



Enhancing Yukon Trade Corridor Resilience to Northern Geohazards:

Hydrology Report 3 - Erosion Assessment, Monitoring, and Mitigation

Final | September 2026



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Photo Credit: Yukon University

Executive Summary

The Department of Highways and Public Works of the Government of Yukon holds responsibility for dozens of erosion protection structures that almost exclusively consist of rock revetments (i.e., riprap) along portions of the lower Dempster Highway and the Klondike Highway west of Dawson. These road segments, among the most vulnerable to hydrological processes in the territory, are costly to maintain and represent safety concerns year round. Historical engineering approaches to counter this process often overlooked fluvial morphology concepts, mostly attempting to control an environment which dynamics were largely misunderstood. This report, co-prepared by the YukonU Research Centre and SLR Consulting (Canada) Ltd., presents a practical transportation engineering best-practice update, with site-specific analysis that complements the work presented by SLR (2026) about erosion risk reduction.

Results can be summarized as follows:

- General riverbank erosion processes along cold region rivers are reviewed in **Section 2**.
- Specific river encroachment sites (87) are identified and characterized in **Section 3**.
- From this inventory, 12 high-risk priority sites are further assessed in **Section 4**.
- After overviewing some of the research team's monitoring results (**Section 5**), an Erosion Monitoring System (EMS; **Fig. 5.5**) and a prototype Early Warning Protocol (EWS, **Fig. 5.6**) are presented. These tools are meant to support erosion risk assessment and management.
- Site-specific erosion mitigation approaches are presented in **Section 6** for the 12 priority sites as well as for additional sites where existing protection structures require intervention.
- **Section 7** of the report presents recommendations.

Efficient, effective, and cold-climate adapted management of erosion hazards requires consideration of unique social, environmental and economic circumstances. The recommendations highlight a balance of education, monitoring and detection, traditional engineering and contemporary nature-based solutions as a suite of responses to maintain highway resilience in a changing climate.

The content of this report aligns with these National, Territorial, and, to some extent, Indigenous priorities. It provides detailed evaluation of riverbank erosion hazards observed along key Yukon highways. It emphasizes the need to better understand, accurately assess, pro-actively manage, and sustainably mitigate the risk or **riverbank erosion** near or against highway. It complements two companion reports about interrelated cold-region hydrological processes that impact the safety and integrity of Yukon highways: aufeis (i.e., winter overflow and icing, or glaciation) and high flows in small streams.

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Appendices

- APPENDIX A INITIAL RIVER ENCROACHMENT INVENTORY AND PRELIMINARY RISK RATINGS (PALMER, 2023)**
- APPENDIX B COMPARATIVE ANALYSIS OF HISTORICAL CHANNEL PLANFORMS AT PRIORITY HIGHWAY ENCROACHMENTS (PALMER, 2024)**
- APPENDIX C SITE-SPECIFIC EROSION MITIGATION RECOMMENDATIONS**

1. Introduction

The Yukon University Research Centre (YRC) retained SLR Consulting (Canada) Ltd. (SLR), formerly Palmer Environmental and Geoscience Services, to provide fluvial geomorphology expertise for riverbank erosion assessment, monitoring, and mitigation along North Klondike and Dempster Highways in the Yukon. Funding for this project was provided by Transport Canada's National Trade Corridors Fund (NTCF, 2022-2026). This study is part of a collaborative, multi-disciplinary initiative ("Enhancing Yukon trade corridor resilience to northern geohazards") aimed at improving the long-term resilience of the Yukon's major trade and travel arteries to geohazards, including those associated with hydrological and fluvial processes.

This research project is taking place at the crossroads of several realities:

- Arctic Security and Territorial Sovereignty are becoming National priorities, and transportation corridors represent key assets in this new geopolitical context, connecting the north, and supporting its economy.
- Climate change is altering the frequency and intensity of natural hazards that affect the safety and integrity of northern infrastructure. As a result, the maintenance of existing - and the construction of new - roads in the North are expected to continue increasing.
- Protecting the fragile subarctic environment while supporting an energy revolution is critical in a world which biodiversity is threatened.

By combining historical geohazard data with ongoing field monitoring, this collaborative effort aims to support the transition of highway management from reactive emergency responses to proactive, environmentally responsible, and resilient strategies.

The current assessment builds upon several previous hydrogeomorphic assessments along the Dempster Highway. It expands upon the comprehensive baseline inventory of mass movement and meander encroachment geohazards along the Dempster Highway (McKillop et al., 2016). Furthermore, the data and insights gained from this assignment helped inform the development of the territory-wide Yukon Riverbank and Lakeshore Erosion Guidance document recently prepared for the Yukon Government (SLR, 2026). In turn, the current report serves as a practical, corridor-specific application of those overarching erosion guidelines.

1.1 Objectives

Changing climate patterns are affecting several components of the water cycle. Intense rain events, thicker snowpacks, warmer temperatures, thawing permafrost, changing vegetation, and wildfires all impact how water flows in small and large watercourses. In addition to gradual trends in these parameters, the occurrence of more frequent extreme runoff events increases the susceptibility of transportation infrastructure to riverbank erosion and lateral channel migration.

To proactively improve infrastructure resilience, the primary objectives of this project are to:

- **Identify, characterize, and prioritize** specific sites where watercourses are actively or will soon be encroaching on the highway embankments.
- **Develop and test** an erosion monitoring program adapted to the priority level of each identified site.
- **Prepare the prototype** of an early warning protocol to assist in the proactive management of erosion events.
- **Identify** current and innovative cold-region-adapted erosion mitigation approaches to protect high-risk erosion sites.

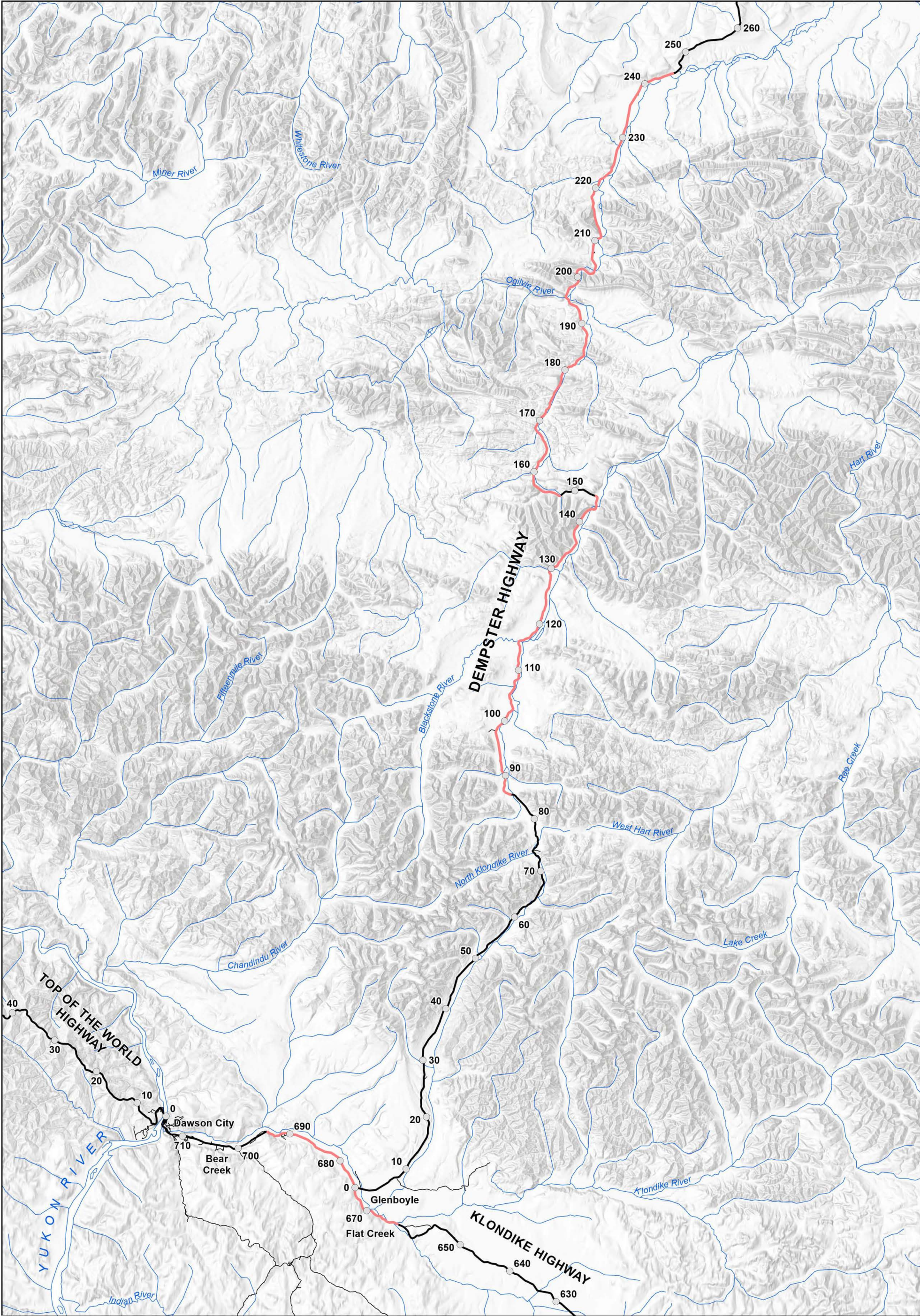
1.2 Study Area

The study area is located within the North Central Yukon and encompasses historically active and geomorphologically unstable watercourses along two primary northern transportation corridors (**Figure 1.1**). Along the North Klondike Highway, the assessment focuses on the segment from KM 664 to KM 694 within the Klondike River valley. Along the Dempster Highway, the study area includes the segments from KM 86 to KM 146 (paralleling the East Blackstone and Blackstone Rivers) and from KM 153 to KM 245 (paralleling Engineer Creek and the Ogilvie River). Additional information on the physical setting and erosion processes within the study areas is provided in Section 2.

1.3 Report Organization

Following this **Section 1 (Introduction)**, the remainder of this report is organized into six main sections supported by four appendices:

- **Section 2 (Physical Setting):** Provides a summary of the physical setting of the study area, including descriptions of the regional physiography, permafrost conditions, valley processes, and hydrology.
- **Section 3 (Erosion Inventory and Prioritization):** Summarizes the methods and results used to inventory and prioritize 87 discrete meander encroachment sites across the study area. The Initial Erosion Inventory memo (Palmer, 2023) is provided in **Appendix A**.
- **Section 4 (Historical Channel Position Analysis):** Describes the methods and results of the historical channel overlay analyses for 12 priority sites. The detailed technical memo documenting these findings (Palmer, 2024) is included in **Appendix B**.
- **Section 5 (Erosion Monitoring and Early Warning Protocol):** Outlines strategic erosion monitoring program components and introduces an early warning protocol developed for erosion sites of varying priority.
- **Section 6 (Mitigation Considerations):** Provides cold-region-adapted erosion mitigation considerations to manage erosional risk, drawing on traditional, indirect, direct, and nature-based approaches. Site-specific erosion mitigation recommendations and visuals for 16 priority sites are compiled in **Appendix C**.
- **Section 7 (Conclusions and Recommendations):** Presents the overarching conclusions and future recommendations of the assessment.



LEGEND

- Highway Kilometre Post
- Highway Network
- Highway of Interest
- Watercourse¹

1 - CanVec 1M Series

KEY MAP

0 5 10 15 20 25

Kilometres

North American Datum 1983
Yukon Albers

Scale: 1:600,000
Page Size: Tabloid (11 x 17 inches)

Drawn: SM
Checked: DM
Date: Jun 24, 2026

Source Notes:
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NORTH

CLIENT	Yukon University
PROJECT	Yukon Erosion Consultant
TITLE	Highways of Interest
REF. NO.	233.V24420-1-1
Figure 1	

FIGURE 1.1. HIGHWAYS OF INTEREST

2 Physical Setting and Riverbank Erosional Processes

The following sub-sections summarize the key physical characteristics and geomorphological processes that govern riverbank instability within the study area. For a more fulsome description of the physical setting of this area, including regional physiography and geomorphological context of the Dempster Highway corridor, the reader is referred to McKillop et al. (2016). The sections of highway that were studied for this work are situated in the Traditional Territory of the Tr'ondëk Hwëch'in First Nation and the First Nation of Nacho Nyak Dun. Each Nation provided approval for this project but had limited active involvement in the implementation of the work. Some sites of interest on the Dempster Highway were located in the Tombstone Territorial Park. Work at these locations was conducted under park permit 22-RE-TP-01.

2.1 Physiography

The North Klondike and Dempster Highways traverse a diverse boreal and subarctic landscape, crossing multiple distinct physiographic regions (Mathews, 1986). The corridor transitions from the steep, high-relief terrain of the Ogilvie and Richardson Mountains to the broad, rolling topography of the Eagle Plains (Burn et al., 2015; Smith et al., 2004). This varied topography directly dictates the existing catchment morphology and valley processes. In the mountainous reaches, watercourses are often confined within narrow, steep-sided valleys flanked by bedrock and colluvial slopes (Burn et al., 2015). These high-relief catchments rapidly deliver water and sediment to valley-bottoms. Conversely, in the unglaciated and rolling plains of the central corridor (e.g., Section of the Ogilvie watershed), rivers flow through much broader, unconfined alluvial valleys. In these flatter areas, the landscape is characterized by expansive floodplains where highly active, wandering gravel-bed rivers continuously rework the valley-bottom (McKillop et al., 2016).

2.2 Hydrology and Fluvial Geomorphology

Watercourses along the North Klondike Highway near Dawson and the lower Dempster Highway drain mountainous, alpine to subarctic catchments. The area receives about 400 mm of precipitation annually (Harris et al. 2020), a significant amount of which is stored in winter months as snow, which is rapidly released in spring as temperature warm. As a result, freshet peak flows can be more than 10 times those occurring in late winter, and transient zero flow events are not uncommon during the cold season in both small creeks and larger rivers. The steep and often barren bedrock and colluvial slopes of these headwaters promote a "flashy" (rapid) hydrological response to snowmelt and intense summer precipitation events (McKillop et al., 2016). The combination of steep gradients and highly active mass movement processes on the surrounding valley walls results in the delivery of **high sediment yields** to the valley-bottoms. This abundance of coarse sediment drives the formation of dynamic, wandering gravel-bed river morphologies—particularly along Engineer Creek and the Ogilvie River—characterized by high bedload transport, multiple channel threads, and highly mobile gravel bars (McKillop et al., 2016). Segments of the East Blackstone and Blackstone Rivers are also very dynamic, with large gravel bars and secondary channels shifting positions in recent years; this also applies to the Klondike River near Dawson.

2.3 Permafrost Distribution

Permafrost extent varies across the study area. Moving northward, the Dempster Highway corridor transitions from a region of extensive discontinuous permafrost (50% to 90% areal coverage) along the North Klondike River valley and North Fork Pass, to a region of continuous permafrost (90% to 100% areal coverage) north of the Ogilvie Mountains (Burn et al., 2015; Heginbottom et al., 1995; McKillop et al., 2016). Permafrost distribution and ice content are heavily influenced by glacial history, local topography (slope and/or aspect), drainage, and surficial materials. Ice-rich permafrost is most prevalent in fine-grained valley-bottom sediments (**Figure 2.1**), wetlands, areas not ice covered during the last glacial maximum, and gentle colluvial aprons (McKillop et al., 2016). Primarily due to increasing global air temperatures and changing precipitation, degradation of this permafrost has significant, continual, direct (e.g., sinkholes, Laurent et al., 2026) and indirect (e.g., channel migration rates) consequences for transportation infrastructure. A drastic and rapid decline in water quality in several headwater streams associated with permafrost thaw is also currently under investigation (e.g., Skierszkan et al., 2026).



FIGURE 2.1. COLLAPSE OF UNDERCUT RIVERBANK ALONG ENGINEER CREEK DUE TO THAWING AND EROSION OF PERMAFROST.

2.4 River Ice

River ice is a primary geomorphological agent in the Yukon, often exerting more significant erosive forces than open-water flood events. Key ice processes include the formation and melt of aufeis (icings, **Figure 2.2**) and dynamic river ice breakup events causing ice jams and ice runs. Soon after freeze-up and until spring onset, the gradual formation of aufeis can block culverts and channel cross-sections, causing significant uplifting forces and deflecting the flow onto the floodplain (Turcotte et al., 2026a).

In the spring, thick aufeis bodies can deflect the entire snowmelt runoff flow toward a riverbank, causing erosion. The melt and collapse of injected ice associated with winter overflow events can

also enlarge aufeis-affected channels by tearing off portions of vegetated banks (**Figure 2.3**). Another issue in the spring, in the context of a floating ice cover, the rising flow breaks the ice and carries it in pieces downstream to form small ice jams. As the flow continues to rise, some ice jams are mobilized to generate larger ice jams downstream. The formation and consolidation of those large jams can push thick ice slabs directly into the banks, often damaging riparian vegetation, removing rock armours, and damaging erosion protection structures such as riprap. Subsequently, the sudden release of these jams unleashes a fast-moving hydrodynamic wave and associated full-concentration (i.e., bank-to-bank) ice run that exerts extreme shear stresses and abrasion constraints on the channel boundaries.



FIGURE 2.2. AUFEIS COLLAPSE AND CALVING ALONG THE BLACKSTONE RIVER.



FIGURE 2.3. INJECTED ICE UNDER ORGANIC LAYER AND RIPARIAN VEGETATION THAT LATER COLLAPSE INTO THE SPRING FLOW, EAST BLACKSTONE RIVER.

2.5 Key Factors Contributing to Embankment Failure

Road embankment failures along the North Klondike and Dempster Highways are rarely the result of a single factor; rather, they are driven by the complex interplay of several highly active geomorphological processes:

- **High flow events:** The erosional power of water in a stream or river is generally not linear with discharge (through water velocity and associated shear stress). At low flow, only fine material can be transported by moving water, whereas above a reach-specific flow threshold, widespread suspended and bedload transport can occur. The progressive lateral encroachment of meandering and wandering rivers, often occurring during short (episodic) runoff events, can undercut the toe of the highway embankment, over-steepening slopes, and eventually triggering collapse (**Figure 2.4**).
- **High Sediment Yields:** Wandering gravel-bed channels (like Engineer Creek) receive large pulses of sediment from steep tributaries and unstable riverbanks. This bedload is temporarily stored in large bars, which rapidly aggrade the channel (raising the riverbed) and force the flow to switch course (avulse) into new paths suddenly. Some of those paths may intersect highway segments located in the valley-bottom. Culverts can also be blocked by sediment that would have normally transited downstream, potentially causing washouts.
- **River Ice Processes:** Winter overflow events in shallow streams can generate significant damage to banks and riparian vegetation during the following spring, mainly through the deflection of the snowmelt runoff towards the banks and the collapse of bankfast ice slabs (frozen against the bank) into the channel beneath (**Figure 2.2**). During the spring breakup period, mainly along the larger and deeper Ogilvie River, ice floes and slabs carried by the water run into or against the banks. This dynamic process may last only a few minutes but can create significant damage. The exact impact of climate change on the frequency and intensity of augeis, ice runs, and ice jams remains uncertain for the study area, but is likely to increase.



FIGURE 2.4. EROSION OF THE DEMPSTER HIGHWAY EMBANKMENT AT KM 166.5 FOLLOWING A HIGH-INTENSITY, MID-SUMMER RAIN EVENT IN AUGUST 2016 (PHOTO CREDIT: HPW).

- **Permafrost Degradation:** Thermally stable permafrost provides mechanical strength to riverbanks. However, when lateral erosion (or highway maintenance operations) exposes ice-rich permafrost to warm air or water, the loss of the ice-bonding structure transitions the bank into a highly unstable state, resulting in gradual thermal degradation, retrogressive thaw slumps, and accelerated bank retreat.
- **Climate Change:** The exact influence of climate change on freshet (i.e., the timing and discharge of annual peak snowmelt flows) remains uncertain. Still, it appears that summer and fall rainstorms are becoming more intense in the study area (e.g., Turcotte, 2025). Climate change also exacerbates permafrost thaw and the degradation of generally frozen banks by extending and warming the summer period and increasing liquid precipitation yields (a wet ground loses more heat than a dry ground, e.g., Douglas et al., 2020).
- **Historical Anthropogenic Activities:** Past engineering practices have exacerbated natural erosive forces. For example, Engineer Creek was historically straightened to force the channel away from the newly built Dempster Highway footprint. The construction of highways, along with the installation of restrictive berms, bridges, and culverts, has artificially confined several dynamic streams and rivers, often increasing the "sharpness" of bends and concentrating tractive forces directly against the road embankment, ultimately contributing to road washouts.
- **Woody debris:** The destabilization of streambanks can cause the entrainment of bushes and large woody debris into the channel. At locations where that woody debris becomes arrested (mainly due to its roots dragging against the channel bed), the flow can be deflected sideways, either promoting further erosion or, conversely, stabilizing a river segment. In the study area, the Klondike River is the watercourse where log jams are the most common, followed by the Ogilvie River and Engineer Creek. Beaver activity, mainly the creation of dams in secondary channels, in the Klondike, Blackstone and Ogilvie Rivers, can also modify flow patterns and influence local bank stability.

In light of what is presented here, bank erosion and migration rates are likely to increase in the coming decades.

3 Erosion Inventory and Prioritization

This section summarizes the methods and findings of the initial river encroachment inventory and preliminary risk rating assessment performed in 2023. Comprehensive site characterizations, tabular inventories, and spatial mapping are provided in the technical memo in **Appendix A**.

3.1 Approach and Key Data

To establish a baseline understanding of fluvial-related hazards, a systematic, desktop-based geospatial assessment was completed to identify and characterize locations where watercourses encroach within a 50 m buffer of the North Klondike and Dempster Highway centerlines (initial proxy for the highway embankment). The assessment focused on meander encroachments, where the potential for severe/sudden erosion and wash-out is higher than along locations where the highway and watercourse are parallel. The spatial analysis utilized high-resolution data, including 0.15 m to 0.20 m ortho-imagery and LiDAR-derived digital elevation models (DEMs) acquired between 2013 and 2019, supplemented by recent satellite imagery (e.g., June 2023) to capture contemporary geomorphological conditions.

Key geomorphological attributes were extracted for each encroachment site, including local channel confinement, relative relief, inferred permafrost presence, and the separation distance measured between the outermost top of the riverbank and the inferred toe of the highway embankment (**Figure 3.1**). Desktop interpretations were subsequently validated via targeted ground-truthing reconnaissance conducted in July 2023.

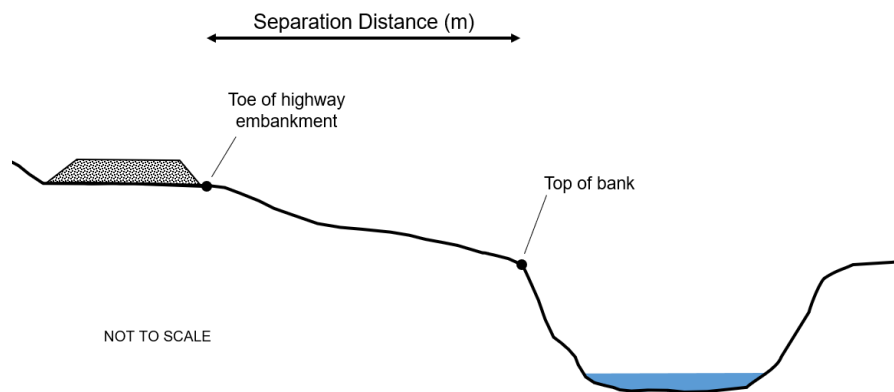


FIGURE 3.1. SCHEMATIC REPRESENTATION OF THE SEPARATION DISTANCE MEASUREMENT.

In a perspective of proactively managing the risk associated with geohazards along highway corridors, this assessment needs to be updated:

1. After a major erosion event (e.g., a 20-year runoff event affecting multiple erosion sites or watercourses),
2. Once an erosion mitigation measure has been implemented (site-specific), or
3. Every five years, or so, otherwise (all encroachment sites), as described in **Section 5** of this report.

3.2 Risk Evaluation Methodology

A preliminary erosion risk rating—ranging from Very Low to Very High—was assigned to each identified site. This classification was derived using a standardized risk evaluation matrix that combines the measured separation distance with the interpreted rate of lateral fluvial erosion toward the highway embankment (**Table 3.1**). The interpreted rate of lateral erosion was qualitatively assessed based on the erodibility of bank materials (including the structural condition and design effectiveness of any existing riprap protection), confining topographic features, localized hydrogeomorphic processes, and the apparent thaw sensitivity of local permafrost.

TABLE 3.1. EROSION RISK EVALUATION MATRIX USED TO ASSIGN A PRELIMINARY RISK RATING.

		Separation distance*		
		Large (31-50)	Moderate (10-30)	Small (<10 m)
Interpreted rate of lateral erosion	High (e.g., unconfined, prominent/recent/fresh meander scrolls low outer bank, erosion-prone material, thaw-sensitive permafrost, outflanked riprap, etc.)	Moderate	High	Very high
	Moderate (e.g., point bar, partly scoured outer bank, erodible material, thaw-stable permafrost, etc.)	Low	Moderate	High
	Low (e.g., competent erosion mitigation present, small/no point bar, partly scoured outer bank, confining topographic features, erosion-resistant material, thaw-stable or no permafrost etc.)	Very low	Low	Moderate

*Distance between top of bank and the toe of the highway embankment in most recent imagery or LiDAR dataset

Site-specific erosion risk evaluation therefore involves an unbiased classification, but also a judgement and experience-based final categorization. It is important to note that the erosion risk, as defined in **Table 3.1**, does not include the level of consequence of erosion hazard. In other words, the risk, as defined here, is not proportional to the cost of site-specific transportation infrastructure repair. Instead, it informs the infrastructure owner about the need to budget for adapted monitoring (**Section 5**) and proactive risk mitigation (**Section 6**).

3.3 Key Results

The geomorphological inventory initially completed in 2023 identified 87 discrete encroachment sites totalling 32.75 km of cumulative length (**Table 3.2**). Twelve sites are located along the North Klondike Highway (Klondike River), while 75 are situated along the Dempster Highway. Notably, well over half of the inventoried sites (52) exhibit a separation distance of less than 10 m.

One important finding of the inventory is that a large proportion of sites are along Engineer Creek. Of the 87 total encroachment sites, 36 are concentrated along this watercourse. Engineer Creek exhibits significantly greater planform instability than any other monitored system, driven by a combination of high sediment supply from steep, barren headwaters and a flashy hydrological regime. In turn, the longest segments of the Dempster Highway located immediately against a watercourse are found in the narrow Ogilvie River valley between Km 197.6 and 245.2. Most of these encroachment sites have been stabilized using riprap; nonetheless, the level of consequence (preventive mitigation or recovery cost) of a washout caused by a major hydrological event would likely be greater there than along other Dempster Highway segments.

TABLE 3.2. DISTRIBUTION OF RISK RATING FOR THE DOCUMENTED ENCROACHMENTS SITES

Risk Rating	# of Encroachment Sites	Percentage of Encroachment Sites	Total Encroachment Site Length (m)
Very High	4	4.6%	660
High	28	32.2%	7,420
Moderate	44	50.6%	22,800
Low	11	12.6%	1,870
Very Low*	0	0.0%	0
Total	87	100.0%	32,750

*Very Low was retained in the results as it is a possibility based on the risk rating matrix (**Figure 2**)

Four sites, all situated along the Dempster Highway (two associated with Engineer Creek), were assigned a "Very High" risk rating, denoting an imminent hazard to transportation infrastructure where separation distances are minimal and vulnerability to rapid lateral migration or mass wasting is severe:

- **KM 115.6 (Blackstone River):** Degradation of ice-rich permafrost and lateral channel migration are driving hillslope failure that is actively compromising the highway embankment. The site elevation is very high relative to the river (~18 m), and a catastrophic failure of the highway, whether or not associated with the drainage of Chapman Lake (e.g., Zhang, 2024), remains a concern, especially during the second half of summer and before freeze-up. The Dempster Highway has been realigned away from the hillslope by the equivalent of one lane as a temporary adaptive measure a few years ago, and the site has been monitored (e.g., ground temperature and weather conditions) in recent years by the Permafrost and Geoscience Research group (PGR) at YukonU (e.g., Laurent et al., 2026).
- **KM 182.1 (Engineer Creek):** Bank scouring is actively occurring upstream and downstream of previously placed riprap, with satellite imagery and field observations/measurements indicating imminent failure of the embankment at the upstream end of the armouring. The downstream bank has receded by more than 2 m between fall 2024 and spring 2026.

Embankment failure can occur at any time between May and October, even during non-flood conditions.

- **KM 193.4 (Engineer Creek):** Rapid lateral meander migration (45 m between 2013 and 2023) has completely consumed the separation distance (0 m), leaving the unarmoured embankment exposed to direct fluvial scour. The bank was temporarily armoured in 2024, with some rocks added after the fall of 2025, albeit with no apparent design criteria. The embankment remains vulnerable, especially upstream and downstream of the riprap.
- **KM 239.5 (Ogilvie River):** A dominant shift in discharge into the northern branch of the river, the likely consequence of an ice jam in 2019, has led to 43 m of lateral migration toward the highway since a previous aerial survey (2013). This bank could fail over a relatively long distance (e.g., more than 100 m) during spring breakup or a significant open-water event.

3.4 Implications for Next Steps

The inventory highlights that numerous sites require high temporal and spatial monitoring resolution or urgent maintenance attention. Also, sites featuring active planform adjustments or thermal degradation of permafrost warrant immediate analytical focus.

Consequently, 12 high- or very high-risk encroachment sites were prioritized for detailed, quantitative channel-overlay analyses to forecast future meander trajectories and estimated timeframes to impact (detailed in **Section 4**). This erosion risk-based short list is also used to define erosion monitoring strategies (**Section 5**) as well as to propose resilient mitigation approaches (**Section 6**).

A recent assessment (fall of 2026) identified three additional high-priority erosion sites; all of which are located along the Ogilvie River beyond the downstream end of an existing erosion protection structure:

- **Km 211.2**
- **Km 214.4**
- **Km 238.6**

4 Historical Channel Position Analysis

This section summarizes the methods, results, and key considerations of the comparative historical channel overlay analyses. The detailed technical memo documenting these findings (Palmer, 2024) is provided in **Appendix B**.

4.1 Approach and Key Data

To forecast where, when, and how much land will be lost to erosion, 12 of the high-risk encroachment sites identified during the initial inventory (**Section 3**) were prioritized for detailed quantitative assessment (**Figure 4.1**). The overlay analysis relied on a dataset of remotely sensed imagery to track historical channel planform evolution. Georeferenced historical aerial photography and high-resolution orthophotography were compared against recent satellite imagery (**Table 4.1**). The assessment utilized imagery from years after the construction of the Dempster Highway.

