshore” to describe lacustrine environments

Sloughing: The relatively shallow, episodic sliding or ravelling of saturated or oversteepened soil down a bank face. While less catastrophic than deep-seated landslides, recurrent sloughing removes the vegetative root mat and prevents long-term bank stabilization.

Stone sizing: The critical engineering process of calculating the required mass and dimensions of rock needed to remain stable under specific hydraulic or wave conditions. Undersized stone is a primary cause of revetment failure, as it is easily mobilized by flood currents or ice impacts.

Suspended sediment: Fine-grained particles, typically silt and clay, that are carried within the water column by the upward components of turbulent flow. High concentrations of suspended sediment increase water turbidity and are commonly an indicator of active upstream bank erosion or mass wasting.

Talik: A layer or body of perennially (year-round) unfrozen ground located within permafrost areas, typically situated between the active layer and underlying permafrost. Taliks commonly exist directly beneath large lakes or deep rivers. The presence and expansion of a talik heavily influence local hydrogeology and the vulnerability of riverbanks or lake shorelines to instability.

Thalweg: An imaginary line connecting the deepest points along a stream channel's bed, usually corresponding to the zone of highest flow velocity and tractive force.

Thermokarst: A landscape characterized by irregular, hummocky topography and depressions formed by differential subsidence of thawing, ice-rich permafrost. Thermokarst processes along a riverbank or lake shoreline can dramatically accelerate bank retreat and complicate the design and installation of erosion mitigation.

Toe erosion: The hydraulic removal of supporting material at the very base, or toe, of a slope or bluff. Because it removes foundational support, toe erosion is the primary catalyst for massive, gravity-driven slope failures higher up the bank. In banks underlain by permafrost, toe erosion can also expose ice-rich ground and initiate active-layer detachments and retrogressive thaw flows (slumps).

Tsunami: A massive, destructive wave triggered by the sudden displacement of a large volume of water. While commonly oceanic, tsunamis in northern lakes and rivers can be generated by massive rockfalls or landslides crashing into the water, causing catastrophic shoreline or riverbank scouring.

Unconfined setting: A river system situated within a broad, flat valley or plain without restrictive valley walls, allowing it to freely meander and migrate laterally over time.

Unmanned aerial vehicle (UAV): A remotely piloted aircraft, or drone, frequently used to efficiently gather high-resolution aerial imagery and topographic models of riverbanks and lake shorelines. UAVs have revolutionized the ability to conduct rapid, detailed geomorphic monitoring and post-flood erosion inspections.

Updrift: Located in the direction from which the net longshore transport of sediment and wave energy is arriving. Updrift features, such as feeder bluffs, provide the essential sediment supply needed to maintain the stability of downdrift beaches and shorelines.

Valley wall: The well-defined slope that laterally borders a river valley, confining the maximum extent of the floodplain and the river's ability to migrate. When a meandering river contacts a valley wall, it can trigger landslides or other geotechnical instabilities.

Wave run-up: The maximum vertical height above the still-water level that a breaking wave rushes up the face of a beach, bank, or protective structure. Accurately calculating wave run-up is essential for determining the necessary crest height of a revetment to prevent overtopping and erosion behind the structure.

Woody debris: Pieces of dead wood, such as fallen branches and trees and root wads, that naturally enter and accumulate within a watercourse. While it provides critical aquatic habitat and helps dissipate flow energy, excessive woody debris can also deflect erosive currents directly into vulnerable banks.

Appendix C Erosion Mitigation Design ‘Typicals’

