470 Granville Street, Suite 630, Vancouver, BC V6C 1V5
Tel: 604-629-9075 | www.pecg.ca

Physical Land Development Constraints Mapping

Whitehorse City Limits Portion of the Kwanlin Dün Traditional Territory, Yukon

Palmer Project #
2211201

Prepared For
Kwanlin Dün First Nation

October 6, 2023

470 Granville Street, Suite 630, Vancouver, BC V6C 1V5
Tel: 604-629-9075 | www.pecg.ca

October 6, 2023

Glenda Koh
Urban Planning and Policy Advisor
Heritage, Lands and Resources
Kwanlin Dün First Nation
35 McIntyre Drive
Whitehorse, YT Y1A 515

Dear Glenda Koh:

Re: Physical Land Development Constraints Mapping
Project #: 2211201

Palmer is pleased to provide Kwanlin Dün First Nation (KDFN) with the final results of our physical land development constraints mapping within the 419 km^2 Whitehorse City Limits portion of the KDFN Traditional Territory. We have updated the previous version based on feedback received from KDFN and Yukon Geological Survey and in association with observations made during a short field reconnaissance trip.

Through this multi-disciplinary assessment, we have considered and examined a diverse range of land development constraints. The enclosed report characterizes and maps constraints associated with bedrock, erosion and mass movements, soil composition, topography, permafrost distribution, water table depth, and flooding recurrence in the Whitehorse City Limits. Further analysis of channel planform evolution and bank recession along portions of Yukon and Takhini Rivers within the study area was completed.

It has been a pleasure working with KDFN on this project. Should you or other members of the project team have any questions, please do not hesitate to contact Robin McKillop (604-355-8788, robin.mckillop@pecg.ca).

Yours truly,

Palmer

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

Table of Contents

List of Figures

List of Tables

List of Appendices

1. Introduction

Palmer is pleased to provide Kwanlin Dün First Nation (KDFN) with the results of our physical land development constraints (LDC) mapping within the 419 km^2 Whitehorse City Limits portion of the KDFN Traditional Territory (the study area; Figure 1). The LDC maps provide a succinct and clearly symbolized representation of ground conditions, topographic constraints, and exposure to potential hazards across the study area. Riverbank erosion trends and associated hazard zones alongside Yukon and Takhini Rivers are also separately mapped. The mapping can be used to inform future land use planning and increase KDFN's confidence in responding to proposed land use interests on and off settlement land. Aspects of the mapping may also be applied to understand potential hazards to existing property and infrastructure.

The LDC mapping takes advantage of 1:15,000-scale surficial geology mapping recently completed by the Yukon Geological Survey (YGS) for the Whitehorse area (Lipovsky, 2023). We understand KDFN is acquiring additional ecosystem and terrain information in the study area, which may also be at least partly derived from surficial geology maps. Utilizing the YGS surficial geology data provides a consistent base layer that ensures our LDC characterizations can be seamlessly integrated with other spatial data analyses and mapping products.

This report describes available data sources and outlines the largely desktop-based approach to LDC mapping and fluvial erosion hazard forecasting (Section 2). Results of the LDC mapping and fluvial hazard forecasting are presented and discussed (Section 3). Finally, follow-up opportunities are presented (Section 4). PDF maps of LDC constraints and fluvial hazard areas within the study area are provided in Appendices A and B, respectively. The corresponding ArcGIS geodatabase has been submitted via email. Appendix C presents a photograph log from a field reconnaissance trip with typical examples of common LDCs.

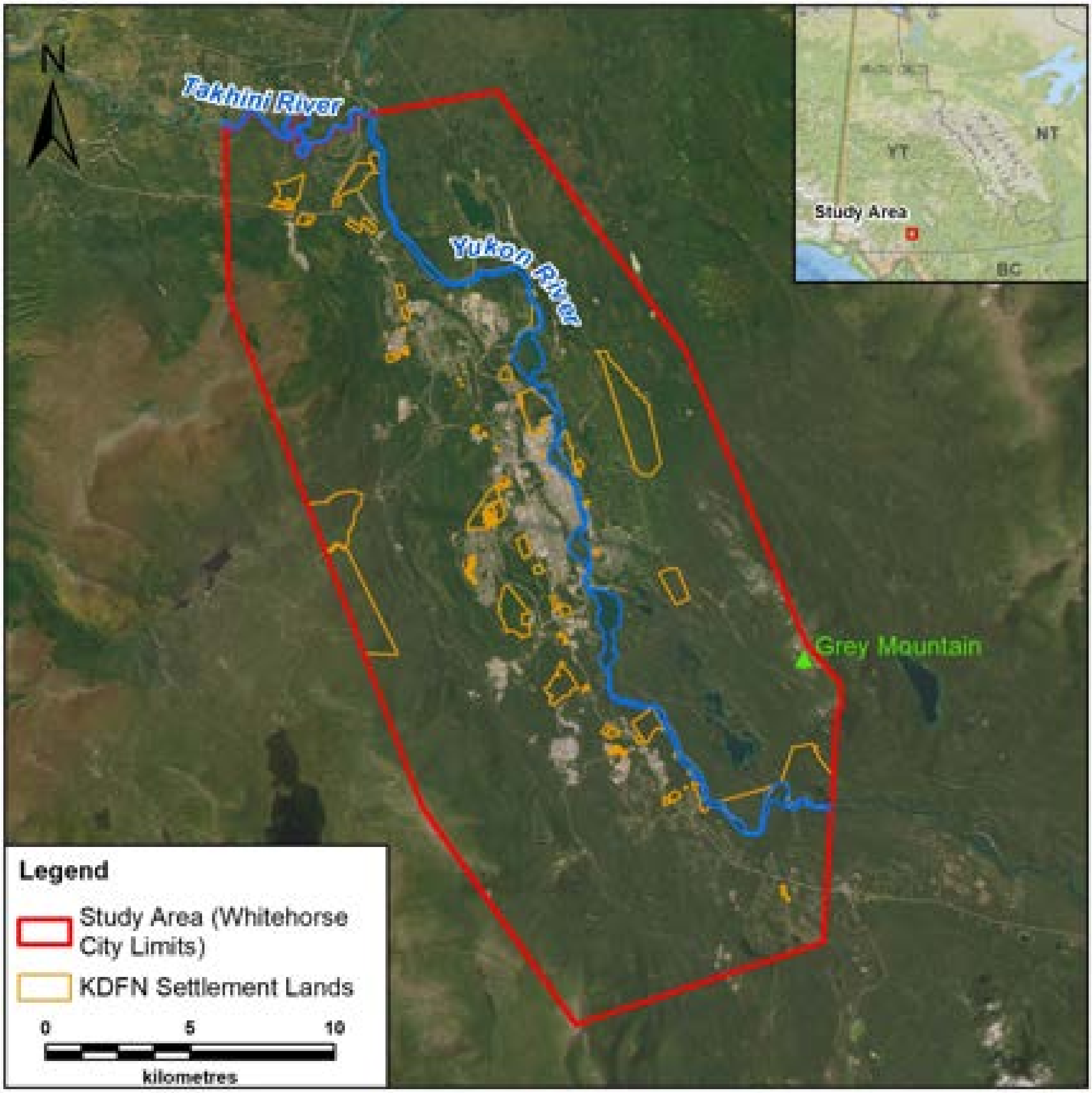


Figure 1. Whitehorse City Limits study area

2. Methods

2.1 Background Review and Data Sources

The project was initiated by reviewing comparable constraints and hazard mapping projects completed in southern Yukon. Methods were developed and adapted from Palmer's prior mapping experience in Carmacks (Palmer, 2020), Fox Lake (Palmer, 2018), and Tagish (Kryotek and Palmer, 2016), as well as similar mapping projects in the Golden Horn (UMA and Gartner Lee, 2004) and Hotsprings Road (UMA et al., 2002) areas.