TABLE 4.1. IMAGERY USED FOR THE CHANNEL OVERLAY ASSESSMENT

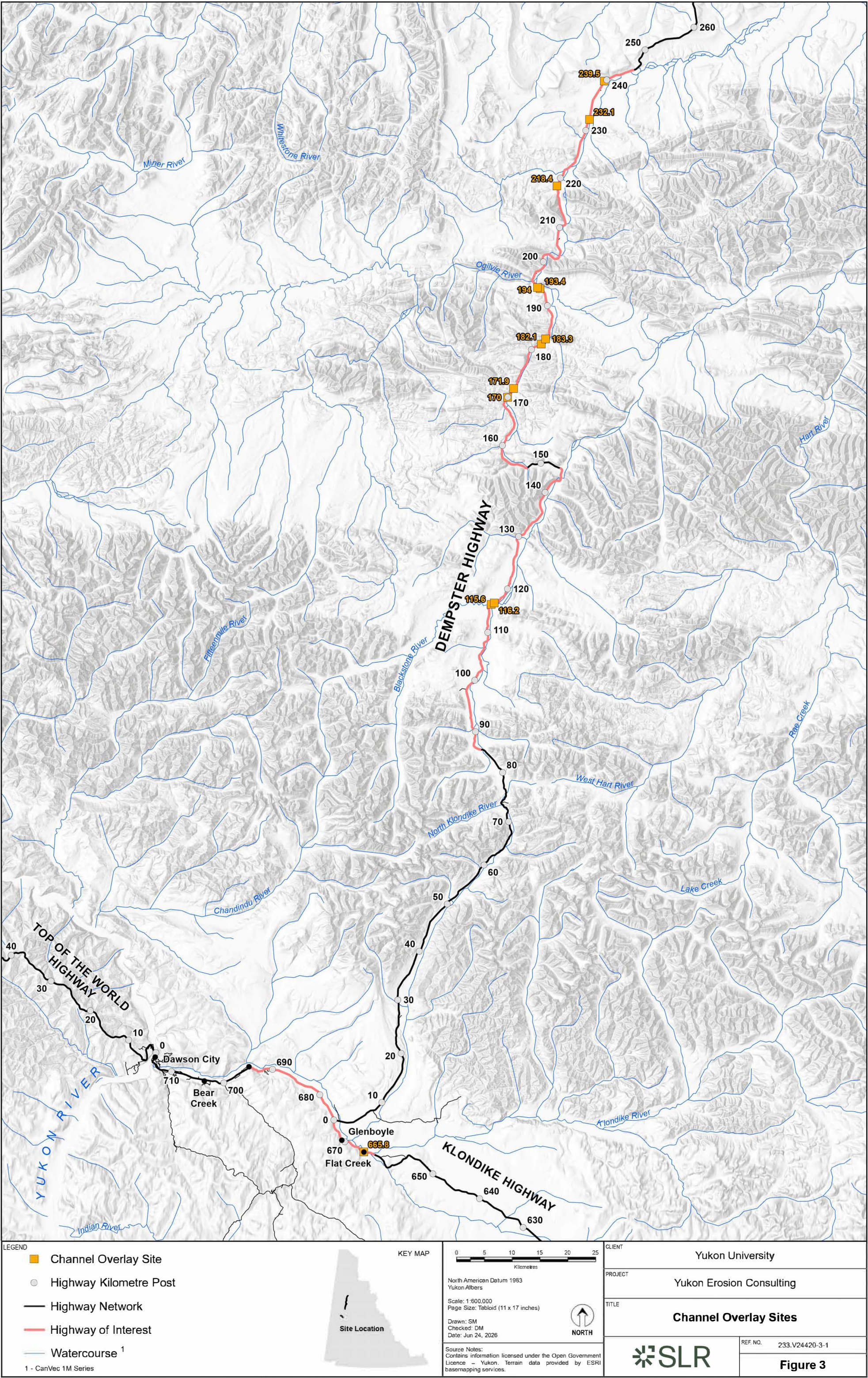
Imagery Type	Year	Scale/Resolution	Source
Satellite Imagery	2023	0.50 m	Google
Orthophotography	2013/2014	0.15 m	GeoYukon
Satellite Imagery ¹	2007/2008	0.60 m	GeoYukon
Aerial photography	1989/1990	1:25,000 to 1:30,000	Yukon EMR
Aerial photography ²	1977	1:15,000 to 1:45,000	Yukon EMR

1 – No coverage for KM 232.1

2 – Due to higher positional uncertainty and documented anthropogenic channel modification prior to 1977, the 1977 imagery was not used to calculate timeframe to impact

4.2 Overlay Analysis Methodology

For each dataset year, the left and right channel banks (based on vegetation boundaries, among other visible features), main channel thalweg, and major side channels were delineated at an appropriate scale to capture geomorphological changes without missing broader spatial patterns (**Figure 4.2**). By measuring the shifts in these delineated boundaries, time-averaged meander migration rates and dominant trajectories toward the highway were calculated. Migration rates were calculated over multiple intervals (e.g., 1989/1990 to 2023 versus 2013/2014 to 2023) to determine if lateral erosion was accelerating. While time-averaged rates are highly effective for estimating timeframes to impact by smoothing out localized "noise," it is critical to recognize that channel migration in these northern systems is inherently episodic. As mentioned in **Section 2**, lateral shifts frequently occur suddenly, driven by peak flows or dynamic ice processes that cause mid-channel bar redistribution and channel avulsions, with the potential for the channel to migrate many more metres in a single event (e.g., 5 m in a few days) than is suggested by the time-averaged rate (e.g., 0.5 m/year). The 2016 event represents an example of fast channel migration.



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FIGURE 4.1. CHANNEL OVERLAY SITES



FIGURE 4.2. EXAMPLE OF TOP OF BANK DELINEATION (2023) AT DEMPSTER HIGHWAY KM 183.3.

4.3 Key Results

The overlay analysis quantified channel migration rates since 1989/90 and estimated the timeframes to highway impact for all 12 priority sites (**Table 4.2**). The data revealed that migration rates at most sites were greater between 2013/2014 and 2023 than over the longer-term period between 1989/1990 and 2023, suggesting an acceleration in lateral erosion over the past decade.

Specific monitoring observations conducted between summer 2023 and fall 2025 have been integrated into **Table 4.2** to provide contemporary context. This recent monitoring period included some noticeable hydrological events, mainly in June 2025 in Engineer Creek, and lateral channel adjustments were observed at several high-priority locations. A notable example of this ongoing channel migration is documented at Dempster Highway KM 194.0 along Engineer Creek (**Figure 4.3**). During these two years, continued outer bend migration reduced the minimum separation distance from 28 m to 23 m.

A quantitative data review from the broader study period (Tipton et al., 2024) revealed an approximate doubling of median erosion rates near erosion priority sites when comparing the historical 1977-1989 interval to the contemporary 2013-2023 period (**Figure 4.4**). This consistent upward trend is particularly apparent along Engineer Creek.

TABLE 4.2. TIME-AVERAGED LATERAL MIGRATION RATES AND ESTIMATES OF TIMEFRAMES TO HIGHWAY IMPACT FOR THE PRIORITY SITES IDENTIFIED IN 2025.

Hwy KM	Watercourse	Min. Separation Dist. in 2023 ¹ (m)	Time-ave. Migration Rates - 1989 to 2023 ² (m/yr)	Time-ave. Migration Rates - 2013 to 2023 ² (m/yr)	Estimated Timeframe to Impact ³ in 2023 (yrs)	Key channel migration observations from 2023 to 2025 monitoring
665.8	Klondike River	34	1.7 to 2.9 ⁴	2.1 to 8.2	5 to 10	Continued outer bend migration since 2023. Distance now < 28 m.
115.6	Blackstone River	9	0.5 to 0.6	0.9 to 1.1	5 to 10	Site monitored by YukonU PGR
116.2	Blackstone River	16	0.3 to 0.4	0.4 to 0.5	>25	Site monitored by YukonU PGR
170.0	Engineer Creek	25	0.9 to 1.6	2.0 to 3.2	10 to 15	Thalweg has locally shifted away from highway. Separation distance from 2023 is unchanged. A berm separates the highway and river.
171.9	Engineer Creek	23	0.8 to 2.5	0.7 to 3.3	5 to 10	Thalweg has locally shifted away from highway. Separation distance from 2023 is unchanged. Bedrock along the toe of the outer bank may limit further migration towards the highway.
182.1	Engineer Creek	0	0.5 to 1.3	0.9 to 2.9	0	Riprap at upstream end of embankment has failed and embankment continues to erode. The highway could be compromised at anytime.
183.3	Engineer Creek	18	0.8 to 2.1	0.8 to 2.3	5 to 10	Separation distance from 2023 is generally unchanged but some vegetation has fallen into the river.
193.4	Engineer Creek	0	2.1 to 2.8	0.6 to 4.8	0	Riprap was installed in 2024 and rocks were added in 2026. Erosion has been observed upstream and downstream of riprap since its installation. Tension cracks and 'slips' were also observed at top of embankment, suggesting bed scour at riprap toe and riprap settlement.
194.0	Engineer Creek	28	3.4	4.9	5 to 10	Continued outer bend migration since 2023. Distance now < 23 m.
218.4	Ogilvie River	13	0.6 to 1.0	0.3 to 1.3	10 to 15	Separation distance from 2023 is generally unchanged but some vegetation has fallen into the river.
232.1	Ogilvie River	23	0.4 to 2.7	0.3 to 3.1	>25	Site only surveyed once (2025)
239.5	Ogilvie River	6	1.8	0.8 to 4.8	<2	Continued outer bend migration since 2023. Distance now < 4 m.

1 – Based on shortest distance measured between the edge of highway embankment and the edge of watercourse in 2023 imagery

2 – Includes some migration vectors that are not migrating towards the highway

3 – Estimated from 2023 bank position based on trajectories and highest migration rate towards the highway

4 – At most sites, migration rates were calculated along multiple migration vectors. The measured rates are presented as ranges.

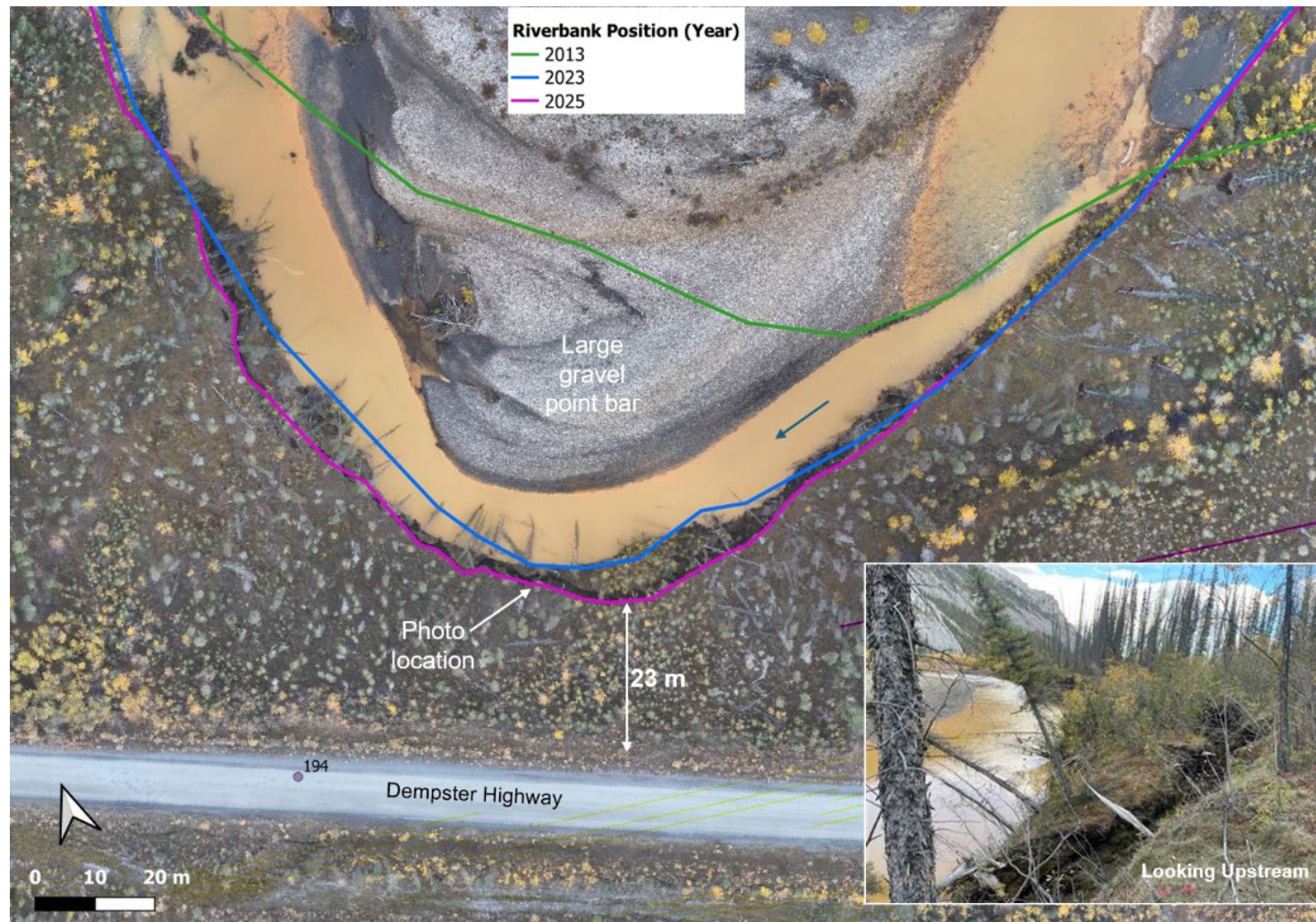


FIGURE 4.3. PROGRESSIVE MEANDER MIGRATION OF ENGINEER CREEK AT DEMPSTER HIGHWAY KM 194.0. THE LARGE GRAVEL BAR GROWTH FURTHER PUSHES THE CHANNEL THALWEG AGAINST THE ERODING OUTER BANK. PERMAFROST THAW MAY BE CONTRIBUTING TO INSTABILITY. A CHANNEL AVULSION IS POSSIBLE THAT WOULD INCREASE THE SEPARATION DISTANCE AND LOCALLY REDUCE THE RISK TO THE HIGHWAY.

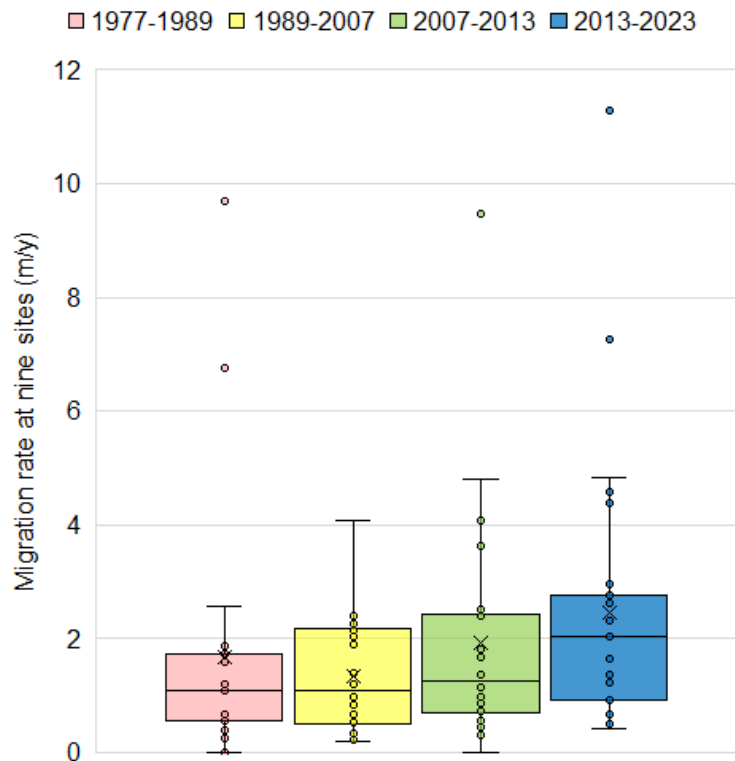


FIGURE 4.4. BOXPLOT SHOWING CHANNEL MIGRATION RATES FOR NINE OUT OF THE 12 EROSION SITES (TIPTON ET AL., 2024).

4.4 Key Considerations

Several interacting factors are driving the observed acceleration in geomorphological changes and must be considered in future mitigation planning:

- **Wandering Gravel-Bed Dynamics:** Half of the priority sites (6 of 12) are located along Engineer Creek. This watercourse exhibits a highly dynamic wandering gravel-bed morphology, characterized by rapid migration, extensive transient gravel bars, and frequent channel avulsions driven by large sediment pulses from steep, barren headwaters.
- **Anthropogenic Alterations:** Historical modifications, such as the artificial straightening of Engineer Creek during initial highway construction (**Figure 4.5**), continue to influence contemporary channel adjustments as the creek re-establishes its natural alignment.
- **Permafrost Degradation:** The thermal degradation of permafrost within the undisturbed outer banks of encroaching meanders is likely contributing to bank instability. Specifically, sites featuring thaw-sensitive, ice-rich permafrost (e.g., KM 115.5 and 116.2) are experiencing rapid retrogressive thaw slumping that exacerbates lateral retreat. Several eroding banks along Engineer Creek are also likely underlain by permafrost.
- **Hydrological Shifts:** The recent acceleration in migration rates may reflect the influence of recent large flood events (e.g., 2016) and/or dynamic ice processes (e.g., 2019). Integrating these geomorphological findings with ongoing Water Survey of Canada hydrometric data and river ice breakup observations will be critical to establishing preliminary flow and weather thresholds for severe channel change (as presented in **Section 5**).

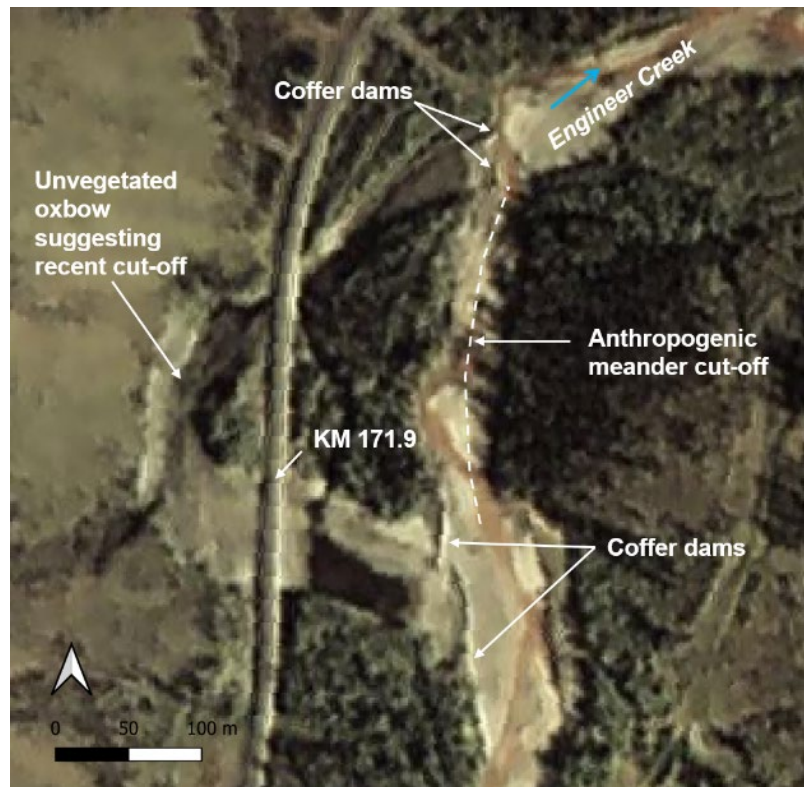


FIGURE 4.5. AN EXAMPLE OF AN ANTHROPOGENIC CUT-OFF ALONG ENGINEER CREEK OBSERVED IN THE 1977 AERIAL PHOTOGRAPHS. SINCE 1977, THE CHANNEL HAS WIDENED AND HAS MIGRATED RAPIDLY TOWARDS THE HIGHWAY AT KM 171.9. NUMEROUS OTHER SIMILAR CUT-OFFS ARE OBSERVED ALONG ENGINEER CREEK, WHICH WOULD HAVE LED TO A NOTABLE REDUCTION IN CHANNEL LENGTH AND, CONSEQUENTLY, AN INCREASE IN SEDIMENT TRANSPORT AND EROSION CAPACITY.

5 Erosion Monitoring and Early Warning Systems

5.1 Monitoring Approaches

There is no standard instrumentation approach to monitor streambank erosion. This invites scientific creativity in a context of diverse erosional processes, hydroclimatic contexts, and streambank characteristics. For instance, one could consider direct/remote ground movement detection/measurement strategies using mechanical/ultrasonic/radiometric/optical technologies.

In a large majority of cases, streambank movements along watercourses in the Yukon will not occur during winter months. Therefore, continuous or periodic monitoring strategies may not need to be adapted to cold weather conditions. However, permanent or semi-permanent instrument deployments (e.g., weather stations) at remote locations may require the devices to survive winter months, at least in a form of hibernation. As presented in **Section 2**, the most significant erosional activity in central Yukon may be associated with river ice breakup, high snowmelt flows, mid-summer rainstorms, or late-fall rain events (when active layer thickness reaches its maximum). This means that devices and cables need to be installed to avoid damage/loss caused by high water levels, ice impacts, and the retreat/collapse of a large portion of streambank during a single erosion event, especially in a context of real-time monitoring that informs emergency responses. Wildlife-resistant casings or other protections for monitoring instrumentation/equipment are also an important consideration in the Yukon.

During the field-work portion of this project (2023-2025), several on-site instrumentation types were considered and tested, based on different criteria, including:

- Purchase cost (ranging from \$250 to more than \$5000) and operation cost (e.g., telemetry)
- Ease of deployment and maintenance (time spent along the watercourses to install and periodically check the instrumentation),
- Adaptation to different physical settings (e.g., low vs. high banks, vegetation type),
- Results reliability (acceptable ratio of false alerts vs. missed events).

This preliminary monitoring strategy involved testing the communication of real-time information and alerts to end users and was meant to comprise erosion prediction approaches (e.g., short-term weather forecasts) as well as post-event documentation (e.g., photos and DGPS or LiDAR surveys).

Table 5.1 presents different real-time or remote monitoring instruments and technologies, including those tested during this project. All monitoring approaches are classified against several criteria:

- **Green coloured cells** indicate low costs, easy deployment or data processing, low vulnerability, or high accuracy.
- **Yellow coloured cells** indicate a moderate level of each criterion.
- **Red cells translate** into high costs, complex deployment or data processing, high vulnerability, or low reliability.

TABLE 5.1. SUMMARY TABLE OF POSSIBLE EROSION MONITORING INSTRUMENTS AND APPROACHES

		Tested	Access to data	Cost of purchase	Adaptability to different sites	Ease of deployment	Cost of operation	Ease of data processing	Vulnerability to wildlife	Vulnerability to hazards	Accuracy / reliability
Real-time access & continuous monitoring	Laser	N	C/Bl + Sat ¹	High	Low	Moderate	Low	Easy	Moderate	High	Moderate
	Inclinometers	N	C/Bl + Sat ¹	Moderate	High	Easy	Low	Easy	Moderate	Low	Moderate
	Accelerometers	N	C/Bl + Sat ¹	Moderate	High	Easy	Low	Easy	Moderate	Low	Low
	Erosion Alert	Y	C/Bl + Sat ²	Moderate	High	Easy	NA	Easy	Moderate	Low	Moderate
	Wire-loops	Y	C/Bl + Sat ¹	Low	High	Moderate	Low	Easy	Moderate	Low	High
	Real-time camera	N	Sat ²	High	Moderate	Easy	High	Moderate	Low	Moderate	High
	Weather station	Y	Sat ²	High	High	Moderate	Moderate	Easy	Moderate	Low	Moderate
	Hydrometric station	N	Cable + Sat ³	Moderate	Moderate	Complex	Moderate	Easy	Low	High	Moderate
	Water quality station	N	Cable + Sat ³	High	Moderate	Complex	Moderate	Moderate	Low	High	Low
Field access & episodic m.	DGPS surveys	Y	On-site only	High	High	Moderate	Moderate	Complex	Low	Low	High
	LiDAR surveys	Y	Post-process ⁴	High	High	Moderate	High	Complex	Low	Moderate	High
	Drone surveys	Y	Post-process ⁴	High	High	Moderate	Moderate	Complex	Moderate ⁵	Moderate	High
	Satellite imagery	Y	Post-process ⁴	Low	Moderate	Easy	Low	Moderate	Low	Moderate	Moderate
	Series of stakes	Y	On-site only	Low	High	Easy	Low	Easy	Moderate	Low	Moderate
	Remote camera	Y	On-site only	Low	Moderate	Easy	Low	Moderate	Low	Low	Moderate

1. Cable or Bluetooth from device to data logger and satellite transmission to access real-time data

2. Cable from device to data logger and satellite transmission to access real-time data

3. Direct satellite connection from device to access the data

4. Information only accessible through the post-processing of spatial data

5. Generally low vulnerability but, in turn, can affect wildlife, so considered as moderately impacted.

Table 5.1 reveals, for instance, that laser detection (measuring an oblique or horizontal distance) is costly and should therefore mostly be deployed at high-risk locations, only if a clear and relatively short line of sight exists. In turn, the wire-loop approach (tying weak electric cable loops to trees or other heavy natural or anthropogenic features that are located at the edge of the eroding bank) is among the most affordable and efficient options. Monitoring water levels or water quality parameters in real-time may not be the most reliable erosion-detection approach. Still, it offers the opportunity to collect hydrological and aquatic information that may be important to other users. Finally, installing a series of stakes at different locations away from the top of the bank represents a very accessible erosion monitoring option. However, it still requires some form of observation or an automated movement-detection device.

5.2 Experimental Monitoring Results – Engineer Creek

The objective of this subsection is not to present a comprehensive dataset but a result subset of erosion monitoring approaches tested during this project. **Figure 5.1** presents a sequence of two pictures from a remote camera, taken 4 days apart, looking perpendicularly towards a fast-migrating meander of Engineer Creek located at Km 194.0 of the Dempster Highway. During that runoff event, a row of trees (see yellow arrows pointing at small spruces) was lost as high-flow induced erosion occurred. **Figure 5.2** presents a view of the same site, looking downstream a couple of months later, and showing the trees that gradually collapsed into the channel. A real-time camera at that location, although more costly to operate in the absence of a cellular network (as stated in **Table 5.1**), would have informed highway crews of current bank movement, triggering a targeted or multi-site investigation. This erosion event coincided with (was caused by) a rain-driven runoff event that generated a higher peak flow than the preceding snowmelt event, as shown in **Figure 5.2** (water level only).



FIGURE 5.1. PICTURES FROM A REMOTE CAMERA REVEALING THE LOSS OF SEVERAL SMALL RIPARIAN TREES TO THE CREEK CHANNEL BETWEEN JUNE 8 AND JUNE 12, 2025 (DEMPSTER H., KM 194.0). FIVE WOOD STAKES ARE VISIBLE ON THE LEFT IMAGE. NO STAKE WAS LOST DURING THIS EROSION EVENT.



FIGURE 5.2. DOWNSTREAM VIEW OF KM 194.0 SHOWING SEVERAL TREES THAT ARE GRADUALLY FALLING INTO ENGINEER CREEK (SEPTEMBER 2025).

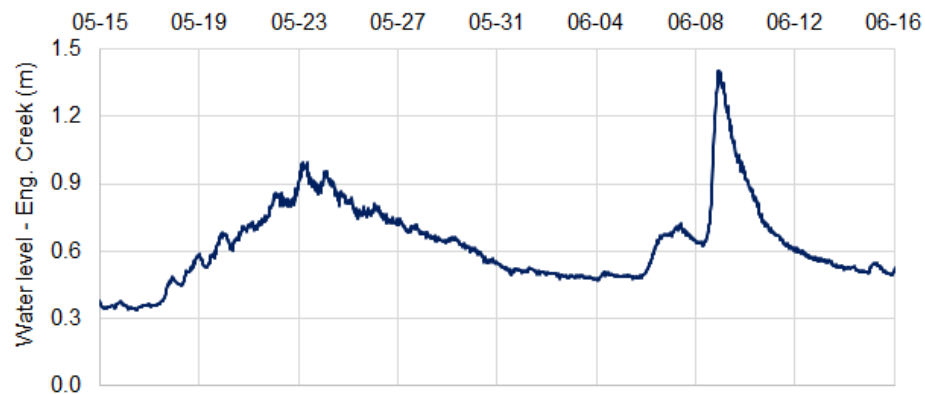


FIGURE 5.3. WATER LEVEL DATA FROM ENGINEER CREEK IN 2025 (AT KM 178 OF THE DEMPSTER H.)

One of the wire-loops (out of five connected to the Campbell Scientific datalogger) tied to small trees at Km 183.3 of the Dempster H. along Engineer Creek broke on June 9, 2025, at 10:00, during the same runoff event as described in **Figure 5.1**. This information came in the form of a sudden change in the binary signal transmitted by the datalogger. The wire was easily reconnected to another tree during the following site visit.

In addition to real-time or continuous monitoring strategies, annual on-site investigations enabled the documentation (quantification) of erosion (erosion rates) at all priority sites listed in **Table 4.2** (in **Section 4** of this report). **Figure 4.3** presents an example of a satellite, LiDAR, or drone-derived analysis to determine the extent and rate of bank migration. Another affordable approach to achieve similar results was to install a series of benchmarks (wood stakes) and reassess their separation distances to the eroding bank during field visits (**Table 5.1**). **Figure 5.4** presents an example where two wood stakes, installed 1 m apart, out of a line of five, were lost to erosion at Km 182.1 of the Dempster H. between 2024 and 2026.



FIGURE 5.4. LEFT BANK OF ENGINEER CREEK IN SEPTEMBER 2024 (LEFT) AND JUNE 2026 (RIGHT) SHOWING THE LOSS OF TWO WOOD STAKES (PINK ARROWS) LOCATED AT DISTANCE 0.0 AND 1.0 M FROM THE BANK EDGE. THAT BANK RECEDED BY 2 M (STAKE 2.0 M WAS AT THE NEW BANK EDGE) IN 1.5 YEARS. PICTURES WERE TAKEN DURING SITE VISITS BY YUKONU AND ALSO REVEAL THE LOSS OF TWO SMALL TREES (OTHER PINK ARROWS).

5.3 Key Considerations

Based on experience acquired during the 2024-26 monitoring campaign at all priority erosion sites, here are some important takeaways. This short list considers that erosion monitoring budgets are limited and need to be strategically allocated while prioritizing the safety of road users, and that, in most cases, only one bank of a stream or river is easily accessible to perform observations and deploy instruments:

- **Wandering Gravel-Bed Dynamics:** Channel migration events are not only episodic in time, but can also shift direction for various reasons, including the formation of log jams or the exposure of a non-erodible rock outcrop that contributes to transferring erosional energy elsewhere. Therefore, the monitoring strategy cannot be finalized remotely and must rely on at least one field visit during which judgement and experience-based observations are completed. The strategy may need to be modified over time to avoid deploying costly instruments in a suboptimal context (e.g., if the channel migration direction changes, cameras may no longer be needed). It is common that erosion will happen near a monitored location, but not exactly where instruments are deployed (e.g., erosion just outside the camera frame).
- **Vulnerability of instruments to wildlife:** Cables or instruments placed on the ground near the bank edge are likely to be moved, pulled, or broken by animals, especially large mammals seeking access to water. Therefore, cables should be buried and anchored, and autonomous instruments should not stand in or close to animal paths. Cables should also be protected from rodents using appropriate methods, including metal protective layers.

- **Instruments lost to erosion:** Losing erosion monitoring devices to erosion is highly frustrating (especially if data is also lost) and not environmentally suitable. Installing something other than a wood stake at or close to the edge of an eroding bank is therefore never recommended. In this context, the wire-loop approach seems appropriate because no instrument meant to measure ground movement falls into the channel when the bank recedes. For the same reasons, lasers and cameras should be installed some distance away from the bank and track the movement of a stake/target rather than the movement of the bank itself.
- **Drone surveys:** Performing annual drone surveys may be considered cost-effective for sites where the separation distance between the stream edge and the road embankment (or another asset) has been quickly decreasing over the years. Comparing drone-derived products over time may reveal subtle processes such as the steepening of a bank (not visible from the road or satellite imagery), the stabilization of a gravel bar by growing vegetation, or changes to channel conditions upstream and downstream of a site of interest. Therefore, the monitoring strategy (described next) for a specific site may also be informed by analyzing a sequence of aerial imagery or topographic data.
- **Weather and flow monitoring:** Hydrometeorological instruments are not the most accurate or reliable for forecasting and detecting erosion events (**Table 5.1**) simply because they track factors that drive erosion, not the erosion process itself. However, they can be deployed at sites that are not immediately subject to erosion (or any other natural hazard), and they are likely to provide critical data to understand (predict) past (future) erosion events over long distances (at multiple sites, unless highly localized ice processes are the cause of erosion). Their deployment, ideally with real-time data access, is therefore recommended at data-sparse locations (e.g., there are no government hydrometric stations along Engineer Creek).

The following subsection compiles some of this information to propose an erosion monitoring system.

5.4 Proposed Erosion Monitoring System (EMS)

The initial step to develop an EMS is to define a spatial domain. This can be restricted to a single erosion site, or it can include a road segment that parallels one or several streams/rivers. It could also include several consecutive or non-consecutive road segments with multiple meander encroachment sites. Then, a domain-wide assessment must be completed to evaluate the erosion risk for each site. The **definition of risk** can correspond to what is described in **Section 3.2** (essentially a time to impact), or it can include both an annual probability of encroachment (e.g., 10%) and a level of consequence associated with road closure and repair (e.g., \$1M; translating into a current risk of \$100K/y, to be updated over time). This initial risk assessment needs to consider existing erosion protection structures, as well as their current integrity and vulnerability.

Once site-specific risk levels have been established, an adapted monitoring strategy is defined within the EMS: Annual or multi-annual, on-site surveys (e.g., georeferenced drone imagery) may

be sufficient to document the erosion rate of slowly migrating banks or along banks still at a safe distance (e.g., >50 m) from the road infrastructure (e.g., low risk because of a low short-term probability of embankment damage). When a drone-based survey can establish baseline information about channel geometry, it is also possible to quickly deploy a drone following a high-impact event to quickly assess if there has been a sudden change. In turn, more costly, real-time and continuous monitoring devices are justified to track bank movements at high-risk sites (such as those identified in **Section 4, Table 4.2**, but also potentially where the level of consequence is far greater than at other sites).

At a watershed or regional (domain-wide) scale, the minimum instrumentation level is to install (or have access to) a remote weather station (measuring at least daily snow depth, hourly air temperatures, and hourly precipitation). One or several hydrometric gauges can also be deployed to document water levels from spring breakup to fall freeze-up. For high-risk sites, as long as mitigation measures have not been implemented, weather forecasts need to be included in the system, and appropriate alarm thresholds (e.g., more than 20 mm of rain in 12 h) must be determined, based on local knowledge, scientific experience, or observations and measurements.

The site-specific erosion risk level within the domain must be reassessed: 1. after a moderate or major runoff/erosion event, 2. once an erosion mitigation measure has been implemented, or 3. on an annual or multi-year (e.g., < 5 years) basis otherwise. This targeted approach aims to optimize monitoring and survey costs while maintaining infrastructure safety and not overwhelming personnel. In other words, the EMS is expected to evolve through update cycles (as streams and riverbanks move within the domain) in a perspective of continuously, cost-effectively, and proactively tackling erosion risks.

