

Photo source: Underhill Geomatics, 2024

Old Crow Flood Mapping Study

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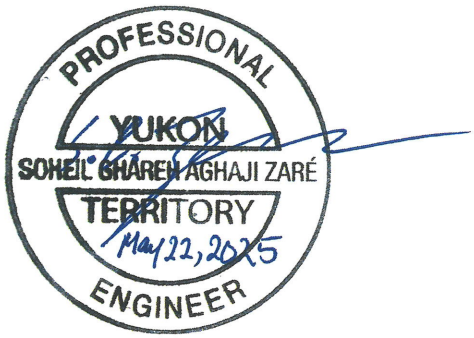
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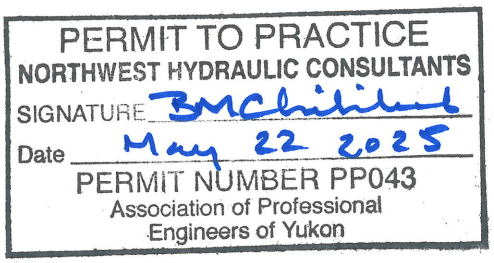
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DISCLAIMER

This report has been prepared by Northwest Hydraulic Consultants Ltd. for the Government of Yukon Department of Environment – Water Resources Branch for specific application to the Old Crow Flood Mapping Study (Porcupine River and Old Crow River), a project funded through the Flood Hazard Identification and Mapping Program. The information and data contained herein represent **Northwest Hydraulic Consultants Ltd.'s** professional judgment in light of the knowledge and information available to **Northwest Hydraulic Consultants Ltd.** at the time of preparation and was prepared in accordance with generally accepted engineering and geoscience practices.

This study and associated project deliverables may be used and relied upon by Government of Yukon Department of Environment – Water Resources Branch, its officers, and employees, as well as all orders of government and other public and private sector organizations, to understand clearwater and ice jam flood hazards for the specific flood scenarios and water bodies assessed in the study. The report and flood maps produced as part of this project are intended to inform decision-making in support of land use planning, flood mitigation, emergency preparedness and response, and adaptation to a changing climate. **Northwest Hydraulic Consultants Ltd.** is not liable in any way whatsoever to any party for any injury, loss, or damages suffered by such parties arising from the misuse, misinterpretation, or reliance upon this report or any of its contents.

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APPENDICES

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ABBREVIATIONS

Acronym / Abbreviation	Definition
AEP	Annual exceedance probability
AHCCD	Adjusted and homogenized Canadian climate data
AOI	Area of interest
CMIP6	Coupled Model Intercomparison Project Phase 6
DDT	Degree day temperature
DEM	Digital elevation model
FFMGS	Federal flood mapping guidelines series
FFA	Flood frequency analysis
HEC-RAS	U.S. Army Corps of Engineers Hydrologic Engineering Center's River Analysis System (software)
HRDEM	High resolution digital elevation model
INAC	Indian and Northern Affairs Canada
LiDAR	Light detection and ranging
LP3	Log-Pearson Type III
NRCan	Natural Resources Canada
NHC	Northwest Hydraulic Consultants Ltd.
PCIC	Pacific Climate Impacts Consortium
PCEX	PCIC climate explorer tool
QPD	Peak daily flow
QPI	Peak instantaneous flow
RCP	Representative concentration pathway
SSPs	Shared Socio-Economic Pathways
SWE	Snow water equivalent
VGFN	Vuntut Gwitchin First Nation
WSC	Water Survey of Canada
WSE	Water surface elevation

SYMBOLS AND UNITS OF MEASURE

Symbol / Unit of Measure	Definition
%	percent
m	metre
m^2	square metres
m^3/s	cubic metres per second
km	kilometre

1 PROJECT SNAPSHOT

Name: Old Crow Flood Mapping Study

Study Area: Porcupine and Old Crow Rivers adjacent to the community of Old Crow, Yukon

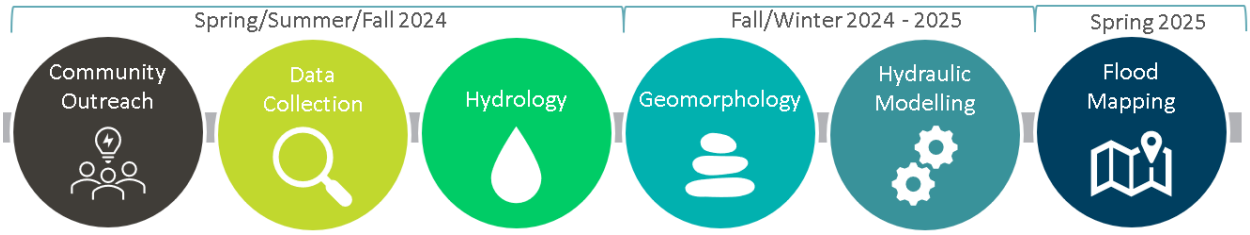
Agency: Government of Yukon Department of Environment – Water Resources Branch

Funding: Flood Hazard Information and Mapping Program (FHIMP), Climate Change Preparedness in the North (CCPN) and Government of Yukon Our Clean Future (OCF)

Objectives: Assess, identify, and map flood hazards for the community of Old Crow

Approach: Collaborative, including stakeholder and public consultation.

Timeline: April 2024 – April 2025



This Report: This summary report provides a high-level overview of the methods undertaken to complete flood mapping for the community of Old Crow. Report sections include: study area overview, community engagement, field investigations and surveys, hydrology, geomorphology, hydraulic modelling, climate change, flood mapping, community flood thresholds, assumptions and limitations and conclusions. Additional technical information describing the detailed hydrologic, river ice, modelling, and geomorphic investigations that have been carried out is summarized in the following appendices.

- Appendix A: Survey and Data Collection
- Appendix B: Hydrology, River Ice, Climate Change and Hydraulic Modelling
- Appendix C: Geomorphic Assessment
- Appendix D: Flood Maps

Prior to applying findings of this work, including the accompanying maps, it is required that the entire report be read and understood. A professional qualified in hydrotechnical analysis should be consulted to address questions or improve understanding of this work.

2 INTRODUCTION

The Government of Yukon, Department of Environment – Water Resources Branch (WRB), retained Northwest Hydraulic Consultants Ltd. (NHC) to complete flood mapping of the Porcupine River and the Old Crow River near the community of Old Crow, Yukon. The objectives of this project are to assess, identify, and map flood hazards for the community of Old Crow with a main deliverable being the development of flood maps for the community.

3 STUDY AREA OVERVIEW

The community of Old Crow lies in the northern part of the Yukon Territory, about 120 kilometres north of the Arctic Circle (Figure 3.1), in the Traditional Territory of the Vuntut Gwitchin First Nation. The community is situated on the right bank of the Porcupine River (Ch'ōdènjik), just downstream of its confluence with the Old Crow River (Chahnjik). Old Crow has a population of approximately 236[1] with fly in access only. The mean annual temperature in Old Crow is -7.7°C, and the mean annual precipitation is relatively low at about 160 mm[2].

The Porcupine River Watershed, covering approximately 118,000 km^2, is a pristine river system within the Yukon River Basin. The Yukon River basin's lower elevations are dominated by coniferous forests, while higher elevations feature Taiga and Alpine Tundra. The basin lies within a region of continuous permafrost in the north and discontinuous permafrost in the south.

The hydrological regime of the Porcupine and Old Crow rivers is nival. Freeze up on the Porcupine River usually takes place in early winter and breakup typically occurs in mid-May. The Porcupine River channel at Old Crow is approximately 600 metres wide and occupies a broad alluvial valley ranging from 6 to 10 km in width. The mean annual discharge of the Porcupine River at this location is around 320 m^3/s, with peak flows reaching approximately 4,200 m^3/s in May or early June. The cause of the highest water levels in Old Crow are from ice jams.

The area of interest (AOI) for this project initially covered approximately 5 km of the Porcupine River and 1 km of the Old Crow River. However, following discussions with the Government of Yukon the study domain was expanded to include additional sites upstream and downstream of the community. The study domain was extended from cabins just upstream of the community to the confluence of the Porcupine and Bluefish River. The extended study boundaries covered approximately 57 km of the Porcupine River.