Lakeshore and Riverbank Erosion in the Yukon

Technical Guidance for Assessment and Risk Mitigation

Government of Yukon

SLR Project No.: 216.030123.00001

May 1, 2026

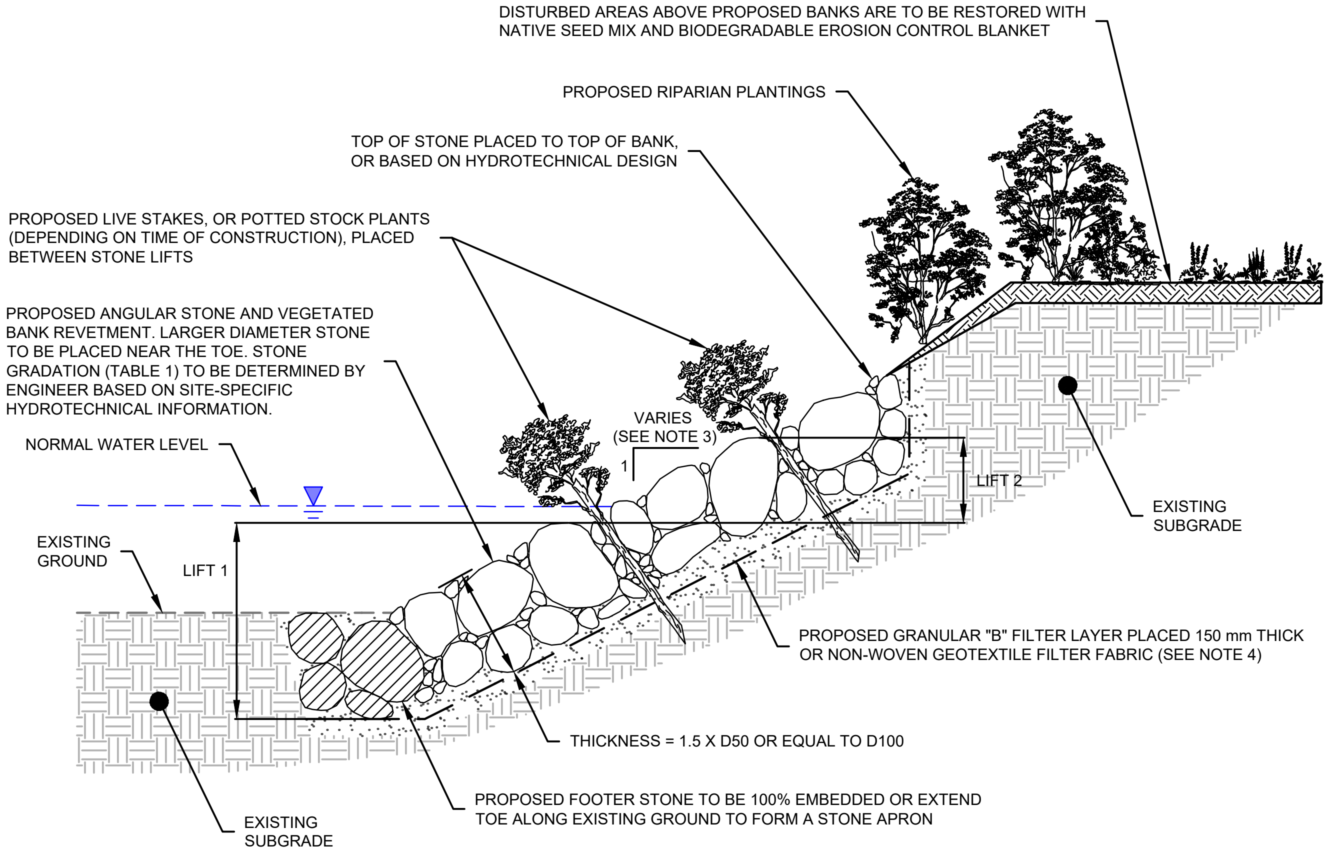


TABLE 1: APPROXIMATE AVERAGE DIMENSION OF YUKON CLASS I, II, AND III - NOMINAL DIAMETER. ROCK CLASS TO BE DETERMINED BY ENGINEER BASED ON SITE-SPECIFIC HYDROTECHNICAL DESIGN.

YUKON CLASS I	NOMINAL SIZE	DIAMTER (mm)	MASS (kg)
		300	40
	ALLOWABLE LOCAL STREAM VELOCITY	≤ 3.0 m/s	
	GRADATION SPECIFICATION	100% SMALLER THAN 450 mm / 130 kg	
		AT LEAST 20% LARGER THAN 350 mm / 70 kg	
		AT LEAST 50% LARGER THAN 300 mm / 40 kg	
		AT LEAST 80% LARGER THAN 200 mm / 10 kg	
YUKON CLASS II	NOMINAL SIZE	DIAMTER (mm)	MASS (kg)
		500	200
	ALLOWABLE LOCAL STREAM VELOCITY	≤ 4.0 m/s	
	GRADATION SPECIFICATION	100% SMALLER THAN 800 mm / 700 kg	
		AT LEAST 20% LARGER THAN 600 mm / 300 kg	
		AT LEAST 50% LARGER THAN 500 mm / 200 kg	
		AT LEAST 80% LARGER THAN 300 mm / 40 kg	
YUKON CLASS III	NOMINAL SIZE	DIAMTER (mm)	MASS (kg)
		800	700
	ALLOWABLE LOCAL STREAM VELOCITY	≤ 4.7 m/s	
	GRADATION SPECIFICATION	100% SMALLER THAN 1,200 mm / 2,300 kg	
		AT LEAST 20% LARGER THAN 900 mm / 1,100 kg	
		AT LEAST 50% LARGER THAN 800 mm / 700 kg	
		AT LEAST 80% LARGER THAN 500 mm / 200 kg	

*TABLE 1 COMPILED FROM GOVERNMENT OF YUKON GENERAL STANDARD SPECIFICATIONS, SECTION 06052 - RIPRAP HAUL AND PLACE, DATED APRIL, 2021.