Figure 5.5 presents the proposed EMS for the lower Dempster Highway and a section of the North Klondike Highway near Dawson. This diagram considers the relatively fast hydrological response of small and steep watercourses, the remoteness and absence of cellular coverage, the current instability of several stream segments, as well as specific erosion processes observed in recent years. Details (e.g., instrument types, weather parameter thresholds) of the system need to be defined using local knowledge, internal resources, and possibly scientific/engineering expertise.

Figure 5.5 also includes an erosion mitigation component (green box), which is presented in detail in **Section 6**, as well as an early warning protocol, defined in blue boxes and described next.

5.5 Proposed Early Warning Protocol (EWP)

The Department of Highways and Public Works (HPW) already has experience in proactively closing roads impacted by geohazards, including floods and unexpected washouts, to reduce the risk of incidents. However, as expressed by highway forepersons, access to a diversity of reliable information can only contribute to more effective and targeted interventions. This section suggests how data and information can be transferred and communicated effectively to inform decision-making when it matters. The authors also acknowledge that weather data collected at a watershed or regional scale and weather forecasts complement Environment and Climate Change Canada's (ECCC) recently updated Colour-coded Weather Alerts.

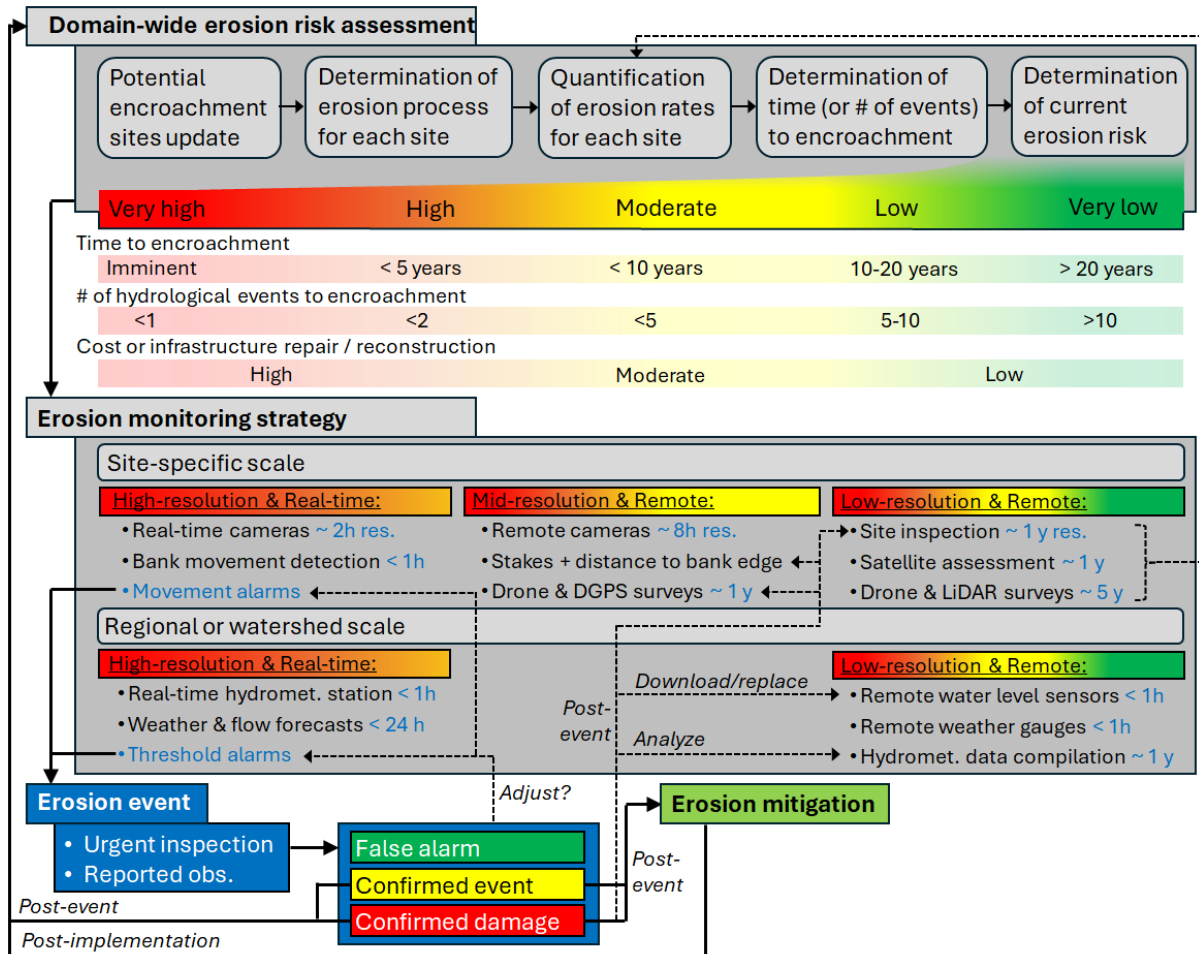


FIGURE 5.5. DIAGRAM PRESENTING THE PROPOSED STREAMBANK EROSION MONITORING SYSTEM (EMS) FOR THE LOWER DEMPSTER HIGHWAY (KM 0 TO 240) AND FOR PARTS OF THE NORTH KLONDIKE HIGHWAY (KM 660 TO 700). COLOUR CODES (RISK LEVEL, FROM GREEN TO RED) ARE HARMONIZED WITH THOSE PRESENTED IN TABLES 3.1 & 3.2. BLUE CELLS REPRESENT A SUMMARY OF THE EARLY WARNING PROTOCOL (EWP) WHEREAS THE GREEN CELL INTRODUCES THE EROSION MITIGATION PART OF THIS REPORT.

Figure 5.6 presents additional information on the blue boxes (i.e., Erosion Event) defined in Figure 5.5. The EWP begins with a **routine assessment** (potentially performed daily by Area Superintendents, depending on the season) of current and short-term conditions. It emphasizes four parameters (i.e., erosion drivers): water or flow, liquid precipitation, temperatures (driving snowmelt rates), and ice conditions (or breakup detection or forecasted intensity). Any forecasted value above site- or watershed-specific thresholds triggers a **forecast erosion protocol**, whereas an alarm (including ice movements reported/detected) triggers an **erosion event protocol**. Site inspections and the verification of monitoring equipment could involve highway forepersons. In turn, a post-event infrastructure inspection may require the expertise of a qualified engineer.

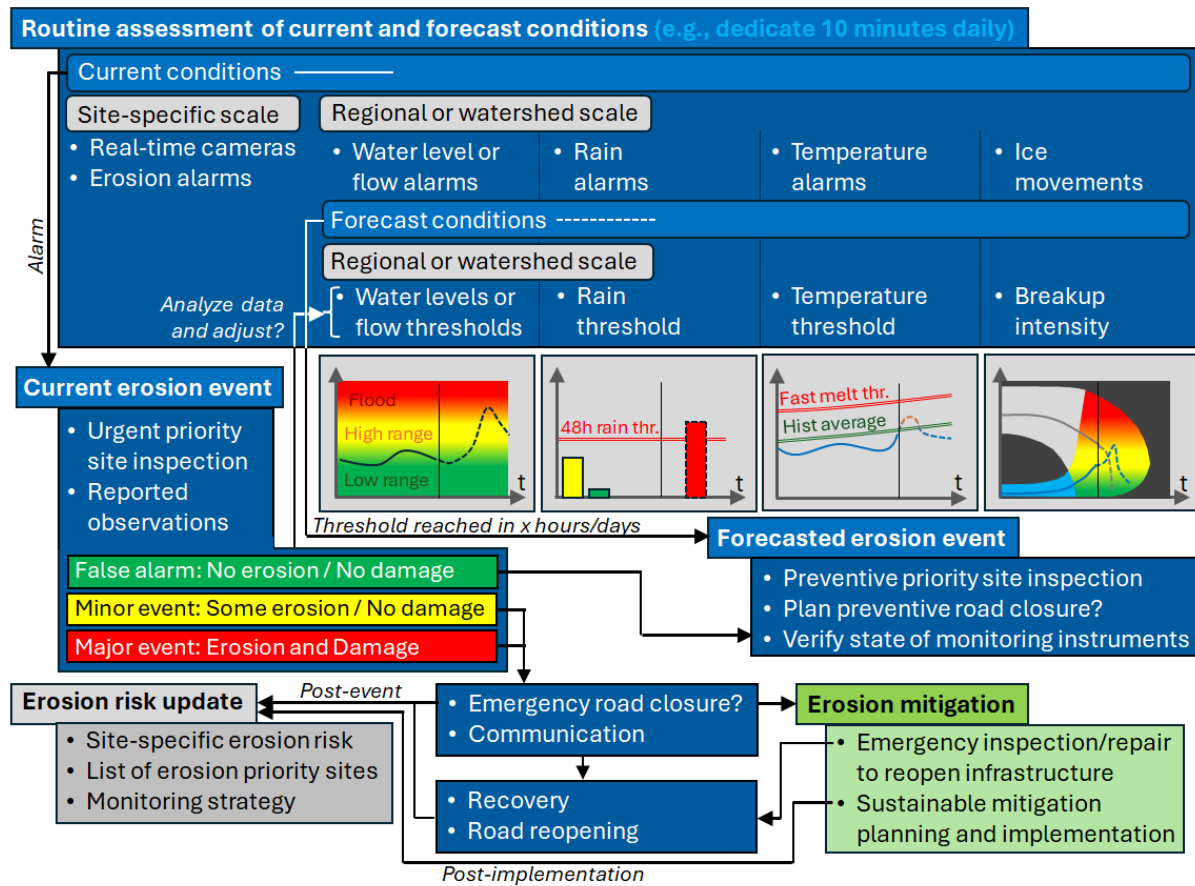


FIGURE 5.6. DIAGRAM PRESENTING THE PROPOSED EARLY WARNING PROTOCOL (EWP) FOR THE LOWER DEMPSTER HIGHWAY (KM 0 TO 240) AS WELL AS FOR PARTS OF THE NORTH KLONDIKE HIGHWAY (KM 660 TO 700).

Readers should be aware that **thresholds for specific sites or watersheds**, depicted in the small graphs in Figure 5.6, are defined in a companion report (Turcotte et al., 2026b) emphasizing open water floods in small watersheds. These thresholds may differ from those defined in ECCC color coded alerts and will need to be confirmed and updated over time. The reason for this is simple: there are very few documented floods in the studied domain, in part because of the lack of historical recorded events and associated hydrometeorological data.

6 Mitigation Considerations

This section outlines considerations, design guidelines, and recommendations for mitigating riverbank erosion risks along the North Klondike and Dempster Highways. It draws heavily upon the foundational framework established in the recent *Yukon Lakeshore and Riverbank Erosion Guidance* document prepared for the Yukon Government (SLR, 2026). While that document provides territory-wide, high-level guidance for managing fluvial hazards, this section specifically addresses the unique geomorphological, thermal, and logistical challenges of the Dempster and North Klondike Highway study area.

Text-based mitigation considerations and recommendations supported by annotated visuals for all 12 priority encroachment sites (**Table 4**)—as well as four other high-priority locations identified during routine field monitoring over the course of this project—are provided in **Appendix C**.

6.1 Traditional Erosion Mitigation Approaches

Historically, erosion mitigation along northern highway corridors has been heavily reactive, characterized by emergency responses to active washouts rather than proactive, highway segment-scale planning. The default traditional approach, which also seems to overlook several channel morphology concepts, has almost exclusively been the application of riprap revetments constructed at the immediate point of failure. However, the remote nature of the Dempster and North Klondike Highways presents severe logistical constraints. There is a distinct scarcity of bedrock sources capable of producing the large-calibre (Class II or III) riprap required to withstand extreme flow and ice forces. This material scarcity frequently results in the application of undersized rock, or the construction of revetments with insufficient longitudinal extent and toe embedment depth, ultimately leading to recurring failures and significant cumulative repair costs.

Engineer Creek presents a particularly challenging environment for traditional mitigation. It is a dynamic, high-energy wandering gravel-bed morphology characterized by large sediment pulses and frequent avulsions. Furthermore, Engineer Creek was anthropogenically straightened in numerous locations before 1977 to accommodate highway construction (e.g., **Figure 4.5**), which artificially shortened and steepened the channel. The river is currently re-adopting a more natural sinuosity, driving exceptionally high lateral migration rates that frequently overwhelm traditional riprap applications. This is occurring as climate change increasingly impacts erosion drivers.

6.2 Lessons Learned from the Dempster Highway

Historical mitigation efforts along the Dempster Highway provide critical lessons that must inform all future designs along the corridor, which are summarized in the bullets below and addressed in the new Yukon Erosion Guidelines (SLR, 2026):

- **Geotextile Slip Planes:** Placing heavy riprap directly on top of smooth, non-woven geotextile fabric on steep embankment slopes has historically created a low-friction "slip plane" (**Figure 6.1**). Without proper terracing or a granular filter layer, the entire rock revetment can slide *en masse* into the channel under its own weight or when subjected to dynamic ice loading.



FIGURE 6.1. RIPRAP HAS BEEN DISPLACED ATOP GEOTEXTILE AT DEMPSTER HIGHWAY KM 107.8.

- **Scour Upstream of Riprap:** Due to material scarcity and budget constraints, historical riprap placements have often lacked sufficient longitudinal length. When the armouring does not extend far enough upstream, high-velocity flows attack the unprotected bank immediately above the structure (**Figures 2.4, 6.2, and 6.3**). This process, known as "outflanking," allows the river to erode behind the riprap.
- **Erosion Downstream of Riprap:** Hardened banks efficiently carry or deflect hydraulic energy downstream rather than absorbing it. This rapidly accelerates lateral erosion along previously stable, unprotected adjacent banks (**Figure 6.2**). This phenomenon is actively threatening the highway at Priority Site KM 182.1 on Engineer Creek, where existing riprap has exacerbated downstream meander migration. Even where the road embankment is not immediately threatened, this anthropogenic instability increases sediment supply to the channel and can generate impacts far downstream.
- **Insufficient Embedment:** Failing to key the toe of the riprap deep enough into the riverbed—specifically, below the maximum anticipated scour depth that accounts for slight flow acceleration along the revetment—is a cause of failure (**Figure 6.4**). During significant hydrological events, the river can undercut the shallow foundation, causing the upper layers to collapse into the channel, and this can lead to road revetment deformation and failure.
- **Episodic Nature of Erosion:** Documented rates of channel migration toward the highway, determined through comparison of planforms in multiple years/decades of aerial/satellite imagery and presented above and in similar studies, represent long-term averages to support prioritization exercises. Event-based erosion can greatly exceed what is suggested by a corresponding time-averaged rate, so action to protect the highway against washouts must be taken well before the channel is near the toe of the embankment.

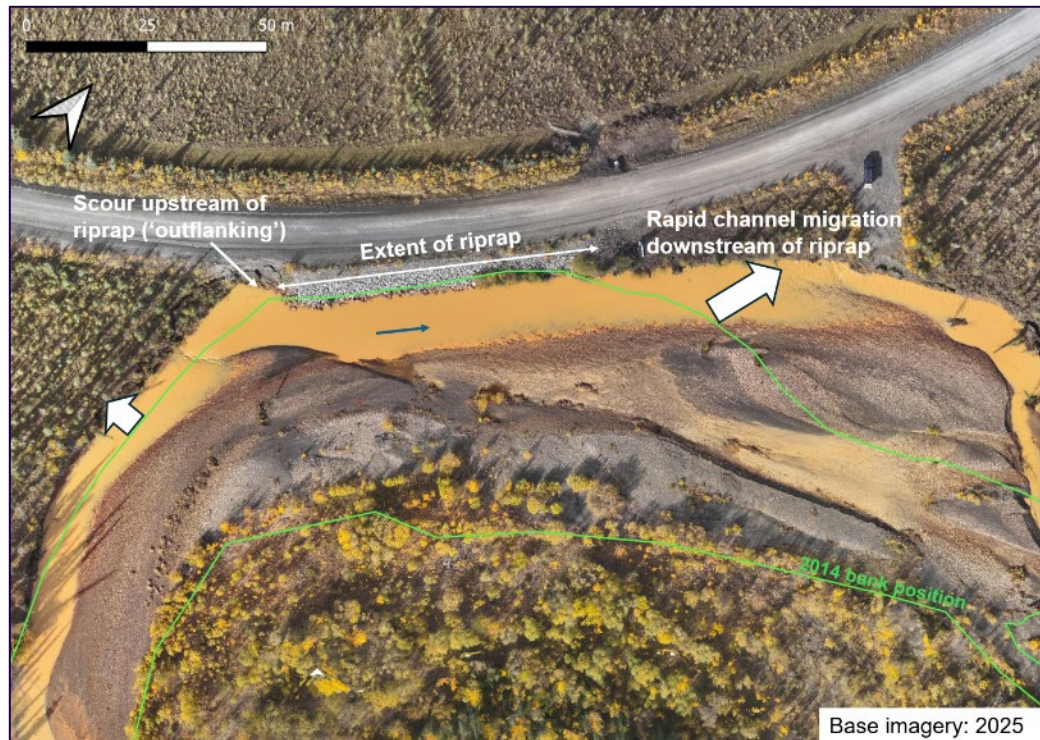


FIGURE 6.2. AERIAL IMAGERY FROM 2025 ILLUSTRATES SCOUR UPSTREAM OF A RIPRAP EMBANKMENT, INITIATING OUTFLANKING OF THE REVETMENT, AND ACCELERATED CHANNEL MIGRATION DOWNSTREAM ALONG THE DEMPSTER HIGHWAY. THE GREEN LINE IS THE 2014 BANK POSITION. RIPRAP WAS INSTALLED IN 2010 AND AGAIN IN 2015.



FIGURE 6.3. SCOUR UPSTREAM OF THE PREVIOUSLY PLACED RIPRAP AT DEMPSTER HIGHWAY KM 182.1



FIGURE 6.4. NEWLY INSTALLED RIPRAP AT DEMPSTER HIGHWAY KM 193.4 WAS LIKELY NOT SUFFICIENTLY EMBEDDED, WHICH HAS CAUSED TENSION CRACKS AND THE RIPRAP TO ‘SLIP’ DOWNWARD BY APPROXIMATELY 25 CM.

6.3 Risk Mitigation Approaches

Modern erosion management underscores the importance of evaluating different risk mitigation strategies beyond traditional, localized riprap placement. Mitigation strategies must be selected based on an evaluation of site-specific constraints, available materials, long-term thermal ground conditions, and ecological/environmental considerations. The primary approaches include:

- **Give Space (Managed Retreat):** Often the most sustainable and cost-effective long-term option, particularly in remote northern environments where mobilizing heavy construction equipment is prohibitively expensive. This approach mitigates risk by removing the vulnerable elements—such as relocating the highway embankment further landward—away from the active hazard zone. By allowing the river to erode and reshape its banks naturally, this strategy preserves the ecological and geomorphological integrity of the system and eliminates the need for repeated structural maintenance. It also negates the risk of transferring erosive energy downstream to unprotected reaches. However, terrain and the potential presence of culturally significant sites can limit the application of this approach.

- Indirect Approaches:** Rather than simply hardening the bank, indirect approaches focus on moving or manipulating the erosive forces of the watercourse. Techniques such as rock vanes, “bendway” weirs, or engineered log jams are utilized to “train” the river, effectively deflecting the high-velocity thalweg away from the vulnerable highway embankment and towards the center of the channel. For instance, along the Mayo River, engineered log ‘spurs’ were constructed along an eroding bank (**Figure 6.5**). In modern designs, these approaches are executed as **Nature-based Solutions (NbS)**, also known as Bio-Engineering), strategically incorporating natural materials—such as native vegetation, rock, soil, and large woody debris—to mimic and work *with* natural system processes. By integrating NbS, indirect approaches not only dissipate hydraulic energy (by increasing channel roughness), but also provide environmental benefits, such as aquatic habitat creation, complex cover for fish, and temperature regulation. NbS and indirect structures are not simple fixes; they require multidisciplinary planning (e.g., pre-emptively farming willows), more spatial area to implement, and a longer time horizon for root systems to establish and provide maximum shear resistance. Their performance in a context of intense and dynamic ice processes remains unclear and needs to be explored through pilot projects. The concept presented in Figure 6.5, although promising in various contexts, has only been proven effective over a short period in a regulated river affected by thermal breakup events (i.e., limited high flow and ice constraints).



FIGURE 6.5. CONSTRUCTED WOOD ‘SPURS’ ALONG THE REGULATED MAYO RIVER THAT DEFLECT ENERGY AWAY FROM THE BANK (PHOTO CREDIT: ECOLOGICAL LOGISTICS AND RESEARCH LTD.).

- Direct Approaches:** These involve constructing hardened and more classic engineered structures directly at the land-water interface to combat erosive forces “head-on”. While effective at arresting bank retreat and protecting critical infrastructure in tightly constrained spaces (such as narrow valleys where highway realignment is impossible), they intentionally create a static riverbank that inhibits natural geomorphological adjustment (**Figure 6.6**). Because hardened banks redirect rather than absorb hydraulic energy, they can inadvertently transfer erosion problems downstream or cause severe localized scour at the base of the structure. Where the cost of importing heavy materials is high, direct approaches (like riprap revetments) should generally be reserved for high-risk situations.



FIGURE 6.6. RIPRAP PLACED ALONG THE BANK OF KLONDIKE RIVER ADJACENT THE NORTH KLONDIKE HIGHWAY DOWNSTREAM OF KM 665.8.

6.4 General Design and Construction Guidance for North Klondike and Dempster Highways

For comprehensive details on designing, procuring, constructing, maintaining, and monitoring erosion mitigation, HPW should refer to the territory-wide *Yukon Lakeshore and Riverbank Erosion Guidance* (SLR, 2026). The following bullets focus specifically on key elements for segments of the North Klondike and Dempster Highways, directly addressing the unique logistical challenges faced by HPW and incorporating regional lessons learned:

- **Emergency Interventions and Long-Term Transition:** The unpredictable nature of northern environments—characterized by extreme hydrological events like the August 2016 floods (**Figures 2.4 and 6.7**)—will inevitably necessitate emergency works. To minimize environmental damage and avoid repeat failure, responders should rely on pre-established "**design typicals**" (e.g., SLR, 2026) to guide rapid interventions. However, because emergency fixes are constructed under adverse conditions, they rarely provide sustainable long-term stability. Once the immediate threat passes, practitioners should return to properly design a permanent structure adapted to the newly altered channel alignment (as indicated in the EWP diagram presented in Figure 5.6).
- **Construction Execution and Material Placement:** Mitigation materials, particularly riprap, must be individually and carefully placed using specialized equipment such as excavators equipped with hydraulic thumbs (**Figure 6.8**). "End-dumping" rock directly from trucks over the embankment (**Figure 6.9**) may be quick. However, it is an unacceptable practice for permanent works, as it causes severe material segregation, poor structural

interlocking, and heightened risk of failure during the next moderate to major runoff or ice run event.

- **Construction Oversight and Field Fits:** To ensure project success, the design team must remain involved throughout the construction phase. Unforeseen subsurface conditions (e.g., permafrost, easily erodible material) or shifting riverbed topography frequently require immediate "field fits" and design adjustments that the original engineering and geomorphology team is best positioned to approve.
- **Proactive Regulatory and Permitting Strategies:** Securing territorial and federal approvals requires significant lead time. To reduce administrative bottlenecks and ensure rapid deployment of maintenance crews, HPW should continue pursuing "reach-scale" or multi-year umbrella maintenance permits for standardized repairs. Additionally, as clarified by Fisheries and Oceans Canada (DFO) in November 2025, regulatory "emergency works" do not require an active washout or severed road; imminent short-term encroachment threats (e.g., expected during subsequent hydrological events) can justify emergency action. For example, the rapid channel avulsion at Priority Site KM 239.5 on the Ogilvie River (**Figure 6.10**) constitutes such an emergency despite embankment damage potentially only starting to occur in 2 years.
- **Lifecycle Monitoring and Maintenance:** Mitigation structures are not "set and forget" assets. Systematic, repeated visual inspections and monitoring are required to track ongoing geomorphological changes around the site and verify the structural integrity of the works. The erosion risk level of those sites should also be reassessed regularly, as presented in the EMS diagram presented in **Figure 5.5** and the EWS diagram presented in **Figure 5.6**.



FIGURE 6.7. TEMPORARY EROSION MITIGATION FOLLOWING A ROAD WASHOUT AT DEMPSTER HIGHWAY KM 180.3 DURING THE AUGUST 2016 FLOOD (PHOTO CREDIT: HPW). 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.



FIGURE 6.8. CAREFUL PLACEMENT OF RIPRAP ON AN EMBANKMENT USING SPECIALIZED EQUIPMENT LEADS TO BETTER LONG-TERM RESULTS (PHOTO CREDIT: HPW). NOTE THAT IN THIS PHOTO, THE RIPRAP IS CAREFULLY BEING PLACED ATOP GEOTEXTILE, WHICH CAN FORM A SLIP-SURFACE AND CONTRIBUTE TO REVETMENT FAILURE. A PROPERLY GRADED STRUCTURE WITH A SUBSTRATE MADE OF SAND AND GRAVEL REPRESENTS A SUITABLE ALTERNATIVE. LOCATION: DEMPSTER HIGHWAY KM 179.6.



FIGURE 6.9. EMERGENCY RIPRAP INSTALLATION UTILIZING END-DUMPING METHODS FOLLOWING THE AUGUST 2016 FLOOD AT DEMPSTER HIGHWAY KM 165.5 (PHOTO CREDIT: HPW). WHILE EXPEDIENT FOR RAPID RESPONSE, THE LACK OF KEYED PLACEMENT AND MATERIAL SEGREGATION TYPICALLY RESULTS IN POOR STRUCTURAL INTERLOCKING AND LIMITED LONG-TERM RESILIENCE.



FIGURE 6.10. AN ERODING BANK OF OGILVIE RIVER IS WITHIN A FEW METRES OF THE ROAD EMBANKMENT AT DEMPSTER HIGHWAY KM 239.5 (PHOTO CREDIT: SLR, 2025). THE NEXT SIGNIFICANT HYDROLOGICAL EVENT MAY LEAD TO A ROAD WASHOUT.

6.5 Site-specific Erosion Risk Mitigation

Appendix C summarizes erosion processes and mitigation recommendations for 16 priority sites: 12 sites from the original prioritization exercise, plus an additional 4 sites identified during routine field monitoring. **Table 6.1** presents a summary of the urgency of mitigation, recommended risk mitigation approaches (as defined in **Section 6.2**), and future monitoring levels for each of these 16 sites (as a complement to what is presented in **Figure 5.5**).

TABLE 6.1. SUMMARY OF PROPOSED MITIGATION URGENCY AND TYPE AND MONITORING METHODS. FURTHER DETAILS AND RECOMMENDATIONS FOR EACH SITE ARE PROVIDED IN APPENDIX C.

Hwy KM	Watercourse	Mitigation Urgency ¹				Recommended Type of Mitigation ²			Monitoring Methods ³	
		Emergency	Priority	Proactive	No Mitigation Required ⁴	Direct	Indirect	Give Space	Real-time	Low-res.
665.8	Klondike River			X		X	X		X	X
86.1	East Blackstone River		X			X				X
107.8	East Blackstone River		X			X				X
108.9	East Blackstone River		X			X				X
115.6	Blackstone River			X				X	X	X
116.2	Blackstone River			X				X	X	X
165.5	Engineer Creek		X			X	X			X
170.0	Engineer Creek				X					X
171.9	Engineer Creek			X			X			X
182.1	Engineer Creek	X				X	X		X	X
183.3	Engineer Creek			X			X			X
193.4	Engineer Creek		X			X	X		X	X
194.0	Engineer Creek			X			X		X	X
218.4	Ogilvie River			X			X			X
232.1	Ogilvie River				X					X
239.5	Ogilvie River	X				X	X		X	X

1. Mitigation Urgency – *Emergency*: before next freshet; *Priority*: mitigation implementation/adjustment within 2 years; *Proactive*: consider mitigation within the next 5 years; *No Mitigation Required*: not currently required but that may change in the future.
2. Recommended Types of Mitigation – See Section 6.2. Some sites can benefit from using both Direct and Indirect Approaches in combination.
3. Monitoring Methods – *Real-time* – install equipment capable of providing continuous, real-time data (e.g., cameras, ErosionAlert); Low-resolution. – desktop methods or simple field approaches (e.g., monumented stakes or photographs); See Figure 5.5 for more detail.
4. After on-site assessments over two years, the risk level of these sites, initially identified as high-risk, can be reduced.

7 Conclusions and Recommendations

The Yukon's road network not only connects communities and supports the territory's economy; it is also a key asset from an Arctic Security and National Sovereignty perspective. New geopolitical and socioeconomic realities make these transportation corridors increasingly valuable, whereas changing climate and hydrological conditions translate into an increasing risk to those assets. This report has: 1. Explained erosion processes that will continue to affect northern roads built along streams and rivers, and 2. Proposed applied solutions to cost-effectively and environmentally respectfully reduce the risk of erosion damage to those roads in a context of increasing use (e.g., population growth) and more frequent extreme weather events. The authors of this report believe that sharing knowledge about river erosion processes and proactively planning erosion risk reduction (i.e., strategic monitoring and informed remediation) can ultimately reduce the short- and long-term costs of highway maintenance.

This project was funded by Transport Canada's National Trade Corridor Fund (NTCF) program. The knowledge, approaches, and tools introduced in this final report are not only applicable to the last segment of the North Klondike Highway (connecting the Yukon to Dawson) and the first segment of the Dempster Highway (connecting the Yukon to one of its most emblematic parks as well as to the Northwest Territories); they are transferable to many other northern roads of Canada. Importantly, while roads generally fall under the jurisdiction of territorial and provincial governments, they are located on the Traditional Territories of the First Nations, Inuit and Metis people of Canada. Local and Traditional knowledge of cold-region watersheds and watercourses cannot be overstated. Inviting Indigenous participation in future infrastructure projects that involve access to their land and water would be mutually welcomed and appropriate. The authors of this work acknowledge that co-developed and First Nation-led studies represent the future of applied research in and outside of the Yukon.

The authors of this report present the following **recommendations**:

➤ **Audience specific training:**

- Read (and access, as needed) the new erosion guidance document prepared by SLR (2026) for the Government of Yukon, Department of Highways and Public Works. The current project serves as a practical, corridor-specific application of this overarching erosion guidelines.
- Promote opportunities to inform and train all levels of HPW personnel directly or indirectly involved in the monitoring, maintenance, and repair of Yukon roads impacted by water-related hazards.
- Set a budget to document the origin and impact of major future erosion events.
- Continue testing existing and new technologies to detect streambank erosion events cost-effectively.

➤ **Erosion Monitoring System (EMS):**

- Test and implement the EMS described in **Figure 5.5** for the Lower Dempster and the Klondike Highway near Dawson.
- Explore opportunities to expand or transfer this EMS to other Yukon (or northern) highway segments that are exposed to streambank erosion.
- Take advantage of this EMS structure to collect useful data for calibrating alarms and thresholds linked to erosion events and erosion damage, and to improve our knowledge of broader hydrogeomorphic processes/drivers in the North.

➤ **Early Warning Protocol (EWP):**

- In collaboration with Yukon First Nations, Environment and Climate Change Canada (ECCC), Yukon Government - Environment's Water Science and Stewardship Branch, and Yukon Government - Community Services' Emergency Measures Organization, refine, adopt, and definite responsibilities for the proposed EWP described in **Figure 5.6**.
- Consider a transfer/adaptation of this EWS to other Yukon highway segments.

➤ **Erosion mitigation:**

- Consider site-specific mitigation options in **Appendix C**.
- Plan for an immediate emergency intervention at very high erosion risk sites (e.g., Km 182.1, 193.4, 211.2, 214.4, 238.6, and 239.5 of Dempster Highway) to prevent incidents and environmental impacts.
- Request, from the Department of Fisheries and Oceans (DFO), clarification around the regulatory definition of emergency interventions involving the implementation of direct or indirect structural erosion control measures in a context of meander encroachment. It is the authors' understanding that moderate-to-high erosion risk sites can qualify for an emergency intervention (not only very high-risk sites, as defined in Table 3.1), which means well before (i.e., a few years or hydrological events) the integrity of the road/embankment or the safety of highway users becomes compromised.
- Fund and support a research project on Nature-based solutions (NbS) for erosion control in cold region streams and rivers. This would involve testing real-scale erosion protection interventions at pilot sites (just like on the Mayo River, as presented in **Figure 6.5**) and initiating the farming of native, ice-resistant plants and bushes in the Yukon, potentially near Dawson, where the climate and resources would support this effort.

Acknowledgements

The authors would like to acknowledge the financial support provided by Transport Canada through their NTCTF program. Yukon Government's Department of Highways and Public Works also supported this work by attending meetings, sharing information, and providing access to Highway camps. YukonU researchers and students, as well as Palmer/SLR employees, participated in this work through the collection of field observations and measurements and the installation of monitoring equipment, including Mederic Girard (researcher), Sasha Masson (student), and Cejay Dumadag (student). The authors would also like to thank all administration staff who worked behind the scenes to support this project. This includes YukonU's Safety and Security personnel.