[1] Statistics Canada (2021 Census)

[2] ECCC (2024 Climate Normals)

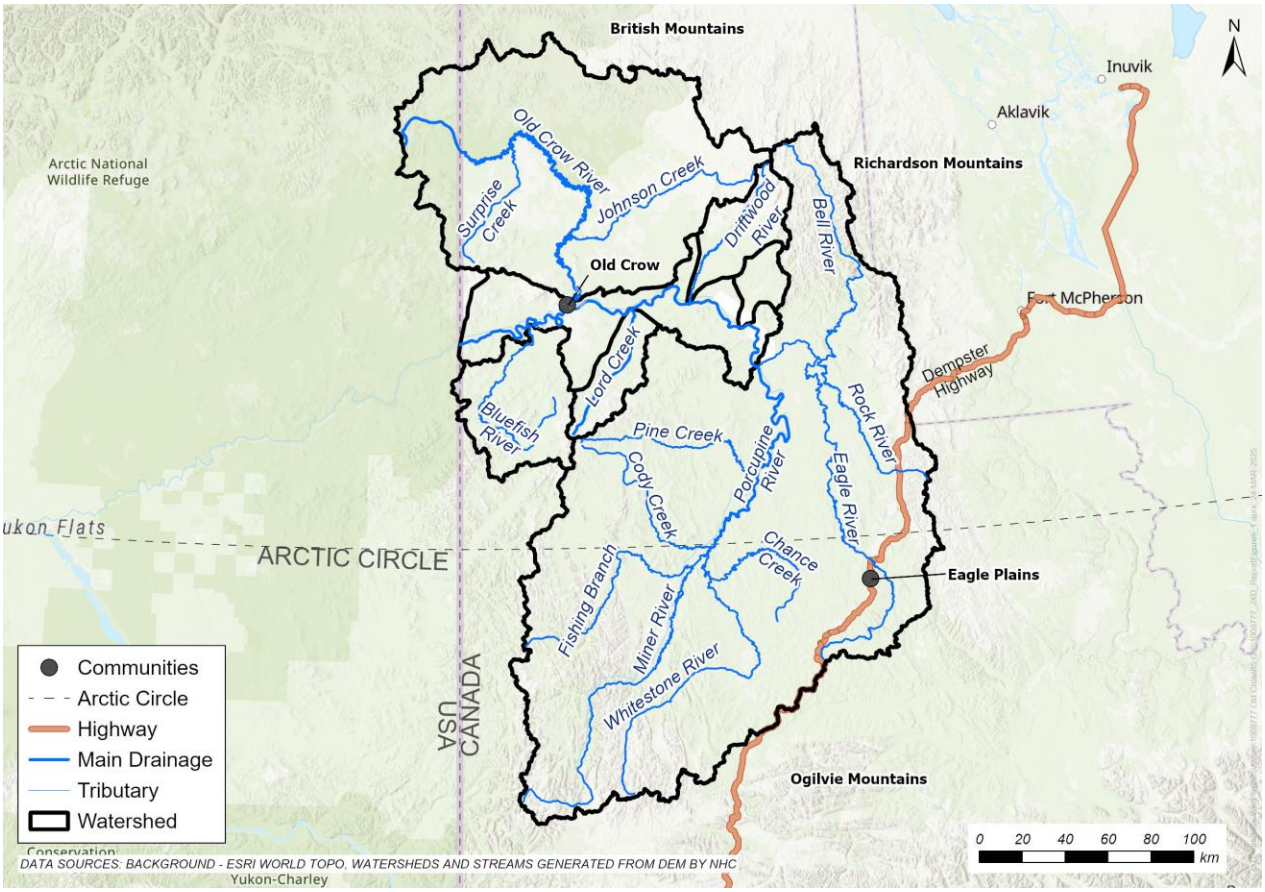


Figure 3.1 Porcupine River watershed and subbasins.

4 COMMUNITY ENGAGEMENT

The Government of Yukon began initial engagement with the community of Old Crow in Spring 2023 to develop study area boundaries and confirm whether any LiDAR acquisition was required. NHC retained Kermode Consulting to lead community engagement for this study (beginning in April 2024). The objectives of engagement were:

- To introduce the project to the community and discuss project benefits.
- To gather technical knowledge.
- To provide a space for information sharing.
- To integrate findings into flood maps.

Community engagement was undertaken through virtual meetings with VGFN staff and public information sessions in the community of Old Crow. The initial phase of engagement took place

in June 2024 coinciding with the field investigations. During June 2024, the Government of Yukon, NHC and Kermode Consulting engaged with Indigenous Knowledge holders on their experiences with past and recent flooding – this input informed the flood history and high-water mark documentation for the study.

The second phase of engagement took place during February to March 2025. An information session and draft maps were shared with members of the VGFN government and draft maps were shared (online) to provide an opportunity for comments. Feedback on draft maps was incorporated into final mapping deliverables. Further information can be found in the What We Heard Report available from the Government of Yukon online via the Yukon Flood Hub: https://flood-atlas.service.yukon.ca/.

5 FIELD INVESTIGATIONS AND SURVEYS

NHC and Underhill Geomatics undertook a series of surveys to gather information about the Porcupine and Old Crow Rivers. Field data collection was completed in June 2024. NHC also competed a site inspection that coincided with the timing of the Underhill survey. The survey information forms the basis of data inputs for the hydraulic model used in this project. Bathymetric and terrestrial surveys were completed and compiled into a Digital Elevation Model (DEM). A brief overview of the types of information collected is outlined below. Further technical information pertaining to the field investigations can be found in Appendix A.

Datum

The Canadian Geodetic Vertical Datum 2013 (CGVD2013) was used for the project.

- Horizontal Datum: North American Datum 83 (NAD83) Yukon Albers CSRS (Epoch 2002)
- Geoid Model: CGG2013a

River Surveys



Figure 5.1 Study team completing bathymetric surveys on the Porcupine River. Photo NHC 2024.

- Bathymetric surveys are measurements of ground elevations that are underwater. Data was collected with conventional bathymetric survey equipment.
- Bathymetric surveys were completed for the Porcupine and Old Crow Rivers.
- Geomorphic field investigations were carried out in June 2024 including photo

documentation of channel bed and bank composition and over bank depressions. A longitudinal profile was collected of the riverbed and water surface elevation from the upstream-most point of the study area to the confluence of the Porcupine and Bluefish Rivers.

Terrestrial Surveys

- Terrestrial surveys, also called ground surveys, collect elevation and distance information for points on the surface of the earth.
- Terrestrial surveys were completed for critical infrastructure, culverts, high water marks, and road centrelines. A series of hydrometric benchmarks were surveyed to shift water level data into the CGVD2013 datum.

LiDAR and DEM

LiDAR (Light detection and ranging) data was used for defining general terrestrial topography over the study area. 2019 LiDAR flown by McElhanney Ltd. was provided by the Government of Yukon that covered the area immediately around Old Crow. The study area not covered by the McElhanney LiDAR was supplemented by using high resolution digital elevation model (HRDEM) data (Natural Resources Canada, 2019).

6 FLOOD HYDROLOGY

A hydrologic analysis was completed for the Porcupine and Old Crow Rivers. The hydrologic analysis provides the required data for input to the hydraulic model. A brief overview of the hydrologic assessment is provided below. Further technical information can be found in Appendix B.

Hydrologic Regime

The hydrological regime of the Porcupine and Old Crow rivers is nival (Figure 6.1). Breakup on the Porcupine River typically occurs in mid-May, triggered by rapid snowmelt. By July, freshet flows typically subside. In fall, flow decreases as air temperature decreases, and river-ice begins to form. Usually, by December, rivers are characterized by low flows and ice cover is formed.

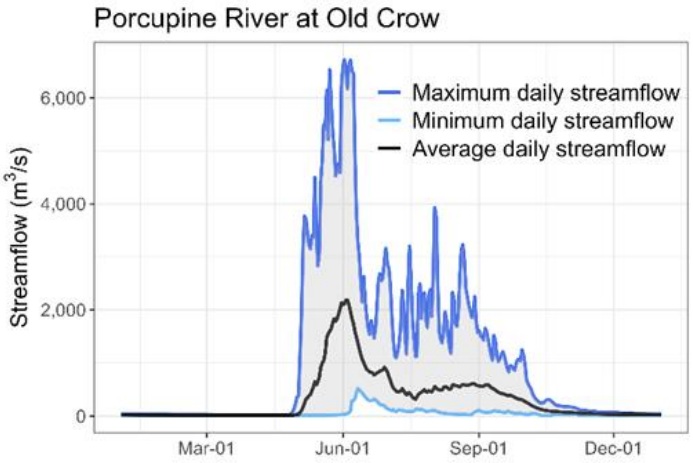


Figure 6.1 Annual hydrograph for the Porcupine River at Old Crow, WSC 09FD001.

Open Water Flooding

- Old Crow has experienced minor open water flooding in the past. Historical flood accounts indicate that open water flooding within the Porcupine River watershed in general, and at the community of Old Crow in particular, has been limited, with the most significant flood events being associated with ice jams during breakup.
- Flood frequency analysis was completed on data from Water Survey of Canada (WSC) gauges to estimate open water Annual Exceedance Probabilities (AEPs).

Ice Jam Induced Flooding

- The ice breakup on the Porcupine River begins when the ice near Old Crow first starts to move. Typically, this movement leads to the formation of an ice jam downstream, which persists until a more forceful breakup front arrives, usually within a few hours. Throughout the winter, aufeis may form in certain segments of the Porcupine River, particularly near the confluence with the Bluefish River. This aufeis formation can constrict the river channel, creating an anchor point for incoming ice floes to accumulate and form a toe for ice jam development.
- Ice induced flooding on the Porcupine River by Old Crow can occur either due to the formation of an ice jam downstream of the community or when an upstream ice jam dislodges, resulting in a heavy ice run near the community. The most severe flooding events in Old Crow have been driven by mechanical breakups, where large increases in discharge from upstream tributaries break up the ice cover and trigger ice jam formation downstream.
- During the most severe flooding in Old Crow in recent decades (May 1991), the ice jam toe was located at the confluence of the Porcupine and Bluefish Rivers, approximately 40 km downstream of Old Crow.
- A wide range of potential ice jam scenarios can contribute to flooding in the community of Old Crow. To evaluate their probability and establish design flood levels, a Monte Carlo analysis was conducted to develop the ice jam-induced flood level frequency curve. This analysis incorporated both historical and hypothetical ice jam events to offer an informed assessment of flood risk.