Additional datasets were compiled and reviewed, including:

- 2019 LiDAR digital elevation model (DEM), 0.5 m resolution (provided by the YGS);
- 2019 orthophotography, 20 cm resolution (provided by the YGS);
- 1:15,000-scale surficial geology mapping encompassing the Whitehorse City Limits (Lipovsky, 2023);
- Yukon University's greater Whitehorse permafrost thaw sensitivity map (Roy et al., 2021);
- Selected historical aerial photographs obtained from GeoYukon (see Table 1 for a complete list); and
- Yukon water well registry (Government of Yukon, 2023).

2.2 Physical Land Development Constraints (LDC) Mapping

LDC mapping was primarily completed through initial queries of the 1:15,000-scale surficial geology mapping recently published by the YGS (Lipovsky, 2023), with refinements based on analysis and interpretation of 2019 LiDAR-derived elevation data and 2019 orthophotography. Permafrost characterization mapping (Roy et al., 2021) and available geotechnical and water well borehole datasets were reviewed to help calibrate interpretations. The foundational YGS surficial geology mapping (Lipovsky, 2023) was based on interpretation of 2013-2019 LiDAR, 2007 aerial photographs, and field investigations during the 2017-2021 field seasons, so anthropogenic disturbances and associated map units reflect the dates of these data sources and are not all fully up-to-date in the resulting LDC mapping.

Seven development constraints were characterized within the study area: bedrock; erosion and mass movements; topography; soil composition; water table depth; flooding recurrence; and permafrost distribution and ice content. LDCs, and their severities (classes) and thresholds, were evaluated for each surficial geology map unit (polygon) (Lipovsky, 2023) based on professional experience and reference to similar mapping projects completed for Yukon Government. Each LDC was assessed individually using a combination of GIS-based queries of surficial geology datasets, analysis of LiDAR-derived DEMs, and expert-based interpretation:

- **Bedrock** mapping identifies map units (polygons) containing significant proportions of exposed or shallow bedrock.
    - This LDC was primarily evaluated through querying of the YGS surficial geology mapping. Classifications were made based on the relative abundance of bedrock outcrop and surficial deposits forming veneers (<1 m thick), blankets (>1 m thick), or aprons (variable thickness, tending to be shallow near the apex). Refinements were made based on interpretation of LiDAR-derived elevation data and orthophotography.
- **Erosion and Mass Movements** mapping identifies map units (polygons) affected or potentially affected by mass movements, and those affected by gullying and rilling processes.
    - This LDC was initially evaluated through querying of the YGS surficial geology mapping. Classifications were initially made based on the presence/absence of mass movement and gullying processes. Interpretation of the LiDAR-derived elevation data and orthophotography additionally helped identify and include potential runout zones, and map units characteristically similar to those with mapped mass movements.
- **Soil Composition** mapping identifies map units (polygons) with highly compressible surface sediments, such as organic deposits and clay-rich soils, or the potential for contamination (e.g., landfill, mine tailings).
    - This LDC was primarily evaluated through querying of the YGS surficial geology mapping. Classifications were made based on the presence/absence and relative abundance of organic materials and clay-rich soil textures. Anthropogenic map units (polygons) were screened for potential sources of contamination based on guidance from the YGS. Refinements were made based on interpretation of LiDAR-derived elevation data and orthophotography.
- **Topography** mapping identifies map units (polygons) with higher average slope gradients.
    - This LDC was evaluated solely through analysis of LiDAR-derived slope gradients within the study area. Classifications were made based on the calculated average slope gradient within each map unit. Anomalous steep or gentle slopes (e.g., low scarps), if relatively small in areal extent and excluded from YGS' original polygon delineations (Lipovsky, 2023), may not be reflected in the topographic constraint classification.
- **Permafrost Distribution** mapping identifies map units (polygons) underlain by permafrost, distinguished according to suspected ground ice content (i.e., ice-rich vs. low to moderate ice content).
    - This LDC was primarily evaluated through querying of the YGS surficial geology mapping. Classifications were made based on the presence/absence of permafrost and associated subclasses (e.g., thermokarst). Refinements were then made based on interpretation of LiDAR-derived elevation data, Whitehorse area thaw sensitivity mapping (Roy et al., 2021), and vegetative indicators.
- **Water Table Depth** mapping identifies map units (polygons) that are seasonally inundated or are affected by a shallow water table.
    - This LDC was initially evaluated through querying of the YGS surficial geology mapping. Classifications were made based on identification of periodically inundated map units such

as wetlands (areas with significant organic materials) and active floodplains. Refinements were made based on interpretation of orthophotography (e.g., vegetation indicators) and LiDAR-derived elevation data to identify and include map units with poor to imperfect drainage and/or surface seepage.

- **Flooding Recurrence** mapping identifies map units (polygons) susceptible to riverine flooding.
  - This LDC was initially evaluated through querying of the YGS surficial geology mapping. Classifications were made based on mapping of active and inactive floodplain and terrace landforms. Refinements were made based on interpretation of the orthophotography (e.g., vegetative indicators) and LiDAR-derived elevation data, with a focus on the proximity to, and relief above, adjacent watercourses.

2.2.1 Limitations

LDCs were initially derived from surficial geology interpretations completed by Lipovsky (2023), which underwent only representative field checks of a small proportion of the entire mapping area, so they share similar limitations and uncertainties. Surficial geology map units (polygons) with internal variability in surficial materials, surface expressions (including steepness and relief), textures, and geomorphological processes may also exhibit variability in LDC severity, which is not captured at this City-wide scale of mapping. For example, a surficial geology map unit (polygon) may include a mixture of wetlands and sand dunes, representing contrasting ground conditions, but the polygon-scale LDC classifications reflect only the most areally extensive landforms (i.e., wetlands or sand dunes). Interpretations of subsurface conditions were based primarily on surface indicators, such as landform expression and vegetation cues; detailed ground investigations (e.g., test pitting, drilling and material testing, well installation, geophysics) could be used to validate and refine LDC interpretations. Approximations of flooding recurrence is characterized qualitatively, based on fluvial landform characteristics, and does not consider local flood hydraulics, regulation of Yukon River by the Whitehorse Hydro Plant (WHP, which affects river levels near Whitehorse), or potential effects of ice jams or climate change.