NOTES

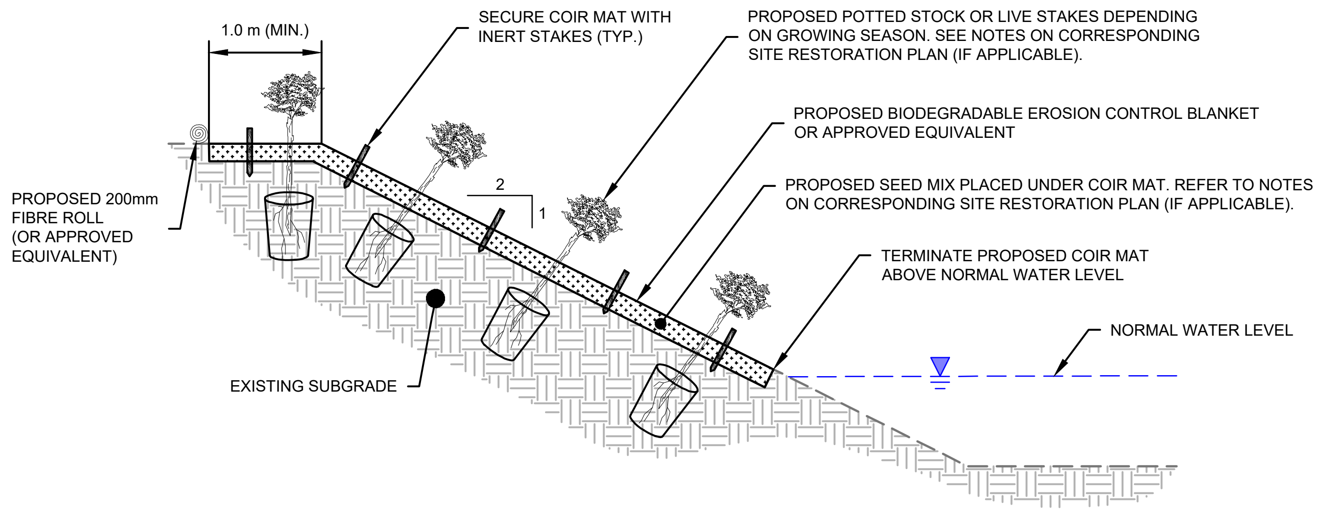
1. VEGETATED BUTTRESS TO BE INSTALLED IN LIFTS.
2. NUMBER OF LIFTS DEPENDENT ON BANK HEIGHT, SLOPE AND STONE SIZE.
3. REVETMENT SLOPE SHALL BE NO STEEPER THAN 1.5H:1.0V.
4. GRANULAR "B" FILTER LAYER PLACED A MINIMUM OF 150 mm THICK OR NON-WOVEN GEOTEXTILE FILTER FABRIC TO BE PLACE UNDER REVETMENT STONE. GRANULAR FILTER IS PREFERRED IF PLANTINGS ARE PROPOSED.
5. FOOTER STONE TO BE 100% EMBEDDED INTO CHANNEL BED. IF EMBEDDING THE FOOTER STONES IS NOT FEASIBLE, THE TOE SHOULD BE EXTENDED ALONG THE RIVER BED TO FORM AN APRON.
6. PLANTS TO BE INSTALLED ONE METRE APART HORIZONTALLY IN EACH LAYER. SPECIES ARRANGEMENT TO BE RANDOM. PLANT PLACEMENT SHALL BE STAGGERED SUCH THAT THEY ARE NOT VERTICALLY ALIGNED.
7. INTEGRATE NATIVE MATERIAL AND TOPSOIL BETWEEN LIFTS WHERE LIVE STAKES OR POTTED STOCK PLANTS ARE INSTALLED. ROOTS TO BE IN FULL CONTACT WITH SOIL MATRIX.