7 GEOMORPHIC AND EROSION HAZARD ASSESSMENT

An overview-level geomorphic assessment was completed based on desktop analyses and supplemented with field data collected at specified locations. The analyses included historic bankline mapping, channel migration analysis, sediment transport analysis, and identified channel bank areas that are vulnerable to erosion. A brief overview of the geomorphic assessment is provided below. Further technical information can be found in Appendix C.

Geomorphic Setting

The Old Crow region is a complex environment that includes unglaciated terrain, a continuous permafrost zone, active river ice processes, and a river system with the headwaters flowing from south to north in a periglacial landscape that is susceptible to a changing climate. Each of these facets contribute to the complex geomorphic character of the region and have the potential to influence the flood and ice regimes.

Key Processes and Potential Hazards

The following is an overview of key processes and potential hazards and how they might change in the future in response to climatic and environmental conditions. Regional trends encompassing the study area include:

- Increasing temperature and precipitation may increase peak flow frequency and magnitude, which could increase bank erosion, channel migration, sediment transport, and risk of avulsions.
- Loss of permafrost and ground-ice within the floodplain and along the channel margins is likely to increase bank instability, potentially resulting in increased erosion and sediment delivery to the channel, channel widening, and increased lateral migration. Permafrost decay may also cause floodplain subsidence, potentially increasing flood risk and the occurrence of channel avulsions.
- Ice jams will likely continue to form at locations where there is increased resistance to ice flow, including tight meander bends, channel constrictions, and slope or flow velocity reductions.

Morphological changes that may occur in the vicinity of Old Crow in response to changing climatic and environmental conditions include:

- Climate change may increase the potential for an avulsion to occur on the Porcupine River, upstream of the confluence with the Old Crow River (Figure 7.1).
- A meander cutoff avulsion is also possible along a tight meander bend on the Old Crow River approximately 2 km upstream of the confluence with the Porcupine River. An avulsion at this location may result in substantial impacts to the channel bed and banks downstream, adjacent to the community of Old Crow.
- The predicted increases in temperature and precipitation are likely to increase the amount of sediment supplied to the rivers. Increased sediment loads in the Old Crow and Porcupine Rivers would likely result in increased deposition at the confluence of the two river systems which in turn is likely to promote channel instability and may impact flood levels of the Porcupine River adjacent to the community of Old Crow.

- The confluence with the Bluefish River will likely continue to be an area prone to ice jamming.
- Increases in the magnitude or duration of peak flows may promote increased erosion and scour along the channel bank along the western end of the airport runway, and further downstream where there is a constriction in the channel width.
- The condition and extent of existing bank protection adjacent to the community of Old Crow is generally inadequate to provide erosion protection against existing, and potential future, high flow and ice breakup events. NHC recommends further assessment and upgrades to existing bank protection.

Further recommendations as well as information regarding setbacks for fluvial geomorphic hazards are discussed in Appendix C.



Figure 7.1 Left: channel banks on the Porcupine River. Right: possible avulsion location upstream of the community of Old Crow. Possible avulsion path shown by red dashed arrow. Community of Old crow in the background. Photos by Underhill 2024.

8 HYDRAULIC MODELLING

Hydraulic modelling was conducted using the U.S. Army Corps of Engineers Hydrologic Engineering Center's River Analysis System (HEC-RAS), Version 6.5 (February 2024). Hydraulic modelling was completed to estimate water levels for open water and ice jam conditions. The hydraulic model used the survey and hydrology information to reconstruct historic floods and simulate various flood scenarios. A brief overview of hydraulic model development and the approach to estimating ice jam water levels is provided below. Further technical information can be found in Appendix B.

Model Development and Calibration

The hydraulic model was developed using LiDAR and 40 surveyed cross sections along the Porcupine River and 4 cross sections along the Old Crow River (Figure 8.1). Additional cross sections were surveyed along the Porcupine River at strategic locations to extend the model to the Bluefish River confluence.

For open water conditions, the hydraulic model was calibrated using water surface elevation data from low flow conditions and rating curves developed at the community of Old Crow. For ice cover conditions, the 1991, 1993 and 2011 ice jam events were selected for model calibration. The model's performance was validated using data collected during the 2024 breakup.

Maximum Water Levels from Various Ice Jam Scenarios

There is a wide range of possible ice jam scenarios that might lead to maximum water levels, and a Monte Carlo simulation was used to model the probability of various ice jam scenarios that would result in maximum water levels.

Using the calibrated hydraulic model, each predefined breakup scenario was simulated across a range of flood discharges derived from the frequency analysis of breakup flows. This process resulted in the development of unique rating curves for each scenario at the community location, representing the floodwater level associated with a specific discharge under the prevailing breakup conditions. These sets of rating curves were directly utilized in the Monte Carlo analysis to translate each randomly selected discharge into the corresponding water level, based on the predefined breakup scenario.

The peak annual ice-affected flood level frequency analysis was conducted by combining the water level data sets from various breakup scenarios. The results of the Monte Carlo analysis were used to define AEPs for ice induced flooding events and to create flood inundation maps for the selected AEPs.

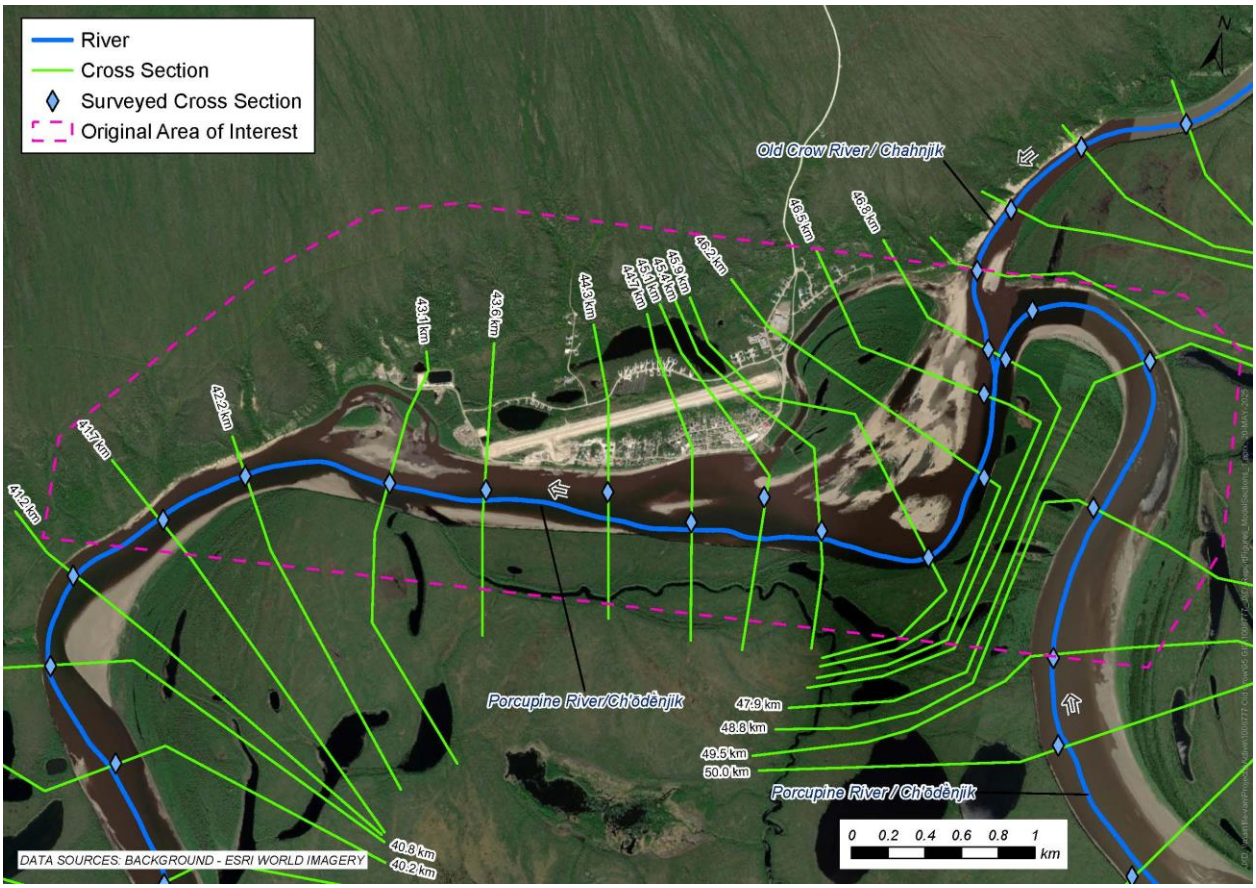


Figure 8.1 Hydraulic model layout illustrating cross sections over the community of Old Crow.

9 CLIMATE CHANGE

There is no standard of practice for applying climate and land cover change adjustments to ice jam flood mapping.

The current standard of practice for applying climate and land cover change adjustments to open water flood mapping is to adjust the design discharge by a percentage that reflects future conditions. The resulting water surface elevations output from the hydraulic model are then mapped. The same approach cannot be adopted for ice jam flood mapping due to the complexity of factors that may lead to ice jam induced flooding.

Unlike open water conditions, it is not possible to ascribe a unique flood level to each flood frequency discharge. Whereas flood *discharge* is the parameter to assess magnitude of open water floods, flood *level* is the key parameter to assess ice jam floods. For an ice jam flood

condition, there are a range of flood levels that could be associated with a single discharge because the flood level magnitude resulting from an ice jam depends on factors other than discharge – for example: ice thickness, ice jam extent (with head and toe locations), toe thickness, and under ice roughness.