2.3 Fluvial Erosion Hazard Forecasting

Channel planform evolution and bank recession along the portions of Yukon River and Takhini River within the study area were assessed using a combination of recent orthophotographs and historical aerial photographs (Table 1). Different years of imagery have different coverages within the study area. Orthophotography from 2001 and 2006 exhibited minimal offsets (<4 m) relative to the most recent 2019 orthophotography used in our basemapping. Historical aerial photographs from 1946 to 1985 were accessed through GeoYukon. Historical aerial photographs required georeferencing to the 2019 orthophotograph using standard GIS tools. Control points were selected along the river valleys to limit image distortion and error along the study corridor. Average imagery offset for historical aerial photographs georeferenced by Palmer ranged from 7 m to 25 m due to scan quality and local image distortion, forcing scrutiny of any apparent trends over time.

Table 1. Aerial imagery obtained from GeoYukon for use in the fluvial hazard assessment.

Type	Year	Average Offset (m)	Study Area Coverage
Colour Orthophotography	2019	N/A	Entire study area
Colour Orthophotography	2006	1	Entire extent of Yukon River within the study area
Colour Orthophotography	2001	4	Entire extent of Takhini River within the study area
Black-and-White Aerial Photography	1985	14	Majority of Yukon River within the study area (upstream extent unavailable)
Colour Aerial Photography	1977	9	Takhini River and majority of Yukon River (upstream extent of Yukon River unavailable)
Black-and-White Aerial Photography	1963	25	Central region of Yukon River (upstream and downstream extents unavailable)
Black-and-White Aerial Photography	1946	17	Entire extent of Takhini and Yukon Rivers within the study area

Both banks of Yukon River and Takhini River were delineated for each year of imagery 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., 1:2,000 to 1:5,000). 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 models.

For sites where the river has been migrating systematically (i.e., shifting across its floodplain in a consistent and predictable direction), migration rates were calculated by dividing the total migration distance by the time period between imagery years. The issues with imagery offsets that were noted above were considered when determining migration distances. Appropriate time periods for estimating channel migration rates were determined on a site-by-site basis, in one of two main ways:

- Migration rates were based on the full period of record (e.g., 1946 to 2019) for sites that exhibited systematic migration from the earliest aerial photograph to the most recent imagery; or
- Migration rates were estimated based on shorter periods of record (e.g., 1977 to 2019) at sites exhibiting irregular or inconsistent migration, or where avulsions had made former patterns and rates of bank erosion unrepresentative.

Three river migration hazard zones were established based on projection from past trends in the rates and directions of erosion: short-term (0 to 10 years), near-term (10-25 years), and long-term (25-50 years). Longer ranges in time were used for the less confident projections farther into the future (e.g., a 25-year period for the long-term, compared to a 10-year period for the short-term). The outer limits of each river migration hazard zone represent the predicted position of the outer riverbank within the respective timeframe. The limits were locally refined based on the potential for contact with valley walls or terrace scarps, interactions with older channels, or avulsion (i.e., sudden change in channel course).

The comparison of past river positions enables forecasting of future river positions, assuming progression at a constant (time-averaged) rate. Bank erosion is more likely to occur suddenly and more variably in response to extreme flows, gravel bar redistribution, and ice jam breaching. A time-averaged rate effectively reduces the 'noise' represented by localized and episodic adjustments.

Areas of suspected localized erosion that may pose a risk to infrastructure and/or potential development, despite no systematic trend in erosion (e.g., due to historical or recent riprap placement), have been annotated in Appendix B.

2.4 Field Reconnaissance

Two Palmer team members experienced in surficial geology, permafrost and fluvial processes conducted a one-day, truck-supported field reconnaissance trip within the study area on July 26, 2023. The weather was warm (22°C) and mostly sunny, without any significant antecedent precipitation. A key purpose of the field reconnaissance was to 'ground truth' representative examples of the various mapped LDCs based on observation of surface indicators (e.g. near-surface water table, bedrock outcrops, active/recent erosion or mass movement, evidence of overbank flooding) and examination of surficial materials in hand-dug test pits and pre-existing exposures (e.g. clay content in road cuts). A 1.2 m-long frost probe was also used to help detect shallow permafrost or bedrock. A secondary purpose was to take photographs representative of the common LDCs as a basis for better illustrating conditions depicted in the mapping. No effort was made to validate the surficial geology mapping on which many of the LDC classifications were based (Lipovsky, 2023), as the YGS had already done so prior to its map finalization and publication.

3. Results and Discussion

3.1 Physical Land Development Constraints Mapping

A poster-sized PDF map presenting the results of the LDC mapping for the Whitehorse City Limits portion of KDFN Traditional Territory is included in Appendix A. Descriptions, severity classes and corresponding mapping codes for each of the seven LDCs are presented in the map legend and below in Table 2. A separate legend file has been included, as well as what is shown on the map, for ease of viewing across two monitors. Appendix C presents field photographs representative of common LDCs depicted in the mapping.

On the PDF map in Appendix A, each surficial geology unit (polygon) is symbolized according to its highest LDC severity level, and labelled with up to three types of LDCs of all those identified in the corresponding GIS file (provided separately via email). A generalized interpretation of each constraint classification is provided in the map legend and below in Table 3.

Table 2. Physical land development constraint (LDC) severity definitions.

LDC Type	LDC Severity	Mapping Code	Description
Bedrock			
	Low	**BL**	Bedrock is commonly 1-3 m from surface
	Moderate	**BM**	Bedrock is commonly <1 m from surface, or up to 1/3 of the polygon is bedrock outcrop
	High	**BH**	Bedrock outcrop dominant
Erosion and Mass Movements			
	Moderate	**EM**	Slope erosion (sheetwash, rilling and/or gullying), steep slopes with landslide or erosion potential
	High	**EH**	Active or inactive mass movements (initiation and/or runout), or steep slopes adjacent to previous mass movements; includes permafrost-related thaw-flow slides and solifluction
Soil Composition			
	Low	**SL**	Clay-rich soils dominant
	High	**SH**	Compressible (organic) soils dominant, or potential soil contamination (e.g., landfill, mine tailings, sewage lagoon berms)
Topography[1]			
	Low	**TL**	Average slope gradient 10-20%
	Moderate	**TM**	Average slope gradient 20-30%
	High	**TH**	Average slope gradient >30%
Permafrost Distribution			
	Moderate	**XM**	Shallow (<1.5 m) permafrost with low to moderate ice content
	High	**XH**	Ice-rich permafrost potentially susceptible to differential ground settlement
Water Table Depth			
	Moderate	**WM**	Water table <2 m from surface
	High	**WH**	Water table at surface (possibly seasonally)
Flooding Recurrence			
	Moderate	**FM**	Flooding recurrence assumed >5 years
	High	**FH**	Flooding recurrence assumed <5 years

[1] Slope classes consistent with those used by Palmer (2020), Kryotek and Palmer (2016), and UMA and Gartner Lee (2004).