Yukon

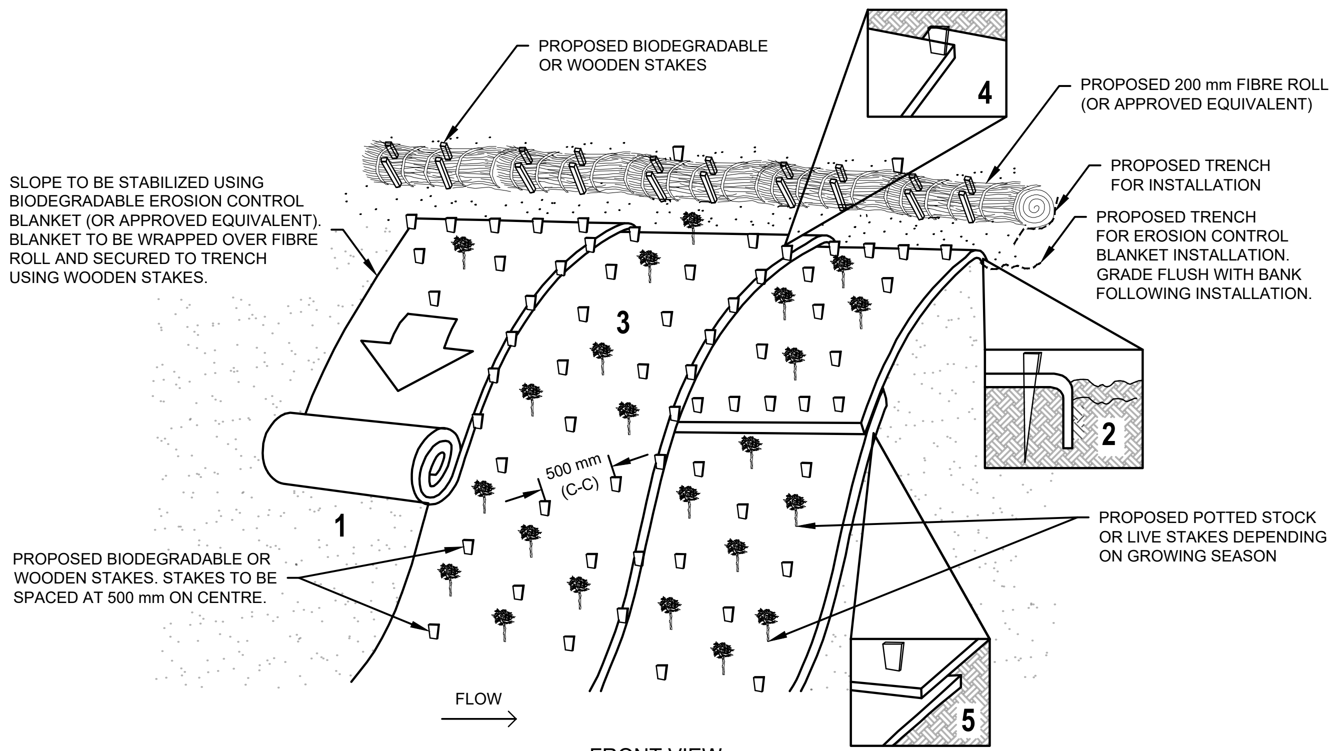
EROSION MITIGATION DESIGN DETAIL #1

VEGETATED COBBLE/BOULDER REVETMENT WITH GRANULAR FILTER OR NON-WOVEN GEOTEXTILE FILTER FABRIC

Erosion Detail #:	1
Designed by:	MO
Drawn by:	TR
Date:	MAY 2026
Scale:	N.T.S.
Drawing:	SLR 2026 - 1



SECTION VIEW



FRONT VIEW

INSTALLATION NOTES:

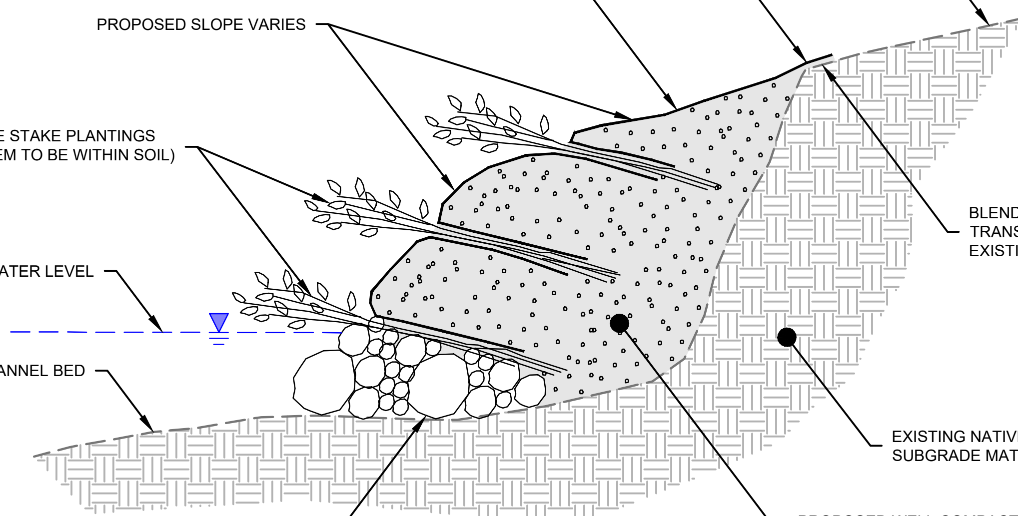
1. PREPARE SOIL BEFORE INSTALLING BLANKETS, INCLUDING APPLICATION OF TERRASEED SLURRY WITH SPECIFIED SEED MIX.
2. BEGIN AT THE TOP OF THE SLOPE BY ANCHORING THE BLANKET IN 150 mm DEEP BY 150 mm WIDE TRENCH. BACKFILL AND COMPACT THE TRENCH AFTER SECURING. TRENCH TO BE GRADED FLUSH WITH BANK AFTER BURYING AND STAKING.
3. ROLL THE BLANKETS DOWN THE SLOPE.
4. THE EDGES OF PARALLEL BLANKETS MUST BE SECURED USING BIODEGRADABLE STAKES OR WOODEN STAKES WITH APPROXIMATELY 50 mm OVERLAP.
5. WHEN BLANKETS MUST BE SPLICED DOWN THE SLOPE, PLACE BLANKETS END OVER END (SHINGLE STYLE) WITH APPROXIMATELY 100 mm OVERLAP. STAKE THROUGH OVERLAPPED AREA APPROXIMATELY 50 mm APART.
6. STAKES TO BE SPACED AT 500 mm ON CENTRE.
7. REFER TO CORRESPONDING SITE RESTORATION PLAN (IF APPLICABLE) FOR PLANT AND SEEDING SPECIES.

Yukon

EROSION MITIGATION DESIGN DETAIL #2

VEGETATED BANK WITH ROLLED EROSION CONTROL PRODUCTS

Erosion Detail #:	2
Designed by:	MO
Drawn by:	TR
Date:	MAY 2026
Scale:	N.T.S.
Drawing:	SLR 2026 - 2