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Appendix A

Initial River Encroachment Inventory and Preliminary Risk Ratings
Klondike and Dempster Highway Erosion Consulting
Palmer, 2023

Memorandum

Date: October 13, 2023

Project #: 2305001

To: Benoit Turcotte – Yukon University

From: Dan McParland and Robin McKillop – Palmer

cc: Ashley Dubnick, Mederic Girard, Stephanie Saal – Yukon University

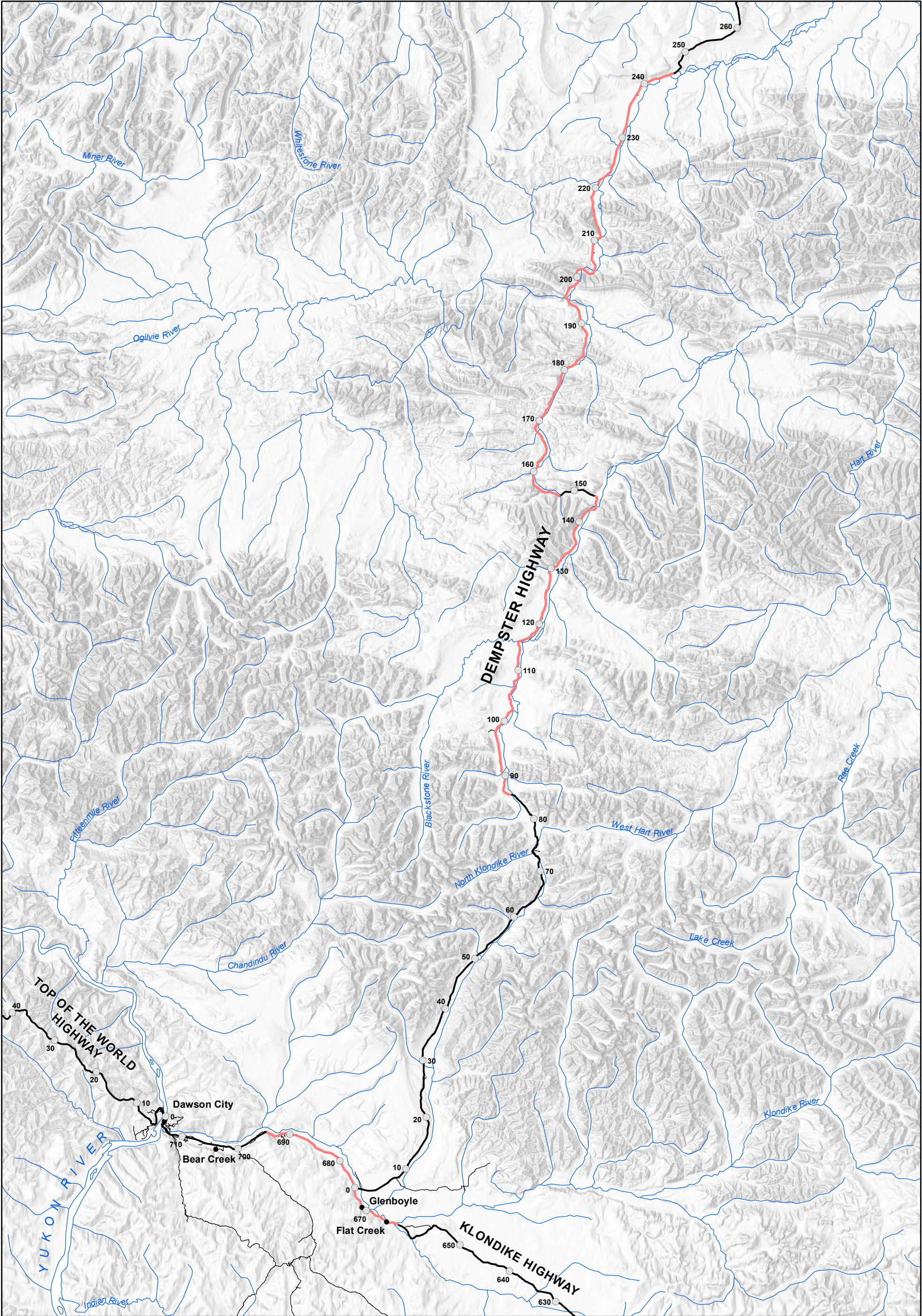
Re: Initial River Encroachment Inventory and Preliminary Risk Ratings
Klondike and Dempster Highway Erosion Consulting

1. Introduction

Palmer was retained by Yukon University Research Centre's Climate Change Research team (YRC-CCR), working in collaboration with representatives from Yukon Government's Department of Highways and Public Works (HPW), National Trade Corridors Fund (NTCF), and First Nation Governments, for fluvial geomorphology assessments, erosion monitoring, and erosion mitigation support along Dempster Highway and Klondike Highway in Yukon. The study area (i.e. highway sections of interest) for this project are Klondike Highway from KM 664 to KM 694 and Dempster Highway from KM 86 to KM 146 and KM 153 to KM 245 (**Figure 1**).

The first stage of this collaborative project was to inventory and characterize locations of highway potentially at risk from riverbank erosion, without intervention. Palmer's geomorphologists utilized available data, such as satellite and aerial imagery, LiDAR data, and surficial geology and permafrost mapping along the river valleys to identify sites where Klondike Highway or Dempster Highway are at risk from watercourse encroachment (i.e. lateral migration). The inventory culminates in a preliminary risk rating and prioritization of sites warranting follow-up actions. This initial phase builds upon an inventory Palmer previously completed for HPW in 2016 (McKillop et al., 2016).

Important background information, including the rationale for the assessment (Section 1), is followed by an overview of the physical setting (Section 2). Section 3 summarizes our methods. Section 4 presents the results of the assessment, including summary tables and figures. Section 5 discusses implications of the assessment and provides recommendations for follow-up actions. Definitions and descriptions of the standardized attributes recorded for each encroachment site (i.e. metadata) are provided in **Appendix A**. The characteristics of each inventoried encroachment site are tabulated in **Appendix B**. A map book showing the location and preliminary risk rating of the inventoried sites is provided in **Appendix C**. Plan view figures of sites recommended for further analyses are provided in **Appendix D**.



LEGEND Highway Kilometre Post Highway Network Highway of Interest Watercourse ¹ 1 - CanVec 1M Series	KEY MAP Site Location	05 Kilometres North American Datum 1983 Yukon Albers Scale: 1:600,000 Page Size: Tabloid (11 x 17 inches) Drawn: SM Checked: DM Date: Oct 2, 2023 Source Notes: Contains information licensed under the Open Government Licence – Yukon. Terrain data provided by ESRI basemapping services.	CLIENT Yukon University
		PROJECT Yukon Erosion Consultant	TITLE Highways of Interest
		Palmer™	REF. NO. 2305001-1-1
		Figure 1	

2. Physical Setting

The sections of North Klondike Highway and Dempster Highway within the study area (**Figure 1**) follow valley bottoms of four larger watercourses (and their tributaries): Klondike River, Blackstone River, Engineer Creek, and Ogilvie River. These rivers exhibit characteristics typical of watercourses that drain mountainous terrain in subarctic environments: relatively high bedloads, mixed single- and multi-thread channel reaches, and vegetation patterns diagnostic of ice effects. Their morphologies are somewhat modified by the presence of extensive discontinuous permafrost, which locally affects bank stability and hydrological processes (Scott, 1978).

The study area traverses large areas of active and inactive fluvial materials, surrounded by slopes comprising colluvium mantling exposed bedrock. Isolated areas of thick till deposits are scattered throughout regions surrounding the Klondike and Blackstone rivers. North of the maximum glacial limit, where Dempster Highway enters the Engineer Creek valley, surficial materials comprise a similar distribution of broad fluvial areas surrounded by colluvial materials, with sporadic bedrock outcrops. Colluvial and periglacial processes are widespread throughout the study area.

The study area transitions from a region of extensive discontinuous permafrost (50-90% areal coverage) as it ascends the North Klondike River valley through North Fork Pass, to a region of continuous permafrost (90-100% areal coverage) north of the Ogilvie Mountains (Heginbottom et al., 1995). Further information relating to physiographic regions, bedrock and surficial geology, glacial history, permafrost dynamics, and mass movement processes along the Dempster Highway can be reviewed in McKillop et al. (2016).

3. Methods

Palmer applied a systematic and comprehensive desktop-based approach to the assessment of river encroachments hazards along the study area. The methods used in each of the main phases of work are described in the sections that follow. A Palmer crew also visited about half of the encroachment sites and captured representative photographs while driving southbound on the Dempster Highway on July 25, 2023.

3.1 Data Compilation and Review

Fundamental to our desktop-based analysis was high-resolution imagery and LiDAR-derived elevation data available through public sources, such as GeoYukon. Along Klondike Highway, high-resolution (0.2 m) ortho-imagery collected in 2019 and LiDAR topographic data collected in 2014 were thoroughly reviewed (additional LiDAR datasets are also available along Klondike Highway and can be utilized for more detailed assessments). For Dempster Highway, high-resolution (0.15 m) ortho-imagery and LiDAR topographic data collected in 2013 or 2014 were utilized. Other imagery readily available through GeoYukon (e.g. SPOT satellite imagery) and in Google Earth, BING and Esri World Imagery, provided additional reference. Google Earth imagery collected in June 2023 covered the majority of the study and provided a very recent snapshot of geomorphic conditions.

In addition, Palmer reviewed data from the following sources to enhance our understanding of the geomorphic, geologic, topographic, and permafrost settings the study highways:

- Surficial geology mapping compilation (Lipovsky and Bond, 2014), providing insight on the regional distribution of different types, textures and thicknesses of surficial materials;
- Permafrost probability mapping of southern Yukon (Bonnaventure et al., 2012), permafrost investigations completed by YukonU (Calmels et al., 2018), and recent permafrost mapping completed by Palmer along the study corridors (for a separate HPW project);
- Existing National Topographic System (CanVec) GIS base data, including digital elevation models, watercourses, waterbodies, topographic contours and transportation corridors, accessed from GeoYukon; and
- Previous geomorphology reports along the study corridors, including the previous erosion hazard inventory (McKillop et al., 2016).

3.2 Identification and Characterization of Encroachment Sites

Using the highway centreline available through GeoYukon, segments of the highway within 50 m of the channel centreline were identified in GIS. Palmer has previously used a 50 m buffer for similar erosion hazard inventories in Yukon and throughout western Canada. At each encroachment site, important attributes were measured (quantitative) or interpreted (qualitative) from the imagery and elevation data sets. The types of recorded data are summarized in **Table 1**. The full metadata set, including all standardized values, is provided in **Appendix A**. A schematic illustrating the separation distance measurements is presented in **Figure 2**.

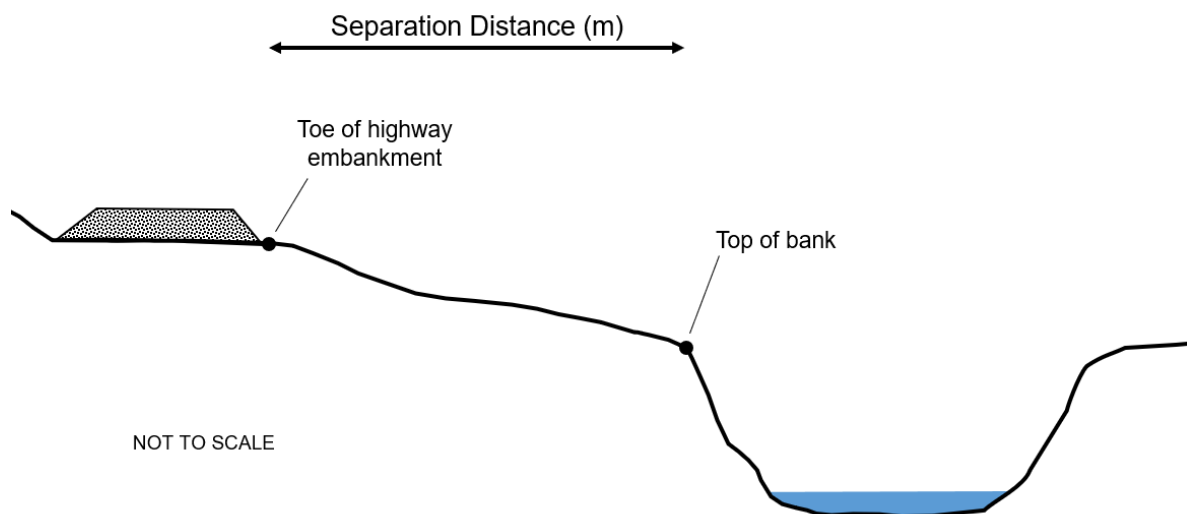


Figure 2. Schematic representation of the separation distance measurement

Table 1. Descriptions of attributes recorded for each encroachment site

Abbreviated Heading	Description
ID	Unique ID given to each inventoried site
Highway	Highway name
Kilometre	Kilometre post at centre of encroachment site (to nearest 100 m)
Start_KM	Kilometre post near the start of encroachment site (to nearest 100 m)
End_KM	Kilometre post near the end of encroachment site (to nearest 100 m)
Seg_Length	Approximate length of at-risk highway segment (to nearest 10 m)
Watercourse	Name of adjacent watercourse
Sep_Dist	Distance between outermost top of bank and inferred edge of highway embankment as measured using the most recent imagery (to nearest 1 m)
Confinemen	Presence/absence of confining topographic features between the highway and the edge of the watercourse
Permafrost	Inferred presence of ice-rich permafrost beneath highway embankment or between watercourse and highway
Rel_Relief	Height between water's edge and proposed highway surface (to nearest 1 m)
Prev_WashO	Evidence or documentation of previous washout from lateral migration
Mitigation	Presence/absence of erosion mitigation
PrevPalmer	Previously inventoried as part of McKillop et al. (2016) study
Factor1*	Physical process or features contributing to observed erosion
Factor2*	Additional physical process or features contributing to observed erosion
Vulnerabil	Interpreted vulnerability of the highway to impact from channel migration based on local morphology, fluvial processes, and permafrost conditions
Risk	Derived from risk evaluation matrix, based on separation distance and interpreted vulnerability

*It is assumed that hydroclimatic conditions (i.e. floods) contribute to erosion at all watercourses. As such, hydroclimatic conditions were not a recorded factor.

3.3 Evaluation of Erosion Risk

Using site-specific characterizations (**Appendix B**), an erosion risk was assigned to each encroachment site – from very high to very low – based on a combination of the recorded separation distance and interpreted vulnerability¹ of the proposed highway segment to impact from fluvial erosion (**Figure 3**). Palmer has applied a similar risk evaluation matrix to erosion hazard projects in Yukon and in several National Parks in western Canada. The results of the evaluation helped prioritize sites for more detailed follow-up assessments.

¹ The term vulnerability reflects how readily an encroaching meander may migrate toward the highway, across its separation distance, considering material properties and evidence of migration.

		Separation distance*		
		Large (31-50 m)	Moderate (10-30 m)	Small (<10 m)
Interpreted vulnerability of highway to lateral erosion	High (e.g., unconfined, prominent/recent/fresh meander scrolls low outer bank, erosion-prone material, thaw-sensitive permafrost, etc.)	Moderate	High	Very high
	Moderate (e.g. point bar, partly scoured outer bank, erodible material, thaw-stable permafrost, etc.)	Low	Moderate	High
	Low (e.g. competent erosion mitigation present, small/no point bar, partly scoured outer bank, confining topographic features, erosion-resistant material, thaw-stable or no permafrost etc.)	Very low	Low	Moderate

*Distance between top of bank and the toe of the highway embankment in most recent imagery or LiDAR dataset

Figure 3. Erosion risk evaluation matrix

4. Results

A total of 87 encroachment sites were identified and inventoried, 12 of which are along Klondike Highway and the remainder are along Dempster Highway. The characteristics of each encroachment site are tabulated in **Appendix B**. The locations of the 87 encroachment sites, symbolized by a point colour-coded according to the risk of impact from watercourse migration, are mapped in **Appendix C**. The total length of encroachment sites along Klondike Highway is 4,620 m, which represents 15.4% of the Klondike Highway study area. The total length of the encroachment sites along Dempster Highway is 28,130 m, which represents 18.5% of the Dempster Highway study area. *Moderate* risk was assigned to 44 sites, followed by *High* (28), *Low* (11), and *Very High* (4) (**Table 2**). No sites were ranked *Very Low* due to the relatively close proximity of the watercourses and the dynamic nature of the watercourses (**Figure 2**). Well over half (52) of the inventoried sites were within 10 m of the highway embankment (**Table 3**).

Table 2. Distribution of risk rating for the documented encroachments sites

Risk Rating	# of Encroachment Sites	Percentage of Encroachment Sites	Total Encroachment Site Length (m)
Very High	4	4.6%	660
High	28	32.2%	7,420
Moderate	44	50.6%	22,800
Low	11	12.6%	1,870
Very Low*	0	0.0%	0
Total	87	100.0%	32,750

*Very Low was retained in the results as it is a possibility based on the risk rating matrix (Figure 2)

Table 3. Separation distance of documented encroachment sites

Separation Distance (m)	# of Encroachment Sites
<10	52
10 to 30	31
31 to 50	4
Total	87

The encroachments sites are located along the following watercourses:

- Blackstone River (9)
- East Blackstone River (12)
- Engineer Creek (36)
- Klondike River (12)
- Ogilvie River (18)

5. Implications and Recommendations

5.1 Distribution of Encroachment Sites

Encroachment sites tend to be clustered where the highway is within the valley bottom adjacent to watercourses that have a dynamic wandering, gravel bed morphology. In particular, Engineer Creek has the most encroachment sites, many of which have a higher risk rating. Engineer Creek exhibits far greater instability than any other watercourse alongside the Dempster Highway. Relatively rapid meander migration, disproportionately large gravel bars, and frequent channel avulsions are likely the result of high sediment supply and a 'flashy' hydrological response to rain events.

McKillop et al. (2016) completed detailed assessments at 26 encroachment sites along Dempster Highway. Four of those sites are outside the study area of this current assignment. The remaining 22 sites are included in this current inventory, with risk ratings that range from *Low* to *Very High* and separation distances that range from 0 m to 26 m. At least nine of the 26 sites have been damaged by lateral migration (either before or following the McKillop et al. (2016) inventory), and at least 11 of the 26 sites now have erosion mitigation (i.e. riprap).

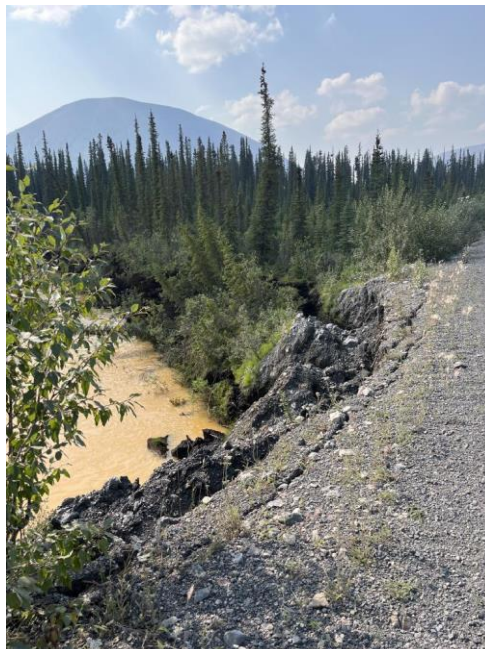
5.2 Sites at Imminent Risk

Four sites have been assigned a preliminary risk rating of *Very High*, all of which are along the Dempster Highway. These are sites that have separation distances of <10 m and a perceived high vulnerability to lateral migration. The four sites are bulleted below with a representative field photograph from July 25, 2023 (immediately below the corresponding bullet), and a plan view map is provided in **Appendix D**. Morphological adjustments during a single flood event could compromise the highway.

- **KM 115.6 (ID # 13) Blackstone River** – Degradation of ice-rich permafrost and river migration are leading to hillslope failure that is compromising the highway. Traffic barriers have already been placed along the highway embankment. Continued slope stability issues are expected.



- **KM 182.1 (ID # 45) Engineer Creek** – Approximately 60 m of riprap was installed along the highway embankment prior to 2013. Erosion has occurred both upstream and downstream of the riprap. Observed erosion in the June 2023 satellite imagery and field photos suggest the highway embankment is already failing at the upstream end of the riprap (see photo below).



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- **KM 193.4 (ID # 54) Engineer Creek** – Rapid lateral migration (45 m between 2013 and 2023) has reduced the separation distance to 0 m. No erosion mitigation is currently present. YRC-CCR informed HPW via email on August 31, 2023 of the imminent erosion risk.



- **KM 239.5 (ID # 73) Ogilvie River** – Near this site, Ogilvie River has two prominent branches. Over the past decade, more flow has been directed into the northern branch, which has contributed to the observed rapid migration towards the highway (43 m of migration between 2013 and 2023).



The 28 *High* risk sites do not appear to represent such imminent risks to the highway. Many of the *High* risk sites have erosion mitigation (i.e. riprap) in place. However, these sites should likely be inspected at least annually and after large floods to document separation distances as morphological adjustments.

5.3 Comparative Overlay Assessments

Historical and recent aerial photography preserves an accurate record of channel changes, providing an effective basis for tracking past channel evolution and forecasting the limits of future bank erosion and associated floodplain and terrace loss. A comparative analysis of historical channel planforms, combined with application of knowledge of fluvial and permafrost processes, can facilitate estimation of where, when and how much land will be lost to erosion adjacent the highways.

Not all *High* and *Very High* risk sites necessarily benefit from comparative overlay analyses, in the context of understanding and forecasting site dynamics. Many of these sites have abutted the highway embankment for decades and many have erosion mitigation measures in place. However, it is recommended that comparative overlay assessments be completed for the 12 sites that have high *vulnerability* to lateral erosion (**Figure 2** and sites identified with an asterisk (*) in the map set in **Appendix C**). These 12 sites are distributed throughout the study area and have separation distances that range from 0 m to 34 m. A plan view map of each of the 12 sites is provided in **Appendix D**. Channel overlay analyses will help refine risk ratings at these sites and help inform the urgency with which erosion mitigation may be needed. Ice-rich permafrost may contribute to bank instability and erosion patterns at at least eight of the 12 sites (KM 115.6, 116.2, 170.0, 182.1, 193.4, 194.0, 232.1, and 239.5). Permafrost investigations and monitoring at these eight locations could be beneficial to help better understand the interaction of fluvial and permafrost processes.

In the upcoming months, 8 to 10 encroachment sites will be prioritized for detailed erosion monitoring programs. The 12 sites proposed for channel overlay assessments may or may not be candidates for the monitoring programs, once considerations are made regarding site accessibility, ground/watercourse conditions, etc.

5.4 Next Steps

The following bullets briefly detail the proposed next steps of this collaborative project to be taken in fall 2023:

- Palmer and YRC-CCR to meet and finalize the encroachment inventory.
- Palmer and YRC-CCR to meet with HPW to brief them on the project, the initial inventory, and the *Very High* risk sites.
- Palmer to complete channel overlay assessments at agreed upon encroachments sites.
- Palmer and YRC-CCR will collaboratively choose 8 to 10 sites for monitoring and begin to establish site-specific monitoring plans for initiation in spring 2024.

6. Certification

This memorandum was prepared, reviewed, and approved by the undersigned.

Prepared By:



Dan McParland, M.Sc., P.Geo.
Senior Fluvial Geomorphologist

**Reviewed and
Approved By:**



Robin McKillop, M.Sc., P.Geo.
Principal Geomorphologist

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Appendix A

Metadata for Standardized Attributes of River Encroachment Sites

Table 1. River Encroachment Site Metadata ('YukonU Initial Erosion Inventory.shp')

Field Name	Description	Values
id	Unique ID given to each inventoried site	Numeric
Highway	Highway name	Klondike Dempster
Kilometre	Kilometre post at centre of encroachment site (to nearest 100 m)	Numeric
Start_KM	Kilometre post near the start of encroachment site (to nearest 100 m)	Numeric
End_KM	Kilometre post near the end of encroachment site (to nearest 100 m)	Numeric
Seg_Length	Approximate length of at-risk road segment (to nearest 10 m)	Numeric
Watercours	Name of adjacent watercourse	Blackstone River East Blackstone River Engineer Creek Engineer Creek Tributary Klondike River Ogilvie River Ogilvie River Tributary
Sep_Dist	Distance between outermost limit of the watercourse and inferred edge of highway embankment as measured using the most recent imagery (to nearest 1 m)	Numeric
Confinemen	Presence/absence of confining topographic features between the road and the edge of the watercourse	U (unconfined) C (confined)
Permafrost	Inferred presence of ice-rich permafrost under of road embankment or between watercourse and road	Null IRP (Ice rich permafrost)
Rel_Relief	Height between water's edge and proposed road surface (to nearest 1 m)	Numeric
Prev_WashO	Evidence or documentation of previous washout from lateral migration	N (no) Y (yes) U (unknown)
Mitigation	Presence/absence of erosion mitigation	N (no) Y (yes) U (unknown)
PrevPalmer	Previously inventoried as part of McKillop et al. (2016) study	N (no) Y (yes)
Factor1*	Physical process contributing to observed erosion	Anthropogenic Avulsion Hillslope Permafrost degradation Tributary
Factor2*	Additional physical process contributing to observed erosion	Anthropogenic Avulsion Hillslope Permafrost degradation Tributary
Vulnerabil	Interpreted vulnerability of the road to impact from channel migration based on local morphology, fluvial processes, and permafrost conditions	L (low) M (moderate) H (high)
Risk	Derived from risk evaluation matrix, based on separation distance and interpreted vulnerability	VL (very low) L (low) M (moderate) H (high) VH (very high)

*It is assumed that hydroclimatic conditions (i.e. floods) contribute to erosion at all watercourses. As such, hydroclimatic conditions were not a recorded factor.

Appendix B

Attributes of River Encroachment Sites

Table 1. Watercourse Encroachment Site Attributes (‘YukonU Initial Erosion Inventory.shp’)

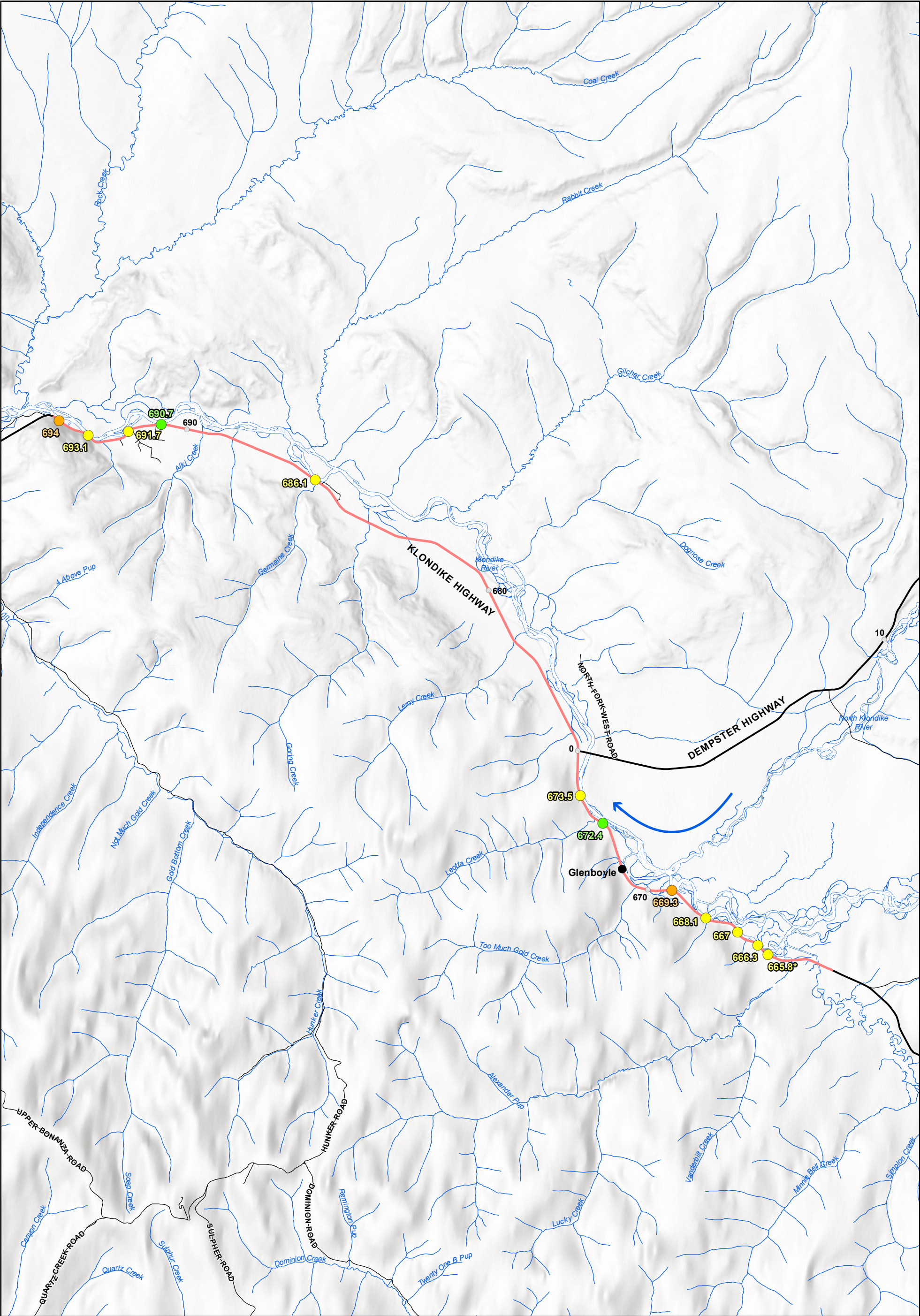
ID	Highway	Kilometre	Start_KM	End_KM	Seg_Length	Watercours	Sep_dist	Confinemen	Permafrost	Rel_relief	Prev_WashO	Mitigation	PrevPalmer	Factor1	Factor 2	Vulnerabil	Risk
1	Dempster	86.3	86.2	86.4	220	East Blackstone River	10	C	N	3	N	N	N	Permafrost		L	L
2	Dempster	87.1	87.0	87.2	180	East Blackstone River	11	U	N	2	N	N	N	Permafrost		M	M
3	Dempster	87.7	87.7	87.7	50	East Blackstone River	12	U	IRP	2	N	N	N	Permafrost		M	M
4	Dempster	88.0	88.0	88.0	80	East Blackstone River	18	C	N	7	N	N	Y	Permafrost		L	L
5	Dempster	89.8	89.8	89.8	80	East Blackstone River	24	U	N	1	N	N	N	Permafrost		L	L
6	Dempster	103.7	103.6	103.8	120	East Blackstone River	20	C	N	7	N	N	N	Permafrost		L	L
7	Dempster	104.6	104.5	104.7	200	East Blackstone River	4	U	IRP	2	Y	Y	N	Permafrost	Tributary	L	M
8	Dempster	105.3	105.2	105.4	120	East Blackstone River	4	U	N	1	U	U	N	Permafrost	Tributary	L	M
9	Dempster	107.3	107.3	107.4	100	East Blackstone River	0	U	N	1	Y	Y	N	Tributary		M	H
10	Dempster	108.8	108.8	108.9	100	East Blackstone River	4	U	N	2	Y	Y	N			M	H
11	Dempster	110.8	110.7	110.9	140	East Blackstone River	20	U	N	1	N	N	N	Tributary		M	M
12	Dempster	111.9	111.9	111.9	90	East Blackstone River	4	U	IRP	2	U	U	N	Permafrost		M	H
13	Dempster	115.6	115.5	115.7	250	Blackstone River	9	C	IRP	17	N	N	N	Permafrost	Hillslope	H	VH
14	Dempster	116.2	116.1	116.3	140	Blackstone River	16	C	IRP	21	N	N	N	Permafrost	Hillslope	H	H
15	Dempster	123.8	123.7	123.9	200	Blackstone River	12	C	IRP	7	N	N	N	Permafrost		M	M
16	Dempster	131.4	131.3	131.5	150	Blackstone River	5	U	N	1	U	Y	Y	Anthropogenic		M	H
17	Dempster	136.1	136.0	136.2	180	Blackstone River	2	U	N	2	Y	Y	Y	Anthropogenic		M	H
18	Dempster	136.9	136.3	137.5	1200	Blackstone River	2	U	N	2	U	Y	N	Anthropogenic		M	H
19	Dempster	138.4	138.3	138.5	130	Blackstone River	21	U	IRP	3	N	N	Y	Avulsion	Permafrost	M	M
20	Dempster	142.3	142.1	142.5	360	Blackstone River	3	U	N	2	U	Y	N	Anthropogenic		M	H
21	Dempster	143.7	143.2	144.3	1100	Blackstone River	7	C	N	4	U	Y	N	Anthropogenic		L	M
22	Dempster	155.0	154.7	155.3	570	Engineer Creek Tributary	21	U	N	4	U	U	N	Hillslope		M	M
23	Dempster	156.5	156.3	156.7	340	Engineer Creek Tributary	21	C	N	3	Y	Y	N	Hillslope		M	M
24	Dempster	164.6	164.6	164.6	80	Engineer Creek	20	U	IRP	3	N	N	N	Permafrost		M	M
25	Dempster	165.5	165.4	165.6	160	Engineer Creek	0	U	N	2	Y	Y	N	Anthropogenic		M	H
26	Dempster	166.5	166.5	166.5	70	Engineer Creek	0	U	N	2	Y	Y	N	Anthropogenic		M	H
27	Dempster	167.3	167.2	167.4	120	Engineer Creek	20	U	N	2	N	N	N			M	M
28	Dempster	169.0	168.8	169.2	360	Engineer Creek	2	U	IRP	1	U	Y	N	Anthropogenic	Permafrost	L	M
29	Dempster	169.7	169.6	169.8	120	Engineer Creek	23	U	N	1	U	U	N			M	M
30	Dempster	170.0	170.0	170.1	100	Engineer Creek	25	U	IRP	1	N	N	N	Permafrost		H	H
31	Dempster	170.3	170.2	170.4	190	Engineer Creek	23	U	N	1	N	N	N			M	M
32	Dempster	171.3	171.0	171.6	660	Engineer Creek	2	U	N	2	Y	Y	Y	Anthropogenic		L	M
33	Dempster	171.9	171.9	171.9	60	Engineer Creek	23	U	N	2	U	U	N	Avulsion		H	H
34	Dempster	172.9	172.8	173.0	110	Engineer Creek	0	U	N	3	Y	Y	Y	Anthropogenic		L	M
35	Dempster	173.4	173.3	173.5	130	Engineer Creek	1	U	N	3	Y	Y	N	Anthropogenic		L	M
36	Dempster	174.7	174.6	174.8	180	Engineer Creek	18	U	N	3	N	N	N	Anthropogenic	Tributary	M	M
37	Dempster	175.4	175.2	175.6	400	Engineer Creek	11	C	N	12	U	Y	Y	Anthropogenic		L	L