Table 3. Generalized implications of physical land development constraint (LDC) severity classifications.

Class	Typical Implications (at the scale of the map unit (polygon))
High	Restrictive for long-term residential or commercial development purposes. Recreational day use, such as hiking/biking trails and parks, may be suitable depending on applicable constraint type. Areas with High constraint due to mass movements (EH) should be avoided for any kind of development, except for carefully planned trail links. Areas with High constraint due to ice-rich permafrost (XH) or flooding (FH) may be suitable for day use recreational development, but pose potential hazards for residential or commercial buildings. Areas with High constraint due to soil composition (SH) or water table (WH) assume saturated and/or organic soils; detailed ground investigations may indicate limited organic deposits or deeper water table, decreasing the constraint. Areas with High constraint due to bedrock (BH) or topography (TH) assume complex ground conditions for building, but may be developed with increased cost for extensive earthworks.
Moderate	Not desirable for residential or commercial buildings but may be developed with special consideration of development constraints and increased costs. Areas with Moderate constraint due to slope erosion (EM) may require erosion control structures and special consideration of the influence of development on slope stability. Detailed ground investigation may suggest some portions of area are suitable for development (e.g., depth to bedrock may vary throughout polygon, permafrost may be deep and of low ice content, flooding may only affect the lowest elevations of the polygon). Suitable for day use recreational development such as hiking/biking trails and parks. Development of areas with Moderate constraint due to bedrock (BM) or topography I is possible, especially if substrates are well-drained sand/gravel, but it may require more costly earthworks.
Low	Suitable for most residential, commercial or recreational development. Areas with Low constraint due to bedrock depth (BL) or topography (TL) may require additional development costs. Areas with Low constraint due to soil composition (SL) assume silty/clayey soils; ground investigations may indicate coarser-grained soils, thus negating the constraint.
None	Area capable of supporting all conventional development (at least 80% of polygon).

Note: Severity classes represent the average, or typical, condition within the map unit (polygon) (e.g. Low); in some cases, actual classes at a specific location within the polygon may be higher (e.g. Moderate) or lower (e.g. None). Classes do not consider proximities to, or potential effects of, anthropogenic features such as sewage lagoons or mine tailings.

3.1.1 General Characteristics and Implications

General characteristics and implications for land development of each of the distinct types of LDCs are summarized below.

Bedrock

Exposed or shallow bedrock was identified as a constraint primarily due to the complexity it can introduce for land development (e.g., Photographs 1 and 2, Appendix C). Extensive bedrock outcrop or shallow bedrock in a map unit may increase construction costs through the need for blasting or other means of bedrock removal to achieve desired grade and/or install underground utilities. Bedrock is considered a constraint that can be fully overcome through increased development costs. Bedrock was generally identified as a constraint within the uplands along the western edge of the study area, and along the eastern edge of the study area near Grey Mountain.

Erosion and Mass Movements

Erosion and mass movement constraints identify map units where such processes may complicate construction, thereby increasing costs, and/or pose a hazard to development for which associated risk may be unacceptable or require mitigation. Both rapid and slow mass movements are hazardous to most development, and areas susceptible to such processes have been assigned the highest LDC severity level. Existing slope failures commonly indicate areas with broader instability and where recurrent events are possible. Mass movements are commonly identified along the steep escarpment slopes adjacent to Yukon River (e.g., Photographs 3 and 4, Appendix C). Mass movements may also pose a risk to existing development, such as along Robert Service Way, Drury Street, and Jeckell Street in Whitehorse, where slides have impacted roads, a playground, and come close to residential buildings (Lipovsky, 2023).

Erosional processes, while generally less catastrophic than mass movements, can increase the cost of development and ongoing maintenance or mitigation requirements. Areas with evidence of erosion are generally undesirable for most development but may be suitable for day use and recreational activity. Erosional processes are most common on steeper slopes composed of fine-grained material.

Soil Composition

Soil composition constraints are associated with highly compressible or potentially deformable soils that complicate land development. Areas underlain by organic materials, typically existing or former wetlands, are considered poorly suited for residential or commercial structures due to soil compressibility and poor drainage in addition to associated hydrological, ecological and other values of wetlands (Government of Yukon, 2022). Development in areas of thin organic cover (veneers) is possible, where unavoidable, through removal (stripping) of organics and replacement with well-drained fill. Clay-rich soils may increase development costs due to particular design and construction considerations for foundations. Map units with high soil composition constraints are scattered through the study area within poorly drained, low-lying areas. Map units with low soil composition constraints are commonly concentrated near Yukon and Takhini Rivers where clay-rich glaciolacustrine deposits are located (e.g., Photographs 5 and 6, Appendix C). Development within former oxbows of Takhini River, such as along Couch Road and Loganberry Lane, may be constructed on layers of clay-rich soils and/or organic lenses. Geotechnical investigations can provide additional site-specific information on the subsurface conditions in map units where soil composition has been identified as a constraint.

Topography

Topography constraints identify map units where ground steepness may complicate land development. Undulating and gently sloping landforms may necessitate costly earthworks to achieve desired grading, and steeper slopes may require design, construction and maintenance of costly retaining walls or similar structures. Management of surface runoff and erosion is also more complicated in steeper topography. Topographic constraints of some severity are common within the study area. Low severity topographic constraints (e.g., Photograph 7, Appendix C) can generally be mitigated through higher construction costs. Moderate to high severity topographic constraints (e.g., Photograph 8, Appendix C) commonly require more extensive regrading and retaining structures, which could affect the stability of upslope and downslope areas.

Permafrost Distribution

Permafrost constraints identify areas underlain by perennially frozen ground. Permafrost can increase the cost of construction. Thawing ice-rich permafrost can require ongoing maintenance and pose hazards. Land development typically results in localized thaw of underlying permafrost. Map units interpreted to be underlain by ice-rich permafrost are classified as highly constrained due to the potential for differential ground settlement (thermokarst) and are best avoided. Units underlain by permafrost with low ice content are classified as moderately constrained and may require additional design, construction and/or maintenance costs to support development. Permafrost constraints are uncommon within the study area. Map units with permafrost constraints are most commonly found at higher elevations along the western border of the study area, particularly on northerly aspects with concave slope morphology, but may be found scattered throughout the study area where organic cover has insulated and preserved underlying permafrost (e.g., Photograph 10, Appendix C).

Water Table

Water table constraints identify areas where high groundwater levels may pose a challenge to land development, at least during construction, and ongoing land management. Water table constraint severity increases with higher groundwater tables; at the highest severity level, the map unit is expected to be at least seasonally inundated. High water table constraints include areas such as wetlands, active floodplains, and/or areas containing significant organics in low-lying areas (e.g., Photographs 11 and 12, Appendix C). Moderate water table constraints are limited, and generally include map units with vegetative indicators of imperfect to poor surface drainage or seepage (e.g., Photograph 13, Appendix C). Any underground construction (e.g., basements) may be subject to groundwater-related flooding, at least seasonally, in areas constrained by an inferred high water table.