NOTES

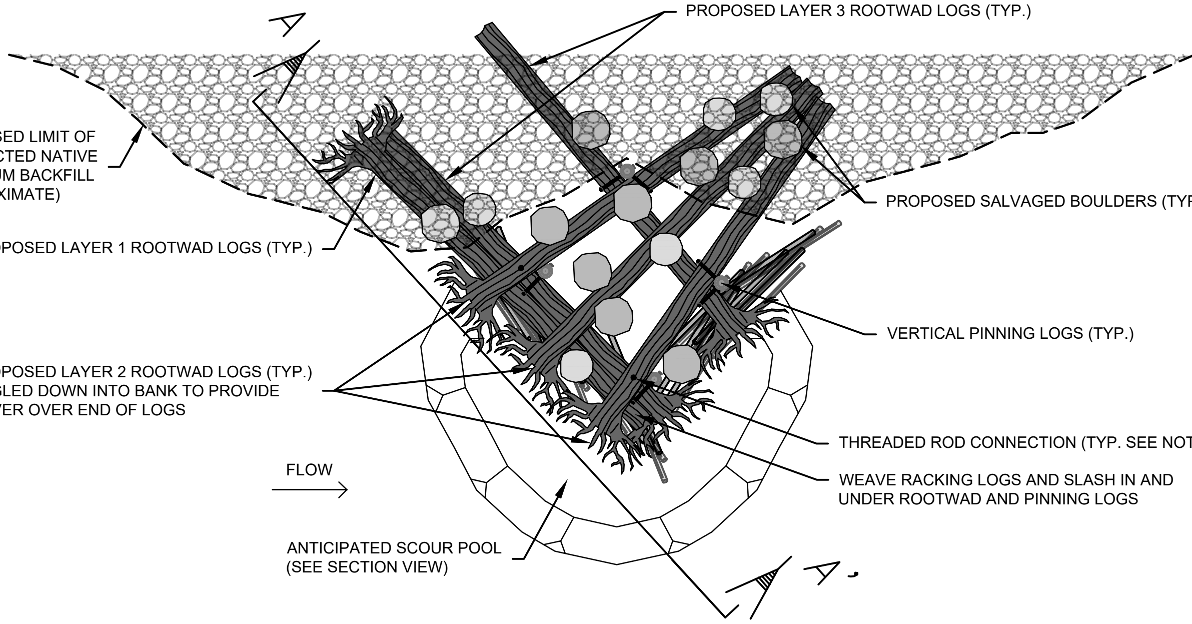
1. BIOENGINEERING TECHNIQUE FOR APPLICATION ON LOW ENERGY STREAM BANKS.
2. VEGETATED BUTTRESS TO BE INSTALLED IN LIFTS.
3. NUMBER OF LIFTS DEPENDENT ON BANK HEIGHT, SLOPE AND STONE SIZE.
4. FOOTER STONE TO BE 100% EMBEDDED INTO CHANNEL BED. IF EMBEDDING THE FOOTER STONES IS NOT FEASIBLE, THE TOE SHOULD BE EXTENDED ALONG THE RIVER BED TO FORM AN APRON.
5. PLANTS TO BE INSTALLED ONE METRE APART HORIZONTALLY IN EACH LAYER. SPECIES ARRANGEMENT TO BE RANDOM. PLANT PLACEMENT SHALL BE STAGGERED SUCH THAT PLANTINGS ARE NOT VERTICALLY ALIGNED.
6. INTEGRATE NATIVE MATERIAL AND TOPSOIL BETWEEN LIFTS WHERE LIVE STAKES OR WHIPS ARE INSTALLED. ROOTS TO BE IN FULL CONTACT WITH SOIL MATRIX.

Yukon

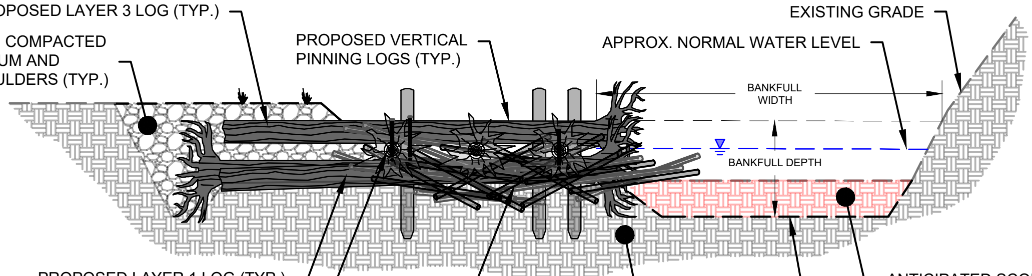
EROSION MITIGATION DESIGN DETAIL #3

VEGETATED (BRUSH) LAYERING

Erosion Detail #:	3
Designed by:	MO
Drawn by:	TR
Date:	MAY 2026
Scale:	N.T.S.
Drawing:	SLR 2026 - 3



PLAN VIEW



SECTION A-A'
N.T.S.

LOG SCHEDULE				
LAYER	SIZE (DBH)	MIN LENGTH (m)	ROOTWAD	QUANTITY (EA.)
1	*TBD	*TBD	YES	1
2	*TBD	*TBD	YES	3
3	*TBD	*TBD	YES	2
PINNING	*TBD	*TBD	NO	4
RACKING	*TBD	*TBD	OPTIONAL	20
SLASH (m^3)	*TBD	*TBD	-	10
LARGE BOULDERS	*TBD	-	-	15

*STRUCTURE DIMENSIONS, LOGS, RACKING, SLASH AND BOULDER SIZING TO BE DETERMINED BY ENGINEER BASED ON SITE-SPECIFIC HYDROTECHNICAL INFORMATION AND MATERIAL AVAILABILITY.