ID	Highway	Kilometre	Start_KM	End_KM	Seg_Length	Watercours	Sep_dist	Confinemen	Permafrost	Rel_relief	Prev_WashO	Mitigation	PrevPalmer	Factor1	Factor 2	Vulnerabil	Risk
38	Dempster	176.4	176.4	176.5	100	Engineer Creek	14	C	N	5	N	N	N			L	L
39	Dempster	177.7	177.3	178.1	760	Engineer Creek	4	C	N	4	U	Y	N	Anthropogenic		L	M
40	Dempster	178.6	178.6	178.7	100	Engineer Creek	43	U	N	3	N	N	N	Avulsion		M	L
41	Dempster	178.9	178.8	179.0	140	Engineer Creek	31	U	N	2	N	N	N			M	L
42	Dempster	179.6	179.4	179.8	450	Engineer Creek	4	U	IRP	3	Y	Y	N	Anthropogenic	Permafrost	L	M
43	Dempster	180.8	180.7	180.9	120	Engineer Creek	0	U	N	3	Y	Y	Y	Anthropogenic		M	H
44	Dempster	181.4	181.4	181.5	100	Engineer Creek	0	U	N	2	Y	Y	Y	Anthropogenic		M	H
45	Dempster	182.1	182.0	182.2	120	Engineer Creek	0	U	IRP	3	Y	Y	Y	Anthropogenic	Permafrost	H	VH
46	Dempster	183.3	183.3	183.4	100	Engineer Creek	18	U	N	2	N	N	Y			H	H
47	Dempster	183.8	183.7	183.9	250	Engineer Creek	5	U	N	2	Y	Y	N	Anthropogenic		L	M
48	Dempster	184.6	184.4	184.8	330	Engineer Creek	2	U	N	3	U	Y	N	Anthropogenic		L	M
49	Dempster	185.2	185.0	185.4	340	Engineer Creek	8	U	N	3	Y	Y	N	Anthropogenic	Tributary	L	M
50	Dempster	185.7	185.6	185.8	200	Engineer Creek	4	U	N	2	U	U	Y			M	H
51	Dempster	188.7	188.5	189.0	500	Engineer Creek	0	U	N	3	Y	Y	Y	Anthropogenic		M	H
52	Dempster	189.4	189.3	189.5	220	Engineer Creek	2	U	IRP	4	U	Y	Y	Anthropogenic	Permafrost	M	H
53	Dempster	193.0	192.9	193.1	130	Engineer Creek	36	U	N	4	N	N	N			M	L
54	Dempster	193.4	193.4	193.4	80	Engineer Creek	0	U	N	1	U	N	N			H	VH
55	Dempster	194.0	194.0	194.0	80	Engineer Creek	28	U	N	1	N	N	N			H	H
56	Dempster	194.5	194.4	194.6	150	Engineer Creek	4	U	N	1	U	Y	N	Anthropogenic		L	M
57	Dempster	195.1	195.1	195.1	50	Engineer Creek	26	U	N	1	N	N	Y			M	M
58	Dempster	198.1	197.6	198.6	1000	Ogilvie River	4	U	N	3	U	Y	N	Anthropogenic		L	M
59	Dempster	200.3	199.6	201.0	1400	Ogilvie River	2	U	N	4	U	Y	N	Anthropogenic		L	M
60	Dempster	201.8	201.7	201.9	110	Ogilvie River	4	U	N	2	U	U	N			M	H
61	Dempster	202.4	202.3	202.5	130	Ogilvie River	11	U	N	4	U	N	Y			M	M
62	Dempster	205.0	204.7	205.3	660	Ogilvie River	5	U	N	4	U	Y	N	Anthropogenic		L	H
63	Dempster	210.0	209.2	210.8	1600	Ogilvie River	1	U	N	4	U	Y	N	Anthropogenic		L	M
64	Dempster	213.5	212.6	214.4	1870	Ogilvie River	3	U	N	3	U	Y	N	Anthropogenic		L	M
65	Dempster	217.3	217.2	217.4	130	Ogilvie River	0	U	N	3	Y	Y	N	Anthropogenic		M	H
66	Dempster	218.4	218.3	218.5	270	Ogilvie River	13	U	N	1	U	U	N	Avulsion		H	H
67	Dempster	220.5	219.0	222.0	3080	Ogilvie River	2	U	N	3	Y	Y	Y	Anthropogenic		L	M
68	Dempster	221.3	221.2	221.4	170	Ogilvie River Tributary	9	U	N	1	U	U	Y			L	M
69	Dempster	224.5	223.9	225.1	1120	Ogilvie River	4	U	N	5	U	Y	N	Anthropogenic		L	M
70	Dempster	232.1	232.0	232.2	260	Ogilvie River	23	U	N	3	N	N	Y			H	H
71	Dempster	236.3	236.3	236.3	80	Ogilvie River	20	U	N	1	U	U	Y	Avulsion		M	M
72	Dempster	238.5	238.1	239.0	900	Ogilvie River	0	U	N	1	Y	Y	N	Anthropogenic		M	H
73	Dempster	239.5	239.4	239.6	210	Ogilvie River	6	U	N	1	U	U	Y	Avulsion		H	VH
74	Dempster	243.0	242.2	243.8	1600	Ogilvie River	2	U	N	4	Y	U	Y	Anthropogenic		L	M
75	Dempster	245.0	244.8	245.2	380	Ogilvie River	0	U	N	4	Y	Y	N	Anthropogenic		M	H
76	Klondike	665.8	665.6	666.0	360	Klondike River	34	U	N	2	N	N	N	Tributary	Avulsion	H	M
77	Klondike	666.3	666.2	666.4	260	Klondike River	4	U	N	2	U	Y	N	Anthropogenic	Avulsion	L	M

ID	Highway	Kilometre	Start_KM	End_KM	Seg_Length	Watercours	Sep_dist	Confinemen	Permafrost	Rel_relief	Prev_WashO	Mitigation	PrevPalmer	Factor1	Factor 2	Vulnerabil	Risk
78	Klondike	667.0	666.7	667.3	510	Klondike River	2	U	N	2	U	Y	N	Tributary	Anthropogenic	L	M
79	Klondike	668.1	667.9	668.3	470	Klondike River	2	U	N	4	U	Y	N	Anthropogenic	Avulsion	L	M
80	Klondike	669.3	669.2	669.4	180	Klondike River	0	U	N	2	U	Y	N	Avulsion	Anthropogenic	M	H
81	Klondike	672.4	672.3	672.5	240	Klondike River	10	U	N	2	N	N	N			L	L
82	Klondike	673.5	673.1	674.0	900	Klondike River	3	U	N	4	U	Y	N			L	M
83	Klondike	686.1	685.9	686.3	360	Klondike River	4	U	N	4	U	Y	N	Avulsion		L	M
84	Klondike	690.7	690.6	690.8	260	Klondike River	13	U	N	4	N	N	N			L	L
85	Klondike	691.7	691.6	691.8	200	Klondike River	11	U	N	4	U	Y	N	Avulsion		M	M
86	Klondike	693.1	692.9	693.3	380	Klondike River	2	U	IRP	4	U	Y	N	Anthropogenic	Permafrost	L	M
87	Klondike	694.0	693.8	694.3	500	Klondike River	2	U	N	4	U	Y	N	Hillslope	Avulsion	M	H

Appendix C

Map Book – Location and Preliminary Risk Rating of Encroachment Sites



LEGEND

Preliminary Risk of Highway Impact from Riverbank Erosion

- Very High
- High
- Moderate
- Low

- Highway Kilometre Post
- Highway Network
- Highway of Interest
- Direction of Flow
- Watercourse ¹

1 - CanVec - 50k Series
* Additional Overlay Analyses Proposed

Main Map Extent

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Kilometres

North American Datum 1983
Yukon Albers

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Page Size: Tabloid (11 x 17 inches)

Drawn: SM
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Date: Oct 2, 2023

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NORTH

CLIENT
Yukon University

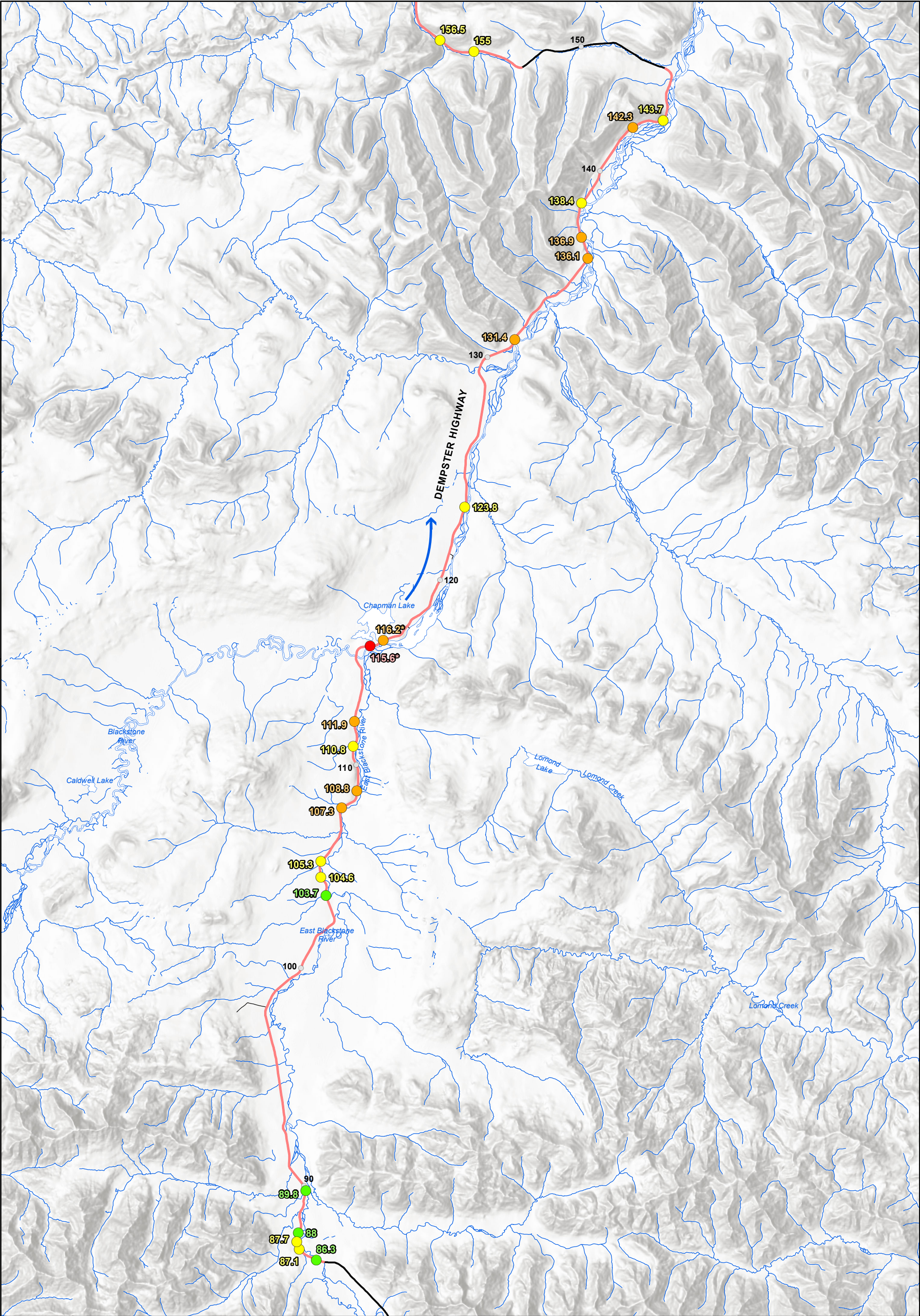
PROJECT
Yukon Erosion Consulting

TITLE
Preliminary Risk of Highway Impact from Riverbank Erosion (Klondike Highway)

Palmer™

REF. NO. 2305001-1-1

Figure 1



LEGEND

Preliminary Risk of Highway Impact from Riverbank Erosion

- Very High
- High
- Moderate
- Low

- Highway Kilometre Post
- Highway Network
- Highway of Interest
- Direction of Flow
- Watercourse ¹

1 - CanVec - 50k Series
* Additional Overlay Analyses Proposed

Main Map Extent

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North American Datum 1983
Yukon Albers

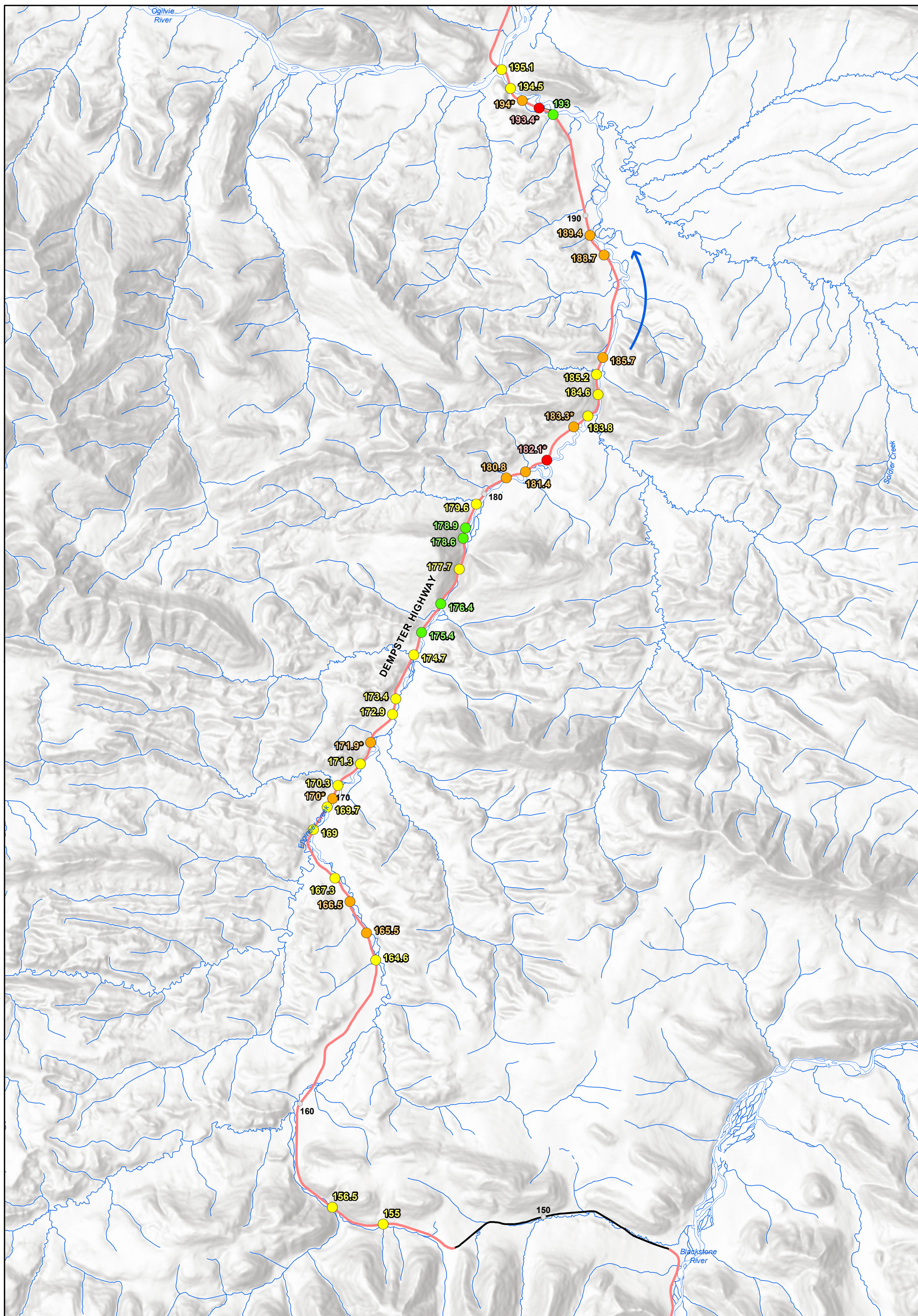
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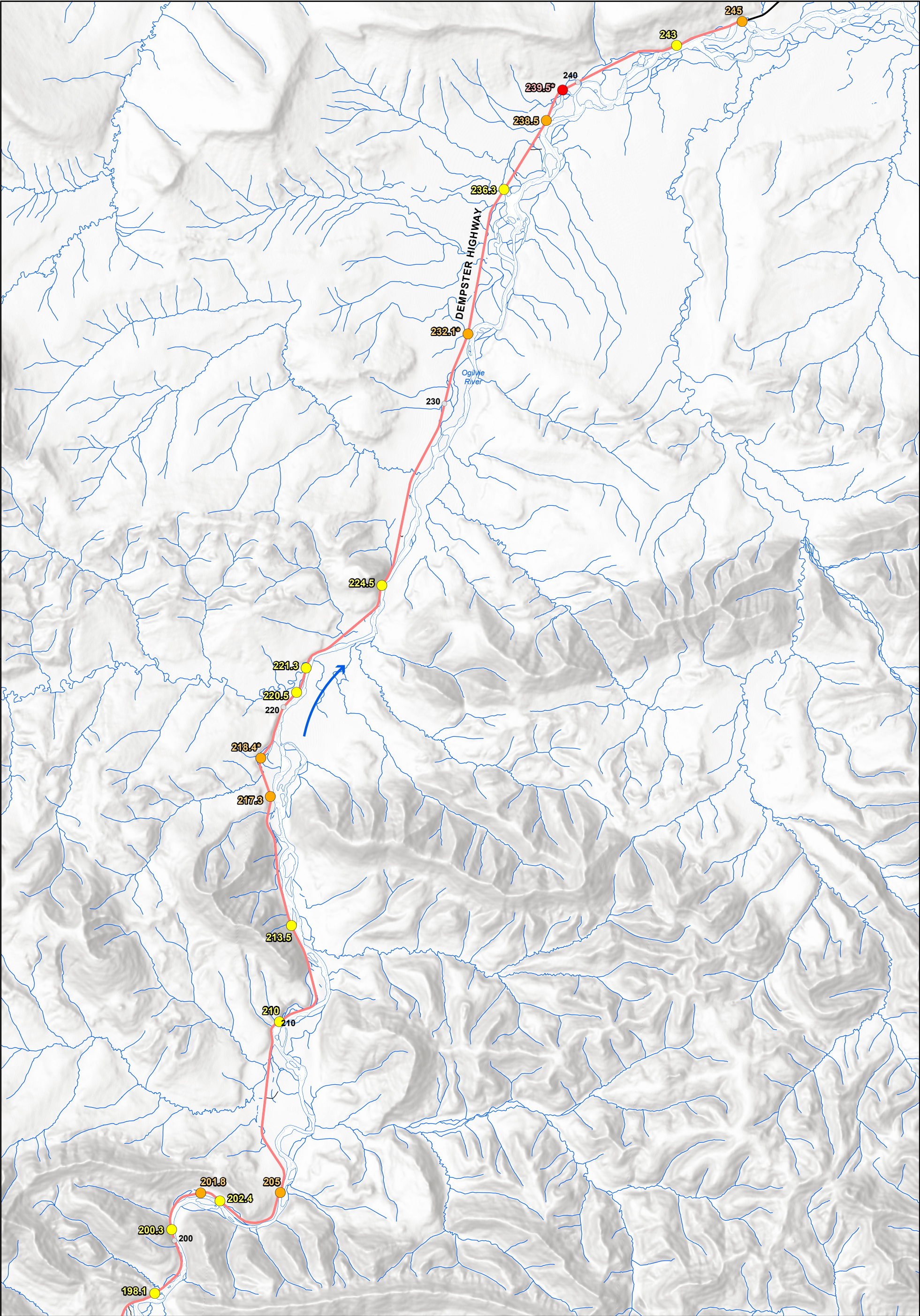
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PROJECT	Yukon Erosion Consulting	
TITLE	Preliminary Risk of Highway Impact from Riverbank Erosion (Dempster Highway - Blackstone River)	
Palmer™	REF. NO.	2305001-2-1
	Figure 2	



LEGEND Preliminary Risk of Highway Impact from Riverbank Erosion - Very High - High - Moderate - Low		LEGEND ● Highway Kilometre Post — Highway Network — Highway of Interest → Direction of Flow ~ Watercourse ¹ ¹ - CanVec - 50k Series * Additional Overlay Analyses Proposed		Main Map Extent		0 1 2 3 4 Kilometres North American Datum 1983 Yukon Albers Scale: 1:100,000 Page Size: Tabloid (11 x 17 inches) Drawn: SM Checked: DM Date: Oct 2, 2023 Source Notes: Contains information licensed under the Open Government Licence – Yukon. Terrain data provided by ESRI global terrain layer. NORTH		CLIENT Yukon University PROJECT Yukon Erosion Consulting TITLE Preliminary Risk of Highway Impact from Riverbank Erosion (Dempster Highway - Engineer Creek) Palmer™		REF. NO. 2305001-3-1 Figure 3	
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LEGEND

Preliminary Risk of Highway Impact from Riverbank Erosion

- Very High
- High
- Moderate
- Low

- Highway Kilometre Post
- Highway Network
- Highway of Interest
- Direction of Flow
- Watercourse ¹

1 - CanVec - 50k Series
* Additional Overlay Analyses Proposed

Main Map Extent

0 1 2 3 4
Kilometres

North American Datum 1983
Yukon Albers

Scale: 1:100,000
Page Size: Tabloid (11 x 17 inches)

Drawn: SM
Checked: DM
Date: Oct 2, 2023

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NORTH

CLIENT	Yukon University
PROJECT	Yukon Erosion Consulting
TITLE	Preliminary Risk of Highway Impact from Riverbank Erosion (Dempster Highway - Ogilvie River)
REF. NO.	2305001-4-1
Figure 4	

Appendix D

Plan View Maps of High Vulnerability River Encroachment Sites



Figure 1. KM 115.6 of Dempster Highway. Separation distance = 9 m, risk rating = Very High, imagery date: June 2, 2023.



Figure 2. KM 116.2 of Dempster Highway. Separation distance = 16 m, risk rating = High, imagery date: June 2, 2023.



Figure 3. KM 170.0 of Dempster Highway. Separation distance = 25 m, risk rating = High, imagery date: June 4, 2023.

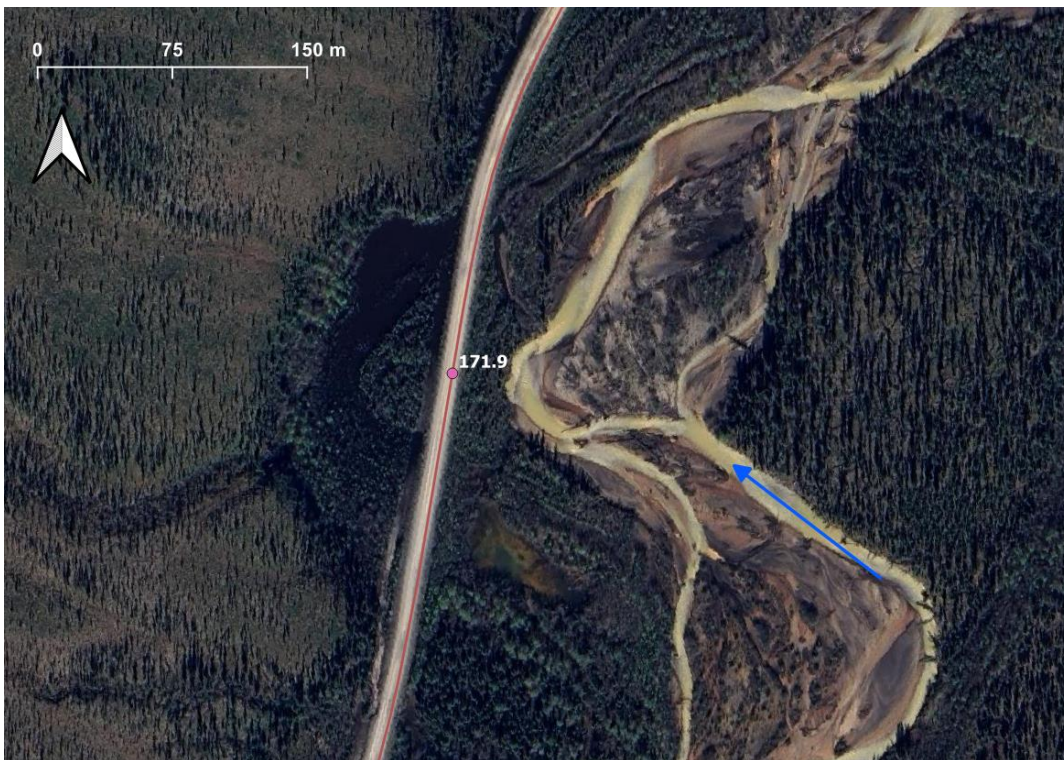


Figure 4. KM 171.9 of Dempster Highway. Separation distance = 23 m, risk rating = High, imagery date: June 4, 2023.



Figure 5. KM 182.1 of Dempster Highway. Separation distance = 0 m, risk rating = Very High, imagery date: June 4, 2023.



Figure 6. KM 183.3 of Dempster Highway. Separation distance = 18 m, risk rating = High, imagery date: June 4, 2023.



Figure 7. KM 193.4 of Dempster Highway. Separation distance = 0 m, risk rating = Very High, imagery date: June 4, 2023.



Figure 8. KM 194.0 of Dempster Highway. Separation distance = 28 m, risk rating = High, imagery date: June 4, 2023.



Figure 9. KM 218.4 of Dempster Highway. Separation distance = 13 m, risk rating = High, imagery date: June 4, 2023.



Figure 10. KM 232.1 of Dempster Highway. Separation distance = 23 m, risk rating = High, imagery date (top half): June 7, 2023.



Figure 11. KM 239.5 of Dempster Highway. Separation distance = 6 m, risk rating = Very High, imagery date: June 7, 2023.



Figure 12. KM 665.8 of Klondike Highway. Separation distance = 34 m, risk rating = Moderate, imagery date: June 4, 2023.

Appendix B

Comparative Analysis of Historical Channel Planforms at Priority
Highway Encroachments Klondike and Dempster Highway Erosion
Consulting
Palmer, 2024

Memorandum

Date: January 30, 2024

Project #: 2305001

To: Benoit Turcotte – Yukon University

From: Dan McParland and Robin McKillop – Palmer

cc: Ashley Dubnick, Mederic Girard, Stephanie Saal – Yukon University

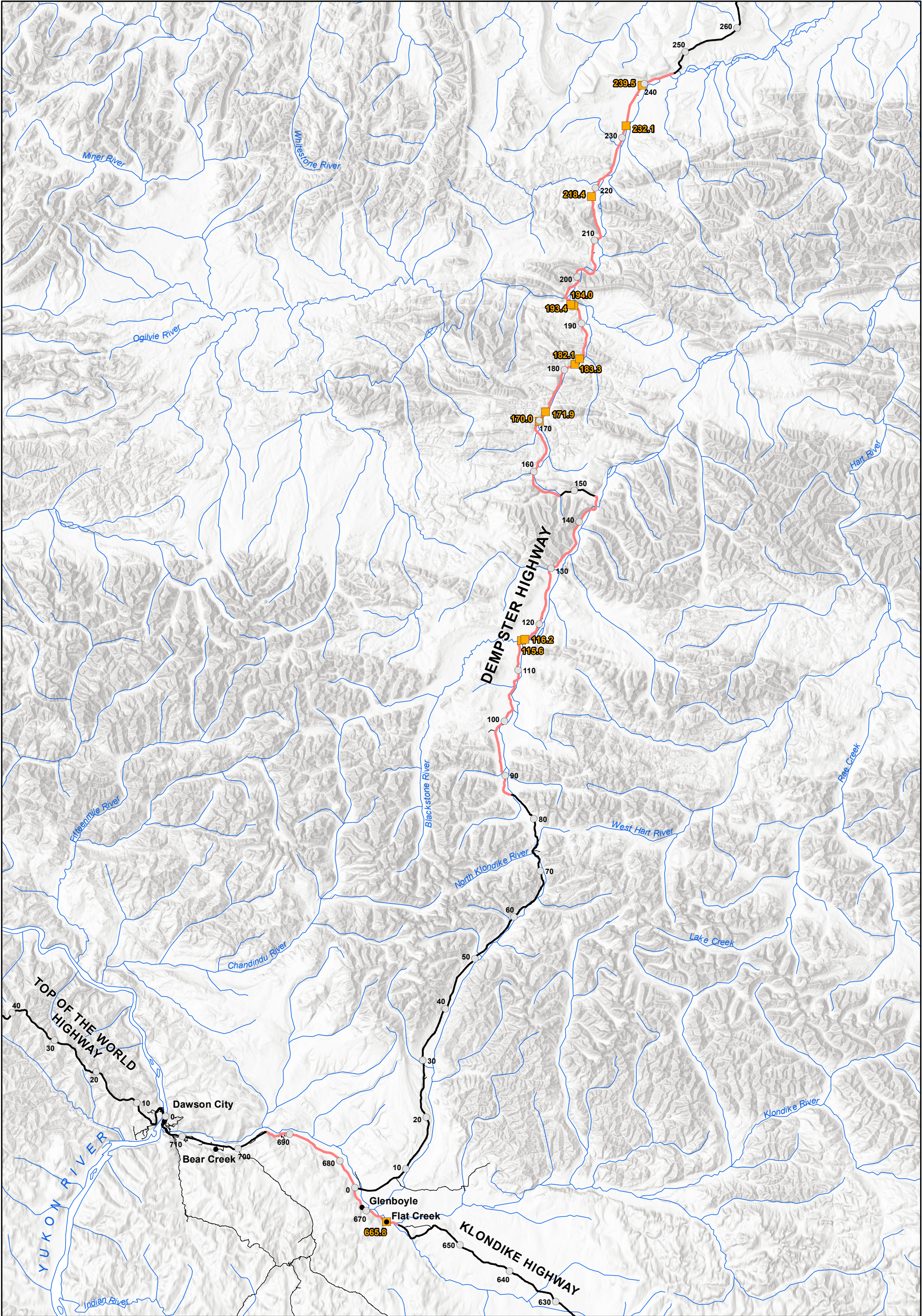
Re: Comparative Analysis of Historical Channel Planforms at Priority Highway Encroachments
Klondike and Dempster Highway Erosion Consulting

1. Introduction

Palmer was retained by Yukon University Research Centre's Climate Change Research team (YRC-CCR), working in collaboration with representatives from Yukon Government's Department of Highways and Public Works (HPW), and First Nation Governments, for fluvial geomorphology assessments, erosion monitoring, and erosion mitigation support along Dempster Highway and Klondike Highway in Yukon. The study area (i.e. highway sections of interest) for this project are Klondike Highway from KM 664 to KM 694 and Dempster Highway from KM 86 to KM 146 and KM 153 to KM 245 (**Figure 1**).

As part of the initial phase of this project, Palmer (2023) identified and characterized 87 locations with the study area potentially at risk from riverbank erosion, without intervention. The inventory culminated in a preliminary risk rating and prioritization of sites warranting follow-up actions. Four *Very High* sites where wash-out may be imminent were flagged for YRC-CCR and HPW. One follow-up recommendation was to complete a time-series analysis of channel planforms for 12 sites that have high vulnerability to lateral erosion (**Figure 1**). These 12 sites are distributed throughout the study area and have separation distances that range from 0 m to 34 m. Historical and recent aerial photography preserves an accurate record of channel changes, providing an effective basis for tracking past channel evolution. A comparative analysis of historical channel planforms (i.e. overlay analyses), combined with application of knowledge of fluvial and permafrost processes, can facilitate estimation of where, when and how much land will be lost to erosion adjacent the highways at the 12 sites.

