YGS Miscellaneous Report 20

Carmacks surficial geology and community hazard susceptibility mapping

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Yukon

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Front cover: Yukon River valley, north of the Village of Carmacks.

Foreword

The Carmacks surficial geology and community hazard susceptibility mapping was completed to support land use planning, but also provides a valuable base map for public education about the origins of the landscape. The Village of Carmacks spans the Yukon River valley at the mouth of the Nordenskiöld River and the landscape reflects the areas recent glacial and post-glacial history. About 16 000 years ago, a large glacier melted in the vicinity leaving behind a complex topography of undulating hills and depressions. This was subsequently eroded through by the Yukon River, and large gravel terraces formed, providing a foundation for the community. Natural changes to the landscape continue and these changes can present public safety hazards and risks to current and future development projects. This map and associated hazard assessment provides the necessary baseline information to make informed land use decisions through identifying which areas of the community are most susceptible to landscape hazards. The most common hazards present in the community include, river erosion and flooding, landslides, and permafrost. It is our goal to provide Yukon communities with accurate geological knowledge concerning these natural processes, with the hope they are referenced in all future planning. Palmer Environmental Consulting has completed the most detailed surficial geology mapping and thorough analyses of potential landscape hazards ever produced for the greater Carmacks area. This product is an excellent foundation for understanding where the community is located in its physical environment and where the risks to sustainable development occur. We are confident that it will be an important community resource for many years to come.

Jeffrey Bond
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Table of Contents

Introduction

Palmer is pleased to present the Yukon Geological Survey (YGS) with the results of our surficial geology mapping and analysis of landscape hazard susceptibility for the Village of Carmacks (Carmacks), Yukon. The maps and supporting report are intended to increase public awareness and appreciation of the geological surroundings and support effective community land use planning. The purpose of this report is to outline the methods and assumptions on which the mapping is based, draw attention to key results with an emphasis on identified geomorphological processes and their implications, and identify and rationalize recommended follow-up work.

Objectives

The objectives of this project are to:

- Refine and field-validate previously completed 1:15 000-scale surficial geology mapping for the Village of Carmacks;
- Analyze susceptibility to hillslope, permafrost, and fluvial hazards within the map area;
- Produce a raster-based composite map of landscape hazard susceptibility, derived from individual models of hillslope, permafrost and fluvial hazard susceptibility; and
- Summarize the results of the mapping and analysis herein and provide recommendations for followup work.

Physical Setting

Climate

The Carmacks map area is located in the central Yukon Plateau. This relatively dry region receives only 250 to 300 mm of precipitation annually, with two-thirds of this occurring during the summer months (Yukon Ecoregions Working Group, 2004). Thin snow cover is generally present from mid-October to mid-April. Mean annual temperature is -4°C, with mean January temperatures as low as -30°C and mean July temperatures up to 15°C. The map area is in a region of extensive discontinuous permafrost, where the probability of permafrost throughout the map area ranges from 40 to 90% (Bonnaventure *et al.*, 2012).

Physiography and Surficial Geology

The map area has been glaciated by the northern Cordilleran ice sheet multiple times, beginning with the pre-Reid glaciations in the latest-Pliocene (Hidy *et al.*, 2013) and early to middle Pleistocene followed by the more recent Reid (Marine Isotope Stage (MIS) 6) and McConnell glaciations (MIS 2). It is unknown whether ice occupied the map area during the Gladstone glaciation (MIS 4). During the McConnell glaciation, ice sculpted the hills around Carmacks and deposited a mantle of till over the landscape. As ice receded, meltwater cut through valley walls and ridges along the margins of the ice. In front of the ice sheet, large glaciofluvial outwash plains formed. These were subsequently incised as the ice withdrew, leaving behind large terraces that fill much of the Yukon River valley. Stagnant ice filled much of the Nordenskiöld and Yukon River valleys, leaving behind topography ranging from terraces with small kettle depressions to large, chaotic, hummocky ice stagnation complexes. During deglaciation large volumes of fine sediment were mobilized by strong katabatic winds from the ice sheet and deposited across much of the map area in thin veneers, rarely forming dune ridges. The present landscape is dominantly modified by fluvial processes, anthropogenic activities including mining and road building, and rare landsliding, particularly where permafrost is present or fluvial undercutting occurs.

Methods

Surficial Geology Mapping

Surficial geology mapping was completed at a scale of 1:15 000 using DAT/EM Summit soft copy 3D photo-interpretation software in conjunction with Esri's ArcGIS. Interpretations were made from 1:40 000-scale black and white aerial photographs from 2007 and 1:20 000-scale colour aerial photographs from 2010. These interpretations were further refined based on a 1 m resolution LiDAR digital elevation model (DEM) covering the Freegold Road corridor and the Village of Carmacks municipal boundaries, and the 2 m resolution *ArcticDEM* (Porter et *al.*, 2018). Borehole logs and previous engineering reports (Golder, 2018; Chilkoot, 2020) were reviewed for field observations and subsurface information. Surficial geology map units were delineated based on surficial material, surface expression, and geomorphological processes in accordance with the *Terrain Classification System for British Columbia* (Howes and Kenk, 1997), with modifications for use in Yukon (Yukon Geological Survey, 2020).

Field validation was completed September 11–12, 2020, to confirm and expand upon desktop interpretations. Weather conditions were cool and sunny without significant antecedent precipitation. Truck-assisted field traverses were planned with the goals of inspecting a maximum diversity of material and processes, and visiting areas where desktop interpretations were uncertain. Surficial materials were observed with the aid of road and mining cuts, soil pits, and natural exposures in landslide scarps and cut banks. A 120 cm frost probe was used to determine the presence and depth of permafrost. Maximum thaw depth typically occurs in late summer, so depth observations are likely to represent the full active layer thickness. Field assistance was provided by Yukon Geological Survey Surficial Geologist, Kristen Kennedy.

The preliminary desktop surficial geology mapping was updated based on the results of the field program. Polygon boundaries and geological attributes were adjusted, as necessary, to reflect field observations.

Fluvial Erosion Hazard Forecasting

To better understand channel planform evolution and bank recession along the portions of Yukon River and Nordenskiöld River within the study area, aerial photography dating back to 1953 was accessed from Yukon Government's online archives (GeoYukon; Table 1). The historical aerial photographs were georeferenced to the recent orthophotographs (2018 and 2019) using standard ArcGIS georeferencing tools. Approximately five control points were used to optimize the spatial match within the valley bottom, where relief and relative image distortion are low. Resultant errors in comparison to the orthophotos were generally ± 3 m.

Table 1. Aerial imagery obtained from GeoYukon used in fluvial hazard assessment

Type	Year	Resolution/ Scale	Roll Number	Study Area Coverage
Colour Orthophotography	2019	0.2 m	N/A	Nordenskiöld River and majority of Yukon River (downstream extent of Yukon River is unavailable)
Colour Orthophotography	2018	0.15 m	N/A	Downstream extent of Yukon River
Black and White Aerial Photography	1994	1:20 000	A28155	Entire study area
Colour Aerial Photography	1977	1:50 000	A37495	Nordenskiöld River and majority of Yukon River (upstream extent of Yukon River is unavailable)
Black and White Aerial Photography	1969	1:15 000	A21019	Upstream extent of Yukon River
Black and White Aerial Photography	1953	1:70 000	A13628	Nordenskiöld River and majority of Yukon River (upstream extent of Yukon River is unavailable)

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., 1:2500 to 1:5000). 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 DEM hillshade models.

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 imagery years. Exactly which time period was appropriate for estimating the migration rate was determined on a site-by-site basis. Some sites exhibited systematic migration from the earliest aerial photograph to the most recent imagery; migration rates, therefore, were based on the full period of record (e.g., 1953 to 2019). Migration rates were estimated based on shorter periods of record at sites exhibiting irregular or unsystematic migration, or where avulsions had made former patterns and rates of bank erosion unrepresentative (e.g., 1977 to 2019). Migration rates were not calculated for meanders that exhibited no systematic change in bank position over the period of record.

Three lateral hazard zones were established based on extrapolation of time-averaged rates and trajectories of erosion: short term (0 to 10 years), near-term (10 to 25 years), and long-term (25 to 50 years). The temporal ranges necessarily lengthen with time in accordance with a gradual decline in predictive accuracy. The outer limits of each lateral hazard zone represent the predicted maximum channel position (*i.e.*, top of outer bank) within the respective timeframe. The projected limits were refined based on consideration of site-specific influences on planform adjustment such as valley walls or terrace scarps, potential for avulsion, or interactions with pre-existing channels. For example, lateral hazard zones were at least partly biased in a down-valley direction where the channel encroaches alongside the base of a high terrace scarp or valley wall. Documented rates and trajectories of erosion across the adjacent floodplain would otherwise have unrealistically suggested considerable recession of the terrace scarp or valley wall. Desktop-based interpretations were 'ground-truthed' at select sites.

The comparative overlay analysis we applied facilitates time-averaged estimation of meander migration, assuming progression at a uniform rate. Bank erosion is more likely to occur episodically in response to extreme flows, thalweg adjustments in association with avulsions or bar redistribution, and upstream ice jam breaching. A time-averaged rate effectively reduces the ‘noise’ represented by localized and episodic adjustments.