We undertook a pragmatic approach to apply climate change adjustments to the ice jam flood frequency through judicious variation of the ice jam parameters used in the Monte Carlo simulations. Ice jam induced AEPs under future conditions were developed by adjusting causal factors used in the Monte Carlo simulation. The causal factors adjusted were two key flood-driving factors: breakup discharge and the probability of the dominant breakup type. The Monte Carlo analysis was then re-executed to generate an updated frequency curve for ice jam-induced flood levels at the WSC gauge location (09FD001) under a future conditions scenario.

The future climate condition was not applied to flood mapping. Instead, it was incorporated into the community flood threshold analysis which is described in Section 11 and Appendix B.

10 FLOOD MAPPING

The Government of Yukon typically undertakes mapping of the 5%, 1% and 0.5% AEP events. The exception to this is if the flood of record exceeds the 0.5% AEP. For this study, the 5%, 1% and 0.5% ice-induced AEP events were mapped. The water surface elevations for the events mapped were determined based upon the ice-induced frequency analysis resulting from the Monte Carlo simulation. To represent an approximation of open water bankfull conditions, the 50% open water AEP is also shown on the maps. The flood maps are presented in Appendix D.

The base map layout for the flood inundation maps is presented in Figure 10.1. The 1:2,500 scale map sheets cover areas of Old Crow that have buildings and allow for sufficient resolution for individual building recognition. The 1:7,500 scale map sheets provide an overall picture of flood inundation for Old Crow that covers both sides of the river channel.

The flood hazard maps show the estimated flood boundary and associated water surface elevations under a defined flood event. These maps are intended for comparing various potential flood scenarios and to support emergency response and planning. Freeboard is not included in any of the flood inundation maps.

The community of Old Crow is relatively flat, which makes it susceptible to flooding even at lower AEPs. The difference in flood inundation extent between the 1% and 0.5% ice-induced AEP events is minor, however the depth of water under the 0.5% AEP event is greater. At the WSC gauge location, the 0.5 % AEP is approximately 0.30 m greater in depth than the 1% AEP.

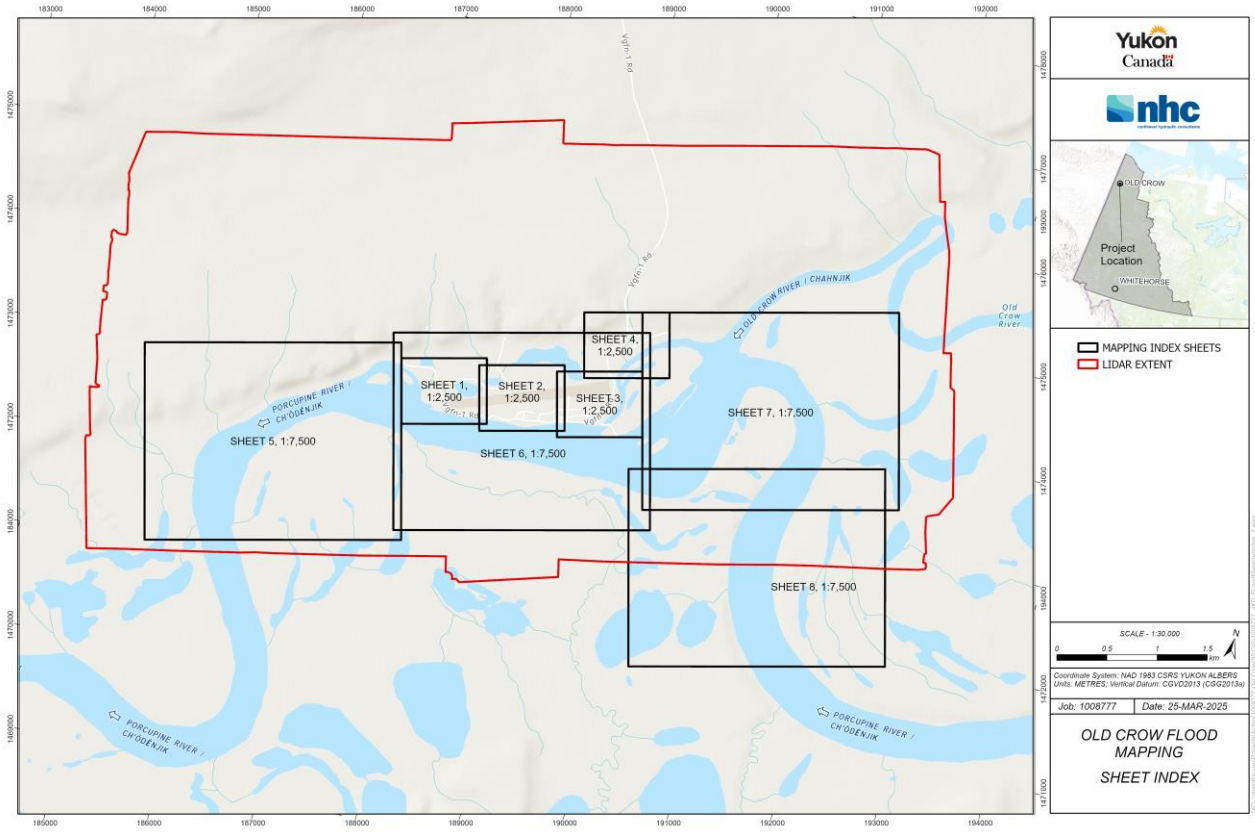


Figure 10.1 Map sheet layout.

11 COMMUNITY FLOOD THRESHOLDS

To support future planning for the community of Old Crow, key infrastructure items were identified, and the incidence of flooding was assessed under a series of AEPs for current and future conditions. Several buildings in the community of Old Crow are constructed on stilts. This results in various buildings appearing to be inundated in the flood maps, when in fact the building floor may not be inundated. The ground and floor elevations of the key infrastructure items were surveyed and compared to the water levels associated with various AEPs to assess the incidence of inundation for each asset (under current conditions and projected climate change conditions). The results of the community flood threshold analysis for the key infrastructure items are summarized in a separate report available from the Government of Yukon upon request.

12 ASSUMPTIONS AND LIMITATIONS

Several key assumptions and limitations must be acknowledged and carefully considered when interpreting the findings of this study. Understanding these assumptions and limitations is crucial for making informed decisions based on the study results. Assumptions and limitations specific to the data collection, hydrology, river ice, climate change, hydraulic modelling, geomorphology and mapping are listed in Appendix A-D. The following outlines some of the key assumptions and limitations of the Old Crow Flood Mapping Project.

- The intent of the field survey, data collected, analyses, and results was for the purposes of flood mapping. The flood maps are not intended for engineering design or construction.
- Industry best practices were followed to develop the flood maps. However, actual flood levels and extents may vary from those shown. Underlying hydraulic analysis assumes channel and shoreline geometry is stationary. Erosion, deposition, degradation, and aggradation are expected to occur and may alter actual observed flood levels and extents. Roads, bridges, new dikes, and future developments on the floodplain can restrict water flow and increase local water levels. Obstructions, such as log-jams, blockages, local storm water inflows, groundwater, other land drainage, and/or tributary flows beyond those indicated were not modelled and may cause flood levels to exceed those indicated on the maps. Additionally, flooding may occur outside of the outlines shown, caused by ponding from rainwater on the floodplain, groundwater seepage, local snowmelt or local drainage courses.
- The model geometry was kept fixed to that surveyed in 2024. Variations of channel geometry from that surveyed in 2024 can alter the expected flood levels and extents. The maps do not provide information on site-specific hazards such as land erosion or sudden shifts in the water courses. Erosion protection structures, dikes, banks, culverts, and other infrastructure within the floodplain were not inspected or evaluated during this study for their ability to protect or withstand flood events and are potentially at risk to flood hazards.
- Flood mapping delineates flood inundation areas, showing the extent of one or more flood scenarios under existing conditions. Flood mapping may be used for emergency response planning and operations. A Qualified Professional must be consulted for site-specific engineering analysis to determine the specific hazard associated with a particular development. Freeboard is not included in any of the flood inundation maps.
- This study is a desktop-based geomorphic assessment, supplemented by field data collected by third parties; field information for the geomorphic desktop assessment, was acquired during the survey and general field inspection, which did not include NHC geomorphology staff. Therefore, geomorphic interpretations are qualitative in nature and reliant upon remote observations and data. The findings of the assessment are also limited to the availability, accuracy, and completeness of data sources. The geomorphic assessment carried out for this study does not include an evaluation of sediment sources, terrain assessment, or

assessment of the potential or frequency of slope instabilities, debris flow, debris flood, potential for channel jamming and outburst flooding, or hyper-concentrated flow.

- The maps delineate flood inundation areas for flood scenarios based on available survey data and water level records. Future changes to the river channels, floodplain, and future climate change will render the maps obsolete. The information on the maps should be reviewed after 5 years have elapsed since publication or after any extreme flood occurrence and are expected to be out of date in 10 years (April 2035).

13 SUMMARY AND RECOMMENDATIONS

Flood maps were developed for sections of the Porcupine and Old Crow Rivers that are adjacent to the community of Old Crow. For this study, the 5%, 1% and 0.5% ice-induced AEP events were mapped. Final flood maps, the technical report, and a What We Heard report are available from the Government of Yukon online via the Yukon Flood Hub: https://flood-atlas.service.yukon.ca/.