This technical memorandum presents the overlay analyses for the 12 prioritized sites. Important background information, including the rationale for the assessment (Section 1), is followed by an overview of the methods (Section 2). Section 3 summarizes and discusses the results of the assessment, including summary tables and figures. Section 4 provides recommendations for follow-up actions. A map book illustrating the overlay analyses at the 12 prioritized sites is presented in **Appendix A**. The results of this assessment do not change the results of the previously submitted priority ranking exercise (Palmer, 2023).



Channel Overlay Site

Highway Kilometre Post

Highway Network

Highway of Interest

Watercourse ¹

1 - CanVec 1M Series

KEY MAP

Site Location

0

5

10

15

20

25

Kilometres

North American Datum 1983

Yukon Albers

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NORTH

CLIENT

Yukon University

PROJECT

Yukon Erosion Consulting

TITLE

Channel Overlay Sites

Palmer™

PART OF

SLR

REF. NO.

2305001-1-1

Figure 1

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2. Methods

Imagery datasets (**Table 1**) were compiled and reviewed as a basis for evaluating meander dynamics at each of the encroachment sites. Historical aerial photography and 2023 satellite imagery were georeferenced to the 2013/2014 orthophotography using standard GIS georeferencing tools. Approximately five control points were used to optimize the spatial match within the immediate vicinity of the valley bottom encroachment sites, where relief and relative image distortion are low. Resultant errors in comparison to the 2013/2014 orthophotography were ± 3 m (1989, 2023) and ± 4 m (1977). The orthorectified 2007/2008 satellite imagery exhibited an error of approximately ± 3 m in comparison to the 2013/2014 orthophotography.

Table 1. Imagery used for the channel overlay assessment

Imagery Type	Year	Scale/Resolution	Source
Satellite Imagery	2023	0.50 m	Google
Orthophotography	2013/2014	0.15 m	GeoYukon
Satellite Imagery ¹	2007/2008	0.60 m	GeoYukon
Aerial photography	1989/1990	1:25,000 to 1:30,000	Yukon EMR
Aerial photography	1977	1:15,000 to 1:45,000	Yukon EMR

1 – No coverage for KM 232.1

Both banks of the main channel and any major side channels were delineated based on each year of imagery. The banks were delineated at a sufficiently large scale to take advantage of detail available in the high-resolution imagery but not so large that the patterns and spatial relations could be missed (e.g., 1:1,000 to 1:2,500). Top-of-bank position was typically based on an obvious change in vegetation corresponding to a scour limit and/or a prominent slope-break visible in the contours or LiDAR-derived hillshade model available from GeoYukon. An example bank delineation is provided in **Figure 2**.

For meanders exhibiting systematic (progressive) migration, time-averaged migration rates were calculated by dividing the total migration distance along a given trajectory by the period between 1989/1990 and 2023. Additionally, a migration rate between 2013/14 and 2023 was calculated along the same trajectory to determine if migration over the past decade is accelerating. The 1977 linework was not used to calculate migration rates because it was based on aerial photography with higher georeferencing error and because anthropogenic modifications and channel avulsions prior to 1977 rendered the 1977 planform less relevant to current meander dynamics. Comparative overlay analysis facilitates time-averaged estimation of meander migration, assuming progression at a uniform rate. Channel migration is more likely to occur episodically in response to extreme flows, thalweg adjustments in association with avulsions or bar redistribution, and/or upstream ice jam breaching. A time-averaged rate effectively reduces the 'noise' represented by localized and episodic adjustments.



Figure 2. An example of top of bank delineation for the year 2023 at Dempster Highway KM 183.3

The predicted timeframe until meander migration impacts the highway embankment was determined by measuring the separation distance between the 2023 delineated bank and the highway embankment *along the meander migration trajectory* and dividing that distance by the higher migration rate (either the 1989/90 to 2023 or the 2013/14 to 2023 rate). The timeframe of impact estimates are reported as 5-year intervals (except for <2 years and 2-5 years) to accommodate annual deviations from the time-averaged migration rate and avoid misrepresenting the accuracy of such estimates. Sites that exhibited an estimated timeframe until impact greater than 25 years were reported together as a single category (>25 years), as the reliability of predictions beyond 25 years is compromised by unforeseen avulsions, anthropogenic disturbance, and the varied effects of climate change. The timeframe until impact estimates assume that *proactive* erosion protection measures are not implemented to stop meander encroachment from reaching the toe of the highway embankment.

3. Results and Discussion

Maps depicting the overlay assessment for each of the 12 priority sites are provided in **Appendix A**. Migration rates, estimated timeframe to impact and unique erosional conditions are summarized in **Table 2**. At most sites, migration rates were greater between 2013/14 and 2023 than between 1989/90 and 2023. A variety of factors could potentially explain this acceleration in erosion, such as recent large flood events and/or responses to anthropogenic channel alterations (as described below). YRC-CCR will be assessing

Water Survey of Canada hydrometric gauges stationed along or near Dempster Highway to better understand changes in regional flow regime from the 1970s to present day. As well, YRC-CCR will look for indicators of dynamic ice break up events at the sites included in this assessment. The findings of YRC-CCR hydrology and ice assessments will be compared to the results of this geomorphological assessment to help better understand drivers of geomorphic change and, potentially, establish specific thresholds for change.

Degradation of permafrost within undisturbed sections of the outer banks of encroaching meanders may also be contributing to bank instability at KM 115.5, 116.2, 182.1, 183.3, 193.4, 194.0, 218.4, 231.1, and 235.5 of Dempster Highway, based on inference of its presence from available imagery and previous investigations (e.g., McKillop et al., 2016). The permafrost at KM 115.5 and 116.2 is ice-rich and particularly thaw-sensitive, based on active retrogressive thaw slumping and the findings of previous research in the area (e.g. Lacelle et al., 2007; Calmels et al., 2018). Furthermore, our selection process likely introduces bias as sites that appeared unstable in recent imagery were chosen for further overlay analyses. It is estimated that, without intervention, meander migration will impact the highway at 10 of the 12 sites within the next 15 years.

3.1 Response of Engineer Creek to Historical Alterations

Six of the 12 priority sites are located along Engineer Creek, which is a dynamic, wandering, gravel-bed channel displaying rapid meander migration, disproportionately large gravel bars, and frequent channel avulsions. Steep and barren headwaters deliver large sediment pulses, which contribute to rapid channel adjustment in the main stem. In both of Palmer's previous erosion hazard inventories along Dempster Highway (McKillop et al., 2016; Palmer, 2023), Engineer Creek had the highest proportion of encroachment sites relative to the other watercourses flowing alongside the Dempster Highway. During the 2016 flood, lateral channel migration of Engineer Creek caused four washouts (Palmer, 2018).

Based on a thorough review of the 1977 aerial photographs, Engineer Creek appears to have been anthropogenically straightened at numerous locations, presumably to relocate the channel away from the newly constructed highway. This type of channel straightening was a common engineering strategy prior to the 1990s. Examples from Engineer Creek are provided in **Figure 3** and **Figure 4**. Cofferdams (or similar flow diversion structures) were observed near anthropogenic cut-offs, suggesting the cut-offs likely occurred in years shortly before 1977. Straightened channels are shorter and steeper, leading to increased erosion potential. Typically, straightened channels will readopt a more sinuous planform in the decades following the straightening. It is anticipated that Engineer Creek will continue to lengthen through meander migration and occupy a larger proportion of its valley floor over the coming decades. The effects of climate change on flood events and permafrost degradation may exacerbate the meander migration.

Table 2. Migration rates and estimates of timeframes to impact for the priority sites. The migration rates from 1989/90 to 2023 are displayed on the overlay mapping in Appendix A.

KM	Watercourse	Minimum Separation Distance ¹ (m)	Migration Rates 1989/90 to 2023 ² (m/yr)	Migration Rates 2013/14 to 2023 ² (m/yr)	Timeframe to Impact ³ (yrs)	Comments
665.8	Klondike River	34	1.7 to 2.9	2.1 to 8.2	5 to 10	The confluence of three watercourses immediately upstream of the encroachment site has contributed to instability and rapid migration. A small side channel currently abuts the highway near the downstream limb of the meander. The channel thalweg could abruptly shift into this side channel, which would greatly increase the potential for washout. Proactive erosion mitigation along this side channel may be warranted.
115.6	Blackstone River	9	0.5 to 0.6	0.9 to 1.1	5 to 10	Both fluvial erosion and degradation of ice-rich permafrost degradation, evident based on retrogressive thaw slumping, appear to be contributing to bank failure at this site. Accelerated permafrost degradation could reduce the timeframe to impact.
116.2	Blackstone River	16	0.3 to 0.4	0.4 to 0.5	>25	Both fluvial erosion and degradation of ice-rich permafrost degradation, evident based on retrogressive thaw slumping, appear to be contributing to bank failure at this site. Accelerated permafrost degradation could reduce the timeframe to impact.
170.0	Engineer Creek	25	0.9 to 1.6	2.0 to 3.2	10 to 15	In the 1977 imagery, the watercourse appeared to be anthropogenically straightened for either erosion mitigation or gravel production proposes. The watercourse has re-adopted a more sinuous planform through time and has rapidly migrated along both banks since 2013. An existing roadside ditch could also attract flood flows and reduce the timeframe to impact.
171.9	Engineer Creek	23	0.8 to 2.5	0.7 to 3.3	5 to 10	Similar to at KM 170.0, the watercourse was anthropogenically straightened shortly before the acquisition of the 1977 imagery. The oxbow lake to the west of the highway was unvegetated and dry in the 1977 imagery, suggesting the anthropogenic realignment occurred in years prior to 1977. The watercourse has re-adopted a more sinuous planform through time and has rapidly migrated along both banks since 2013. A small side channel is currently positioned between the main thread and the highway could attract flood flows and accelerate channel migration.
182.1	Engineer Creek	0	0.5 to 1.3	0.9 to 2.9	0	Engineer Creek has eroded the bank immediately upstream of the previously placed riprap. This scour may compromise the highway in the coming years. The presence of riprap has also accelerated down-valley channel migration. The longitudinal extent of riprap is insufficient and is exacerbating erosion downstream and, locally, upstream.
183.3	Engineer Creek	18	0.8 to 2.1	0.8 to 2.3	5 to 10	The watercourse was anthropogenically straightened shortly before the acquisition of the 1977 imagery. The oxbow lake to the west of the highway was unvegetated and dry in the 1977 imagery, suggesting the anthropogenic realignment occurred in years prior to 1977. The watercourse has re-adopted a more sinuous planform through time and has rapidly migrated along both banks since 2013.
193.4	Engineer Creek	0	2.1 to 2.8	0.6 to 4.8	0	Near this site, the length of Engineer Creek has been greatly reduced around the time of highway construction through both natural and anthropogenic meander cut-offs. Engineer Creek is re-adopting a more sinuous planform. The channel is rapidly migrating towards an oxbow lake on the south side of the highway. Installing erosion mitigation at this meander is highly recommended.
194.0	Engineer Creek	28	3.4	4.9	5 to 10	Engineer Creek was anthropogenically straightened prior to 1977 to better align the approach to the downstream bridge. Similar to at KM 193.4, Engineer Creek is re-adopting a more sinuous planform and is rapidly migrating towards the highway.
218.4	Ogilvie River	13	0.6 to 1.0	0.3 to 1.3	10 to 15	Since 2013, more flow has been diverted through this major side channel of Ogilvie River after breaching of a beaver dam that persisted for decades. Both of these factors have increased outer bank migration.
232.1	Ogilvie River	23	0.4 to 2.7	0.3 to 3.1	>25	The encroaching meander is migrating relatively quickly, albeit with more of a down-valley than a lateral trajectory (i.e. not directly towards the highway).
239.5	Ogilvie River	6	1.8	0.8 to 4.8	<2	This site is located where Ogilvie River has two dominant branches. The branch adjacent to the highway appears to have received more flow in recent decades, which has led to rapid migration.

1 – Based on shortest distance measured between the edge of highway embankment and the edge of watercourse in 2023 imagery

2 – Includes some migration vectors that are not migrating towards the highway

3 – Estimated from 2023 bank position based on trajectories and largest migration rate towards the highway

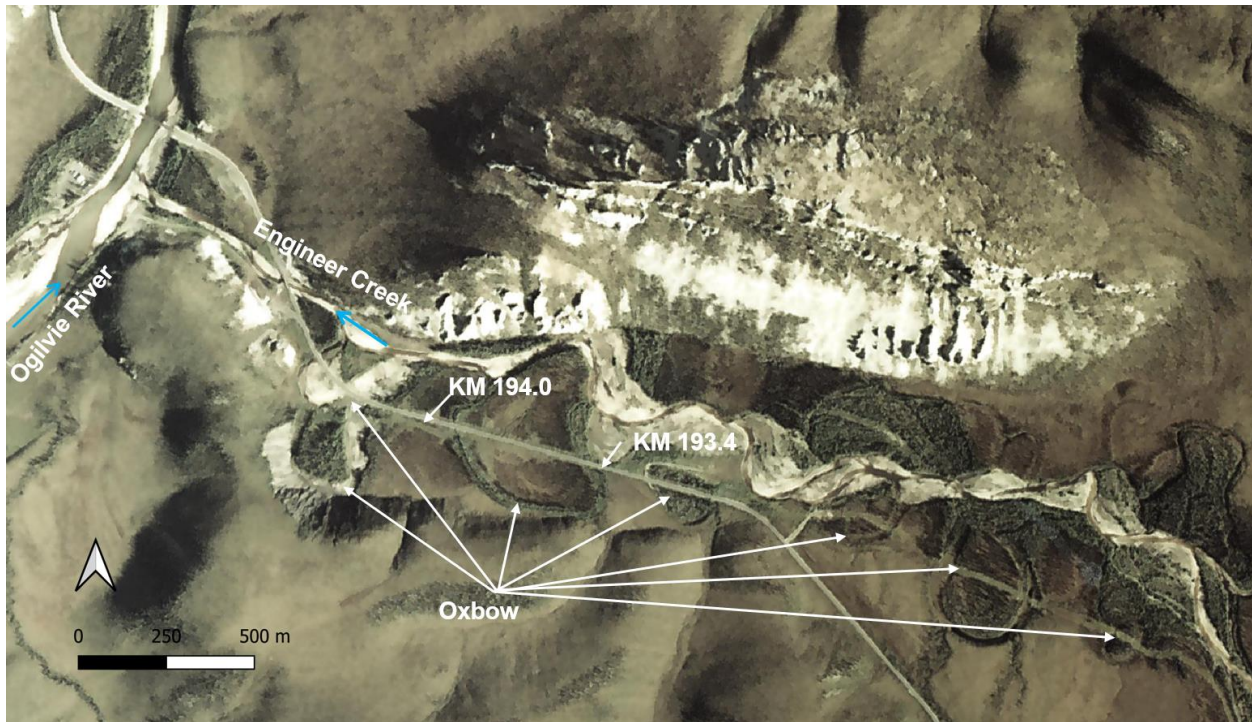


Figure 3. *In the 1977 aerial photographs (excerpt above), numerous oxbow features were observed along the south and north side of Engineer Creek, upstream of its confluence with Ogilvie River. It is inconclusive which oxbows were formed through natural processes and which were forced through anthropogenic straightening. It is likely some anthropogenic modifications were made to the channel to increase the separation distance between the newly constructed highway and the creek and to straighten the approach to the downstream vehicle crossing. This section of Engineer Creek has rapidly evolved in recent decades, which has led to high erosion vulnerability at KM 193.4 and KM 194.0 (Appendix A).*

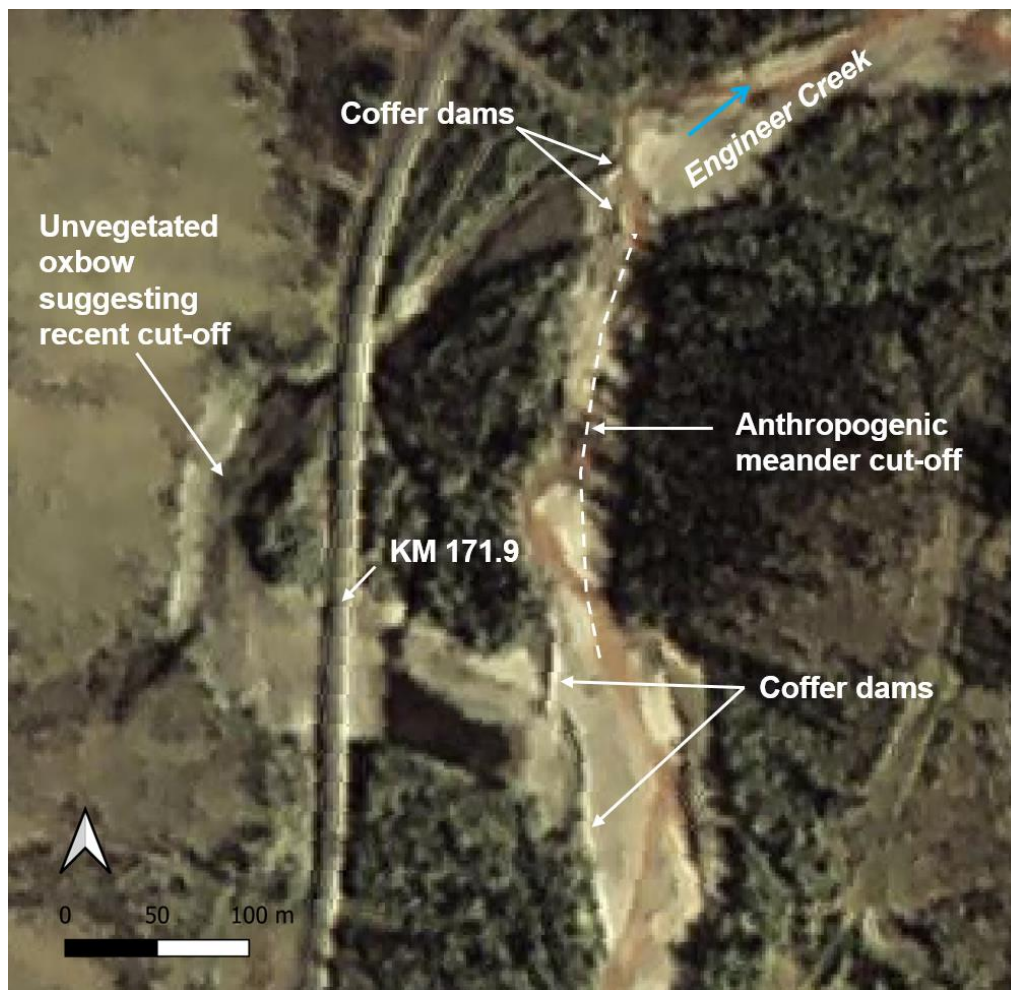


Figure 4. *An example of an anthropogenic cut-off along Engineer Creek observed in the 1977 aerial photographs. Since 1977, the channel has widened and has migrated rapidly towards the highway at KM 171.9 (Appendix A). Numerous other similar cut-offs are observed along Engineer Creek, which would have led to a notable reduction in channel length.*

4. Recommendations and Next Steps

The next major step in this project is to collaboratively select 8 to 10 sites for erosion monitoring and begin to establish site-specific monitoring plans for initiation in spring 2024. The two sites where the channel has already impacted the highway (KM 182.1 and KM 193.4) may not warrant monitoring. However, monitoring at these sites could help track the channel response to any implemented erosion mitigation. The eight sites where the channel is expected to impact the highway within the next 15 years are strong candidates for monitoring. These eight sites are distributed throughout the study area and are situated in a wide variety of settings. The two sites where highway impact is not expected within the next 25 years (KM 116.2 and KM 232.1) are lower priority for erosion monitoring, although it is worth taking advantage of permafrost instrumentation YukonU installed around Chapman Lake (i.e. near KM 116.2) to monitor ground temperatures and permafrost degradation in that area.

Memorandum

Page 9 | January 30, 2024

Comparative Analysis of Historical Channel Planforms at Priority Highway Encroachments

To better understand historical and potential future morphological adjustments along Engineer Creek, the total channel length could be measured from the vehicle crossing near KM 161 to the confluence with Ogilvie River in GIS for 1951 (pre-highway conditions), 1977 (following highway construction and associated straightening), and 2023. The pre-highway channel length will likely be considerably longer than the 1977 channel length. We anticipate Engineer Creek is lengthening towards a pre-highway (i.e. pre-disturbance) total length. However, the presence of the highway will limit such readjustment and total lengthening. This analysis is beyond the initial scope of the project and would require the acquisition and georeferencing of additional aerial photographs. Palmer and YRC-CCR can discuss the merits of this additional analyses at the next quarterly meeting.

5. Certification

This memorandum was prepared, review, and approved by the undersigned.

Prepared By:



Dan McParland, M.Sc., P.Geo.
Senior Fluvial Geomorphologist

Reviewed and
Approved By:



Robin McKillop, M.Sc., P.Geo.
Vice President, Principal Geomorphologist

References

Camels, F., Roy, L.P., Grandmont, K. and Pugh, R., 2018. A summary of climate- and geohazard-related vulnerabilities for the Dempster Highway corridor. Yukon Research Centre, Yukon College, 204 p.

Lacelle, D., Lauriol, B., Clark, D., Cardyn, R., and Zdanowicz, D., 2007. Nature and origin of a Pleistocene-age massive ground-ice body exposed in the Chapman Lake moraine complex, central Yukon Territory, Canada. Quaternary Research, 68: 249-260.

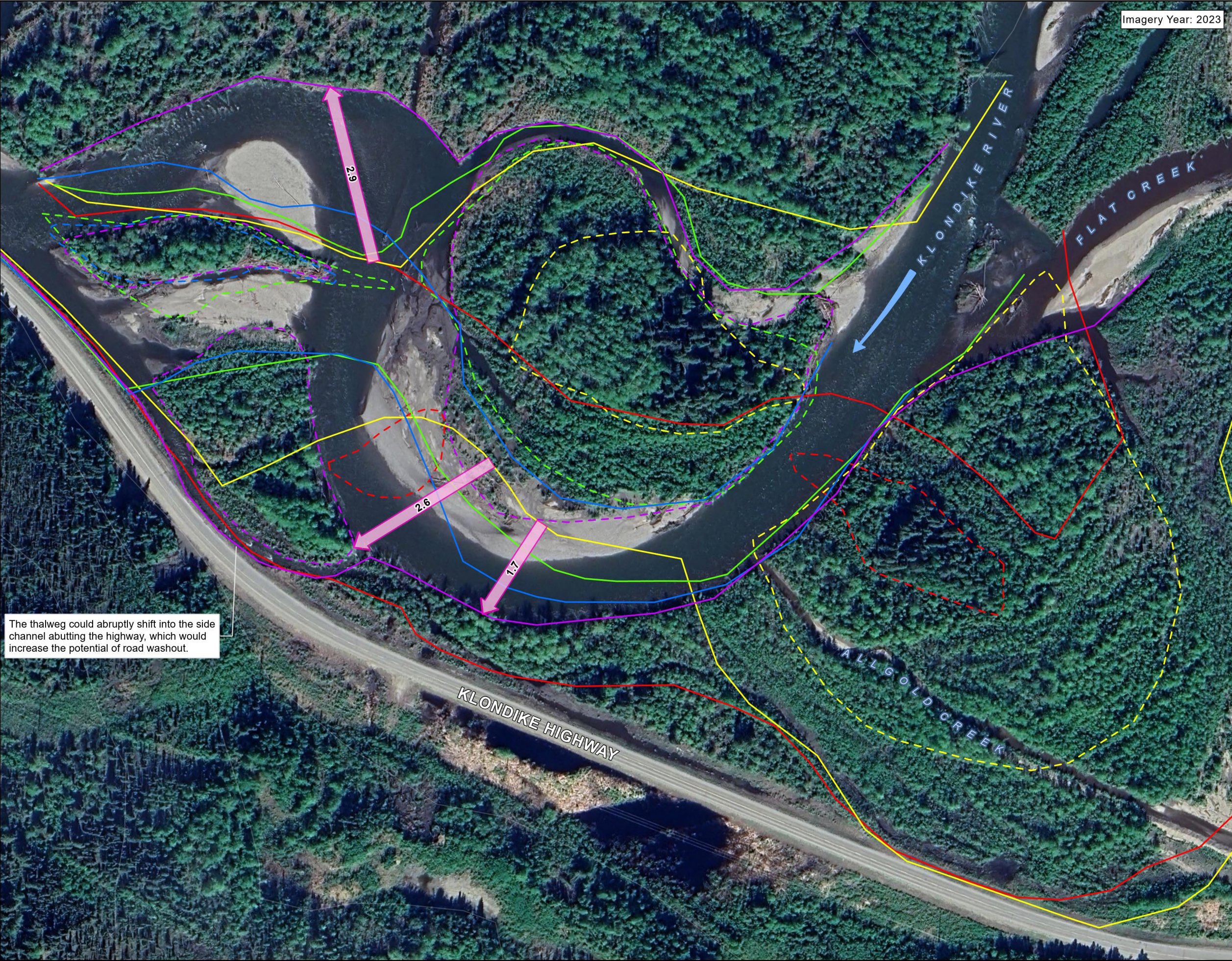
McKillop, R.J. Brown, C.E., McParland, D.J., Sacco, D.A., and Coates, J., 2016. Inventory of mass movement geohazards along the Dempster Highway. Yukon Geological Survey Miscellaneous Report 17.

Palmer, 2018. Hydrogeomorphic Assessment of August 2016 Flood Damage along the Dempster Highway – Preliminary Desktop Assessment. Prepared for Yukon Highways and Public Works – Transportation Engineering Branch, April 2018.

Palmer, 2023. Initial River Encroachment Inventory and Preliminary Risk Ratings – Klondike and Dempster Highway Erosion Consulting. Prepared for Yukon University, October 2023.

Appendix A

Comparative Analysis of Historical Channel Planforms



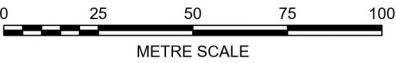
Imagery Year: 2023



LEGEND

- Direction of Flow
- Migration Rate (m/yr)
- Contour (20 m) ¹
- Channel Planform Year ²**
 - 2023
 - 2014
 - 2007
 - 1990
 - 1977
- Vegetated Islands/Bars Within Channel

Note:
1 - Contour data provided by CanVec 50k series (2017).
2 - Channel migration rates are based on observed migration from 1990 to 2023.



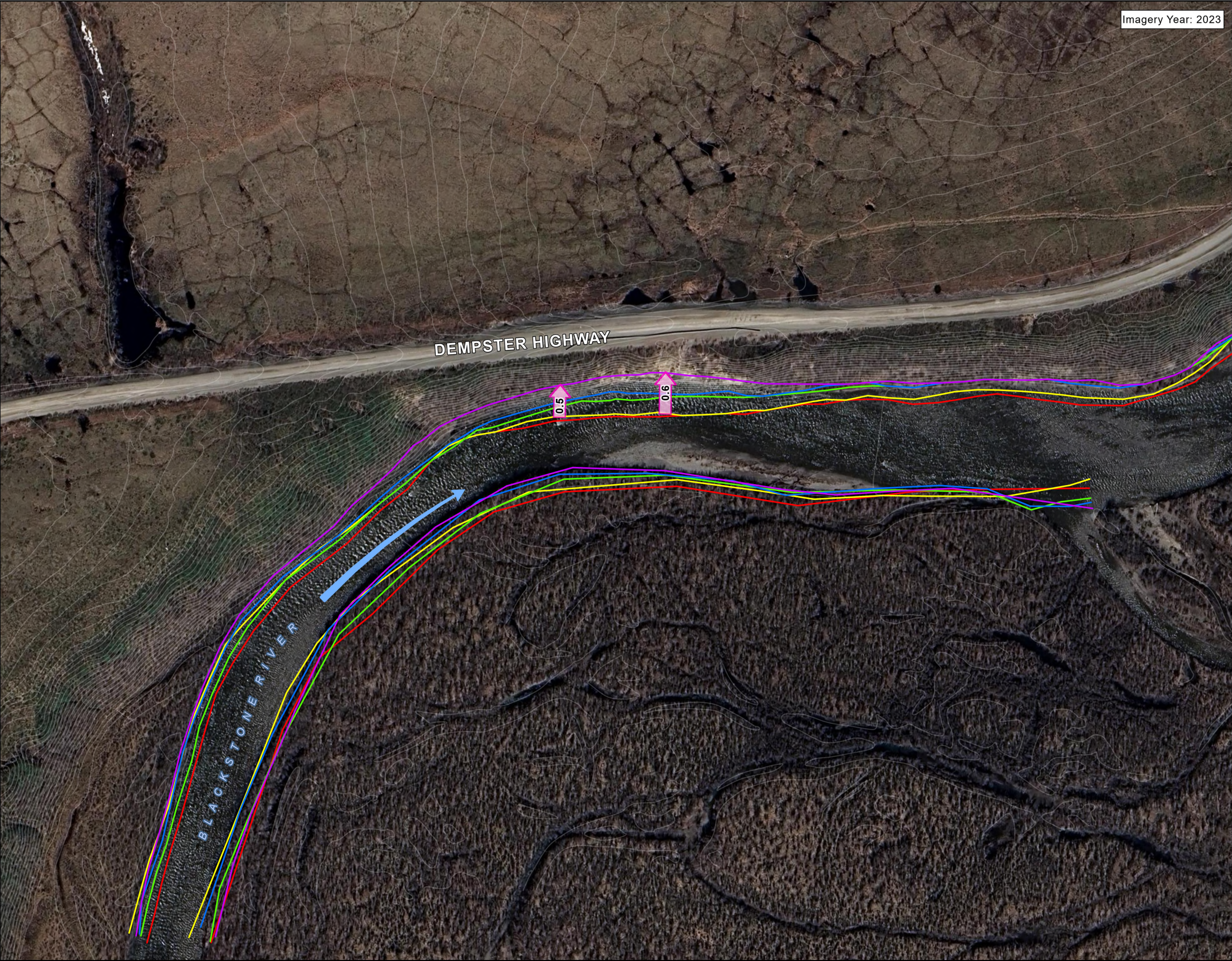
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Checked: DM
Date: Sep 11, 2026

Source Notes:
Imagery provided by Google Earth imagery (2023) and ESRI base mapping services (2018/2019). Contains information licensed under the Open Government Licence - Canada



NORTH

CLIENT	Yukon University	
PROJECT	Yukon Erosion Consulting	
TITLE	Channel Overlay Analysis (Klondike Highway KM 665.8)	
	REF. NO.	233.V24420-A(1)-2
	Appendix A-1	



Imagery Year: 2023



LEGEND

- ➡ Direction of Flow
- ➡ Migration Rate (m/yr)
- Contour (1 m) ¹

Channel Planform Year ²

- 2023
- 2013
- 2007
- 1989
- 1977

--- Vegetated Islands/Bars Within Channel

Note:
1 - Contour data provided by the Government of Yukon (2023).
2 - Channel migration rates are based on observed migration from 1989 to 2023.

0 25 50 75 100
METRE SCALE

North American Datum 1983 Universal Transverse
Mercator Projection Zone 17
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Date: Sep 11, 2026

Source Notes:
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NORTH

CLIENT	Yukon University	
PROJECT	Yukon Erosion Consulting	
TITLE	Channel Overlay Analysis (Dempster Highway KM 115.5)	
	REF. NO.	233.V24420-A(2)-2
	Appendix A-2	



Imagery Year: 2023



LEGEND

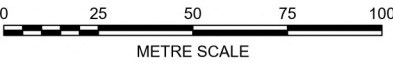
- Direction of Flow
- Migration Rate (m/yr)
- Contour (1 m)¹

Channel Planform Year²

- 2023
- 2013
- 2007
- 1989
- 1977

Vegetated Islands/Bars Within Channel

Note:
1 - Contour data provided by the Government of Yukon (2023).
2 - Channel migration rates are based on observed migration from 1989 to 2023.
3-Southern bank was not delineated due to complex, multi-thread morphology persistent over the period of record.