Landscape Hazard Susceptibility Analysis

Landscape hazard susceptibility was analyzed using the newly produced surficial geology and fluvial erosion maps and existing datasets including permafrost probability (Bonnaventure, *et al*., 2012) and DEMs. “Hazard susceptibility”, not to be confused with “hazard”, is the tendency of an area to be affected by hazardous processes. Susceptibility considers only the spatial aspects of hazardous processes, not the temporal aspect or magnitude, whereas “hazard” considers probability of occurrence and magnitude of a hazardous process in a given area and period of time (Hervas and Bobrowsky, 2009).

The modelling process was modified from the raster-based approach of Benkert *et al*. (2015) to model landscape hazard susceptibility in the Dawson region through combination of separate susceptibility analyses of hillslope, fluvial, and permafrost processes, allowing for separate outputs for each hazard process and easier refinement of individual hazard susceptibilities. The model rules for the individual hazard susceptibilities are outlined in sections below.

Hillslope Hazard Susceptibility Analysis

The hillslope hazard susceptibility model uses the variables of slope angle, surficial material and process, and permafrost probability to evaluate the relative susceptibility to initiation of hillslope mass movement processes (Table 2). This model implicitly considers landslide runout susceptibility through the recognition of colluvial deposits, but does not include calculation of landslide runout susceptibility where they have not previously occurred. Slope angles were calculated from 1 m LiDAR DEMs covering the Village of Carmacks and the Freegold Road corridor, and the 2 m *ArcticDEM*. Surficial geology polygons were ranked by material type and process. Where a process is present in a map unit, the higher of the material or process ranks was selected for the polygon. The ranked polygons were then rasterized. The ranked variables were each weighted based on expert judgement of their relative contributions to hillslope hazard susceptibility with contextual reference to previous work by Blais-Stevens and Behnia (2016), and Benkert *et al.* (2015). The ranked and weighted variables were then combined additively to produce a semi-quantitative susceptibility output. This output was then reviewed and assigned a qualitative classification based on expert judgement and comparison to observed hillslope process distributions.

Table 2. Input variables and values for hillslope hazard susceptibility model.

1 - Input Variables	Slope Angle		Surficial Geology		Permafrost Probability	
	Slope Angle (°)	Ranking	Surficial Material or Process	Ranking	Permafrost Probability	Ranking
	0–3	0	Eolian	6	0.0–0.1	0
	4–15	2	Colluvium	9	0.1–0.2	1
	16–26	5	Organics	1	0.2–0.3	2
	27–35	7	Moraine	5	0.3–0.4	3
	>35	9	Anthropogenic	1	0.4–0.5	4
			Fluvial	3	0.5–0.6	5
			Glaciofluvial	3	0.6–0.7	6
			Rock	1	0.7–0.8	7
			-R, -F, -L	9	0.8–0.9	8
			-V	6	0.9–1.0 (or -X)	9
2 - Variable Weights	**0.5**		**0.3**		**0.2**	

3 - Semi-Quantitative Output

Model Value	% of Map Area	Area (ha)
1	5	1704
2	11	4158
3	25	9009
4	26	9578
5	13	4791
6	10	3451
7	6	2162
8	3	1168
9	1	291

4 - Qualitative Susceptibility Classification

Model Value	Susceptibility Class	% of Map Area	Area (ha)
1	Low	67	24 448
2	Moderate	13	4791
3	Moderately High	10	3451
4	High	10	3621

Permafrost Hazard Susceptibility Analysis

The permafrost hazard susceptibility model evaluates the relative susceptibility of ground subsidence resulting from permafrost degradation, or “thermokarst”. This model uses permafrost probability and surficial materials and their textures as input variables (Table 3). Where permafrost is indicated in the surficial geology mapping, the map polygon is given the highest permafrost probability rank. Fine-grained matrix-supported surficial materials and organics were ranked higher due to poor drainage and the increased probability of segregated ice exceeding their low pore space, making them more thaw sensitive. Active fluvial and anthropogenic materials were ranked as very low (1), as permafrost is unlikely to be present in these recently deposited materials. Rock is also ranked very low (1) as it is unlikely to experience thaw subsidence. Hillslope hazard susceptibility resulting from permafrost thaw is captured in the hillslope hazard susceptibility model (Section 3.3.1). The ranked variables were each weighted based on expert judgement of their relative contributions to permafrost hazard susceptibility and combined additively to produce a semi-quantitative susceptibility output. This output was then reviewed and assigned a qualitative classification based on comparison to observed permafrost process distributions, natural breaks in the data, and expert judgement.

Fluvial Hazard Susceptibility Analysis

Fluvial hazard susceptibility evaluates the susceptibility of the map area to fluvial erosion and flooding and lacustrine-style inundation. This model uses fluvial erosion forecasting data, developed in this study, along with a landformbased flood susceptibility analysis based on surficial geology map units and their heights above adjacent watercourses (Table 4). This model incorporates two separate processes, which have been manually categorized into susceptibility ratings. These inputs are combined with the highest value selected for the semi-quantitative output. This output was reviewed and assigned a qualitative susceptibility classification based on expert judgement.

Table 3. Input variables and values for permafrost hazard susceptibility model.

1 - Input Variables	Permafrost Probability		Surficial Material	
	Permafrost Probability	**Ranking**	**Surficial Material**	**Hazard Ranking**
	0.0–0.1	0	Organics	9
	0.1–0.2	1	Matrix-supported	4
	0.2–0.3	2	Clast-supported	2
	0.3–0.4	3	Rock, Anthropogenic, Active Fluvial	1
	0.4–0.5	4		
	0.5–0.6	5		
	0.6–0.7	6		
	0.7–0.8	7		
	0.8–0.9	8		
	0.9–1.0 (or mapped -X)	9		
2 - Variable Weights	**0.7**		**0.3**	

3 - Semi-Quantitative Output

Model Value	% of Map Area	Area (ha)
1	-	-
2	-	-
3	-	-
4	45	16 347
5	47	17 166
6	2	859
7	2	843
8	2	833
9	1	225

4 - Qualitative Susceptibility Classification

Model Value	Susceptibility Class	% of Map Area	Area (ha)
1	Low	83	30 290
2	Moderate	10	3770
3	Moderately High	6	2038
4	High	1	225

Table 4. Input variables and values for fluvial hazard susceptibility model.

1 - Input Variables	Erosion		Flooding and Inundation	
	Forecast Window (Years)	Ranking	Landform/Process	Ranking
	0–10	9	FAp, H, -U	9
	10–25	9	FAf	7
	25–50	8	Fp	5
	>50	1	Ft, Ff, Fa	3
			Other	1

2 - Highest variable for a given cell is selected for output

3 - Semi-Quantitative Output

Model Value	% of Map Area	Area (ha)
1	71	25 753
2	-	-
3	12	4392
4	-	-
5	2	822
6	-	-
7	>1	74
8	>1	46
9	14	5220

4 - Qualitative Susceptibility Classification

Model Value	Susceptibility Class	% of Map Area	Area (ha)
1	Low	71	25 753
2	Moderate	12	4392
3	Moderately High	2	897
4	High	15	5267

Combined Landscape Hazard Susceptibility

The combined landscape hazard susceptibility map was created by merging the three process-specific qualitative susceptibility models and selecting the highest value cell for the combined output value. This approach was adopted, rather than a cumulative score, as the process-specific susceptibilities cannot be mathematically compared with each other. For example, a map unit highly susceptible to permafrost subsidence and hillslope processes but with low susceptibility to flooding is not necessarily of greater concern than a map unit with high fluvial hazard susceptibility but low permafrost subsidence and hillslope hazard susceptibility.

Results

Surficial Geology Mapping

Surficial geology for the Carmacks map area is provided in Appendix A. Figure 1 summarizes the areal proportion of each dominant surficial material. Eolian loess deposits overlie 25% of the map area. This accounts only for where loess is in mappable thicknesses (>20 cm). Approximately 7% of the map area is mantled by till. Considerably more till is present than is indicated by this proportion; however, it is commonly overlain by loess (eolian) or colluvium. Fluvial deposits occupy 17% of the map area and water bodies including lakes and rivers occupy 11% of the map area. Glaciofluvial deposits comprise 18% of the map area, occupying much of the Nordenskiöld and Yukon river valleys. Colluvial deposits are common on and below steeper slopes and occupy 20% of the map area. Together, bedrock, organics, and anthropogenic deposit occupy only 2.4% of the map area. Organics occur in non-mappable thicknesses (<50 cm) on poorly drained sites and often overlie permafrost.