Flooding Recurrence

Flooding constraints identify map units interpreted to be susceptible to riverine flooding on a frequent (<5 years) to infrequent (>5 years) basis, without consideration of the depth or velocity of floodwater (refer to Section 2.2.1 for limitations of flood constraint mapping). Map units with flooding constraints may not require additional development costs at the outset, but may be exposed to recurring hazards associated with flooding and, in some cases, bank erosion or avulsions. Structural mitigations may be required to reduce risks. Such areas are more suitable for day use or recreational development. Construction of habitable structures should consider the potential impacts of flooding where this constraint has been identified. Flooding is generally identified as a constraint in the low-lying areas adjacent to Yukon and Takhini Rivers (e.g., Photograph 9, Appendix C). Flood-prone areas along significant tributaries with defined floodplains are also included.

3.2 Fluvial Erosion Hazard Forecasting

Yukon River exhibits a planform with low sinuosity, natural pinch-points (rapids), and multi-branched sections with vegetated bar complexes. The southern bank of Takhini River, which exhibits a tortuous meandering planform with meander scrolls and scars present along its floodplain, functions as the northern boundary of Whitehorse City Limits to its confluence with Yukon River (Appendix B). A residential development, near this confluence, has been constructed within a meander scar.

Yukon River, in Whitehorse City Limits, is regulated by the WHP. The WHP was constructed at a natural, bedrock-controlled rapid (Whitehorse Rapids) in 1958. Upstream of the associated dam, Schwatka Lake reservoir backwaters Yukon River for approximately 17 km. Downstream of the WHP, Yukon River's overall planform has remained relatively stable over the historical record. Factors that have contributed to localized and relatively minor adjustments over the historical record include upstream regulation altering seasonal flow regime (e.g., reduced floods), channel deepening and narrowing associated with reduced sediment supply, increased urban development within the floodplain requiring bank protection, and pre-existing variability in channel boundary materials (e.g., glaciolacustrine and colluvial escarpments). Erosion along Takhini River has been concentrated along the outer banks of meanders, resulting in progressive lateral and down-valley migration.

Historical channel planforms and delineated erosion hazard zones are illustrated in Appendix B. Comparative overlay analysis of historical channel planforms revealed six areas along Yukon River (

Table 4) and three meanders along Takhini River (Table 5) that exhibit systematic migration. Meanders excluded from these summary tables have either exhibited little to no migration over the period of record (i.e., 1946 to 2019) or exhibited unsystematic erosion from which a trend cannot be ascertained for forecasting purposes (e.g., anthropogenic alteration).

Time-averaged erosion rates along Yukon River range from 0.5 to 0.9 m/year, with an overall average of 0.7 m/year. Time-averaged rates of erosion along Takhini River range from 0.3 to 0.8 m/year, with an overall average of 0.5 m/year The absence of a long-term, 25-50 year hazard zone at meander T1 is due to an avulsion that is predicted to occur during the near-term, 10-25 year time period. Avulsions locally steepen the channel and temporarily increase sediment supply, which can accelerate erosional processes and the migration rates of downstream meanders.

Table 4. 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	NE	50	1946	2019	73	0.7
Y2	E	20	1977	2019	42	0.5
Y3	NE	34	1977	2019	42	0.8
Y4	NE	27	1977	2019	42	0.6
Y5	NW	30	1977	2019	42	0.9
Y6	SSE	69	1946	2019	73	0.9
Average						**0.7**

Notes: 1. Meanders are labelled in Appendix B from upstream to downstream

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

Meander Number	Trajectory	Erosion Distance (m)	Start Date	End Date	Period (yrs)	Average Erosion Rate (m/yr)
T1	ENE	14	2001	2019	18	0.8
T2	SE	20	1946	2019	73	0.3
T3	SW	23	1936	2019	73	0.3
Average						**0.5**

Notes: 1. Meanders are labelled in Appendix B from upstream to downstream

3.2.1 General Implications of Fluvial Hazard Zones

Comparison of changes in river positions over time has revealed eight of nine locations where progressive erosion could impact existing infrastructure, private property and/or planned development over the next 50 years (Table 6). The remaining site (Y6) is located at an anomalous widening along Yukon River, where a vegetated island divides flow. This area (Y6) is likely unsuitable for future development due to its proximity to the receding bank.

Table 6. Characterization of eight sites where continued riverbank erosion may pose a risk to existing or proposed development.

Erosion Site1	Drivers of Erosion	Features at Risk
Y1	Downstream transfer of erosive energy (development and bank protection upstream); bar complex stabilization and growth leading to better definition of thalweg (deepest part of channel) and its shift toward outer bank.	Trail, any further development.
Y2/Y3/Y4	Bar complex stabilization and growth leading to better definition of thalweg and its shift toward channel bank.	Residential dwelling, any future development.
Y5	Downstream transfer of erosive energy (development and bank protection upstream), point of erosion concentration along channel bank, thalweg contact with bank.	Any future development.
T1	Point of erosion concentration (outer bank of short-radius meander), thalweg contact with bank. Potential meander 'cut-off' in 10-25 years.	Any future development
T2	Point of erosion concentration (outer bank of meander). Erosion is occurring at the low-relief 'neck' of a former river meander, now mostly developed.	Field and potentially nearby residential development.
T3	Thalweg contacts bank.	Any further development

[1] Refer to Appendix B for site locations.

Trends in erosion observed along Yukon River, downstream of WHP, are generally consistent with effects associated with flow regulation (e.g., Williams and Wolman,1984; Brandt, 2000; Grant, 2003; Graf et al., 2006). A more focused and detailed assessment would be required, however, to attribute documented erosion (e.g., Y1 to Y5) to flow regulation, natural variability or both (as further explained in Section 4).

4. Recommendations and Follow-up Opportunities

Mapping of physical development constraints within the Whitehorse City Limits was completed to inform upcoming land use planning studies and increase the general understanding of the types and distributions of terrain well to poorly suited to different forms of development. Several follow-up initiatives are identified for consideration:

- **Targeted field investigations** within areas of potential development interest to collect information that cannot be interpreted remotely and provide local- to site-scale characterizations of ground conditions and associated LDCs. Depending on the nature of the areas of interest and particular land use interests, investigations could involve visual examination of surface conditions, geophysics surveys, test pitting, or shallow drilling using lightweight equipment. Regardless of any post-field refinements, it must be reiterated that LDC mapping is not a substitute for ground-based observations, particularly in areas potentially exposed to hazards. Site-specific assessments should be conducted prior to development of any portions of the map area.
- Establishment of **guidelines** for the types of site-specific studies or investigations that should be completed prior to approval of any new development within KDFN Settlement Lands. For example, a table could be prepared to succinctly highlight the applicability of different considerations or investigations specific to each parcel.
- A follow-up **fluvial geomorphological study** to assess the degree to which flow regulation and erosion mitigation efforts along Yukon River may have caused, or at least contributed to, documented erosion of riverbanks. Such a study could involve examination of pre- and post-regulated flows, the nature and patterns of erosion, apparent changes in bed materials and bar complexes, previously completed fluvial geomorphological studies, and available local and Traditional Knowledge.
- **Open File publication** of the Whitehorse City Limits LDC map through YGS, following any field-based updates, if of interest to KDFN.