WOOD DEFLECTOR NOTES:

FIELD FIT AND ADJUST AS REQUIRED TO ACCOMMODATE EXISTING CONDITIONS, AS DIRECTED BY DESIGN ENGINEER ON SITE.

PURPOSE:

- REDIRECT HIGH FLOWS AWAY FROM BANKS.
- CREATE SCOUR POOLS TO ENHANCE FISH HABITAT.
- PROVIDE COVER AND SHADE.

DESIGN SPECIFICS:

1. RACKING LOGS AND SLASH MUST HAVE IRREGULAR AND NATURAL APPEARANCE AND NOT BE STACKED.
2. BACKFILL WITH COMPACTED NATIVE ALLUVIUM AND SALVAGED BOULDERS.
3. PINNING LOGS MUST BE INSTALLED IN A MANNER THAT DOES NOT DISTURB THE SURROUNDING SOIL. AFTER STRUCTURE BACKFILL, TOPS OF PINNING LOGS MUST BE BROKEN OFF TO NO MORE THAN 600 mm ABOVE FINISH GRADE.
4. RODS MUST BE 1-INCH DIAMETER MINIMUM FULLY THREADED STEEL RODS (ASTM A193, GRADE B7) WITH STEEL NUTS (ASTM A194, GRADE 2H) AND 4-INCH WASHERS (ASTM F436) ON EACH END. VISIBLE PORTIONS OF HARDWARE MUST BE GREY OR OTHER APPROVED NEUTRAL COLOUR. RODS MUST BE FLUSH CUT AT THE NUTS AND SHARP EDGES GROUND FLUSH.

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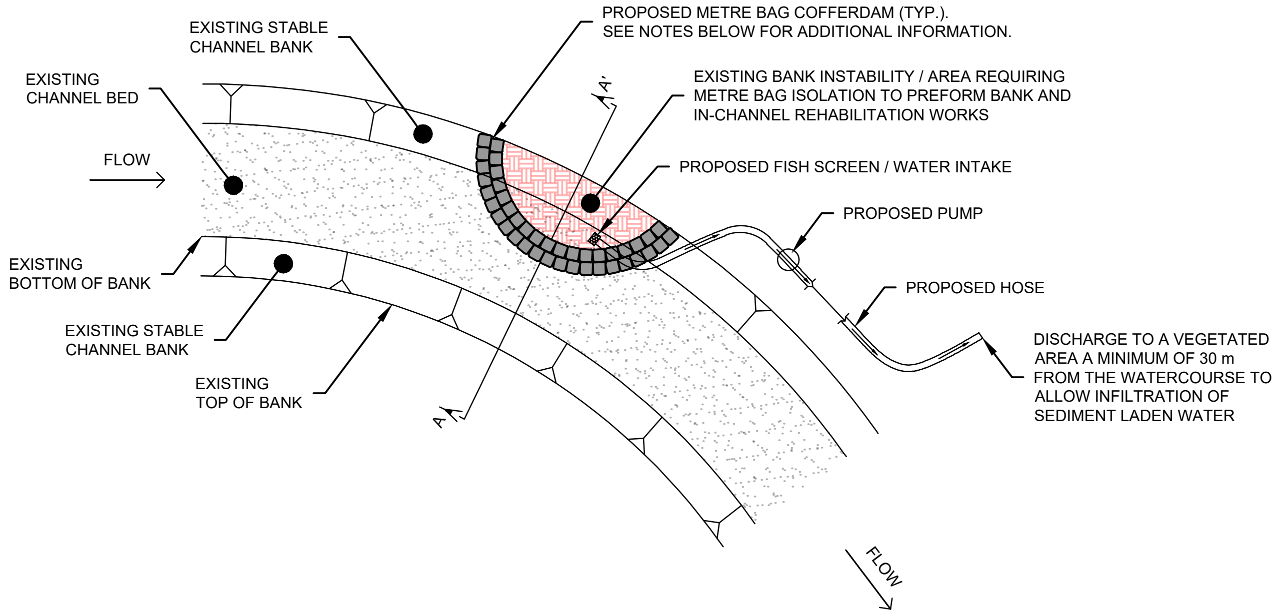
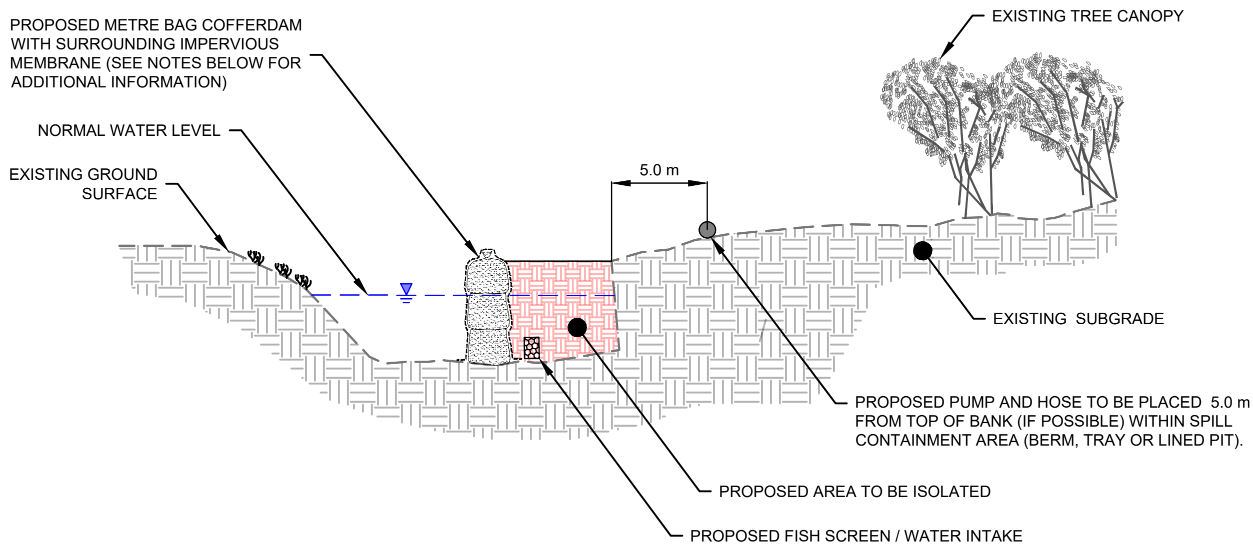
EROSION MITIGATION DESIGN DETAIL #4