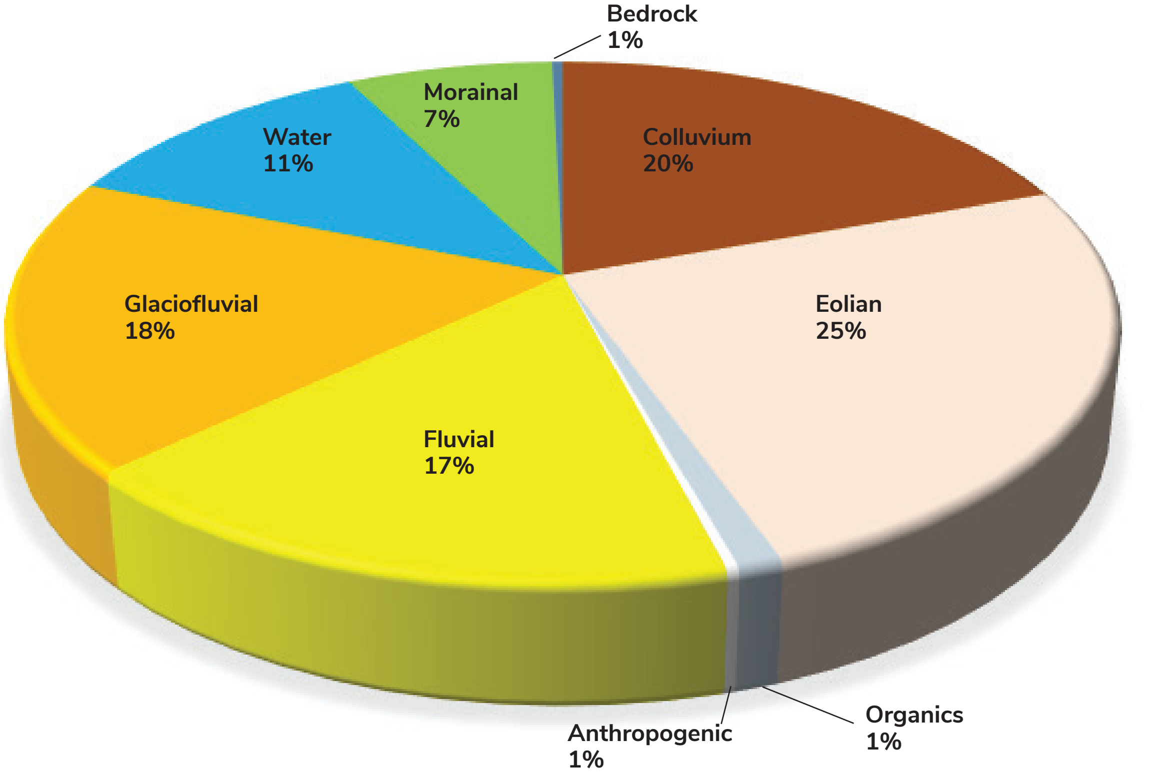

Figure 1. Areal proportions of surficial materials in the Carmacks map area.

Mass movements in the study area consist of active layer detachments, debris flows, debris slides, slumps and rare rockslides. Active layer detachments initiate only in permafrost terrain and commonly transform into debris flows. Debris slides are common where fluvial undercutting of outwash terraces occurs along the Yukon River. One rockslide complex consisting of at least two separate movements was identified in Carmacks group volcanics in the west portion of the map area. At least two large slumps exists in the glaciofluvial outwash terraces in the Yukon River valley. These slumps appear to be old, likely occurring shortly after deglaciation, based on their loess cover and subdued morphology.

Fluvial Erosion Forecasting

Historical channel planforms and delineated erosion hazard zones are illustrated in Appendix B. Comparative overlay analysis of historical channel planforms revealed five meanders along Yukon River (Table 5) and 16 meanders along Nordenskiöld River (Table 6) that exhibit systematic migration. Meanders excluded from these summary tables have either exhibited little to no migration over the period of record (*i.e.*, 1953 to 2019) or exhibited unsystematic erosion from which a trend cannot be ascertained for forecasting purposes.

Time-averaged erosion rates along Yukon River range from 0.4 to 0.7 m/year, with an overall average of 0.5 m/year. Time-averaged rates of erosion along Nordenskiöld River range from 0.3 to 2.8 m/year, with an overall average of 1.1 m/year. Channel migration rates and associated erosion hazard delineations are larger along Nordenskiöld River relative to Yukon River due a steeper gradient, an unregulated flow regime, and lack of channel confinement. Flow regulation along Yukon River at Whitehorse starting in 1958 has likely slowed channel migration near Carmacks. As well, Yukon River is confined along the majority of its length within the study area by fluvial and glaciofluvial terraces and colluvial slopes.

Two notable avulsions occurred along Nordenskiöld River over the period of record: one near N3 between 1953 and 1977 and one downstream of N5 between 1994 and 2019. Avulsions locally steepen the channel and increase sediment supply, which can accelerate erosional processes and the migration rates of downstream meanders.

Table 5. Rates and trajectories of meander migration along Yukon River.

Meander Number	Trajectory	Erosion Distance (m)	Start Date	End Date	Period (yrs)	Average Erosion Rate (m/yr)
Y1	SW	47.1	1953	2019	66	0.7
Y2	S	24.8	1953	2019	66	0.4
Y3	NE	35.2	1953	2019	66	0.5
Y4	SSE	30.4	1953	2019	66	0.5
Y5	SSE	26.7	1953	2019	66	0.4
Average						0.5

Notes: 1. Meanders are labelled in the downstream direction

Table 6. Rates and trajectories of meander migration along Nordenskiöld River.

Meander Number	Trajectory	Erosion Distance (m)	Start Date	End Date	Period (yrs)	Average Erosion Rate (m/yr)
N1	NNE	72.0	1953	2019	66	1.1
N2	WNW	88.6	1977	2019	42	2.1
N3	ENE	117.5	1977	2019	42	2.8
N4	W	35.3	1953	2019	66	0.5
N5a	NE	89.3	1977	2019	42	2.1
N5b	NNW	84.0	1953	2019	66	1.3
N6	N	45.1	1977	2019	42	1.1
N7a	NW	61.7	1977	2019	42	1.5
N7b	NE	56.1	1977	2019	42	1.3
N8	SSE	55.6	1953	2019	66	0.8
N9	N	47.8	1977	2019	42	1.1
N10	NW	21.7	1953	2019	66	0.3
N11a	NE	33.9	1977	2019	42	0.8
N11b	NNW	39.7	1953	2019	66	0.6
N12	NNE	29.9	1977	2019	42	0.7
N13	NW	48.1	1977	2019	42	1.1
N14	N	86.8	1953	2019	66	1.3
N15	NW	30.5	1977	2019	42	0.7
N16	ENE	16.7	1953	2019	66	0.3
Average						**1.1**

Notes: 1. Meanders are labelled in the downstream direction
2. N5, N7, and N11 contain two smaller meanders (a and b) that will likely coalesce in the coming decade

Landscape Hazard Susceptibility

The combined landscape hazard susceptibility model is provided in Appendix C. The prevalence and areal extent of hazard susceptibility classes are shown in Table 7.

Table 7. Prevalence of hazard susceptibility classes in the map area.

Class	% Area	Area (ha)
Low	32	2917
Moderate	30	2685
Moderately High	13	1205
High	25	2277

Discussion

Surficial Geology

Previous mapping (Jackson, 1997) identified considerable loess cover throughout much of the Carmacks are, as is common in ice-marginal outwash settings. Loess cover is present on nearly all surfaces except the steepest slopes and those with more recent erosion or deposition (e.g., active fluvial plains). Loess deposits are thickest (>1.5 m) in valley bottoms and gently sloping sheltered locations on valley walls. Dune forms present rarely on the largest glaciofluvial terraces. Loess cover has been identified in the surficial geology mapping when the cover exceeds approximately 20 cm and is relatively continuous. Ice stagnation deposits tend to have thinner loess cover, suggesting that ice was still present in these locations during the time when loess deposition was at its peak.

Fluvial Hazards

The channel overlay analysis revealed four locations where continued channel migration could impact existing infrastructure or private property over the next 50 years:

- N3 – Rapid channel migration (2.8 m/yr) towards Klondike Highway has been observed since the channel avulsion between 1953 and 1977. If erosion mitigation works are not implemented, the highway embankment will likely be impacted by the river in the mid-2020s.
- N8 – Cleared land on private property may be eroded in the next 50 years.
- N9 – Cleared land on private property may be eroded in the next 50 years.
- Y5 – Continued erosion of a glaciofluvial terrace scarp could lead to recession of its crest impacting an adjacent gravel road.

Avulsions are another natural fluvial process that warrant consideration in the Carmacks map area. An avulsion involves a sudden change in channel position, such as occurs when a meander gets cut off. Several avulsions occurred along Nordenskiöld River over the period of photographic record and will likely occur over the coming century within the active fluvial plain. Two locations where an avulsion may be possible, with significant consequences, were identified. Along Yukon River, a low fluvial terrace could be overtopped during an extreme flow event (Fig. 2a). The elevation of the crest of the terrace is as low as 523.2 m. Review of manual discharge measurements taken between 1952 and 1995 at the Water Survey of Canada Gauge (09AH001) immediately downstream of the potential avulsion site revealed that the water surface elevation reached 522.1 m during a manual measurement taken on July 5, 1962 (3310 m^3/s). The discharge of the manual measurement (3310 m^3/s) is slightly less than the highest recorded discharge at this gauge (3600 m^3/s). The gauge stopped recording discharge in 1994. During an extreme flow event (>3600 m^3/s) the low terrace could be overtopped, which could induce an avulsion. Such an avulsion could severely disrupt a key transportation corridor (Klondike Highway) and could impact private property and dwellings.