5. Statement of Limitations

This report has been prepared by Palmer for Kwanlin Dün First Nation 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 land development constraints based on desktop analyses and only one day of field reconnaissance. Interpretations of subsurface conditions have been made based on surface indicators and limited, second-hand subsurface information 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.

6. Certification

This report was prepared, reviewed, and approved by the undersigned:

Prepared By:

Patrick Dunbar, G.I.T.
Terrain Scientist

Prepared By:

Jenna Whitney, M.Sc., G.I.T.
Earth Scientist

Reviewed & Approved By:

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

7. References

Bond, J., Morison, S. and McKenna, K. 2005. Surficial Geology of Upper Laberge (NTS 105D/14), Yukon (1:50 000 scale). Yukon Geological Survey, Geoscience Map 2005-8.

Brandt, S.A., 2000. Classification of geomorphological effects downstream of dams. Catena, 40, 375-4.

Government of Yukon, 2022. A policy for the stewardship of Yukon's wetlands. Government of Yukon, Whitehorse, Yukon, Canada.

Government of Yukon, 2023. Water well registry. Accessed May 26, 2023 from https://yukon.maps.arcgis.com/apps/webappviewer/index.html?id=51322dfb133d42c4ad184fee9986048b.

Graf, W.L., 2006. Downstream hydrologic and geomorphic effects of large dams on American rivers. Geomorphology, 79, 336-360.

Grant, G.E., Schmidt, J.C., and Lewis, S.L., 2003. A geological framework for interpreting downstream effects of dams on rivers. Water Science and Application, 7, 209-225.

Kryotek Arctic Innovation Inc. (Kryotek) and Palmer Environmental Consulting Group Inc. (Palmer), 2016. Terrain and Development Constraints Mapping for the Tagish Local Area Plan Boundary. Memorandum prepared for Yukon Department of Energy Mines and Resources – Land Planning Branch, 2016.

Lipovsky, P.S. 2023. Surficial geology and geohazards of the greater Whitehorse area. Yukon Geological Survey, Open File 2023-1, 67 p. plus appendices.

Palmer Environmental Consulting Group Inc. (Palmer), 2018. Terrain and Development Constraints Mapping for the Fox Lake Local Area Plan Study Area. Report prepared for Yukon Department of Energy Mines and Resources – Land Planning Branch, August, 2018.

Palmer Environmental Consulting Group Inc. (Palmer), 2020. Carmacks Surficial Geology and Community Hazard Susceptibility Mapping. Report prepared for Yukon Geological Survey, November, 2020.

Roy, L.-P., Lipovsky, P.S., Calmels, F., Laurent, C., Humphries, J. and Vogt, N. 2021. Greater Whitehorse area permafrost characterization. Yukon Geological Survey, Miscellaneous Report MR-22, 185 p., including appendices.

UMA Engineering Ltd. (UMA) and Gartner Lee Limited (Gartner Lee), 2004. Golden Horn Local Area Plan. Report prepared for Yukon Government, December 1999, revised May 2004.

UMA Engineering Ltd. (UMA), Applied Ecosystem Management Ltd. (AEM), Gartner Lee Limited. (Gartner Lee), and Mougeot GeoAnalysis, 2002. Hotsprings Road Local Area Plan. Report prepared for Yukon Government, January 2002.

Williams, G.P. and Wolman, M.G., 1984. Downstream effects of dams on Alluvial Rivers. Geological Survey Profession Paper 1286, 83.

Palmer™

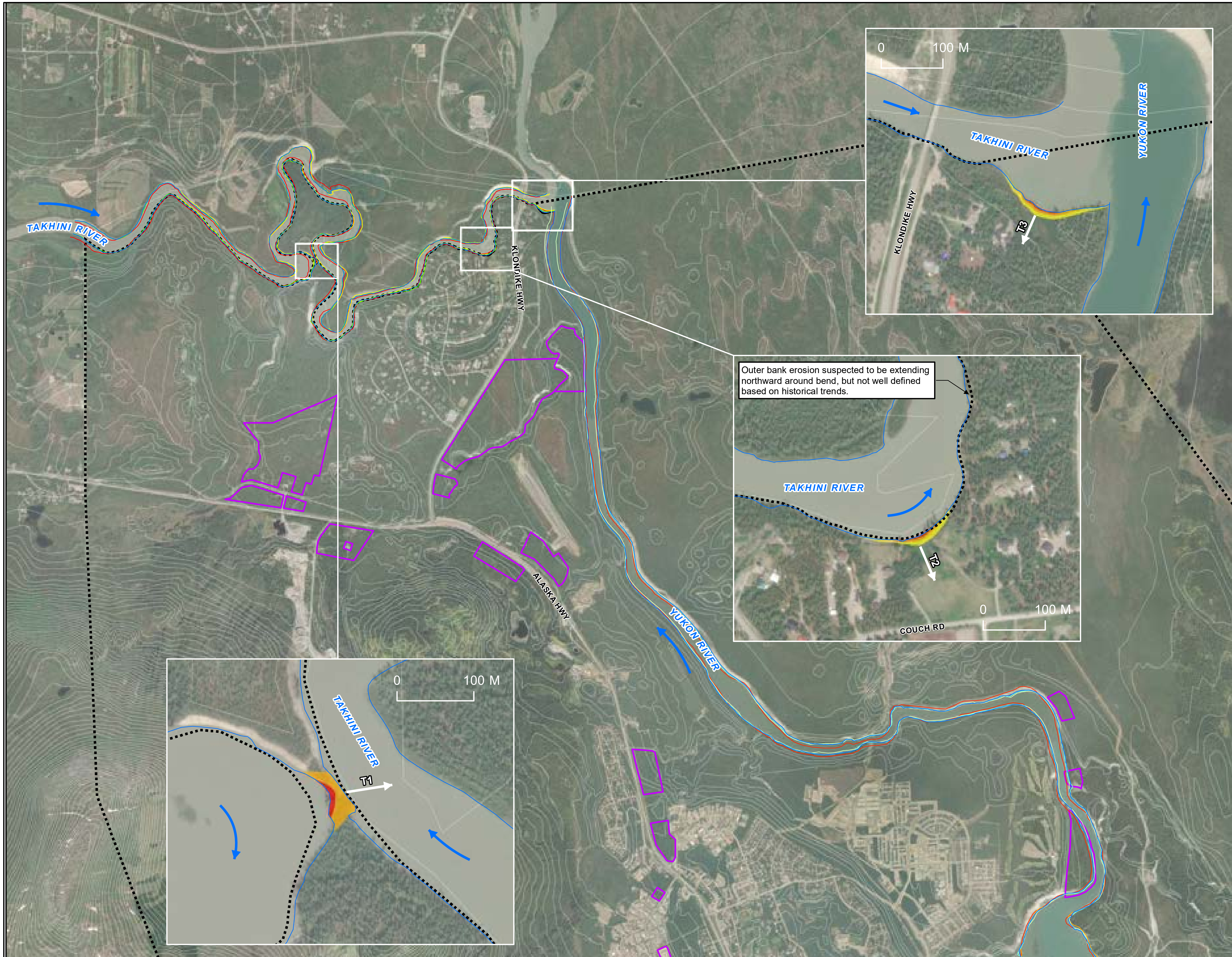
Appendix A

Physical Land Development Constraints of Whitehorse

(poster-sized map sheet provided separately)