WOOD DEFLECTOR

Erosion Detail #:	4
Designed by:	MO
Drawn by:	TR
Date:	MAY 2026
Scale:	N.T.S.
Drawing:	SLR 2026 - 4



PLAN VIEW



SECTION A-A'
N.T.S.

NOTES

1. METRE BAGS TO BE FILLED WITH PEA GRAVEL, SAND, OR OTHER AVAILABLE CLEAR STONE.
2. HEIGHT OF METRE BAG ISOLATION COFFERDAMS SHALL MATCH THE 2-YEAR WATER SURFACE ELEVATION, AS DEFINED BY SITE-SPECIFIC HYDROTECHNICAL INFORMATION.
3. IMPERVIOUS MEMBRANE SHALL COVER THE METRE BAGS TO LIMIT WATER ENTRY INTO WORK AREA.
4. FISH SALVAGE OF ISOLATED AREA TO BE COMPLETED BY A QUALIFIED PROFESSIONAL PRIOR TO DEWATERING FOR INITIATION OF IN-WATER WORK.
5. PUMPING CAPACITY TO BE A MINIMUM OF 1,000 L/s. SITE-SPECIFIC PUMPING REQUIREMENTS TO BE SPECIFIED BY THE ENGINEER.
6. SCREEN TO BE INSTALLED IN ACCORDANCE WITH DFO GUIDELINES.
7. PUMPED WATER SHALL BE DISCHARGED TO A VEGETATED AREA A MINIMUM OF 30 m AWAY FROM WATERWAY, PREFERABLY NOT WHERE THICK MOSS MAY BE INSULATING UNDERLYING PERMAFROST. SITE-SPECIFIC ATTENTION SHALL BE REQUIRED BY THE CONTRACTOR TO ENSURE FLOW DISSIPATION AND PROVIDE EROSION MITIGATION FROM DISCHARGING WATER.
8. THE CONTRACTOR SHALL MONITOR THE WEATHER FORECAST AND WILL HALT WORK TO STABILIZE THE SITE IN THE EVENT OF A STORM EVENT (>20 mm OF RAIN OVER 24 HOURS), OR IF IT IS ANTICIPATED THAT FLOWS WILL OVERTOP THE ISOLATED WORK AREA.

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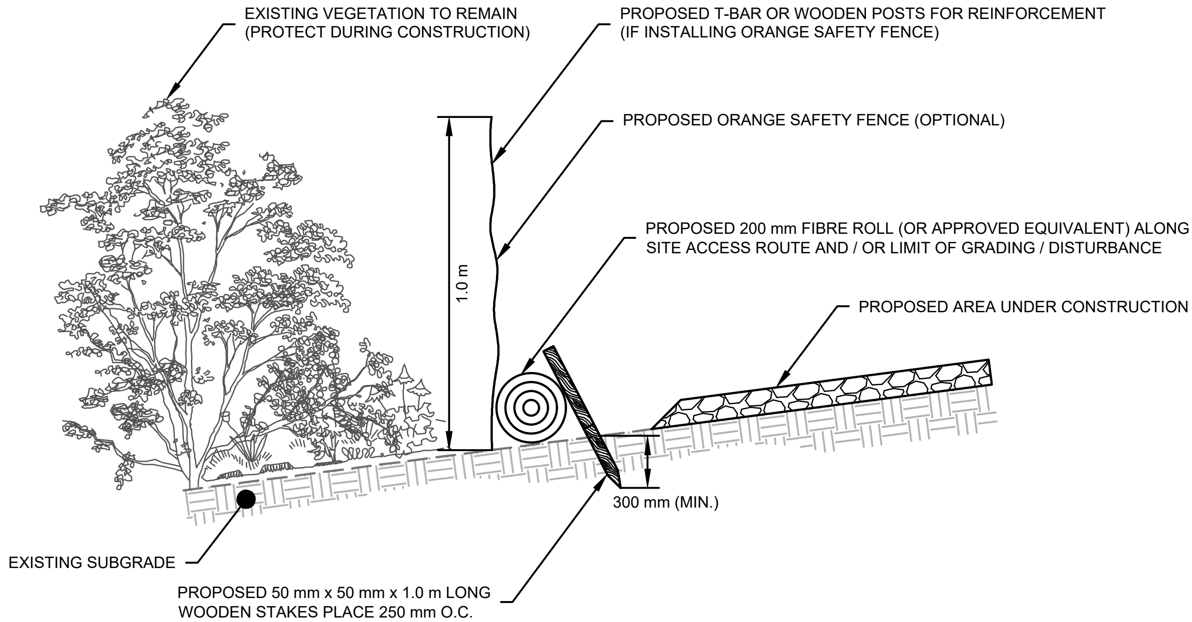
EROSION MITIGATION DESIGN DETAIL #5