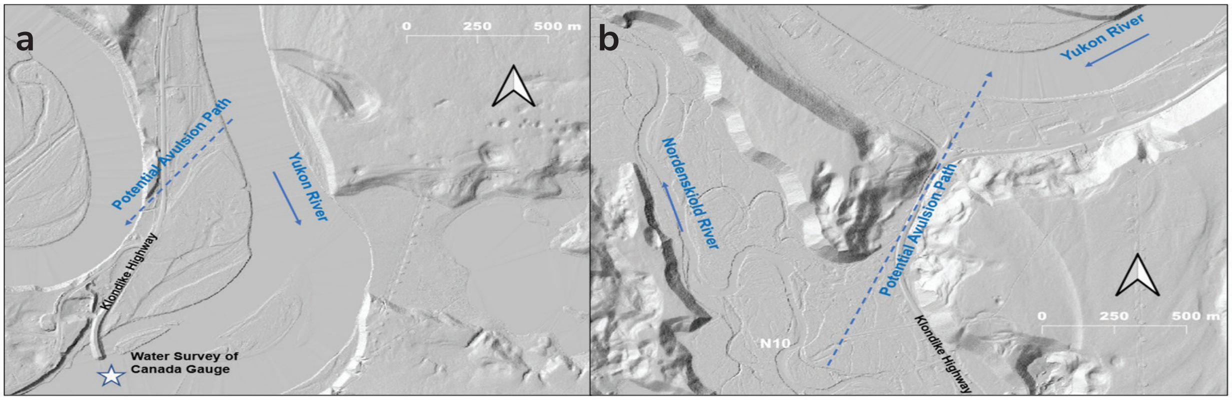

*Figure 2. Potential avulsion pathways along Yukon River (**a**) and Nordenskiöld River (**b**).*

Along Nordenskiöld River, a potential avulsion pathway was identified along Klondike Highway (Fig. 2b). Based on available LiDAR data, the water surface elevation of Nordenskiöld River near N10 is approximately 534.8 m. If the water surface were to reach 536.5 m during an extreme flow event, the nearby fluvial plain of Nordenskiöld River would be inundated and water could flow unimpeded along Klondike Highway to Yukon River. This potential avulsion, although unlikely, could be catastrophic. The rise in water levels necessary to induce an avulsion at either of these locations could occur in response to meteorological controls and/or an anomalous ice jam.

Landscape Hazard Susceptibility Modeling

The landscape hazard susceptibility model provides a credible assessment of multi-hazard susceptibility through the map area. The model considers the susceptibility to fluvial erosion and flooding, hillslope processes, and permafrost subsidence. Other potential hazards exist within the study area that are not considered in this model due to a lack of information or the difficulty of incorporation. For example, previous work identified several large landslides (>1 km^2) on the periphery of the study area (Jackson, 1997 and 2000). These large landslides are associated with weak bedrock of the Carmacks group and Selkirk volcanic rocks and likely occurred during or soon after deglaciation. Susceptibility to large landslides of this type is not represented in our hillslope or cumulative landscape hazard susceptibility modelling.

Ice stagnation deposits throughout the map area show evidence of historic faulting as buried ice melted and removed support from these materials causing subsidence. No recent subsidence activity associated with these materials was noted in the map area; however, it is possible that buried glacial ice is present in some locations and subsidence may occur. Potential for melt-out of buried glacial ice is not considered in the hazard susceptibility model.

Historic wildfires have occurred within the map area. Wildfires influence the slope stability, permafrost and flooding, as well as presenting their own hazard; however, wildfire hazard and its affect on other geomorphological processes has not been considered in the model.

Historic coal mining on Tantalus Butte has left a series of open mineshafts, some containing burning coal seams. These mine workings have the potential to collapse resulting in ground subsidence. This subsidence and fire hazard associated with burning coal seams are not considered in the hazard susceptibility model. Development in the vicinity of the historic mining on Tantalus Butte should take these hazards into consideration.

Recommendations

A number of recommendations naturally follow from the community hazard mapping presented and described herein for the Village of Carmacks:

- Detailed site-specific hazard and development suitability assessments should be conducted prior to development of any portions of the map area regardless of hazard susceptibility classification. Community-scale hazard mapping is not a substitute for ground-based investigations.
- Development of ice stagnation complexes should consider the potential for buried glacier ice and continued movement of faulted sediments.
- Detailed flood mapping using LiDAR and detailed bathymetric data should be completed for both Yukon River and Nordenskiöld River within the study area in accordance with accepted protocols (*e.g.*, EGBC, 2017). The flood mapping would provide further insights into risks associated with flood hazards within the study area and would establish the flows at which the potential avulsions discussed in Section 5 could occur. Yukon Energy Corporation should be made aware of the flow conditions capable of overtopping the low fluvial terraces along Yukon River so that discharge from Schwatka Lake at Whitehorse can be managed accordingly.
- Monitoring benchmarks for tracking channel migration should be established at N3 and Y5, at a minimum. Monitoring benchmarks could also be established at other meanders showing systematic migration, including N8 and N9. The distance between the top of bank and the monitoring benchmark (*e.g.*, survey stake, secure tree) should be measured every 1 to 2 years, as well as after any anomalously large flood events or rapid ice break-up. The monitoring program would help identify when risks associated with channel migration become unacceptable.
- Highway and Public Works (HPW) should be alerted to the rapid channel migration and potential for embankment failure at N3. HPW can proactively evaluate conceptual mitigative strategies to mitigate riverbank erosion in the likely scenario that the river poses unacceptable risk to the highway in the coming years.

Statement of Limitations

This report has been prepared by Palmer for Government of Yukon in accordance with the agreement between Consultant and Client, including the scope of work detailed therein (the “Agreement”). The report and the information it contains may be used and relied upon only by Client, except (1) as agreed to in writing by Consultant and Client, (2) as required by-law.

The extent of this study was limited to the specific scope of work for which Palmer was retained and is described in this report. Palmer has assumed that the information and data provided by the client or any secondary sources of information are factual and accurate. Palmer accepts no responsibility for any deficiency, misstatement or inaccuracy contained in this report as a result of omissions, misinterpretations or negligent acts from relied-upon data. Judgment has been used by Palmer in interpreting surficial geology, geomorphological processes and hazard susceptibility based on desktop analyses and limited field reconnaissance at many but not all sites. Interpretations of subsurface conditions have been made based on surface observations and limited subsurface exposures and may not fully capture the variability in the study area or within a given map unit (polygon).

Palmer is not a guarantor of site conditions or projected hazard susceptibility but warrants only that our work was undertaken and our report prepared in a manner consistent with the level of skill and diligence normally exercised by competent geoscience professionals practicing in Yukon. Our findings, conclusions and recommendations should be evaluated in light of the limited scope of our work.

Certification

This report was prepared and reviewed by the undersigned

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Prepared By:

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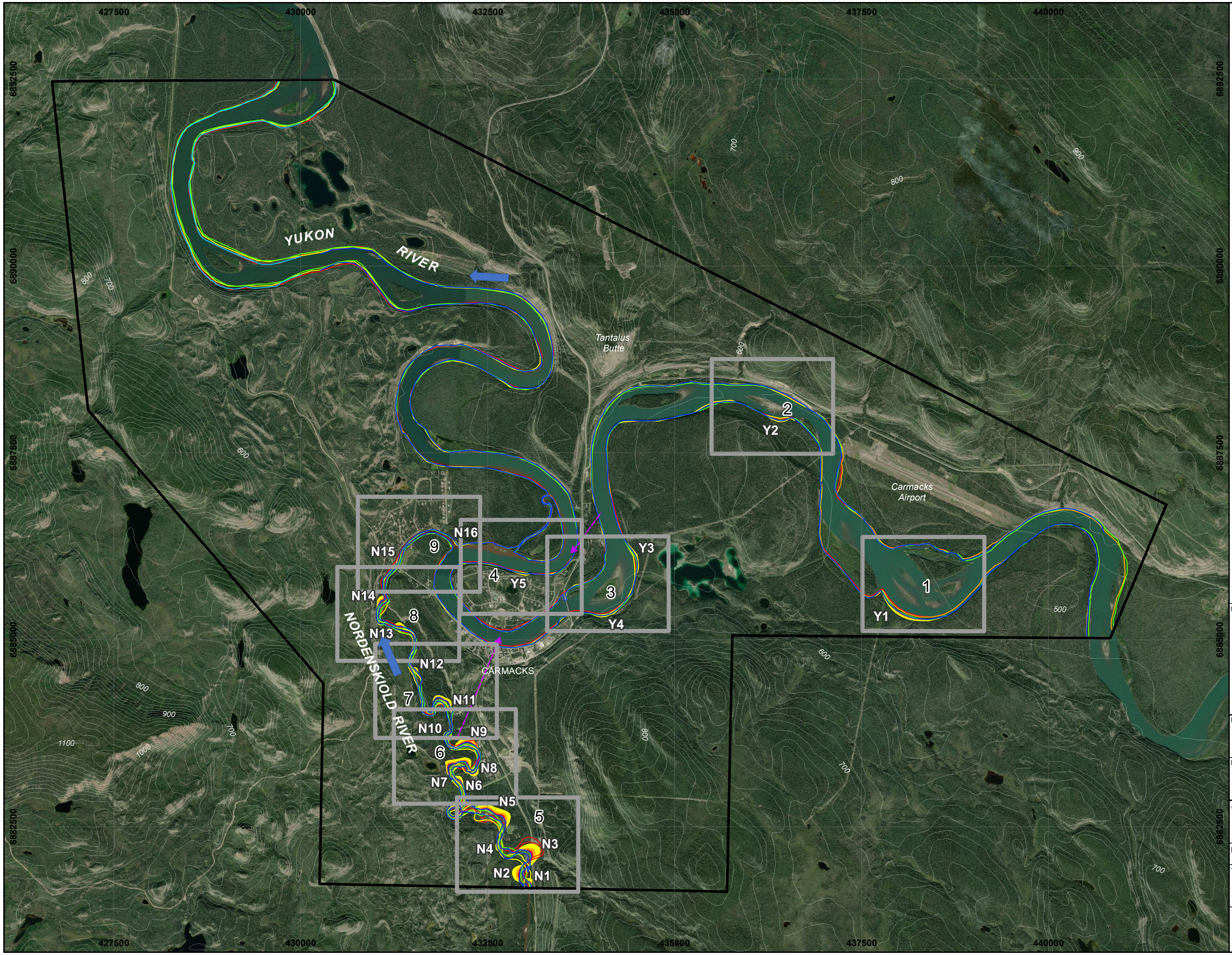
Appendix A.