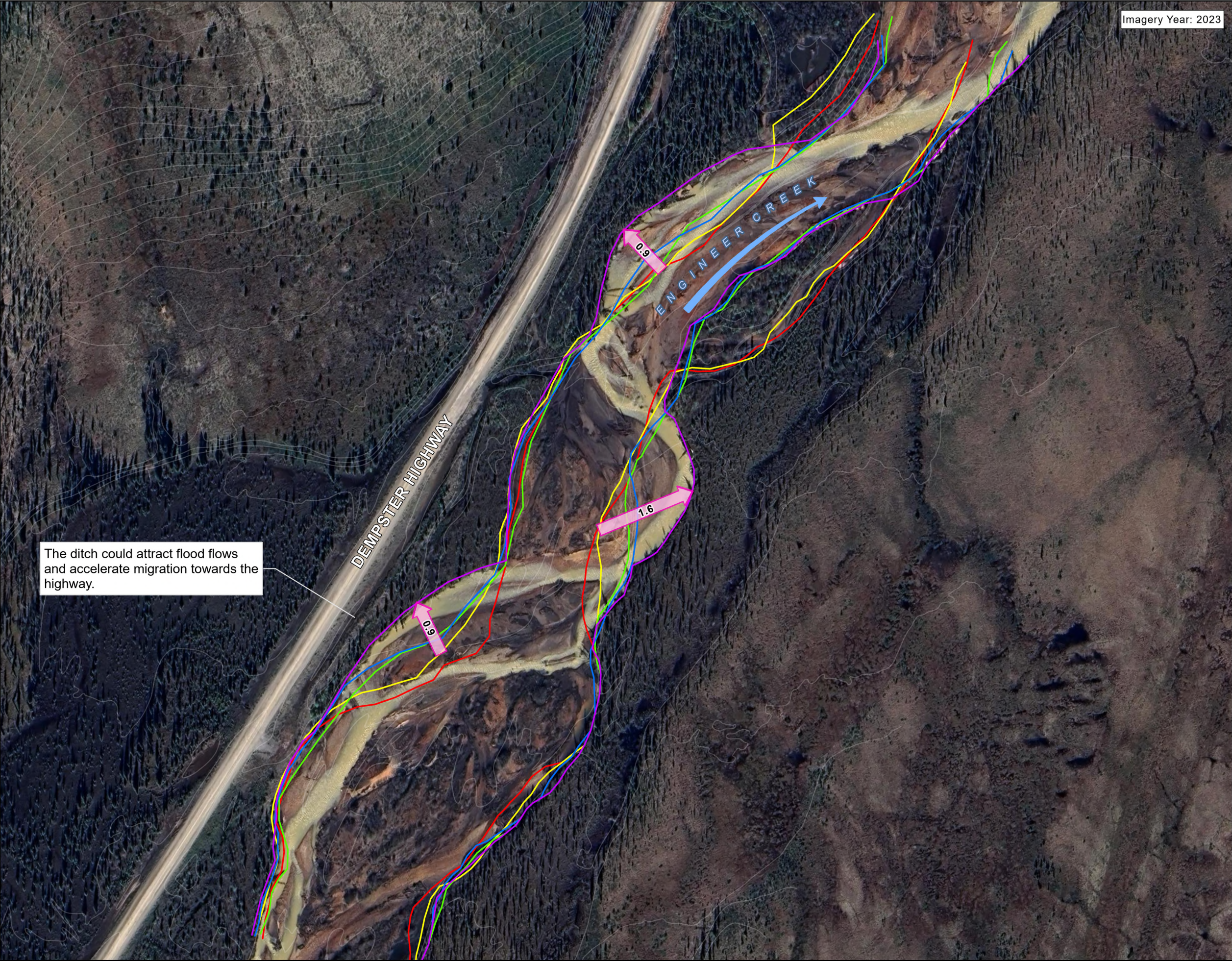
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Mercator Projection Zone 17
Scale: 1:2,000
Page Size: Tabloid (11 x 17 inches)
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Date: Sep 11, 2026



NORTH

Source Notes:
Imagery provided by Google Earth imagery (2023) and ESRI base mapping services (2018/2019). Contains information licensed under the Open Government Licence – Canada

CLIENT	Yukon University	
PROJECT	Yukon Erosion Consulting	
TITLE	Channel Overlay Analysis (Dempster Highway KM 116.2)	
	REF. NO.	233.V24420-A(3)-2
	Appendix A-3	

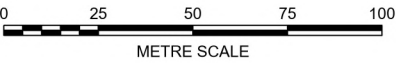


Imagery Year: 2023



- LEGEND
- ➡ Direction of Flow
 - ➡ Migration Rate (m/yr)
 - Contour (1 m)¹
 - Channel Planform Year²**
 - 2023
 - 2013
 - 2007
 - 1989
 - 1977
 - - - Vegetated Islands/Bars Within Channel

Note:
1 - Contour data provided by the Government of Yukon (2023).
2 - Channel migration rates are based on observed migration from 1989 to 2023.

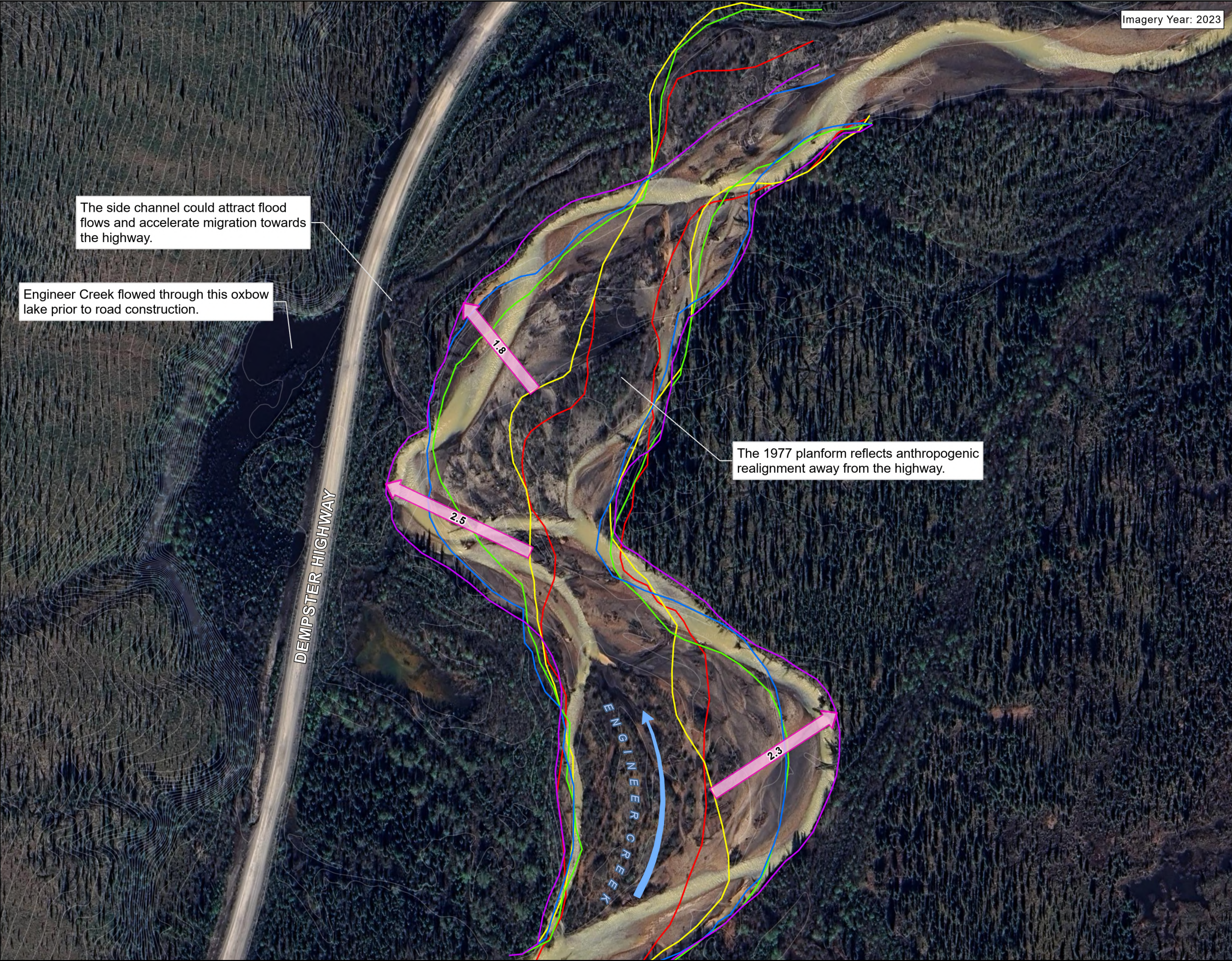


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Checked: DM
Date: Sep 11, 2026

Source Notes:
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CLIENT	Yukon University	
PROJECT	Yukon Erosion Consulting	
TITLE	Channel Overlay Analysis (Dempster Highway KM 170.0)	
	REF. NO.	233.V24420-A(4)-2
	Appendix A-4	



Imagery Year: 2023



LEGEND

➡ Direction of Flow

➡ Migration Rate (m/yr)

— Contour (1 m)¹

Channel Planform Year²

- 2023
- 2013
- 2007
- 1989
- 1977

--- Vegetated Islands/Bars Within Channel

Note:
1 - Contour data provided by the Government of Yukon (2023).
2 - Channel migration rates are based on observed migration from 1989 to 2023.

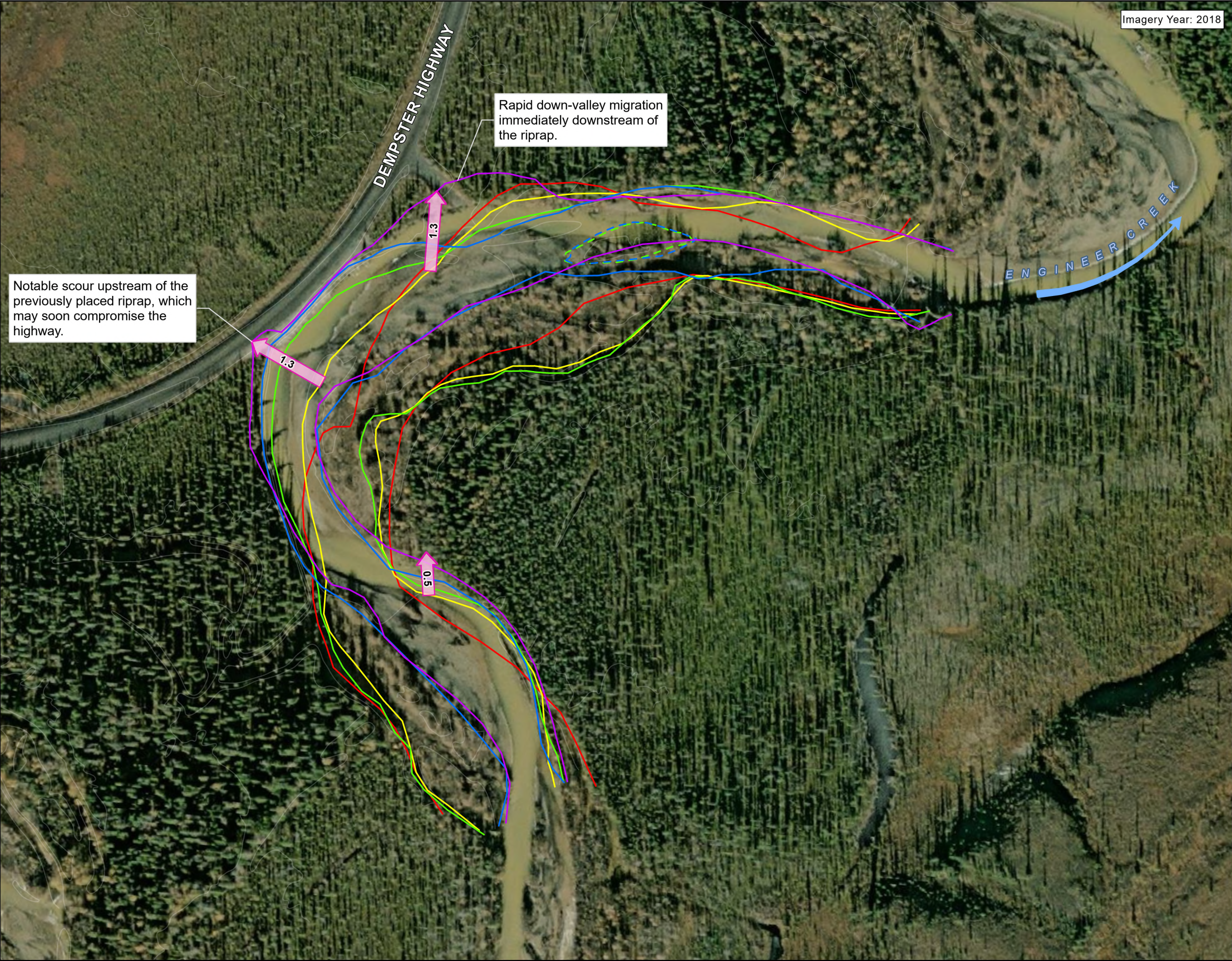
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North American Datum 1983 Universal Transverse
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Drawn: SM
Checked: DM
Date: Sep 11, 2026

Source Notes:
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NORTH

CLIENT	Yukon University	
PROJECT	Yukon Erosion Consulting	
TITLE	Channel Overlay Analysis (Dempster Highway KM 171.9)	
	REF. NO.	233.V24420-A(5)-2
	Appendix A-5	



Imagery Year: 2018

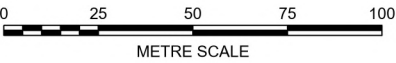
Rapid down-valley migration immediately downstream of the riprap.

Notable scour upstream of the previously placed riprap, which may soon compromise the highway.



- LEGEND
- Direction of Flow
 - Migration Rate (m/yr)
 - Contour (1 m)¹
 - Channel Planform Year²
 - 2023
 - 2013
 - 2007
 - 1989
 - 1977
 - Vegetated Islands/Bars Within Channel

Note:
1 - Contour data provided by the Government of Yukon (2023).
2 - Channel migration rates are based on observed migration from 1989 to 2023.



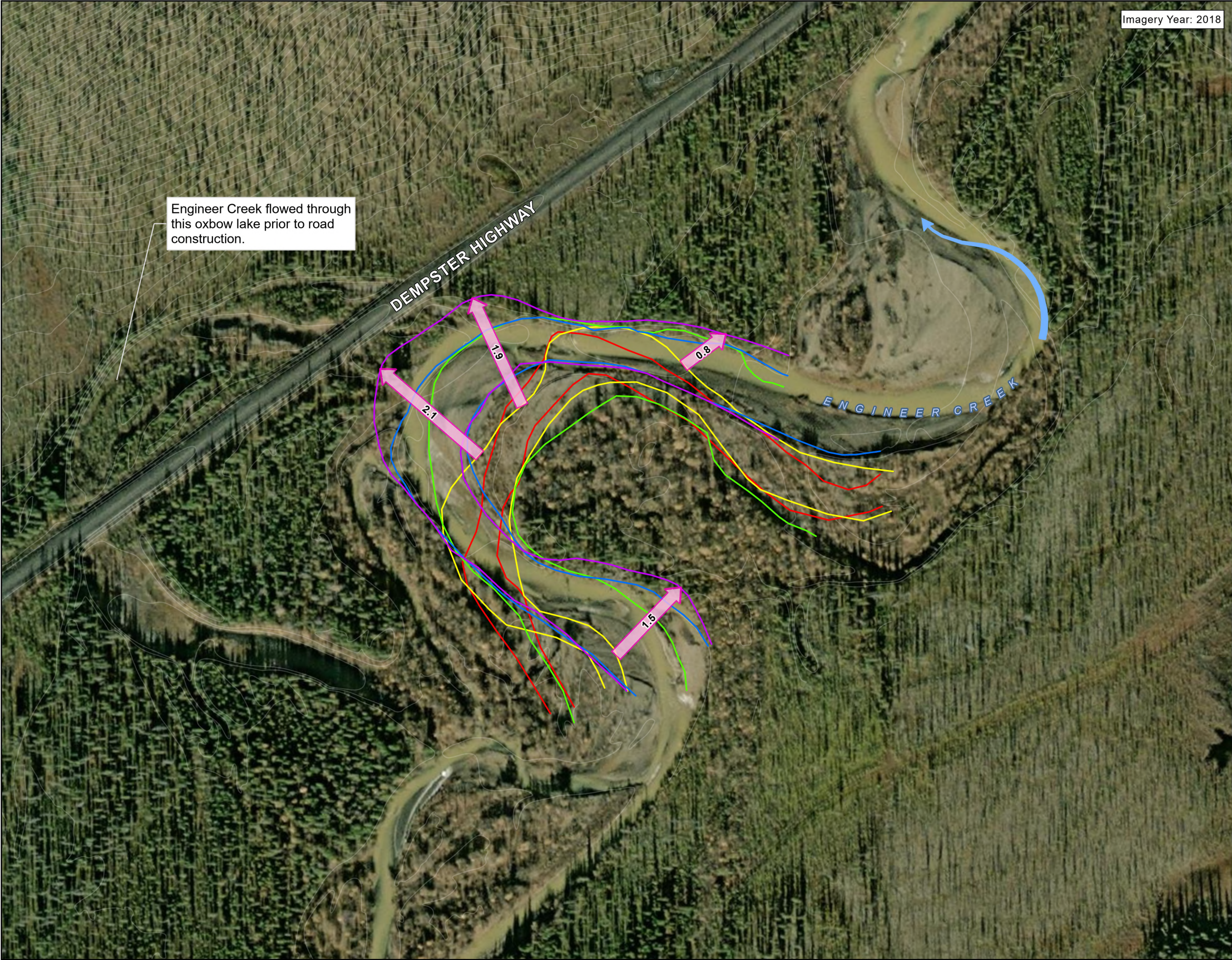
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Page Size: Tabloid (11 x 17 inches)
Drawn: SM
Checked: DM
Date: Sep 11, 2026

Source Notes:
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NORTH

CLIENT	Yukon University	
PROJECT	Yukon Erosion Consulting	
TITLE	Channel Overlay Analysis (Dempster Highway KM 182.1)	
	REF. NO.	233.V24420-A(6)-2
	Appendix A-6	



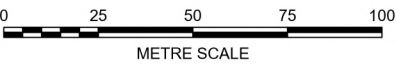
Imagery Year: 2018

Engineer Creek flowed through this oxbow lake prior to road construction.



- LEGEND
- Direction of Flow
 - Migration Rate (m/yr)
 - Contour (1 m)¹
 - Channel Planform Year²**
 - 2023
 - 2013
 - 2007
 - 1989
 - 1977
 - Vegetated Islands/Bars Within Channel

Note:
1 - Contour data provided by the Government of Yukon (2023).
2 - Channel migration rates are based on observed migration from 1989 to 2023.

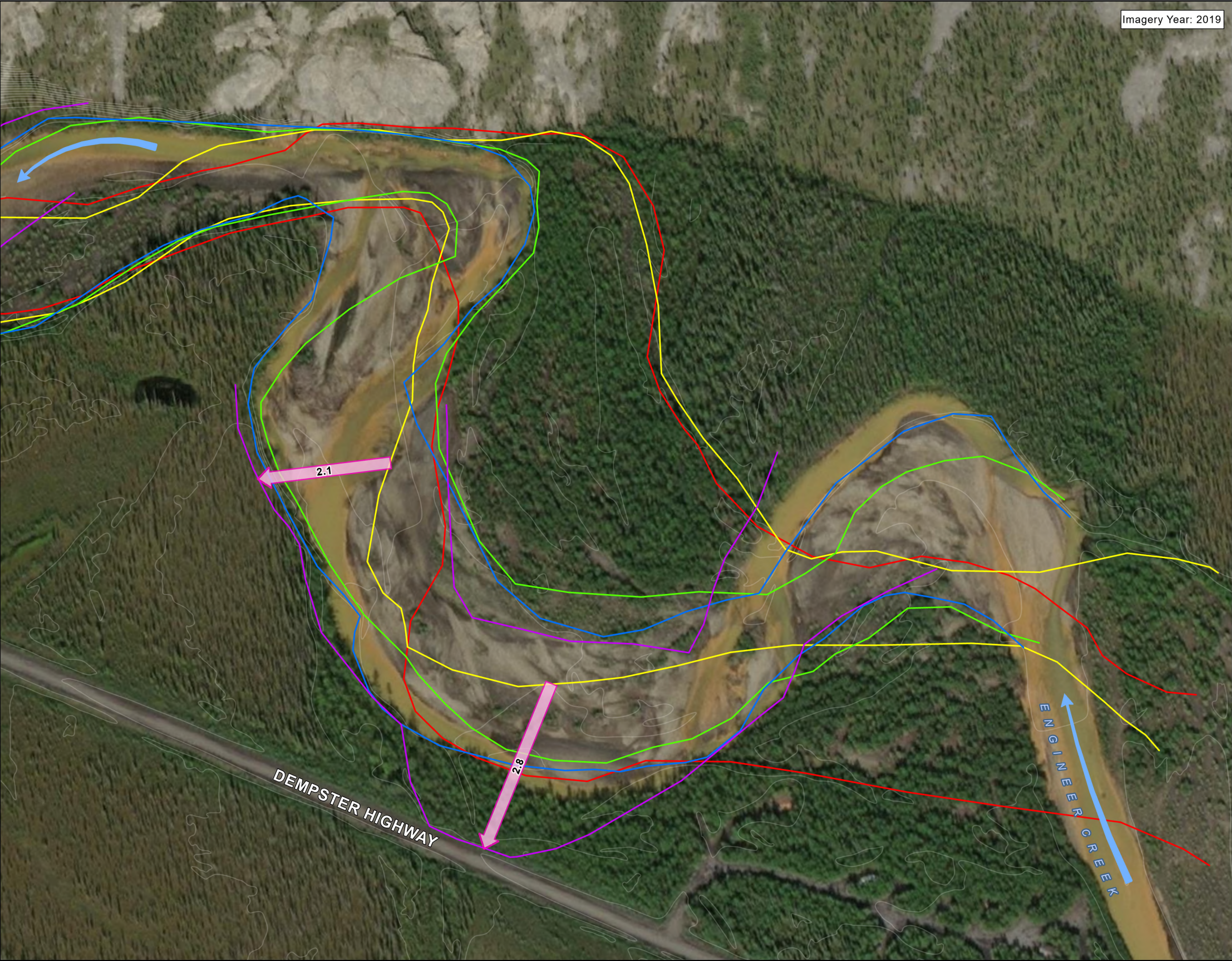


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Date: Sep 11, 2026

Source Notes:
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CLIENT	Yukon University	
PROJECT	Yukon Erosion Consulting	
TITLE	Channel Overlay Analysis (Dempster Highway KM 183.3)	
	REF. NO.	233.V24420-A(7)-2
	Appendix A-7	

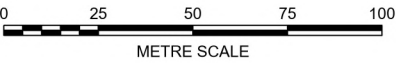


Imagery Year: 2019



- LEGEND
- Direction of Flow
 - Migration Rate (m/yr)
 - Contour (1 m)¹
 - Channel Planform Year²**
 - 2023
 - 2013
 - 2007
 - 1989
 - 1977
 - Vegetated Islands/Bars Within Channel

Note:
1 - Contour data provided by the Government of Yukon (2023).
2 - Channel migration rates are based on observed migration from 1989 to 2023.

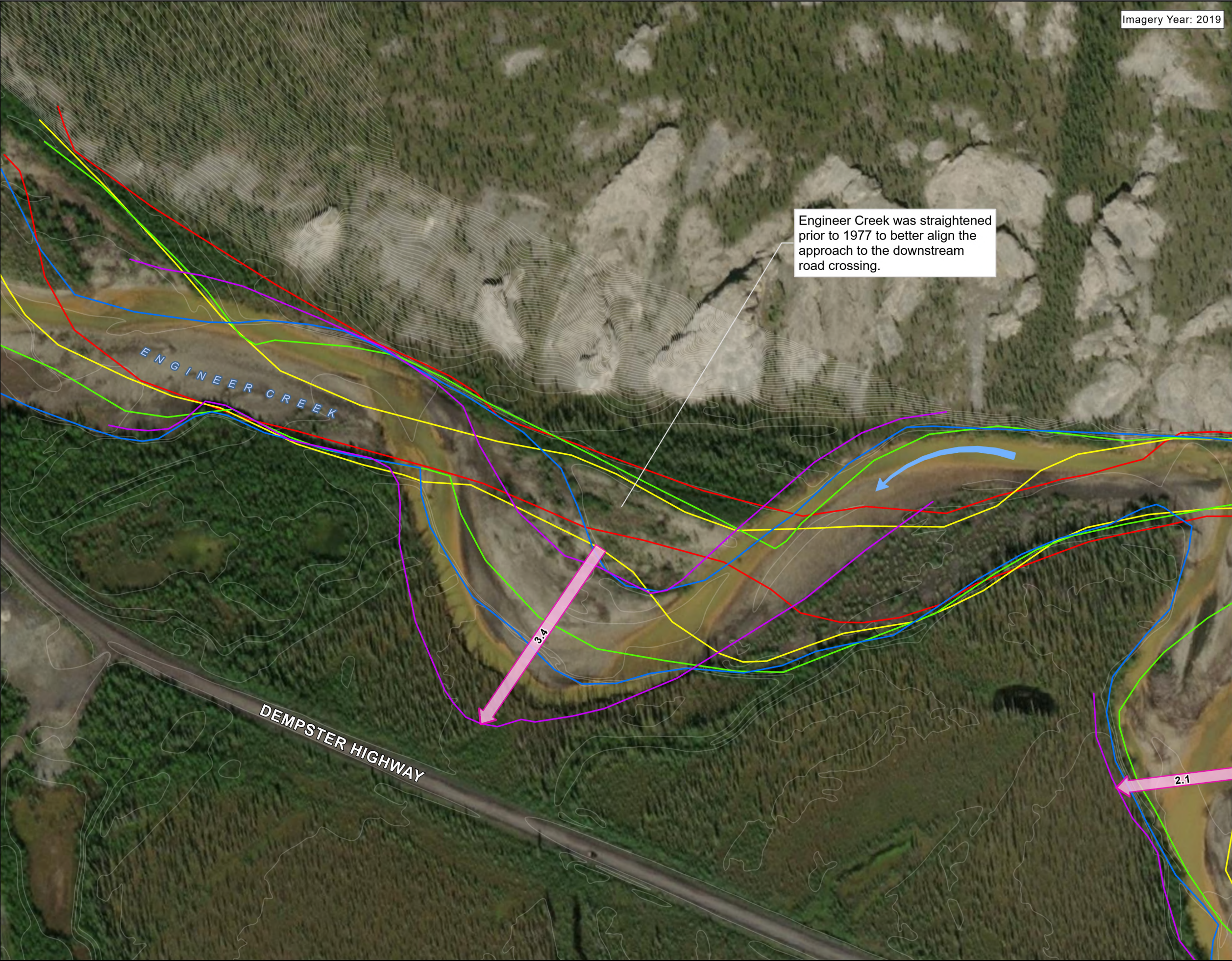


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Date: Sep 11, 2026

Source Notes:
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CLIENT	Yukon University	
PROJECT	Yukon Erosion Consulting	
TITLE	Channel Overlay Analysis (Dempster Highway KM 193.4)	
	REF. NO.	233.V24420-A(8)-2
	Appendix A-8	



Imagery Year: 2019

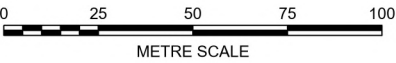
Engineer Creek was straightened prior to 1977 to better align the approach to the downstream road crossing.



LEGEND

- Direction of Flow
- Migration Rate (m/yr)
- Contour (1 m)¹
- Channel Planform Year²**
 - 2023
 - 2013
 - 2007
 - 1989
 - 1977
- Vegetated Islands/Bars Within Channel

Note:
1 - Contour data provided by the Government of Yukon (2023).
2 - Channel migration rates are based on observed migration from 1989 to 2023.

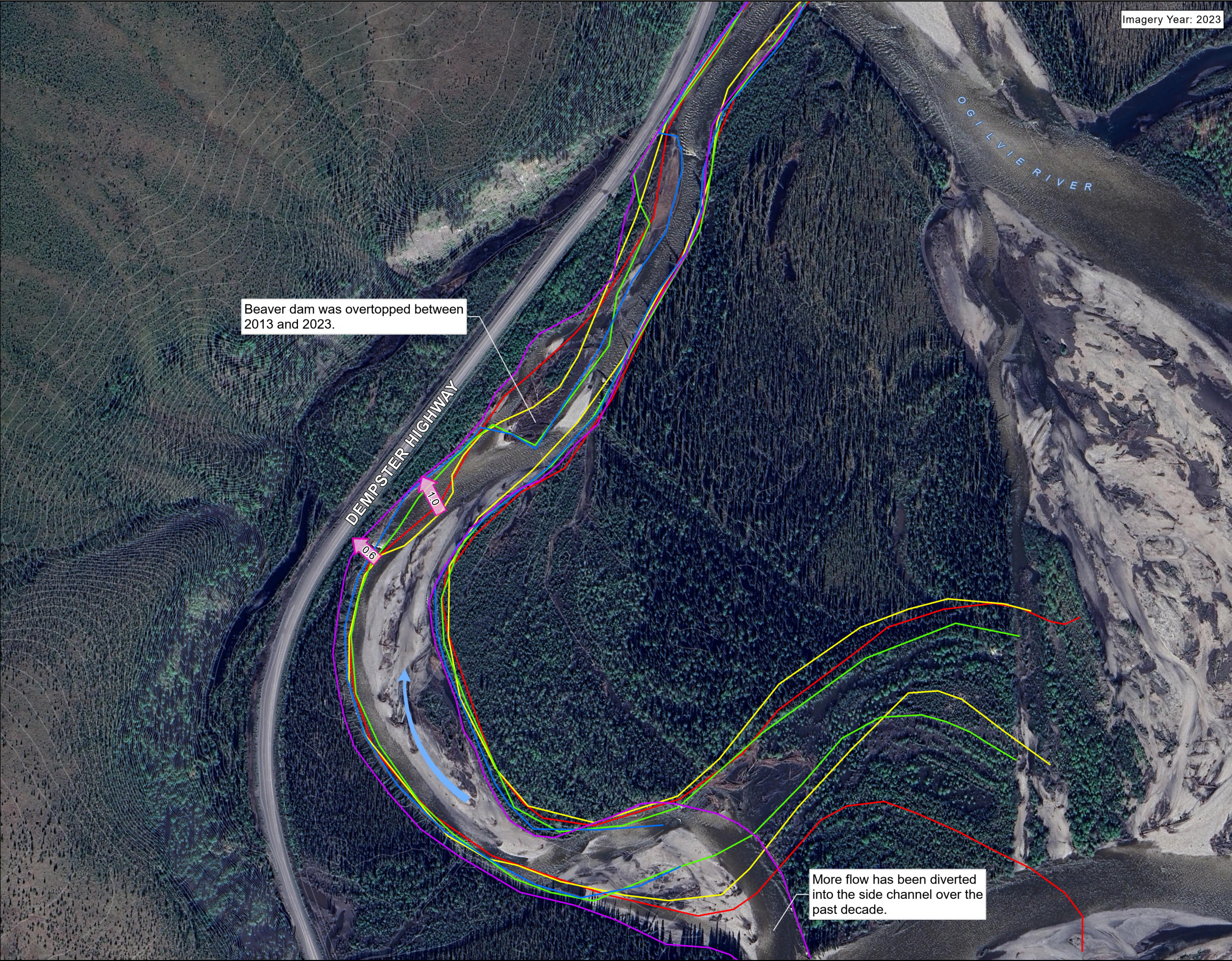


North American Datum 1983 Universal Transverse
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Checked: DM
Date: Sep 11, 2026

Source Notes:
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CLIENT	Yukon University	
PROJECT	Yukon Erosion Consulting	
TITLE	Channel Overlay Analysis (Dempster Highway KM 194.0)	
	REF. NO.	233.V24420-A(9)-2
	Appendix A-9	

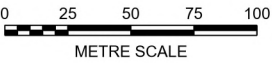


Imagery Year: 2023



- LEGEND
- Direction of Flow
 - Migration Rate (m/yr)
 - Contour (1 m)¹
 - Channel Planform Year²**
 - 2023
 - 2013
 - 2007
 - 1989
 - 1977
 - Vegetated Islands/Bars Within Channel

Note:
1 - Contour data provided by the Government of Yukon (2023).
2 - Channel migration rates are based on observed migration from 1989 to 2023.