Appendix B

Riverbank Erosion Trends and Hazard Zones



KEY MAP

LEGEND

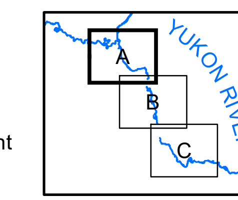
Channel Planform Year
- 2019
- 2006
- 2001
- 1985
- 1977
- 1963
- 1946

Erosion Hazard Zone
- 0 to 10 Years
- 10 to 25 Years
- 25 to 50 Years

Direction
- Meander ID and Trajectory (Displayed as white line on map)
- Flow Direction

Base Data
- Contour (10 m)
- Study Area
- KDFN Settlement Lands

Main Map Extent



0 1 2
KILOMETRE

North American Datum 1983
Universal Transverse Mercator Projection Zone 17

Scale: 1:40,000
Page Size: Tabloid (11 x 17 inches)

Drawn: SM
Checked: MB
Date: Oct 6, 2023

Source Notes:
Base imagery (2021) provided by ESRI basemapping services. Contains information licensed under the Open Government Licence – Yukon.
Contours derived at 5 m intervals based off bare earth LiDAR DEM in study area.

NORTH

CLIENT
Kwanlin Dün First Nation

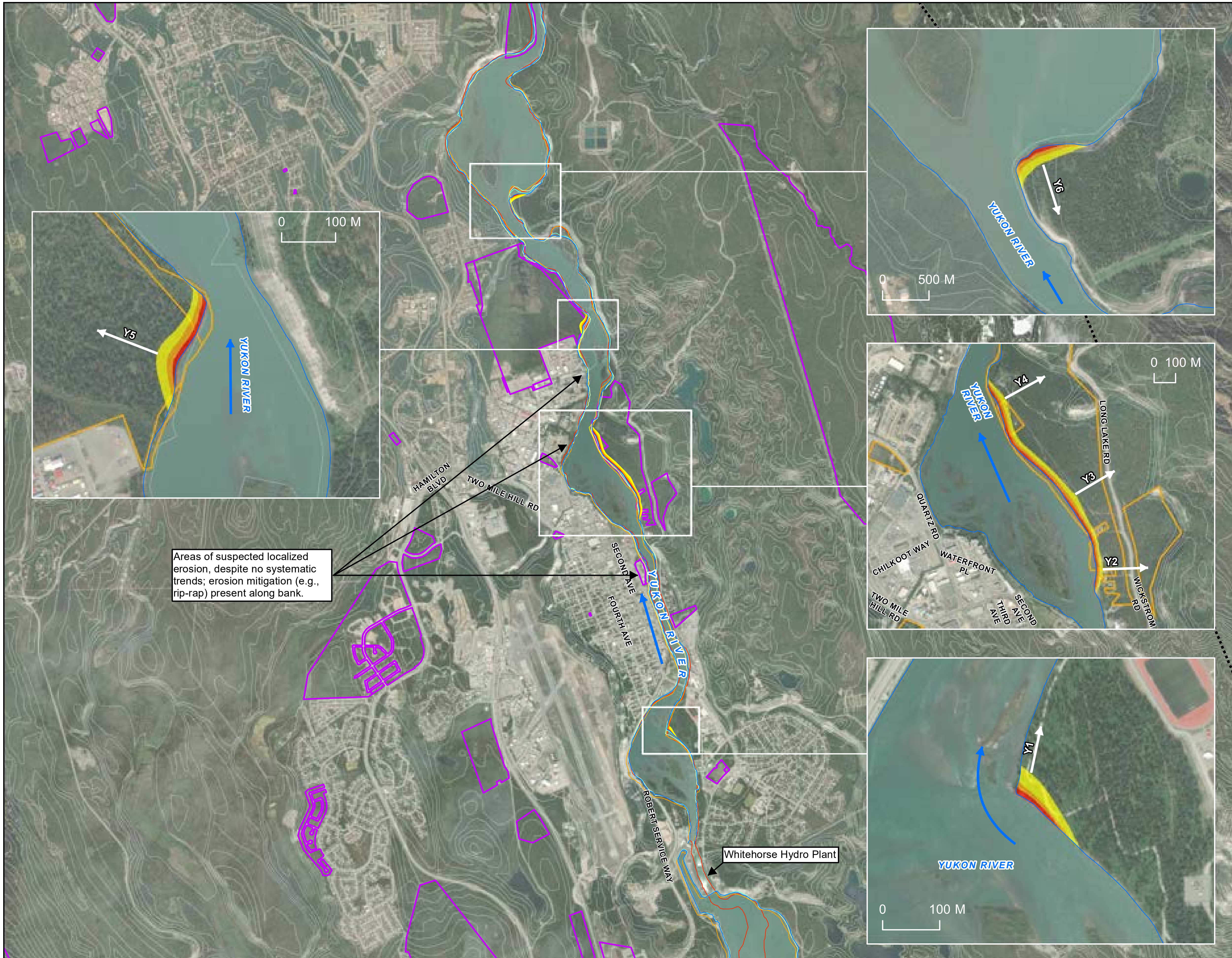
PROJECT
Constraints Mapping of Whitehorse

TITLE
Riverbank Erosion Trends and Hazard Zones

Palmer™

REF. NO. 2211201-1-3

Figure 1A



KEY MAP

Key Map

Site Location

0 100 km

LEGEND

Channel Planform Year
- 2019
- 2006
- 2001
- 1985
- 1977
- 1963
- 1946

Erosion Hazard Zone
- 0 to 10 Years
- 10 to 25 Years
- 25 to 50 Years

Direction
- Meander ID and Trajectory (Displayed as white line on map)
- Flow Direction

Base Data
- Contour (10 m)
- Study Area
- KDFN Settlement Lands

Main Map Extent

A B C YUKON RIVER

0 1 2
KILOMETRE

North American Datum 1983
Universal Transverse Mercator Projection Zone 17

Scale: 1:40,000
Page Size: Tabloid (11 x 17 inches)

Drawn: SM
Checked: MB
Date: Oct 5, 2023

NORTH

Source Notes:
Base imagery (2022) provided by ESRI basemapping services. Contains information licensed under the Open Government Licence – Yukon.
Contours derived at 5 m intervals based off bare earth LiDAR DEM in study area.