Surficial Geology, Carmacks, Yukon. Yukon Geological Survey Open File 2020-43. See accompanying pdf.

Appendix B. Fluvial Erosion, Carmacks, Yukon



Legend

- Study Area
- Contour (20 m)
- Potential Avulsion Path
- Index

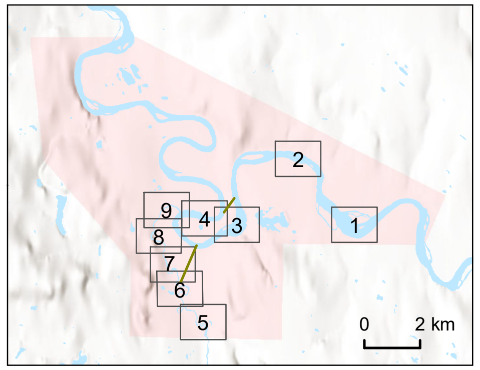
Erosion Hazard Zones

- 0–10 years
- 10–25 years
- 25–50 years

Channel Planform Year

- 2019
- 2018
- 1994
- 1977
- 1969
- 1953

Map Index



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CLIENT: Government of Yukon

PROJECT: Carmacks Community Hazards Mapping

TITLE: **Erosion Hazard Zones Overview**

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MAP A-0

REVISION: 1-3

Legend

- Study Area
- Contour (10 m)

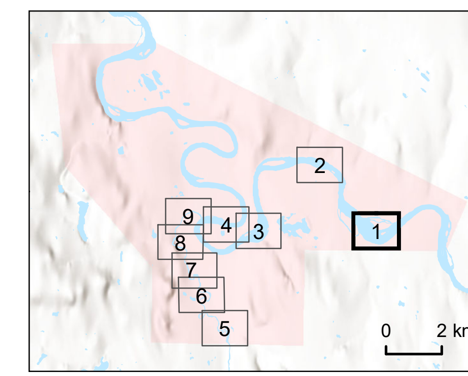
Erosion Hazard Zones

- 0–10 years
- 10–25 years
- 25–50 years

Channel Planform Year

- 2019
- 2018
- 1994
- 1977
- 1969
- 1953

Map Index



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CLIENT: Government of Yukon

PROJECT: Carmacks Community Hazards Mapping

TITLE: **Erosion Hazard Zones**

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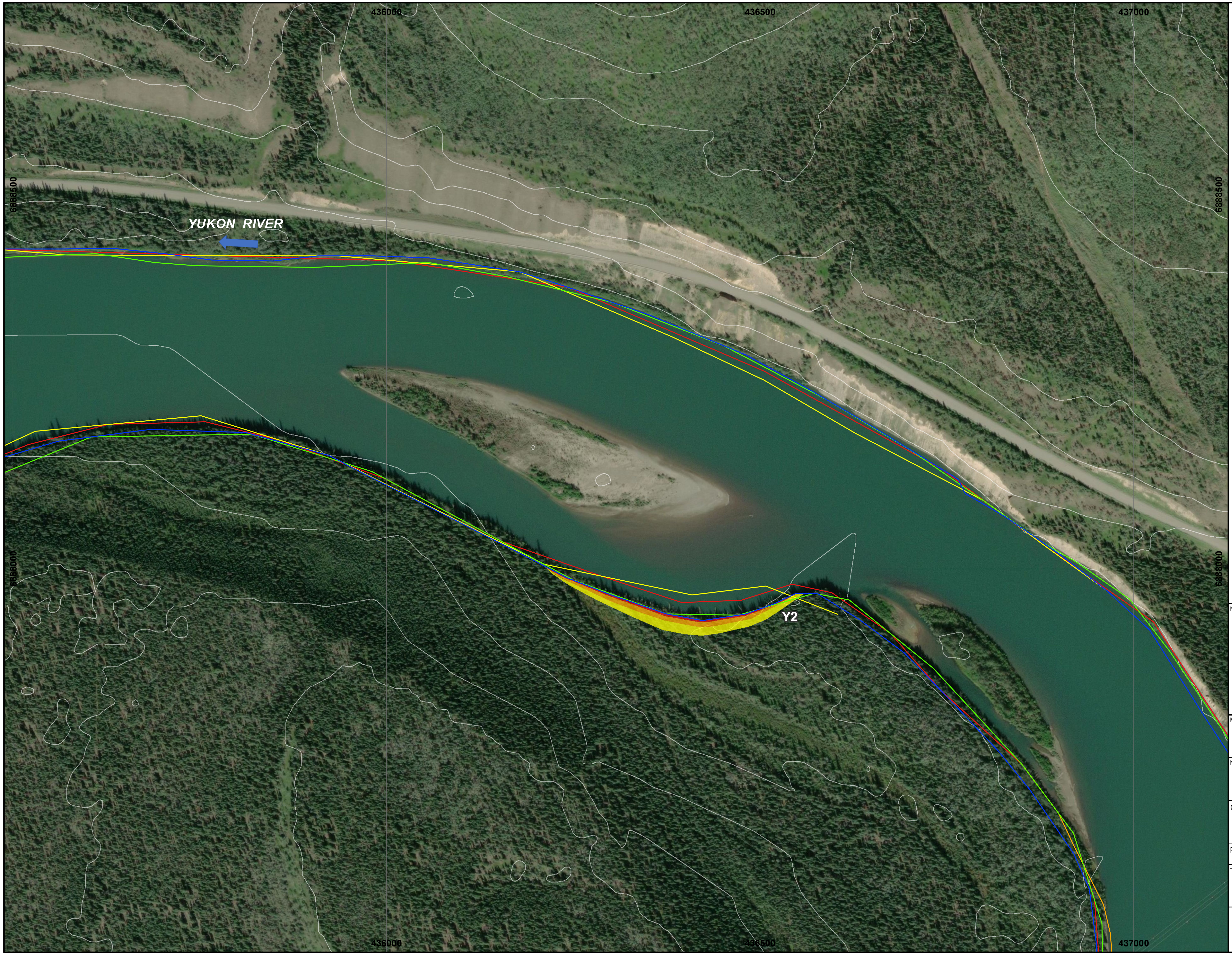
MAP A-1

REVISION: 1-1



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Study Area

Contour (10 m)

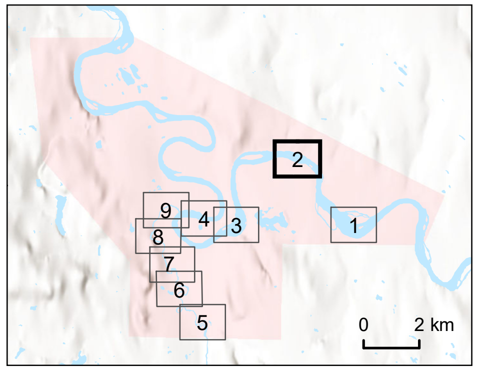
Erosion Hazard Zones

- 0–10 years
- 10–25 years
- 25–50 years

Channel Planform Year

- 2019
- 2018
- 1994
- 1977
- 1969
- 1953

Map Index



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NORTH:

CLIENT: Government of Yukon

PROJECT: Carmacks Community Hazards Mapping

TITLE: Erosion Hazard Zones

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MAP A-2

REVISION: 1-1

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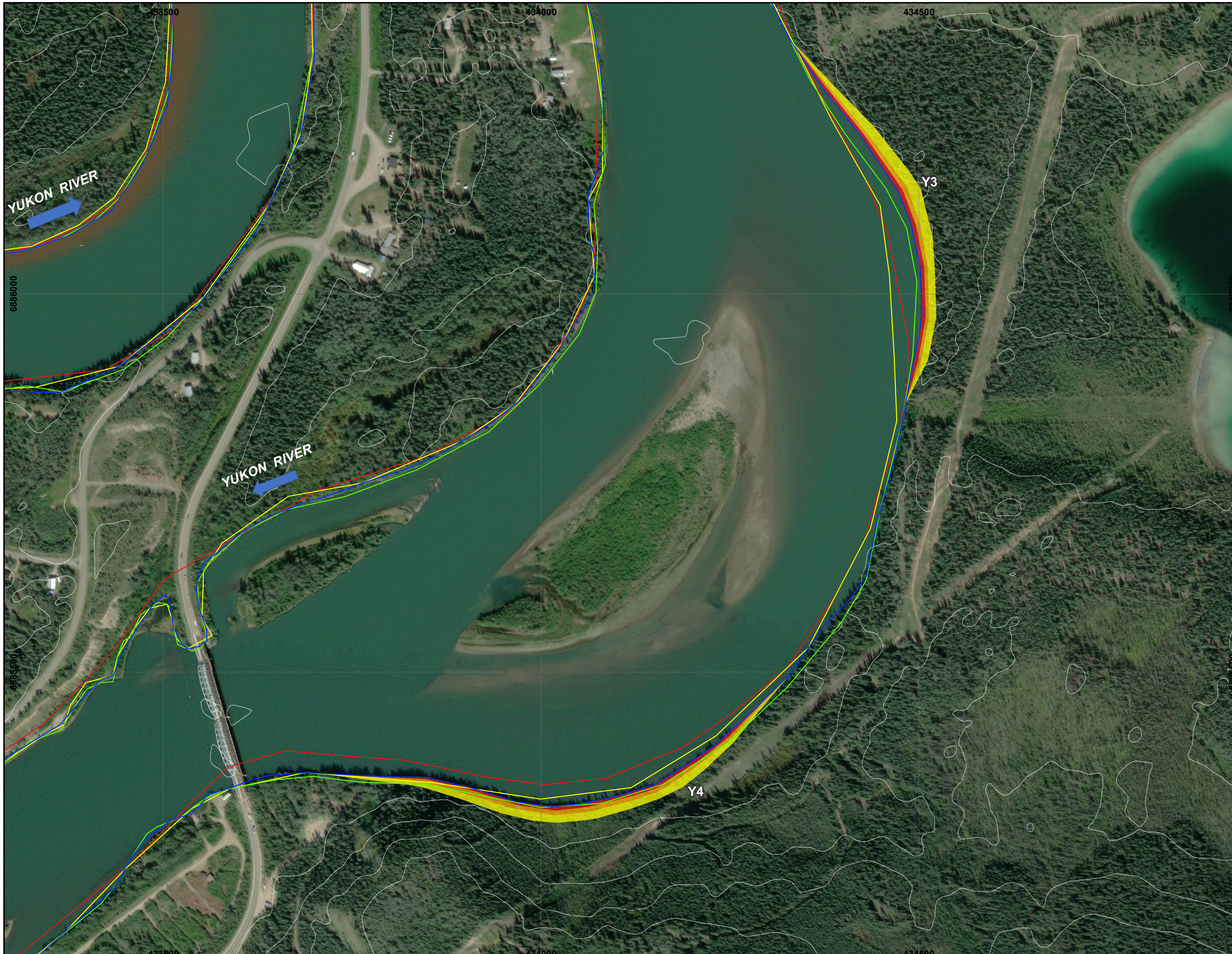


Legend

Study Area
Contour (10 m)

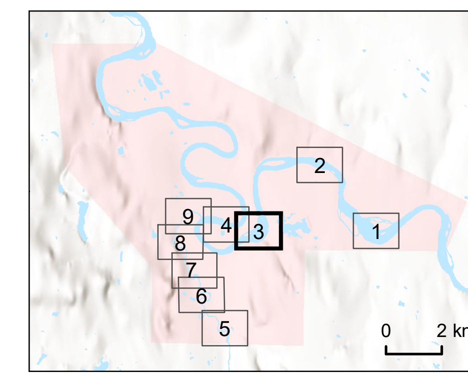
Erosion Hazard Zones

0–10 years
10–25 years
25–50 years

Channel Planform Year

2019
2018
1994
1977
1969
1953

Map Index



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CLIENT:
Government of Yukon

PROJECT:
Carmacks Community Hazards Mapping

TITLE:
Erosion Hazard Zones

Palmer™

PROJECT NO. 1201716

MAP A-3

REVISION: 1-1

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Legend

Study Area
Contour (10 m)

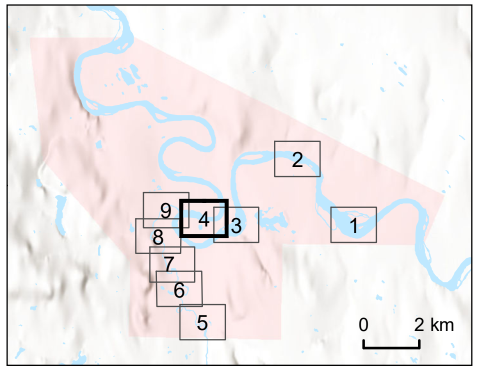
Erosion Hazard Zones

0–10 years
10–25 years
25–50 years

Channel Planform Year

2019
2018
1994
1977
1969
1953

Map Index



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PROJECT: Carmacks Community Hazards Mapping

TITLE: **Erosion Hazard Zones**

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MAP A-4

REVISION: 1-1

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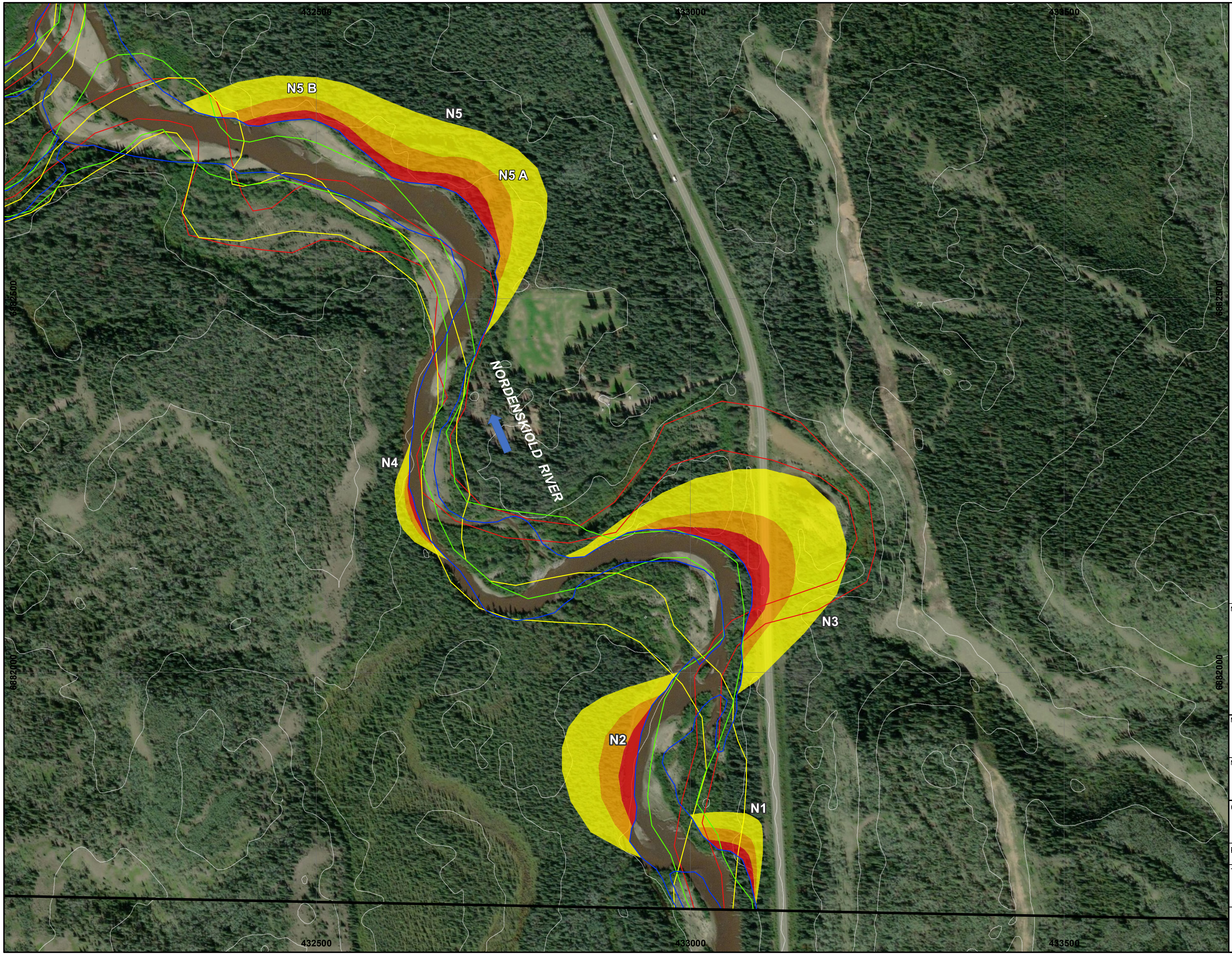

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Study Area
Contour (10 m)

Erosion Hazard Zones

0–10 years
10–25 years
25–50 years

Channel Planform Year

2019
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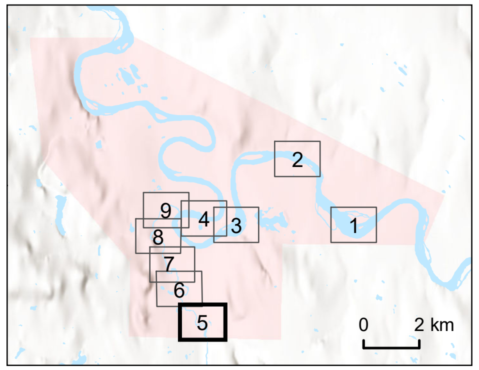
1953

Map Index



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CLIENT:
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PROJECT: Carmacks Community Hazards Mapping