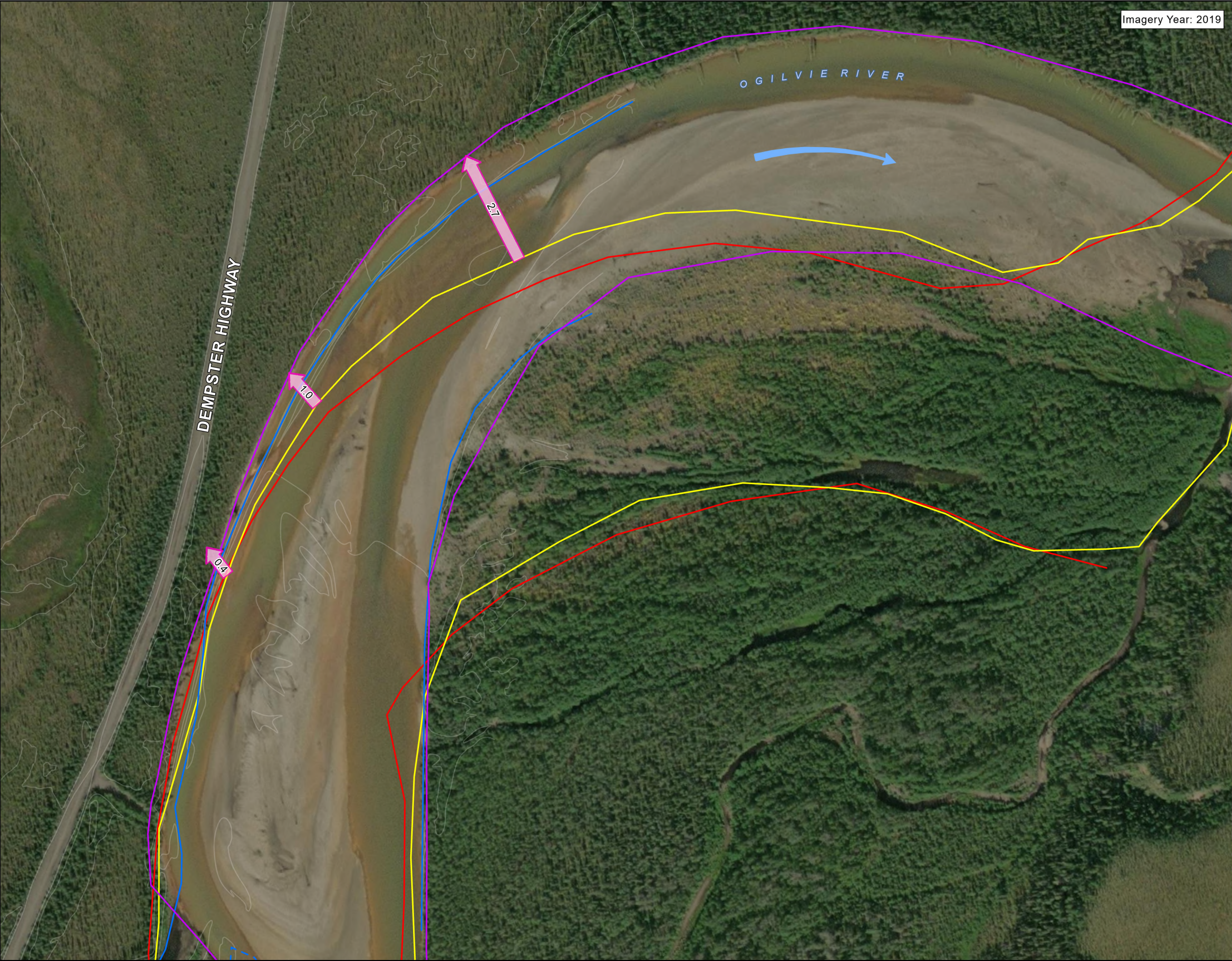


North American Datum 1983 Universal Transverse
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Date: Sep 11, 2026

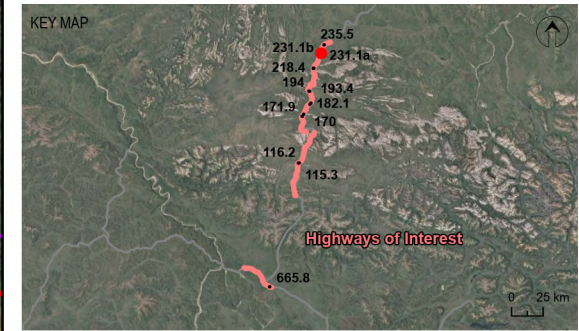
Source Notes:
Imagery provided by Google Earth imagery (2023) and ESRI base mapping services (2018/2019). Contains information licensed under the Open Government Licence – Canada



CLIENT	Yukon University	
PROJECT	Yukon Erosion Consulting	
TITLE	Channel Overlay Analysis (Dempster Highway KM 218.4)	
	REF. NO.	233.V24420-A(10)-2
	Appendix A-10	



Imagery Year: 2019



LEGEND

- ➡ Direction of Flow
- ➡ Migration Rate (m/yr)
- Contour (1 m) ¹

Channel Planform Year ²

- 2023
- 2013
- 2007
- 1989
- 1977

--- Vegetated Islands/Bars Within Channel

Note:
1 - Contour data provided by the Government of Yukon (2023).
2 - Channel migration rates are based on observed migration from 1989 to 2023.

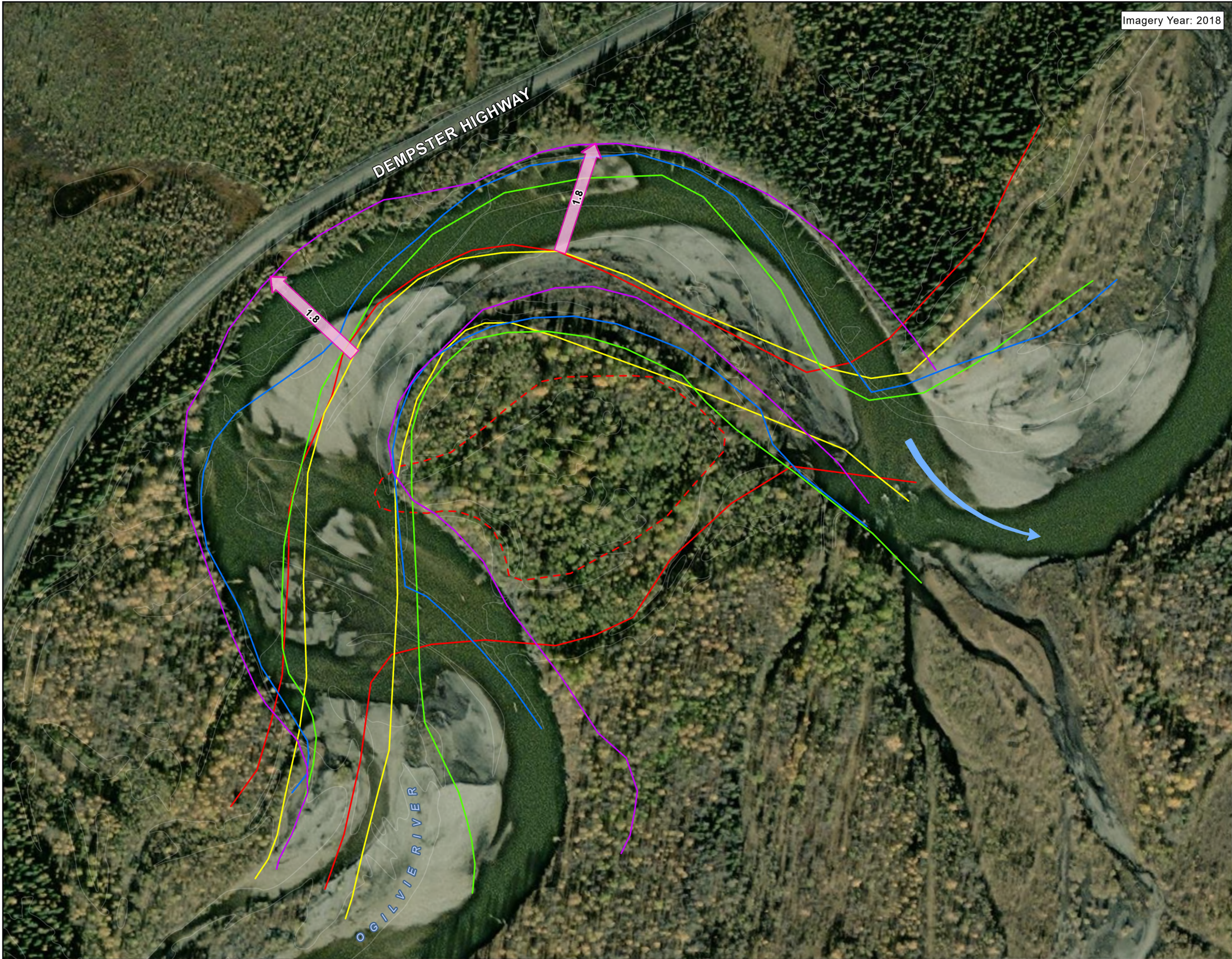
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METRE SCALE

North American Datum 1983 Universal Transverse
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Drawn: SM
Checked: DM
Date: Sep 11, 2026

Source Notes:
Imagery provided by Google Earth imagery (2023) and ESRI base mapping services (2018/2019). Contains information licensed under the Open Government Licence – Canada

NORTH

CLIENT	Yukon University	
PROJECT	Yukon Erosion Consulting	
TITLE	Channel Overlay Analysis (Dempster Highway KM 232.1)	
	REF. NO.	233.V24420-A(11)-2
	Appendix A-11	



Imagery Year: 2018



LEGEND

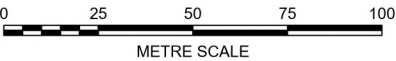
- Direction of Flow
- Migration Rate (m/yr)
- Contour (1 m)¹

Channel Planform Year²

- 2023
- 2013
- 2007
- 1989
- 1977

-- Vegetated Islands/Bars Within Channel

Note:
1 - Contour data provided by the Government of Yukon (2023).
2 - Channel migration rates are based on observed migration from 1989 to 2023.



North American Datum 1983 Universal Transverse
Mercator Projection Zone 17
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Date: Sep 11, 2026



NORTH

Source Notes:
Imagery provided by Google Earth imagery (2023) and ESRI base mapping services (2018/2019). Contains information licensed under the Open Government Licence – Canada

CLIENT	Yukon University	
PROJECT	Yukon Erosion Consulting	
TITLE	Channel Overlay Analysis (Dempster Highway KM 239.5)	
	REF. NO.	233.V24420-A(12)-2
	Appendix A-12	

Appendix C

Erosion processes and mitigation recommendations for
16 priority sites

Highway and KM	Klondike Highway KM 665.8
Watercourse	Klondike River
Min. Separation Distance in 2023	34 m (decreased to 28 m in 2025 drone imagery)
Previous Erosion Mitigation	None
Erosional Processes	- Located within a multi-thread channel reach near tributary confluences. - The channel may avulse away from the highway, reducing long-term erosion risk. - Spring ice runs may contribute to bank erosion and channel adjustment. - Active outer-bank migration (> 2m/year) is occurring adjacent to the highway. - The thalweg could migrate into the side channel adjacent to the road embankment, potentially accelerating future erosion rates.
Mitigation Considerations and Recommendations	- Continue monitoring channel dynamics, particularly during freshet and ice cover breakup; consider real-time monitoring equipment. - Consider proactive armouring of the side channel using a vegetated boulder revetment. - Consider flow-deflection log spurs upstream of the side-channel inlet to shift the thalweg toward mid-channel; construction access may be challenging.
Representative Visual	Riverbank Position 2014 (green line) 2023 (blue line) 2025 (magenta line) Additional flow into side-channel along the highway could increase erosional risk Imagery Year: 2025



Highway and KM	Dempster Highway KM 86.1
Watercourse	East Blackstone River
Min. Separation Distance in 2023	0 m
Previous Erosion Mitigation	None
Erosional Processes	• Complex hydraulics downstream of undersized CSP culverts likely lead to toe erosion and induce bank slumping. • Aufeis formation may lead to overbank flows and erosion of the slope. • Drainage from highway and rip-rap on the opposite bank may contribute to instability.
Mitigation Considerations and Recommendations	• Undertake subsurface investigations to characterize materials and permafrost conditions. • Regrade the slope to 2H:1V or flatter and provide toe protection (e.g., vegetated boulder revetment). • Incorporate riparian plantings (e.g., willow staking) to improve near-surface shear strength. • Upgrading the upstream crossing may reduce aufeis formation and redistribute erosion power.
Representative Visual	



Highway and KM	Dempster Highway KM 107.8
Watercourse	East Blackstone River
Min. Separation Distance in 2023	0 m (currently protected but needs intervention)
Previous Erosion Mitigation	Angular riprap (presumably Class I) atop geotextile (year unknown)
Erosional Processes	• Active outer-bank erosion is occurring along the meander bend. • Previously installed riprap has been displaced along the downstream limb of the meander. • Erosion is occurring downstream of the existing protection. • Geotextile appears to have created a slip plane within the revetment.
Mitigation Considerations and Recommendations	• Remove exposed geotextile and reconstruct the riprap using granular filter layers; extend protection downstream, ending with a flow deflector. • Incorporate riparian plantings, if feasible. • Consider removal of inner-bank gravel deposits to increase hydraulic capacity and reduce outer-bank shear stresses.
Representative Visual	 Displaced riprap and exposed geotextile Erosion downstream of riprap that should be addressed in coming years



Highway and KM	Dempster Highway KM 108.9
Watercourse	East Blackstone River
Min. Separation Distance in 2023	0 m (currently protected but needs intervention)
Previous Erosion Mitigation	Angular riprap (presumably Class I) atop geotextile (year unknown)
Erosional Processes	• Active outer-bank erosion is occurring along the meander bend. • Previously installed riprap has been displaced. • Geotextile appears to have created a slip plane within the revetment.
Mitigation Considerations and Recommendations	• Remove exposed geotextile and reconstruct the riprap using granular filter layers and a gentler slope (if possible). • Incorporate riparian plantings, if feasible. • Consider removal of inner-bank gravel deposits to increase hydraulic capacity and reduce outer-bank shear stresses.
Representative Visual	 Displaced riprap and exposed geotextile

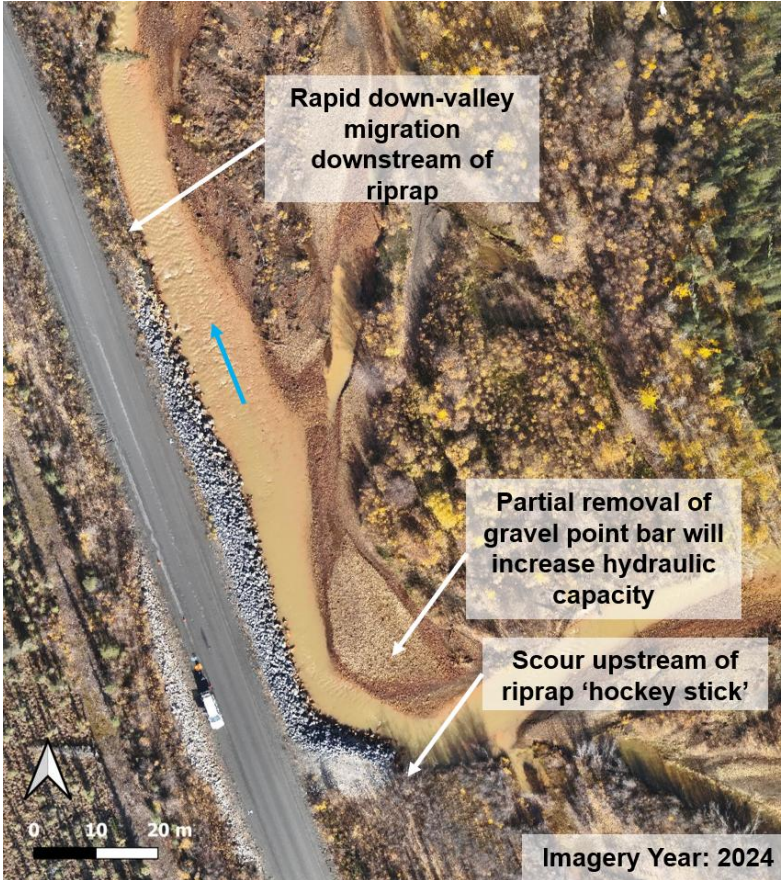


Highway and KM	Dempster Highway KM 115.5
Watercourse	Blackstone River
Min. Separation Distance in 2023	9 m
Previous Erosion Mitigation	Various slope stabilization measures and highway relocation
Erosional Processes	• A high and steep slope adjacent to Chapman Lake is actively failing. • The contribution of toe erosion to overall slope instability remains uncertain. • Degradation of ice-rich permafrost appears to be the dominant driver of instability.
Mitigation Considerations and Recommendations	• Relocate the highway further away from the slope crest where feasible. • Continue monitoring and coordinate with YukonU PGR investigations.
Representative Visual	 High, unstable slope. The contribution of toe erosion to slope instability is unclear. Permafrost thaw appears to be driver of instability.



Highway and KM	Dempster Highway KM 116.2
Watercourse	Blackstone River
Min. Separation Distance in 2023	16 m
Previous Erosion Mitigation	Various slope stabilization measures
Erosional Processes	• A high and steep slope adjacent to Chapman Lake is actively failing. • The contribution of toe erosion to overall slope instability remains uncertain. • Degradation of ice-rich permafrost appears to be the dominant driver of instability and has likely caused the formation of sink holes.
Mitigation Considerations and Recommendations	• Relocate the highway further away from the slope crest where feasible. • Continue monitoring and coordinate with YukonU PGR investigations.
Representative Visual	 High, unstable slope. The contribution of toe erosion to slope instability is unclear. Permafrost thaw appears to be driver of instability.

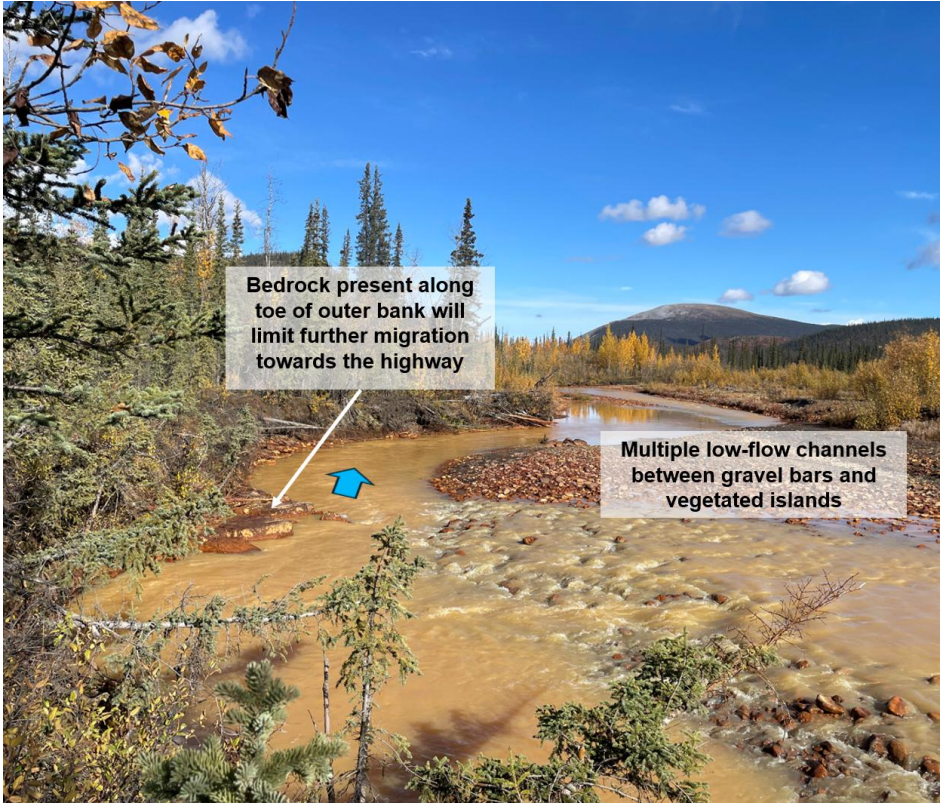


Highway and KM	Dempster Highway KM 165.5
Watercourse	Engineer Creek
Min. Separation Distance in 2023	0 m (currently protected but needs intervention)
Previous Erosion Mitigation	Angular riprap (presumably Class I or II) with upstream deflector (2017)
Erosional Processes	- Channel migration is resulting in scour behind the riprap at the upstream end. - Rapid downstream migration has occurred beyond the existing riprap protection. - Based on channel planform geometry, an avulsion through the eastern floodplain is possible.
Mitigation Considerations and Recommendations	- Consider removal of inner-bank gravel deposits to increase hydraulic capacity and reduce bend severity at least for the short-term. - Remove or modify the riprap that extends upstream away from the highway to reduce outflanking risk; a deflector may be more effective near the downstream end of the revetment. - Extend riprap downstream and/or add a deflector to shift the thalweg away from the highway.
Representative Visual	



Highway and KM	Dempster Highway KM 170.0
Watercourse	Engineer Creek
Min. Separation Distance in 2023	25 m
Previous Erosion Mitigation	Berm (alluvium) along highway upstream of the site
Erosional Processes	- The site is located within a depositional reach prone to lateral migration and avulsion. - An anthropogenic berm separates the channel from the highway; however, the berm appears to consist of erodible alluvial material, and it ends at Km 169.9. - Bedrock along the outer-bank toe will likely limit further migration toward the highway, risk level may need to be reassessed.
Mitigation Considerations and Recommendations	- Monitor using desktop methods or simple field approaches (e.g., monumented stakes). - Consider trial implementation of alternative mitigation approaches such as wood deflectors; construction access is locally favourable.
Representative Visual	



Highway and KM	Dempster Highway KM 171.9
Watercourse	Engineer Creek
Min. Separation Distance in 2023	23 m
Previous Erosion Mitigation	None
Erosional Processes	- The site is located within a depositional reach prone to lateral migration and avulsion. - Bedrock along the outer-bank toe will likely limit further migration toward the highway, risk level may need to be reassessed.
Mitigation Considerations and Recommendations	Monitor using desktop methods or simple field approaches (e.g., monumented stakes).
Representative Visual	 Bedrock present along toe of outer bank will limit further migration towards the highway Multiple low-flow channels between gravel bars and vegetated islands

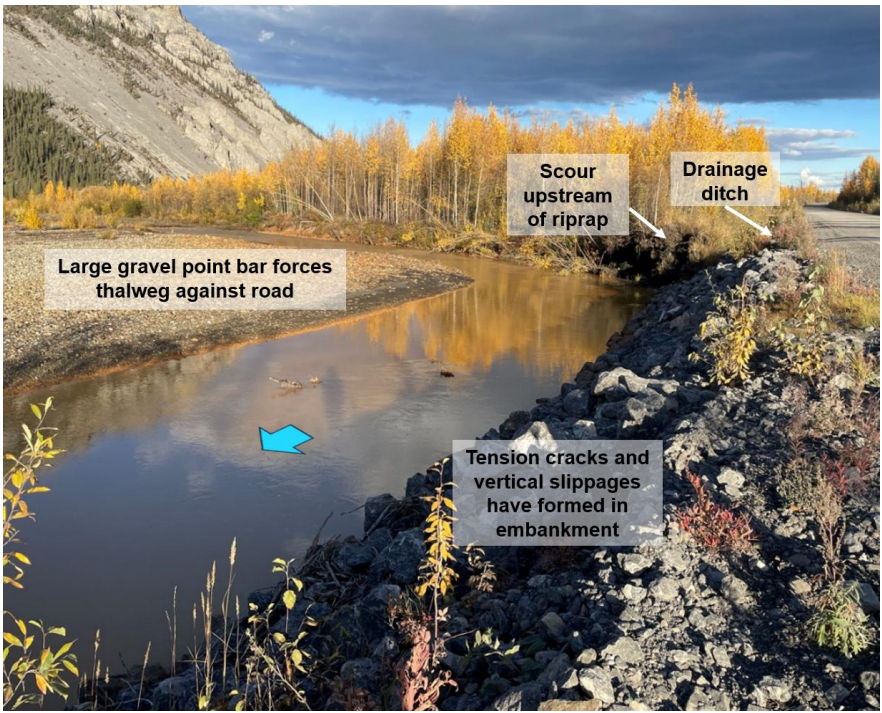


Highway and KM	Dempster Highway KM 182.1
Watercourse	Engineer Creek
Min. Separation Distance in 2023	0 m (emergency site)
Previous Erosion Mitigation	Angular riprap (2010 & 2015)
Erosional Processes	- Scour around the upstream end of existing riprap (outflanking) contributed to embankment failure. - Rapid, down-valley migration is occurring downstream of the revetment. - It remains unclear whether channel incision is undermining the riprap toe.
Mitigation Considerations and Recommendations	Emergency: address active scour at the upstream end of the riprap by regrading the slope and constructing a vegetated boulder revetment. - Extend riprap farther upstream to reduce future outflanking risk. - Monitor downstream migration to determine whether additional protection is required; a riprap or wood deflector may be warranted near the downstream culvert outlet. - Consider removal of inner-bank gravel deposits to increase hydraulic capacity and reduce bend severity at least in the short-term.
Representative Visual	

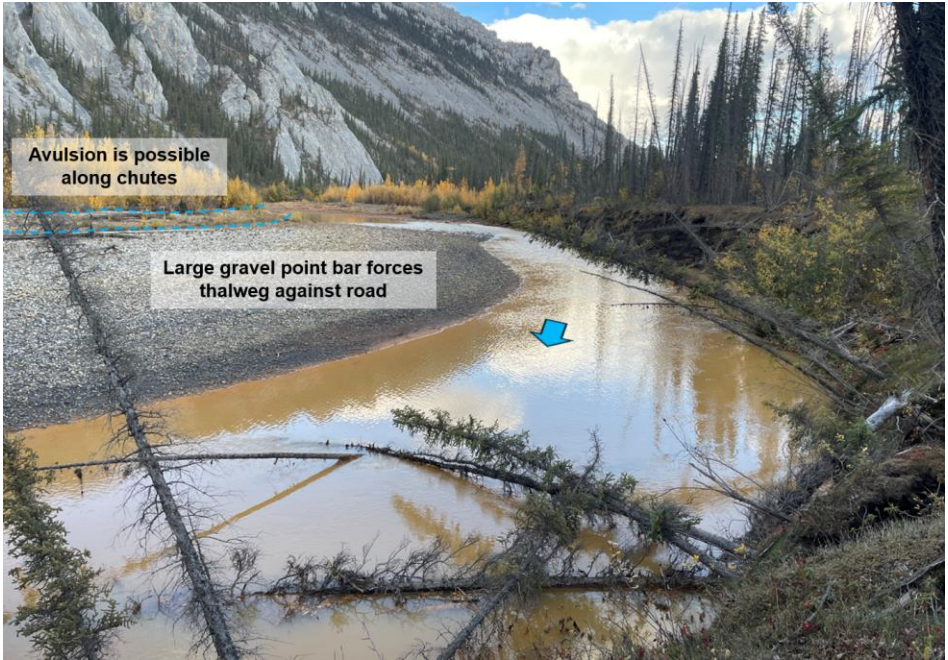


Highway and KM	Dempster Highway KM 183.3
Watercourse	Engineer Creek
Min. Separation Distance in 2023	18 m
Previous Erosion Mitigation	None
Erosional Processes	• Historical outer-bank erosion has resulted in rapid lateral migration. • The channel now abuts a low terrace that limits further outer-bank migration and may promote down-valley migration. • A meander neck cutoff or avulsion is possible.
Mitigation Considerations and Recommendations	• Monitor using desktop methods or simple field approaches (e.g., monumented stakes). • Consider testing alternative mitigation approaches such as wood deflectors; construction access is favourable.
Representative Visual	 A photograph of Engineer Creek showing a low terrace between the river and highway, down-valley migration, and a monitoring stake. The image includes three callout boxes: 'A low terrace between the river and highway limits lateral migration' pointing to the left bank, 'Down-valley migration' pointing to the river's path, and 'Monitoring stake' pointing to a wooden stake in the foreground.

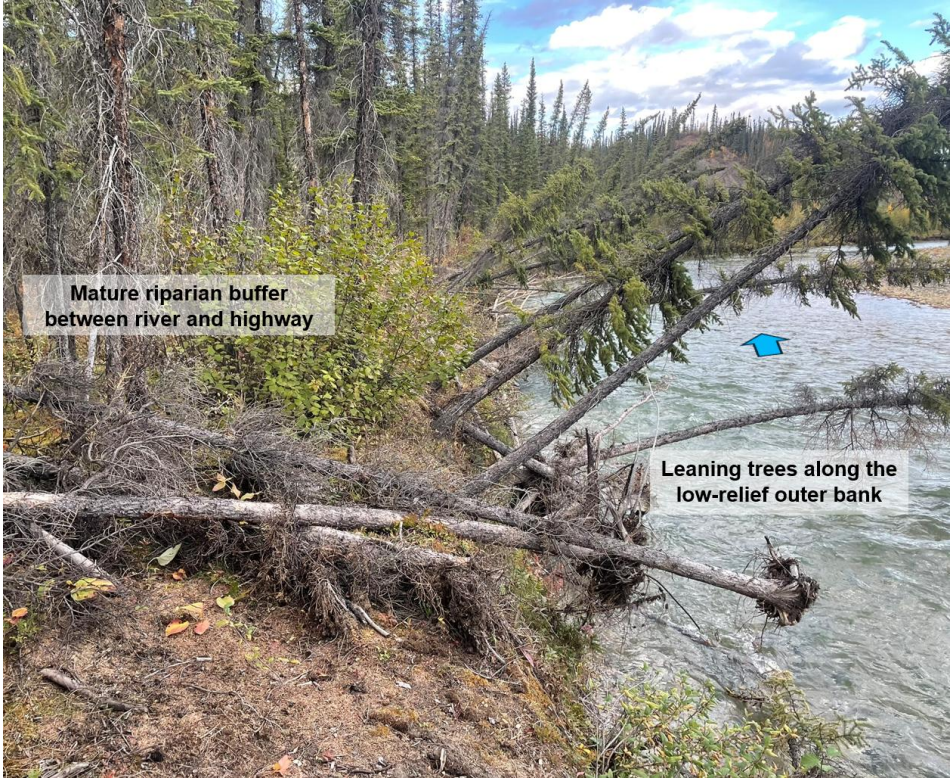


Highway and KM	Dempster Highway KM 193.4
Watercourse	Engineer Creek
Min. Separation Distance in 2023	0 m (currently protected, but needs intervention)
Previous Erosion Mitigation	Angular riprap (presumably Class II) (2024 and 2025/2026)
Erosional Processes	- The site is located along a dynamic reach of Engineer Creek where migration rates exceed 2 m/year, and avulsion is likely within the coming years. - Riprap installed in 2024 is already being outflanked at its upstream and downstream ends; upstream erosion may soon intercept the highway drainage ditch. Additional riprap was placed near the upstream end of the revetment in late 2025 or early 2026. - Tension cracks and rotational slumping near the revetment crest suggest active toe scour or settlement.
Mitigation Considerations and Recommendations	- Extend riprap protection into the highway ditch upstream and monitor downstream erosion progression. - Consider embedding the revetment toe or constructing a riprap apron. - Consider installation of a wood or riprap deflector near the downstream end of the protection. - A wood or riprap deflector could also be installed along the upstream meander limb using access through Engineer Creek Campground.
Representative Visual	 The photograph shows a riverbank with a gravel point bar on the left, a drainage ditch on the right, and a riprap revetment. Labels indicate 'Scour upstream of riprap', 'Drainage ditch', 'Large gravel point bar forces thalweg against road', and 'Tension cracks and vertical slippages have formed in embankment'.



Highway and KM	Dempster Highway KM 194.0
Watercourse	Engineer Creek
Min. Separation Distance in 2023	28 m (decreased to 23 m in 2025 drone imagery)
Previous Erosion Mitigation	None
Erosional Processes	- The site is located along a dynamic reach of Engineer Creek where migration rates exceed approximately 3 m/year and avulsion is likely within the coming years. - Permafrost is likely present within the outer bank between the channel and highway. - The presence of a man-made ditch near (~20 m) of the site may affect erosion rates in coming years
Mitigation Considerations and Recommendations	- Continue proactive monitoring; real-time monitoring equipment may be justified at this location. - Consider removal of inner-bank gravel deposits to increase hydraulic capacity and reduce outer-bank shear stresses at least in the short-term. - Engineered log jams or wood spurs along the upstream meander limb may help deflect erosive forces away from the highway. Site access is complex, but emergency interventions are already justifiable.
Representative Visual	 Avulsion is possible along chutes Large gravel point bar forces thalweg against road



Highway and KM	Dempster Highway KM 218.4
Watercourse	Ogilvie River
Min. Separation Distance in 2023	13 m
Previous Erosion Mitigation	None
Erosional Processes	• Lateral migration is occurring along a secondary channel. Straight-trunked trees (indicating consistent erosion) are leaning throughout the site. • The secondary channel was previously backwatered by a beaver dam, but this dam has been destroyed. • The distribution of flow between the primary and secondary channels (difficult to foresee) influences erosion risk.
Mitigation Considerations and Recommendations	• Monitor using desktop methods or simple field approaches (e.g., monumented stakes). • Consider building one or a series of weirs made of small boulder and wood in the secondary channel to slow water velocity.
Representative Visual	 Mature riparian buffer between river and highway Leaning trees along the low-relief outer bank



Highway and KM	Dempster Highway KM 232.1
Watercourse	Ogilvie River
Min. Separation Distance in 2023	23 m
Previous Erosion Mitigation	None
Erosional Processes	- Channel migration is predominantly down-valley rather than toward the highway. - The site is located within a multi-thread reach where flow distribution between channels controls erosion potential. - Ice jams may modify the disposition of gravel bars in coming years and accelerate channel migration towards the road.
Mitigation Considerations and Recommendations	- Monitor using desktop methods or simple field approaches (e.g., monumented stakes). - Consider testing alternative (ice-run resistant) mitigation approaches such as large wood deflectors; construction access is favourable.
Representative Visual	



Highway and KM	Dempster Highway KM 239.5
Watercourse	Ogilvie River
Min. Separation Distance in 2023	6 m (decreased to 4 m in 2025 drone imagery)
Previous Erosion Mitigation	None
Erosional Processes	• Rapid lateral migration is occurring toward the highway. • A former secondary channel has become the dominant flow path. • Ice runs may contribute to bank erosion and channel adjustment.
Mitigation Considerations and Recommendations	• Emergency: a single high-flow event could compromise the embankment (last documented in 2025). • Construct a vegetated boulder revetment along the outer bank. Consider incorporating wood or riprap deflectors; construction access is favourable.
Representative Visual	 Large gravel bars force thalweg against road Highway