CLIENT
Kwanlin Dün First Nation

PROJECT
Constraints Mapping of Whitehorse

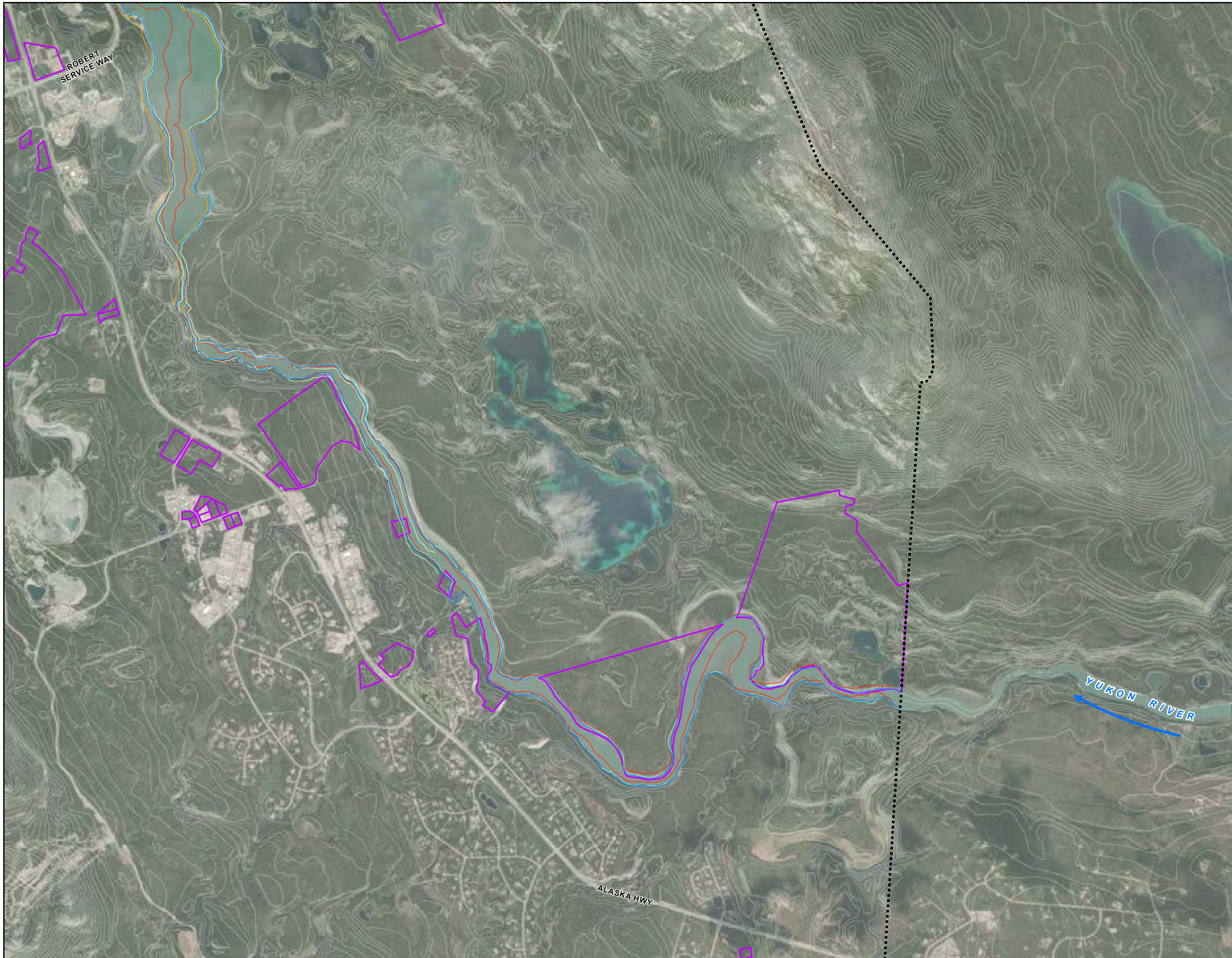
TITLE
Riverbank Erosion Trends and Hazard Zones

Palmer

REF. NO. 2211201-1-3

Figure 1B

Document Path: G:\Shared drives\Projects 2022\22112 - Kwanlin Dun First Nation\2211201 - Whitehorse Constraints Mapping\GIS\1_Workspace\Task 6 - Figures\(2023-05) Erosion Hazards\2211201-1B-1-Erosion Hazard Limit.mxd



KEY MAP

LEGEND

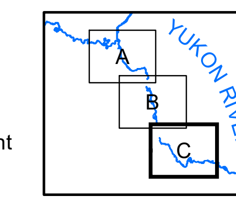
Channel Planform Year
- 2019
- 2006
- 2001
- 1985
- 1977
- 1963
- 1946

Erosion Hazard Zone
- 0 to 10 Years
- 10 to 25 Years
- 25 to 50 Years

Direction
- Meander ID and Trajectory (Displayed as white line on map)
- Flow Direction

Base Data
- Contour (10 m)
- Study Area
- KDFN Settlement Lands

Main Map Extent



0 1 2
KILOMETRE

North American Datum 1983
Universal Transverse Mercator Projection Zone 17

Scale: 1:40,000
Page Size: Tabloid (11 x 17 inches)

Drawn: SM
Checked: MB
Date: Oct 5, 2023

NORTH

Source Notes:
Base imagery (2022) provided by ESRI basemapping services. Contains information licensed under the Open Government Licence – Yukon.
Contours derived at 5 m intervals based off bare earth LiDAR DEM in study area.

CLIENT
Kwanlin Dün First Nation

PROJECT
Constraints Mapping of Whitehorse

TITLE
Riverbank Erosion Trends and Hazard Zones

Palmer

REF. NO. 2211201-1-3

Figure 1C

Document Path: G:\Shared drives\Projects 2022\22112 - Kwanlin Dun First Nation\2211201 - Whitehorse Constraints Mapping\GIS\1_Workspace\Task 6 - Figures\(2023-05) Erosion Hazards\2211201-1C-1-Erosion Hazard Limit.mxd

Appendix C

Photograph Log of Common Land Development Constraints

Photograph 1. High bedrock constraint. Area is outcrop dominant.

Photograph 2. Moderate bedrock constraint. Outcrop occupies less than 1/3 of the area.

Photograph 3. High erosion constraint. Steep slope with visible sloughing.

Photograph 4. Erosion area, showing transition from moderate (left foreground) to high (right background) constraint with a transition from stabilizing vegetation to a lack of vegetation, respectively.

Photograph 5. Low soil constraint, clay-rich material.

Photograph 6. Low soil constraint, clay-rich material.

Photograph 7. Low topographic constraint, average slope gradient 10-20%.

Photograph 8. High topographic constraint, average slope gradient >30%.

Photograph 9. ***Moderate floodplain recurrence constraint area, adjacent to and slightly elevated above Yukon River.***

Photograph 10. ***High permafrost constraint. Organic-covered, undulating, suspected ice-rich ground.***

Photograph 11. ***High water table depth constraint. Localized surface ponding.***

Photograph 12. High water table depth constraint. Water is present at surface.

Photograph 13. Moderate water table depth constraint. Water table is <1 m from surface.