The following is a synthesis of key observations and recommendations:

- It is recommended that the Government of Yukon continue to communicate the project findings with agencies and organizations that have flood management roles and responsibilities.
- The condition and extent of existing bank protection adjacent to the community of Old Crow is generally inadequate to provide erosion protection against existing, and potential future, high flow and ice breakup events. NHC recommends further assessment and upgrades to existing bank protection.
- Future development in Old Crow should consider flood inundation extents, associated water surface elevations and proximity to the top of bank. A generalized minimum setback of 30 m from the top of bank is suggested for planning of infrastructure and development. High-level guidance documents for flood hazard mapping in British Columbia state that a minimum 30 m setback should be applied to all major watercourses (APEGBC, 2017; MFLNRORD, 2018). At the time of writing, there are no equivalent guidelines published for the Yukon that NHC is aware of. While this does provide initial guidance, APEGBC (2017) also state that if there is active bank erosion, setbacks should be informed by fluvial geomorphic analysis. Land within the setback area should be designated as unsuitable for further development; where exemptions to the setback are applied for, potential geomorphic hazards should be further assessed, understood, and mitigated (if and where applicable). For further information on areas of erosion vulnerability, see Appendix C of the associated project report.
- The community is situated on a flat floodplain along the right bank of the Porcupine River, just downstream of the Old Crow River confluence. The channel geometry and physiographic

conditions near the community make it susceptible to flooding, even during moderate ice-jam related events.

- The community benefits from a detailed annual flood monitoring program during the breakup period. It is recommended that this program continue and be enhanced by incorporating technologically advanced instrumentation and monitoring techniques.
- Flood thresholds have been established for critical community infrastructure. These thresholds should be used for flood planning and preparedness efforts.
- At the time of writing this report, we are unaware of any long-term survey control monuments in Old Crow. Establishing a survey control monument with repeat annual surveys may help inform changes in the floodplain such as subsidence.
- The Bluefish River confluence with the Porcupine River will likely continue to be prone to the development of ice jams and aufeis formation due to its morphology and associated constriction of the Porcupine River; however, the specific environmental conditions leading to extensive aufeis formation at the Bluefish River delta are not well understood.
- Increases in the magnitude or duration of peak flows may promote increased erosion and scour along the channel bank along the western end of the airport runway, and further downstream where there is a constriction in the channel width. These two areas may be particularly prone to erosion and scour during high flow events and should continue to be monitored on an annual and event-specific basis to help establish erosion rates and trends in morphological change.
- Climate change may increase the potential for an avulsion to occur on the Porcupine River, upstream of the confluence with the Old Crow River and in a meander bend on the Old Crow River approximately 2 km upstream of the confluence between the Porcupine and Old Crow Rivers. Bank erosion monitoring at these locations is recommended on an annual and event-specific basis. If notable increase in bank erosion is detected over time, additional studies are recommended to further assess the potential impacts of an avulsion, including potential erosion mitigation and risk reduction measures.

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APPENDIX A

SURVEY AND DATA COLLECTION

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1 INTRODUCTION

The Government of Yukon, Department of Environment – Water Resources Branch (WRB), has retained Northwest Hydraulic Consultants Ltd. (NHC) to complete flood mapping of Porcupine River and Old Crow River near the community of Old Crow, Yukon. The objective of this project is to develop flood maps for the community of Old Crow.

NHC retained Underhill Geomatics Ltd. to undertake field data collection in the community of Old Crow. Field data collection was completed in June 2024. NHC also competed a site inspection that coincided with the timing of the Underhill survey.

The purpose of this document is to provide a summary of the field data collected for this study. The acquisition of topographic, bathymetric and hydrographic information forms the basis of inputs for the hydraulic modelling component.

2 ASSUMPTIONS AND LIMITATIONS

The following assumptions and limitations have been made as part of the study:

- Old Crow is defined as medium risk and the cabins at Tl'oo K'at and the Bluefish/Porcupine confluence are defined as low risk (NRCan and Public Safety Canada, 2022)
- The intent of the survey and data collected was for the purposes of flood mapping.
- The elevation data relies on the accuracy of the instrumentation. The Trimble TRK GPS has a horizontal accuracy of +/- 8mm and a vertical accuracy of +/- 15 mm. The bathymetric data instrumentation (single beam Echo Sounder) has an accuracy of 0.01 m +/- 0.1% of depth. Further instrumentation details are summarized in the Underhill Geomatics survey report which forms part of the deliverables for this project.

Additional survey data requested by the Government of Yukon, Department of Highways and Public Works, (road centre lines and ditch surveys) submitted on July 31, 2024 is subject to the following limitations:

- The data has not undergone any quality assurance or quality control by NHC. Underhill Geomatics summarizes field accuracies in their associated survey report.
- The intent of the survey and data collected was for the purposes of flood mapping.
- The data provided is not intended for design or construction.

3 DATUM AND COORDINATE SYSTEM

The work performed for the Project was done in CGVD2013 as required in the federal guidelines and as per the Project's Request for Proposals. As noted by Underhill, almost all other work in the Yukon has been done in CGVD28(HTv2.0). There is a vertical shift between the two and that shift depends on location, and it is not consistent across the community of Old Crow.

Coordinates (XY) are UTM Zone 7 North, NAD 83 (CSRS) derived from Real Time Kinematic GNSS observations holding UGL Control Point "1101" fixed in 3D. Elevations are Orthometric derived from CGVD2013 Datum using the CGG2013A Geoid Model. Coordinates and elevations of 1101 are derived at the time of survey from NRCan's Precise Point Position Service.

4 LIDAR

LiDAR flown in 2019 by McElhanney was provided by the Government of Yukon that covered the area immediately around Old Crow. The study area not covered by the McElhanney LiDAR was supplemented by using high resolution digital elevation model (HRDEM) data (Natural Resources Canada, 2019). The HRDEM data is derived from optical digital images using photogrammetry and is available as a 2 metre geoTIFF raster for the northern portions of Canada. Table 4.1 provides an overview of the LiDAR data and how the point density compares to the federal airborne LiDAR data acquisition guidelines (NRCan and Public Safety Canada, 2022). Old Crow is defined as medium risk according to the federal airborne LiDAR data acquisition guideline as such the LiDAR meets the point density specifications (NRCan and Public Safety Canada, 2022)[1]. The cabins at Tl'oo K'at and the Bluefish/Porcupine confluence were added on as an additional scope item part way through the study. Flood maps were not produced for the cabins. Instead, the hydraulic model was used to simulate various flood scenarios to inform planning. The HRDEM data was sufficient to support the assessment of flood scenarios for planning purposes.

Note, that the digital surface model generated for the HRDEM does not filter out vegetation. When comparing the HRDEM to LiDAR in areas of overlap, slight discrepancies in the elevation exist between these two data sets due to the low-lying vegetation in the HRDEM. A difference grid was generated based upon land classification polygons in the areas of overlapping LiDAR and HRDEM data and applied that to the remaining HRDEM data. This allowed for a height correction to account for the low-lying vegetation.

[1] High Flood Risk Category: All urban areas and rural areas that are protected by diking; Medium Flood Risk Category: All other rural areas that include settlements and agricultural lands; Low Flood Risk Category: Sparsely populated areas (NRCan and Public Safety Canada, 2022).

Table 4.1 Summary of LiDAR data and federal guideline specifications (NRCan and Public Safety Canada, 2022).

LiDAR Source	Point Density	Federal Guidelines (Medium Risk)	Federal Guidelines (Low Risk)	Format	Type
2019 McElhanney	7.9 pts/m^2	2-4 pts/m^2	2 pts/m^2	LAS	Digital terrain model (DTM, Bare Earth)

Federal Guideline Definitions:

High Flood Risk Category: All urban areas and rural areas that are protected by diking;
Medium Flood Risk Category: All other rural areas that include settlements and agricultural lands;
Low Flood Risk Category: Sparsely populated areas.