TITLE:
Erosion Hazard Zones

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PROJECT NO. 1201716

MAP A-5

REVISION: 1-1

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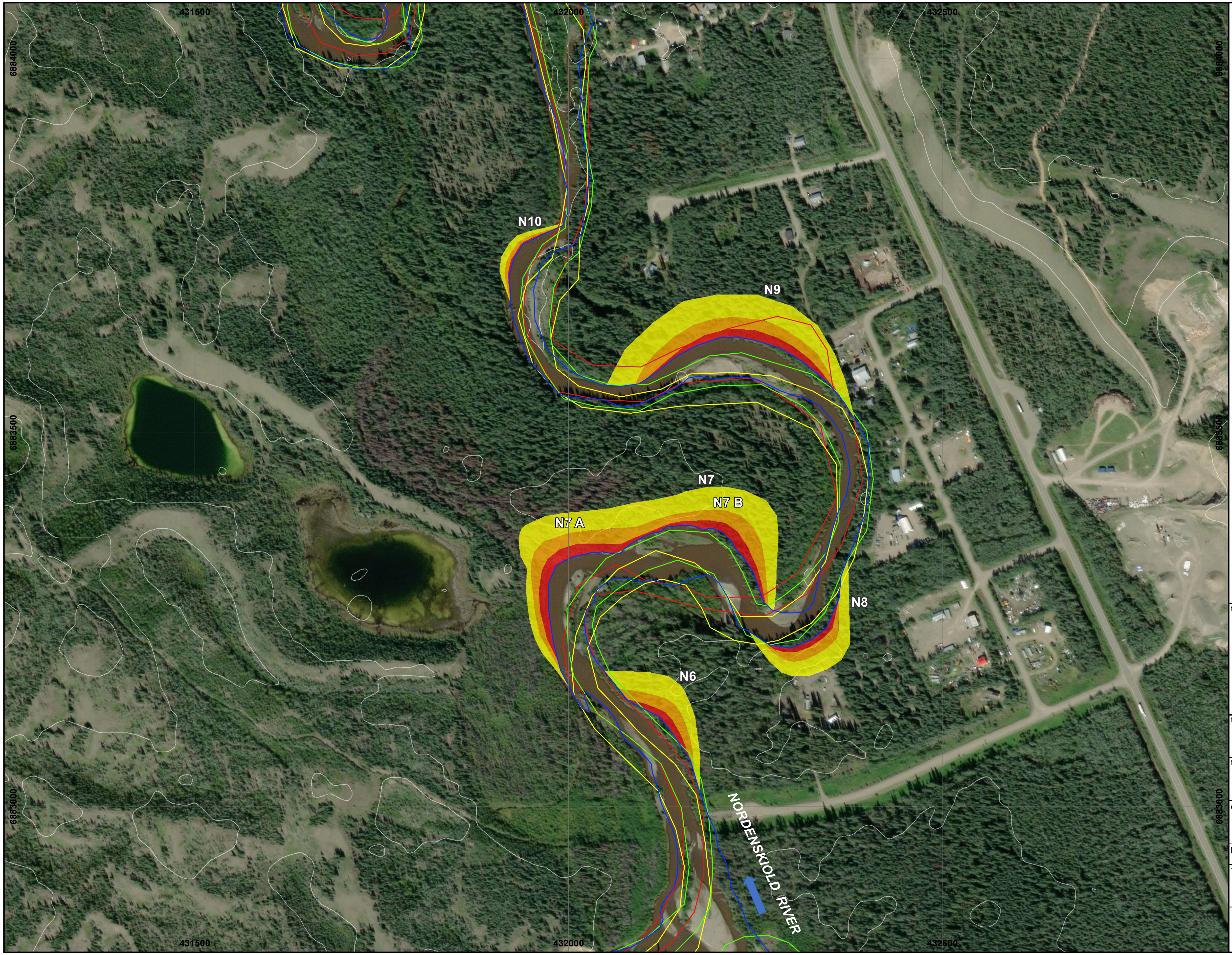

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Study Area

Contour (10 m)

Erosion Hazard Zones

0–10 years

10–25 years

25–50 years

Channel Planform Year

2019

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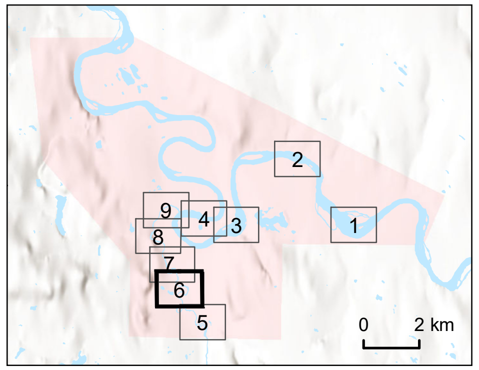
Map Index



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TITLE: **Erosion Hazard Zones**

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MAP A-6

REVISION: 1-1

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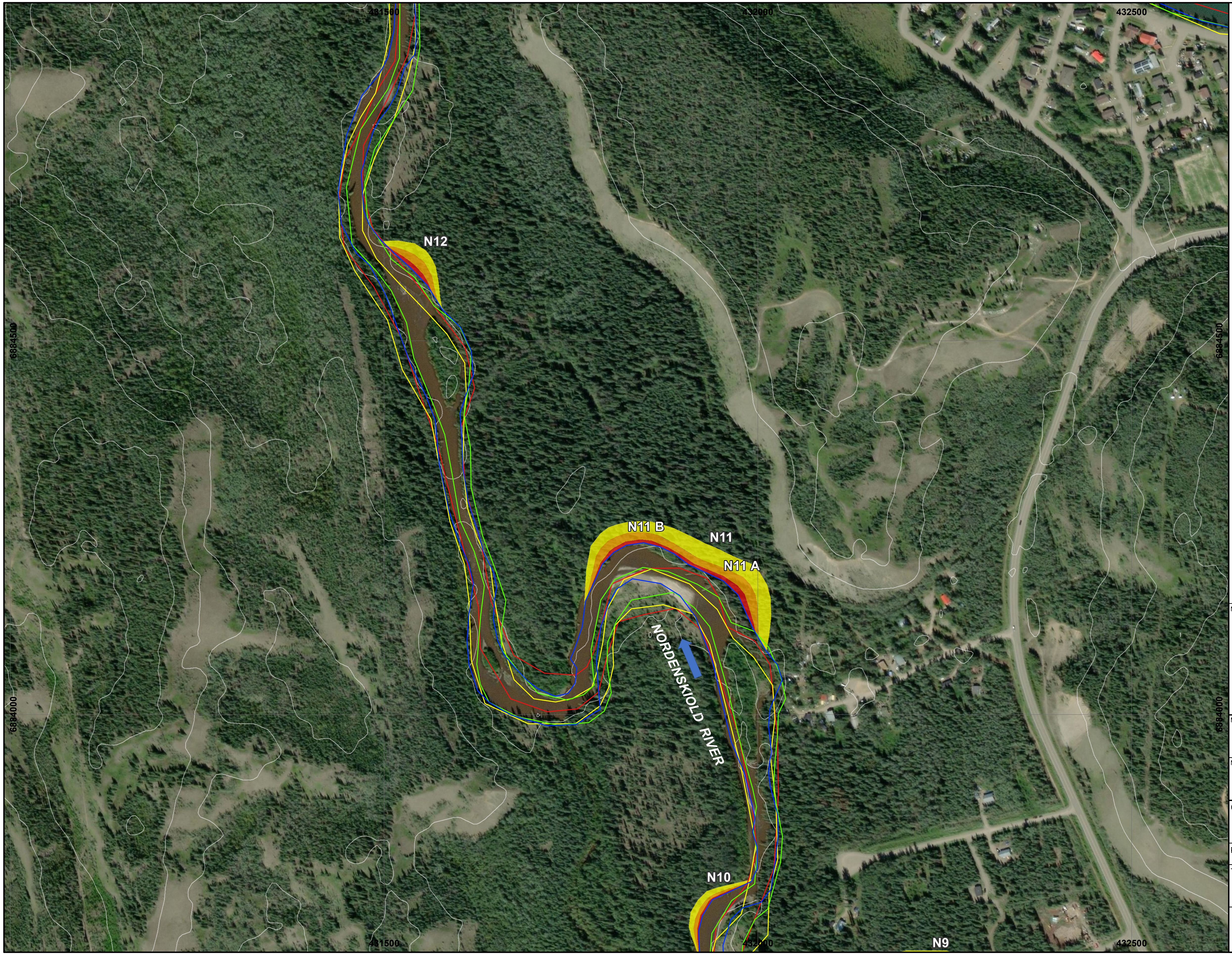

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Study Area

Contour (10 m)

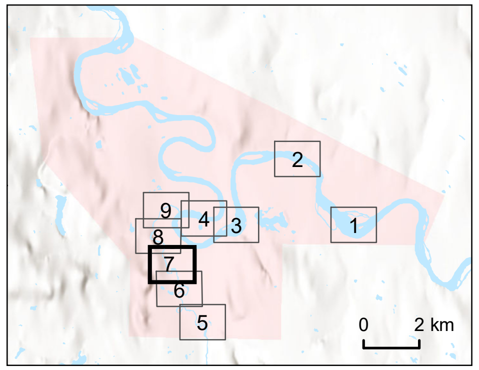
Erosion Hazard Zones

- 0–10 years
- 10–25 years
- 25–50 years

Channel Planform Year

- 2019
- 2018
- 1994
- 1977
- 1969
- 1953

Map Index



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TITLE: **Erosion Hazard Zones**