SITE ISOLATION FOR EROSION MITIGATION PROJECTS

Erosion Detail #:	5
Designed by:	MO
Drawn by:	TR
Date:	MAY 2026
Scale:	N.T.S.
Drawing:	SLR 2026 - 5

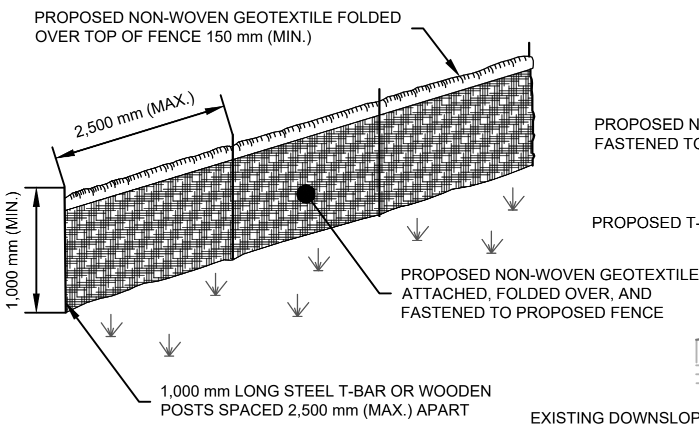
OPTION 1: FIBRE ROLL



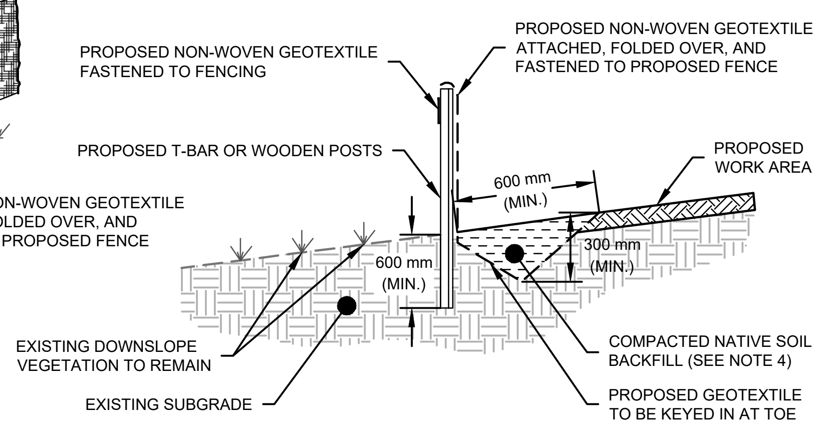
NOTES

1. PROPOSED 200 mm FIBRE ROLL (OR APPROVED EQUIVALENT) REQUIRED ON DOWNSLOPE SIDE OF ACCESS NEAR EXISTING WATERCOURSE

OPTION 2: SILT CONTROL FENCE



FRONT VIEW



SECTION VIEW

NOTES

1. SILT CONTROL FENCE SHOULD BE ALIGNED WITH CONTOURS FOR OVERLAND SHEET FLOW, UNLESS ALSO USED TO DELINEATE WORK AREA.
2. SILT CONTROL FENCE SHALL BE INSTALLED WITH NON-WOVEN GEOTEXTILE TOED INTO THE SOIL A MINIMUM DEPTH OF 300 mm BY EITHER STATIC SLICING OR TRENCH METHODS WITH COMPACTION OF BACKFILL MATERIAL, MEETING 95% STANDARD PROCTOR DENSITY.
3. STEEL T-BAR OR WOODEN POSTS TO BE SPACED AT A MAXIMUM OF 2,500 mm APART.
4. FROZEN GROUND CONDITIONS REQUIRE TRENCHING AT TOE OF SILT FENCE TO BE BACKFILLED WITH CLEAR STONE.
5. NON-WOVEN GEOTEXTILE TO BE U.V. STABILIZED WITH WEAVE DENSITY OF 270R EQUIVALENT.
6. NON-WOVEN GEOTEXTILE TO BE FOLDED OVER TOP OF FENCE AT A MINIMUM OF 150 mm AND FASTENED TO FENCING.
7. ENDS OF GEOTEXTILE SECTIONS TO OVERLAP A MINIMUM OF 2,000 mm.

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EROSION MITIGATION DESIGN DETAIL #6

EROSION AND SEDIMENT CONTROL DETAILS FOR EROSION MITIGATION PROJECTS

Erosion Detail #:	6
Designed by:	MO
Drawn by:	TR
Date:	MAY 2026
Scale:	N.T.S.
Drawing:	SLR 2026 - 6

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