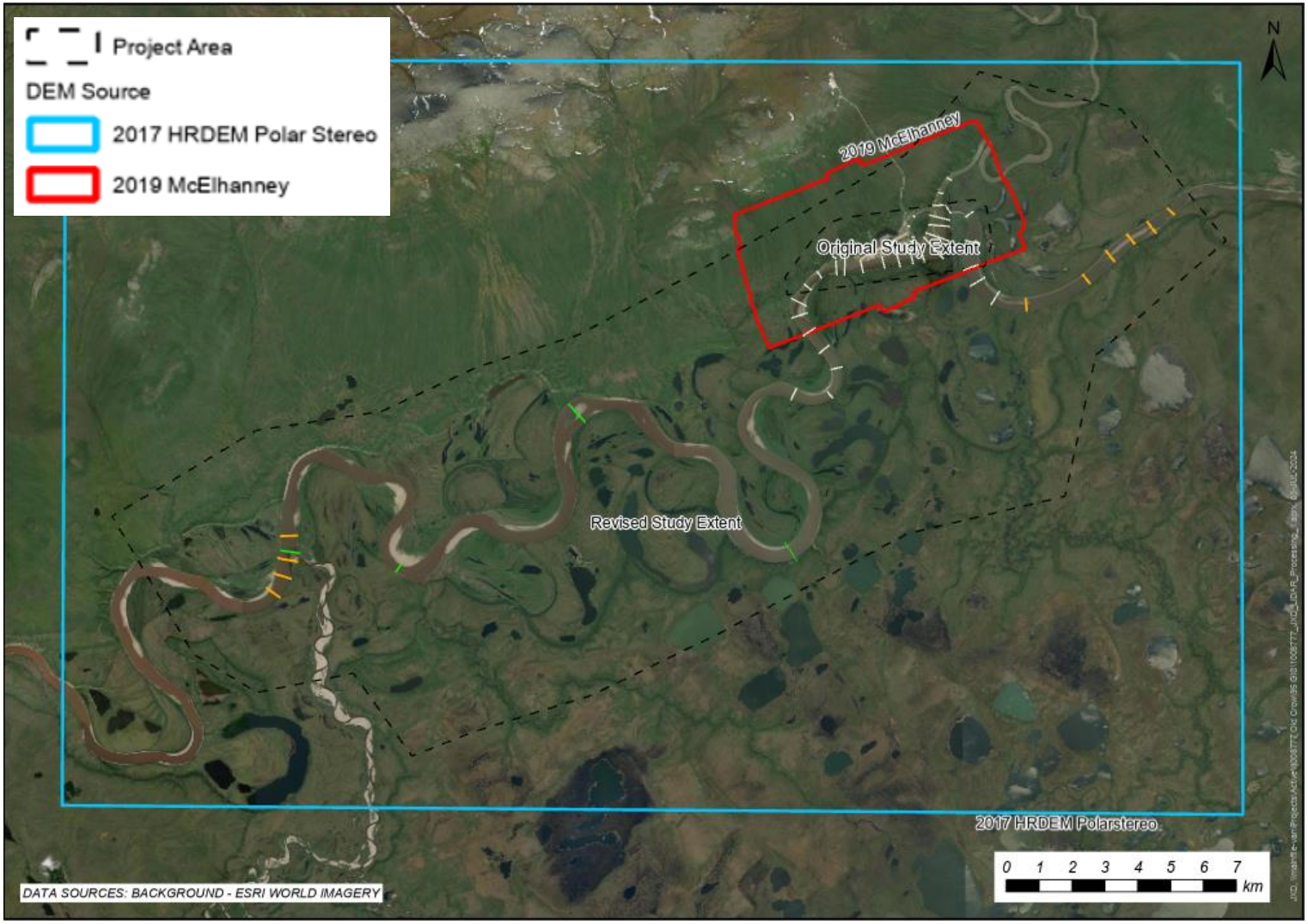


Figure 4.1 Overview of the McElhanney LiDAR coverage (red) and HRDEM coverage.

5 BATHYMETRY DATA

River bathymetry surveys were completed for the cross-section locations shown in Figure 5.1.

- Green= cross sections near Old Crow to support flood map creation.
- Orange = cross sections at two additional study sites where family cabins are situated, these include cabins at Tl'oo K'at just north of Old Crow and the cabins at the Porcupine/Bluefish confluence.
- Blue = key river locations of historic ice jams.

The bathymetric survey captured the receding limb of the Porcupine River freshet using a single beam echosounder where water depths were greater than 1 m. At water depths less then 1 m a RTK GNSS was used. Sound speed corrections were verified daily by measuring river temperature and completing a bar check.

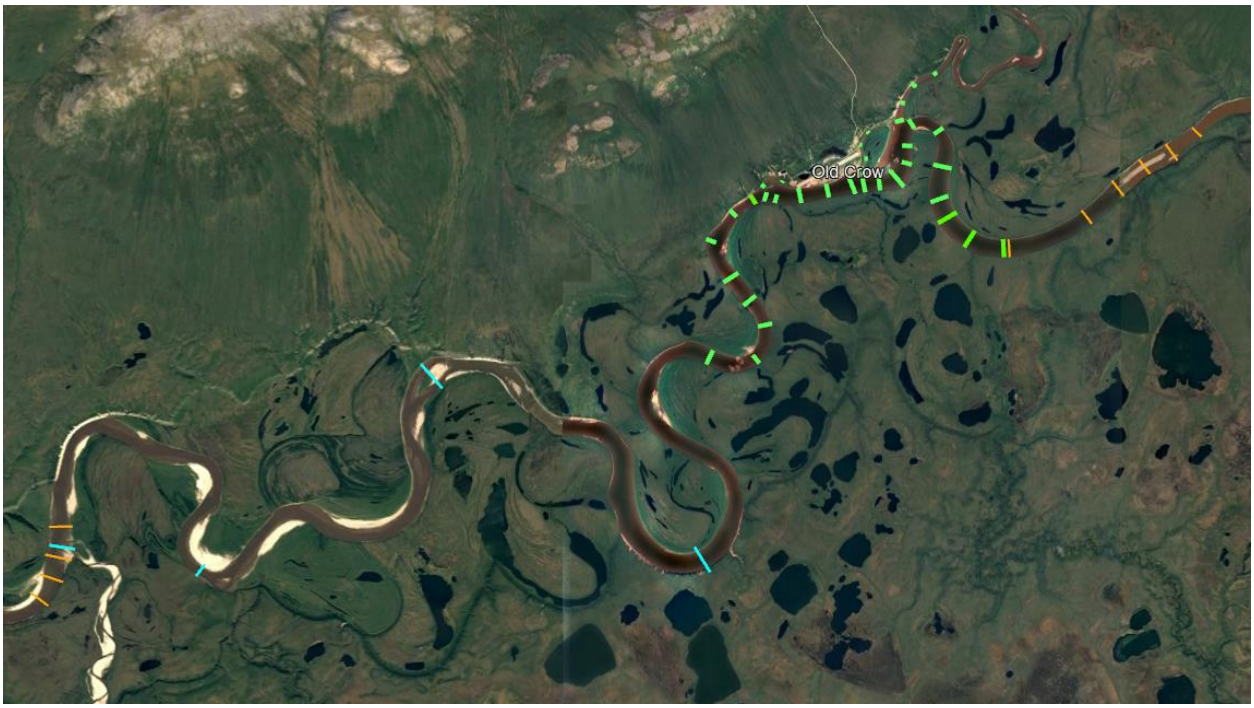


Figure 5.1 Overview of cross section locations.

6 TERRESTRIAL SURVEYS

A series of terrestrial surveys were completed to support development of the hydraulic model. Additional survey data was also requested by the Government of Yukon, Department of Highways and Public Works, (road centre lines and ditch surveys). The following is a summary of the terrestrial data collection:

- A control survey was completed for the project area using territorial monuments.
- High water marks were surveyed based upon photo documentation and local knowledge and used to support model calibration.
- All critical infrastructure that was originally surveyed by Turcotte and Saal (2022) was re-surveyed for this study. This included culvert locations documented in the report along with additional culvert locations identified during the site inspection.
- The centre lines of the majority of roads in Old Crow were surveyed along with the ditch around the new health centre.
- Topographic points taken from the roads and runway were used to form the basis of the LiDAR check survey.

7 GEOMORPHIC SURVEY

A geomorphic survey was completed as outlined below:

- Photo documentation of channel bank composition and overbank depressions.
- Photo documentation of channel bed composition.
- Longitudinal profile of the riverbed and water surface elevation from upstream-most point to the confluence of the Porcupine and Bluefish Rivers.

Locations of photo documentation and geomorphic observations are shown in Figure 7.1.