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MAP A-7

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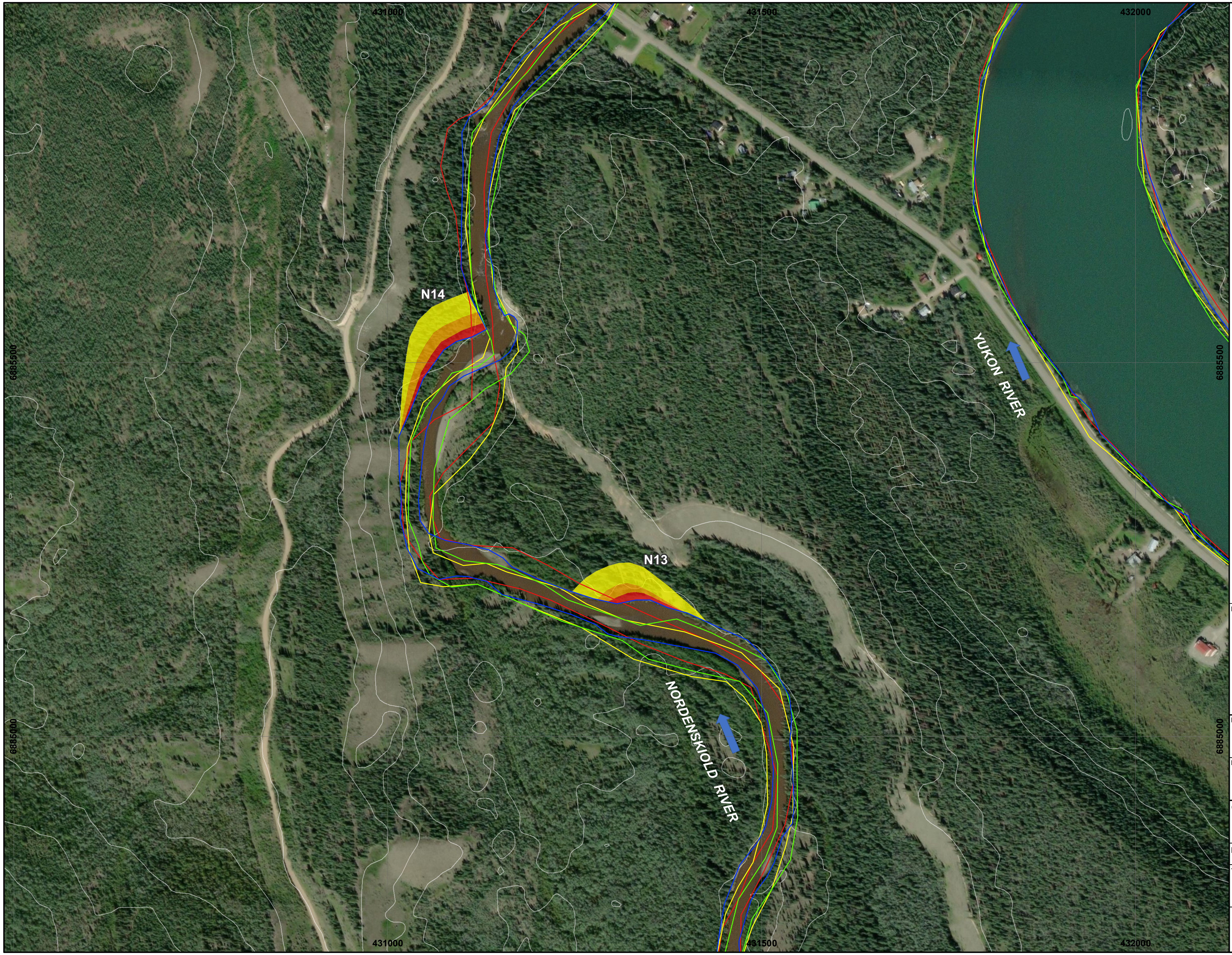

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Study Area

Contour (10 m)

Erosion Hazard Zones

0–10 years

10–25 years

25–50 years

Channel Planform Year

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2018

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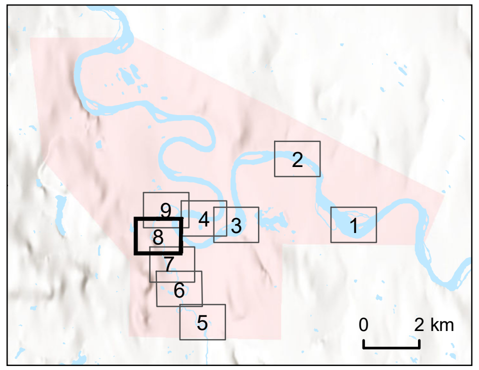
1977

1969

1953

Map Index



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TITLE: **Erosion Hazard Zones**

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PROJECT NO. 1201716

MAP A-8

REVISION: 1-1

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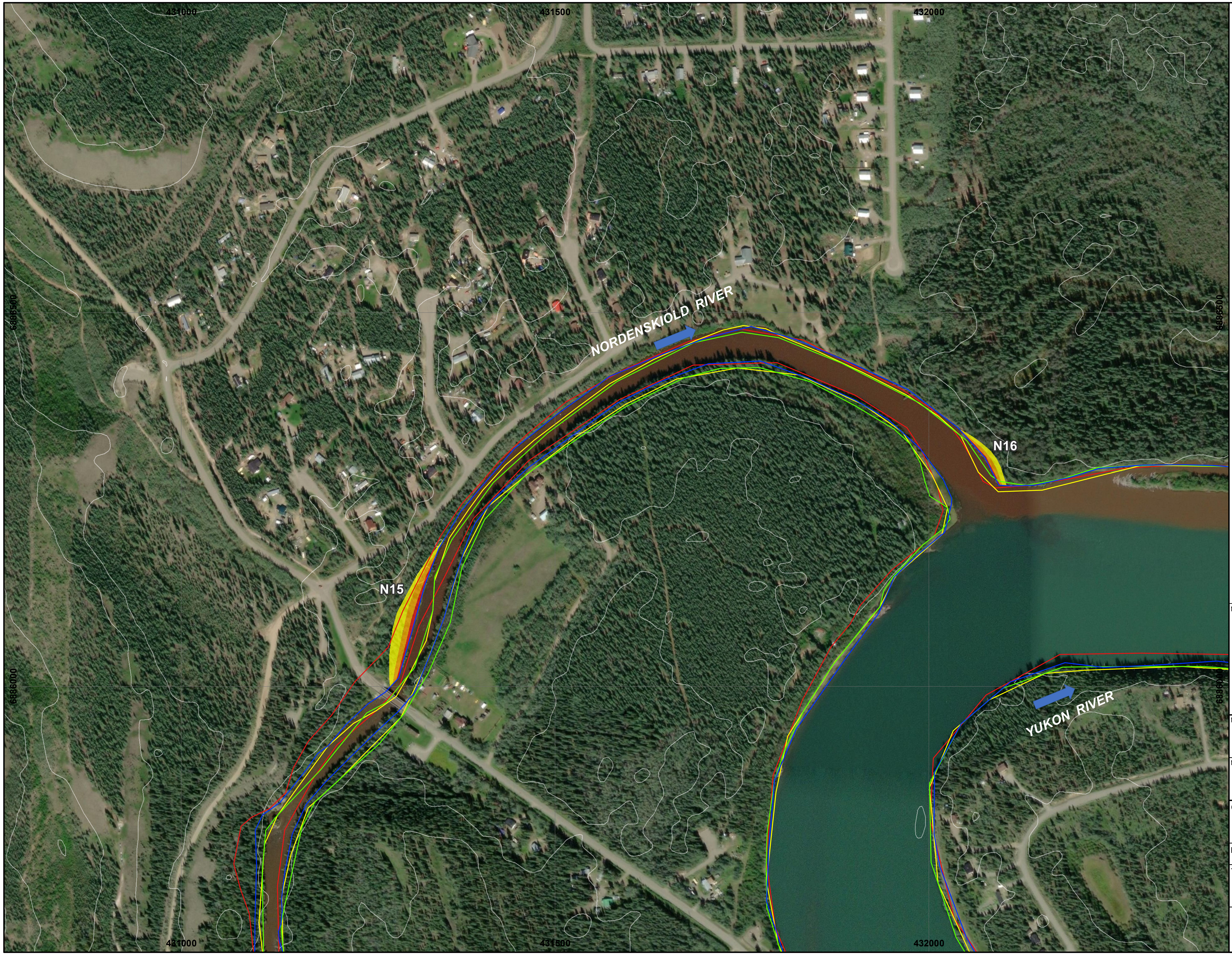


Legend

Study Area
Contour (10 m)

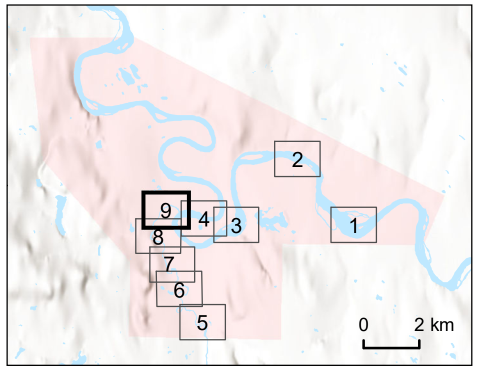
Erosion Hazard Zones

0–10 years
10–25 years
25–50 years

Channel Planform Year

2019
2018
1994
1977
1969
1953

Map Index



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CLIENT:
Government of Yukon

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Carmacks Community Hazards Mapping

TITLE:
Erosion Hazard Zones

Palmer

PROJECT NO. 1201716

MAP A-9

REVISION: 1-1

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Appendix C. Landscape Hazard Susceptibility, Carmacks, Yukon. See accompanying pdf.