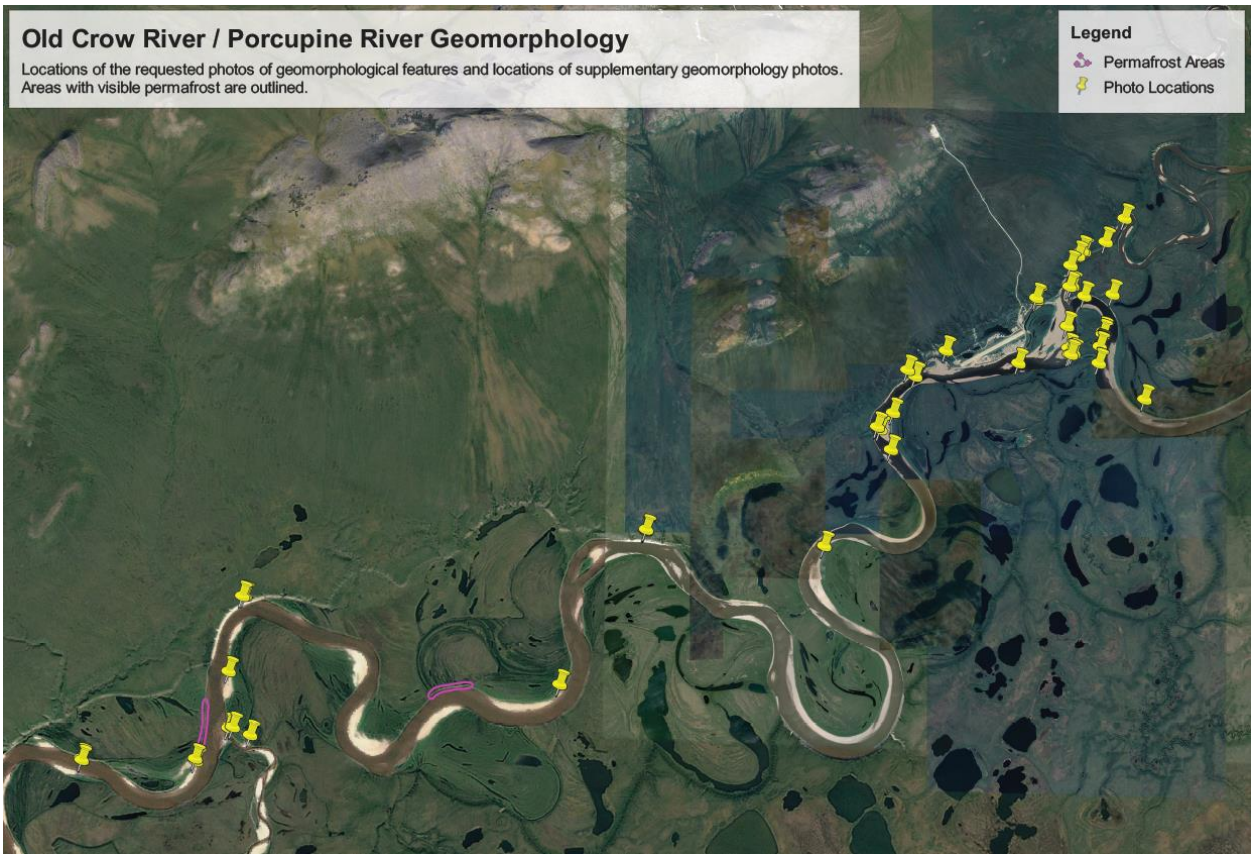


Figure 7.1 Locations of geomorphic data collection.

8 HYDROMETRIC DATA

Hydrometric data for this project was provided by Water Survey of Canada and the Government of Yukon. The Yukon government installed two water level stations in May 2024 for the purpose of capturing water levels during the 2024 freshet. The hydrometric stations listed in Figure 8.1 and Table 8.1 are the stations where benchmark surveys were required to shift the water level data into CGVD2013 datum to support model calibration.

Hydrometric benchmark surveys were completed for WSC 09FD003 Porcupine River below Old Crow River to shift the water level data into CGVD2013 datum. Benchmarks for 09FD001 Porcupine River at Old Crow were destroyed.

Benchmark surveys were also completed for the Yukon downstream hydrometric station. The upstream hydrometric station was found damaged, and data was not recoverable, so no benchmark survey occurred.

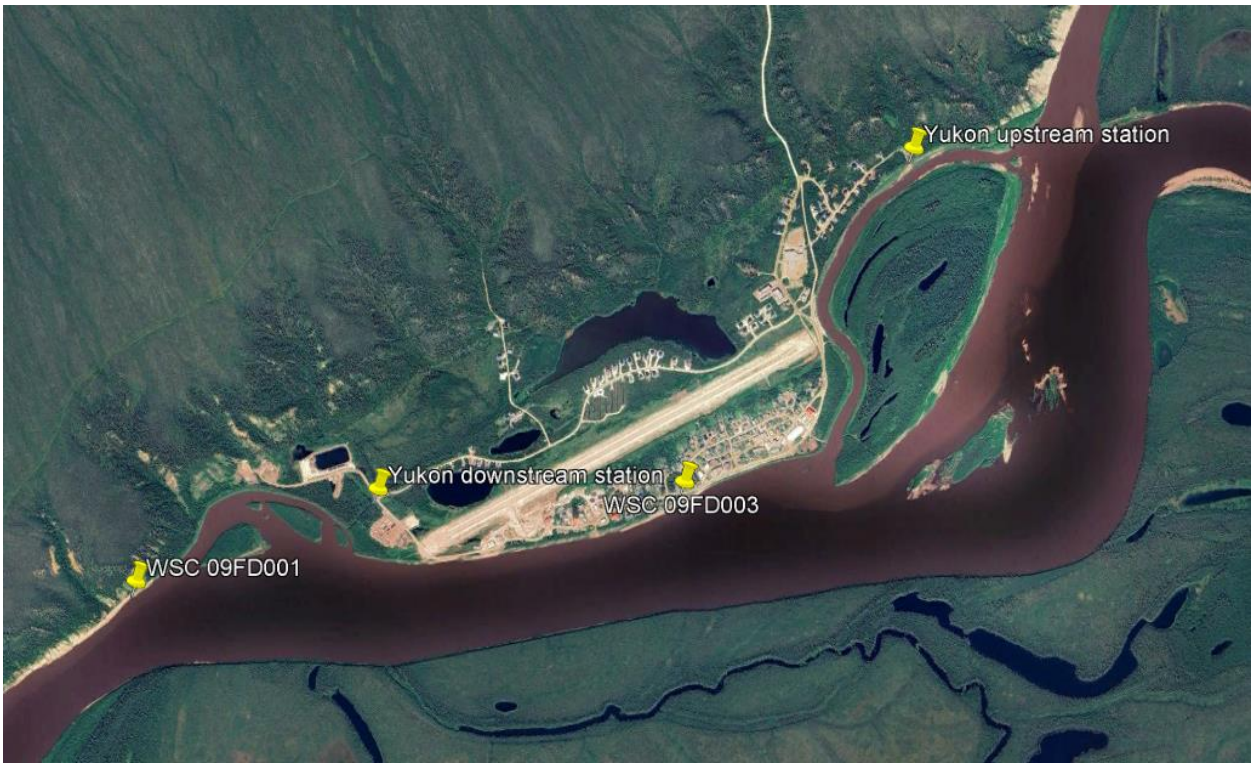


Figure 8.1 Location of hydrometric gauges that have water level data that requires datum shift.

Table 8.1 Summary of hydrometric gauges that have water level data that requires datum shift.

Gauge Name	Existing datum	Benchmark survey
WSC 09FD001, Porcupine River at Old Crow	Local	Attempted, benchmarks destroyed
WSC 09FD003, Porcupine River below Old Crow River	Local and CGVD2013	Completed
Government of Yukon, downstream gauge	Local	Completed
Government of Yukon, upstream gauge	local	Attempted but station damaged

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APPENDIX B

HYDROLOGY, RIVER ICE, CLIMATE CHANGE AND HYDRAULIC MODELLING

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1 INTRODUCTION

The Government of Yukon, Department of Environment – Water Resources Branch (WRB) (herein after will be referred as the "Client"), has retained Northwest Hydraulic Consultants Ltd. (NHC) to complete floodplain mapping of the Porcupine River and the Old Crow River near the community of Old Crow, Yukon. The objectives of this project are to assess, identify, and map flood hazards for the community of Old Crow with a main deliverable being the development of flood maps for the community.

The purpose of this document is to provide a summary of the hydrologic and river ice analysis that informed hydraulic modelling and generation of flood hazard mapping for the community of Old Crow. This document also provides an assessment of potential future changes to climate and land cover, with a primary aim to understand potential impacts to the timing and magnitude of ice jam and open water floods and how the changes may affect recommended design flows.

1.1 Objectives

The objectives of the hydrologic, river ice, and climate change assessment are:

- Identify calibration events and determine flood frequency estimates for open-water and ice jam flooding to inform hydraulic modelling for the Old Crow and Porcupine rivers.
- Document the ice jam history and explain the underlying mechanisms contributing to ice jam floods.
- Summarize how climate change processes might influence the timing and magnitude of open water and ice jam floods.
- Recommend design hydrological conditions for flood mapping for historic and future conditions.

1.2 Scope Overview

Based on the objectives, NHC has outlined the following project scope:

1. **Open Water Hydrologic Assessment**
    a. Deriving flood frequency analysis (FFA) input at points of inflow
    b. Selection of calibration events

2. **Ice Regime Assessment:**
    a. Breakup Chronology: Includes creating a breakup narrative, documenting the timing and types of breakup processes, identifying ice jam mechanisms, developing carrier discharge records, and selecting events for calibration and validation.
    b. Breakup Discharge Frequency Analysis: Involves the statistical analysis of the breakup carrier discharge records.
    c. Breakup Rating Curve Development: Enables the conversion of carrier discharges into flood levels for various plausible flooding mechanisms in the river.
    d. Generation of Synthetic Breakup Level Population: A Monte Carlo analysis to generate a synthetic dataset of breakup flood levels, utilizing the information obtained from the previous steps.
    e. Breakup Level Frequency Analysis: Development of the ice jam flood level frequency curve, which incorporates the probabilities of breakup discharges and breakup types, to determine the magnitude and likelihood of flooding at the project site.
3. **Future Conditions**
    a. Review of guidelines and standards.
    b. Complete a background review of relevant climate change studies.
    c. Identify the potential impacts of different hydrometeorological variables as well as physiographical conditions on the critical flood mechanisms.
    d. Assess how the dominant flood hydrology may change under a changing climate.
4. **Design Scenario Selection**
    a. Compare open water and ice FFA results to identify whether open water or ice jam floods result in the highest water levels.
5. **Hydraulic modelling and flood mapping**
    a. Design Flood Selection and Modelling: Involves selection of the design flood event based on the Annual Exceedance Probability (AEP) for the project site (three AEPs are considered for this project).
    b. Numerical Modelling: This task uses the design flood level identified earlier to select the hydraulic modelling parameters needed to generate the scenario or adjust the closest historical event to simulate the water surface profile along the study reach.
    c. Flood Map Production: Preparation of flood maps involved determining flood inundation extents corresponding to the design flood level profile and creating flood hazard maps based on water depth and velocity criteria, in accordance with federal flood mapping guidelines.

2 ASSUMPTIONS AND LIMITATIONS

Similar to other flood hazard assessment projects, several key assumptions and limitations must be acknowledged and carefully considered when interpreting the findings of this study. Understanding these assumptions and limitations is crucial for making informed decisions based on the study results. The following outlines some of the key assumptions and limitations of the hydrology, river ice and hydraulic modelling component of the Old Crow Flood Mapping Project.

Assumptions:

- **Hydrological Estimates and Hydraulic Modelling:** Assumes that hydraulic conditions remain unchanged, even though they may change in the future. Simplifications in modelling complex river systems are often necessary, potentially omitting smaller tributaries or local variations.
- **Elevation Data:** Relies on the accuracy and resolution of available topographic and bathymetric data, which may limit the precision of flood extent predictions.
- **Design Event Selection:** Assumes that selected design flood events, based on AEP, are appropriate for the site. These are typically derived from historical records, therefore, may not fully capture potential future variations, particularly under changing climate conditions.
- **Ice Formation and Breakup Processes:** Assumes that the observed historical patterns of ice formation and breakup are suitable to inform flood mapping.
- **Ice Jam Locations:** Assumes that ice jams will form in certain locations based on historical records. However, variations in winter conditions or river morphology may alter these locations.

Limitations:

- **Data Gaps:** The limited availability of historical hydrometric and ice jam data can introduce uncertainties in accurately estimating AEPs, as well as in modelling and scenario development. In this project, significant data gaps exist due to relocations of the Water Survey of Canada (WSC) hydrometric gauges, variation in type and continuity of the recordings as well as inconsistencies in datum between recordings. Past flood water levels were often reported relative to arbitrary datums, such as gauge elevation, top of bank, and inactive and obliterated benchmarks, making it challenging to convert historical observations to the project's current datum.
- **Hydrologic data and flood frequency analysis:** The flood frequency analysis provides estimates of design flows based on the available data. The record length, inaccuracies in the measured data, and distribution fit contribute to uncertainty in the value of peak flow at any given AEP.
- **Climate Change Impacts:** While potential climate change effects are considered, the extent and nature of these impacts remain uncertain, potentially affecting flood magnitude and

frequency. Any projections of climate change are subject to large uncertainty. The main sources of uncertainty relate to unknown future global emissions of greenhouse gases, uncertain response of the global climate system to increases in greenhouse gases, and incomplete understanding of the regional manifestation that will result from the changes in the global climate system.

- **Modelling Simplifications:** Ice jam processes are highly complex, involving dynamic interactions between ice, water, and riverbed morphology. Modelling these processes often requires significant simplifications, which may limit the ability to predict localized flooding accurately.
- **Model Uncertainty:** All models have inherent uncertainties due to the assumptions made and the limitations of the input data. These uncertainties must be considered when interpreting flood hazard maps and making risk management decisions.

3 STUDY AREA OVERVIEW

Old Crow, a small community with a population of around 236[1], is situated on the right bank of the Porcupine River, also known as Ch'ōdènjik , just downstream of its confluence with the Old Crow River, also known as Chahnjik. It lies in the northern part of the Yukon Territory, about 120 kilometres north of the Arctic Circle. The mean annual temperature in Old Crow is -8.3°C[2], and the mean annual precipitation is relatively low at about 272 mm.

The Porcupine River Watershed, covering approximately 118,000 km^2, is a pristine river system within the Yukon River Basin. At the Yukon-Alaska Border, the basin encompasses around 60,000 km^2, bounded to the north by the British Mountains, to the west by the Richardson Mountains, and to the south by the Ogilvie Range. The basin's lower elevations are dominated by coniferous forests, while higher elevations feature Taiga and Alpine Tundra, with the treeline occurring between 450 and 600 metres above sea level. The Porcupine River, the primary drainage arm of the basin, is fed by major tributaries such as the Old Crow, Bell-Eagle, Miner, and Whitestone Rivers (Figure 3.1). The basin lies within a region of continuous permafrost in the north and discontinuous permafrost in the south.

The basin's hydrology is heavily influenced by its physiographic setting. The hydrological regime of Porcupine and Old Crow rivers is nival. Breakup on the Porcupine River typically occurs in May, triggered by rapid snowmelt. By July, freshet flows typically subside. In fall, flow decreases as air temperature decreases, and river-ice begins to form. Usually, by December, rivers are characterized by low flows and ice cover is often formed.

The Porcupine River channel at Old Crow is approximately 600 metres wide and occupies a broad alluvial valley ranging from 6 to 10 km in width. The mean annual discharge of the Porcupine River at this location is around 320 m^3/s, with peak flows reaching approximately 4,200 m^3/s in May or early June and low flows around 15 m^3/s in April (Jasek, 1997).

The original Area of Interest (AOI) for this project, as defined in the Contract Service Agreement, encompassed approximately 11.6 km^2, including ~5 km of the Porcupine River and ~1 km of the Old Crow River. However, following discussions with the client, the AOI was expanded to include points of interest to the community, both upstream and downstream of the main study area. This adjustment was made to incorporate the newly identified sites and to fulfill the updated requirements for hydraulic simulations under the revised study conditions. To accurately assess the ice jam impacts on flooding at the community as well as including the additional sites of interest, the main study reaches were extended, encompassing 60 km of the Porcupine River, 1.5

[1] Statistics Canada (2021 Census)

[2] ECCC (2013)

Km of the Old Crow River and the Bluefish River confluence. The project domain and the extent of the study reaches are shown in Figure 3.2

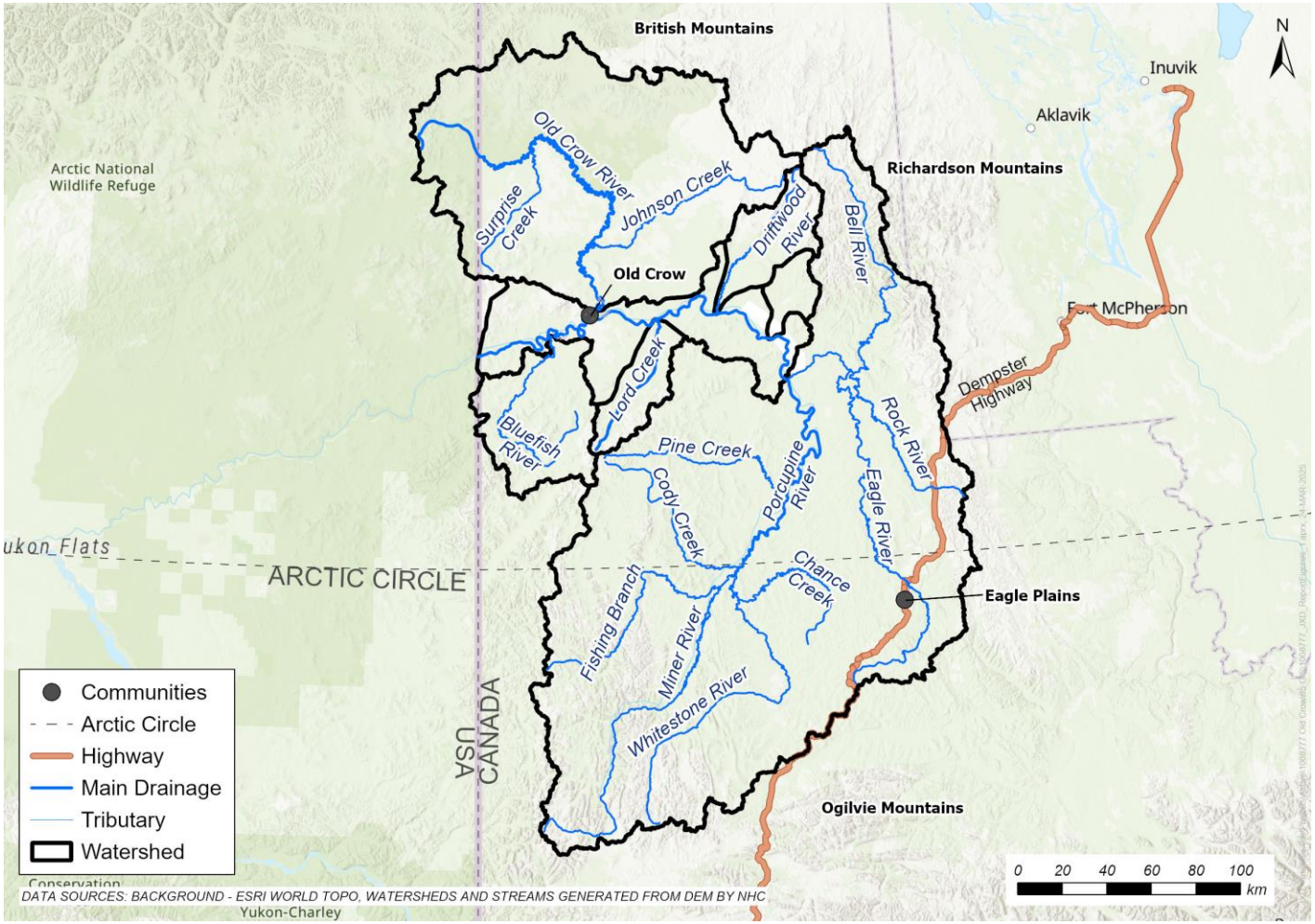


Figure 3.1 Porcupine River watershed and subbasins.

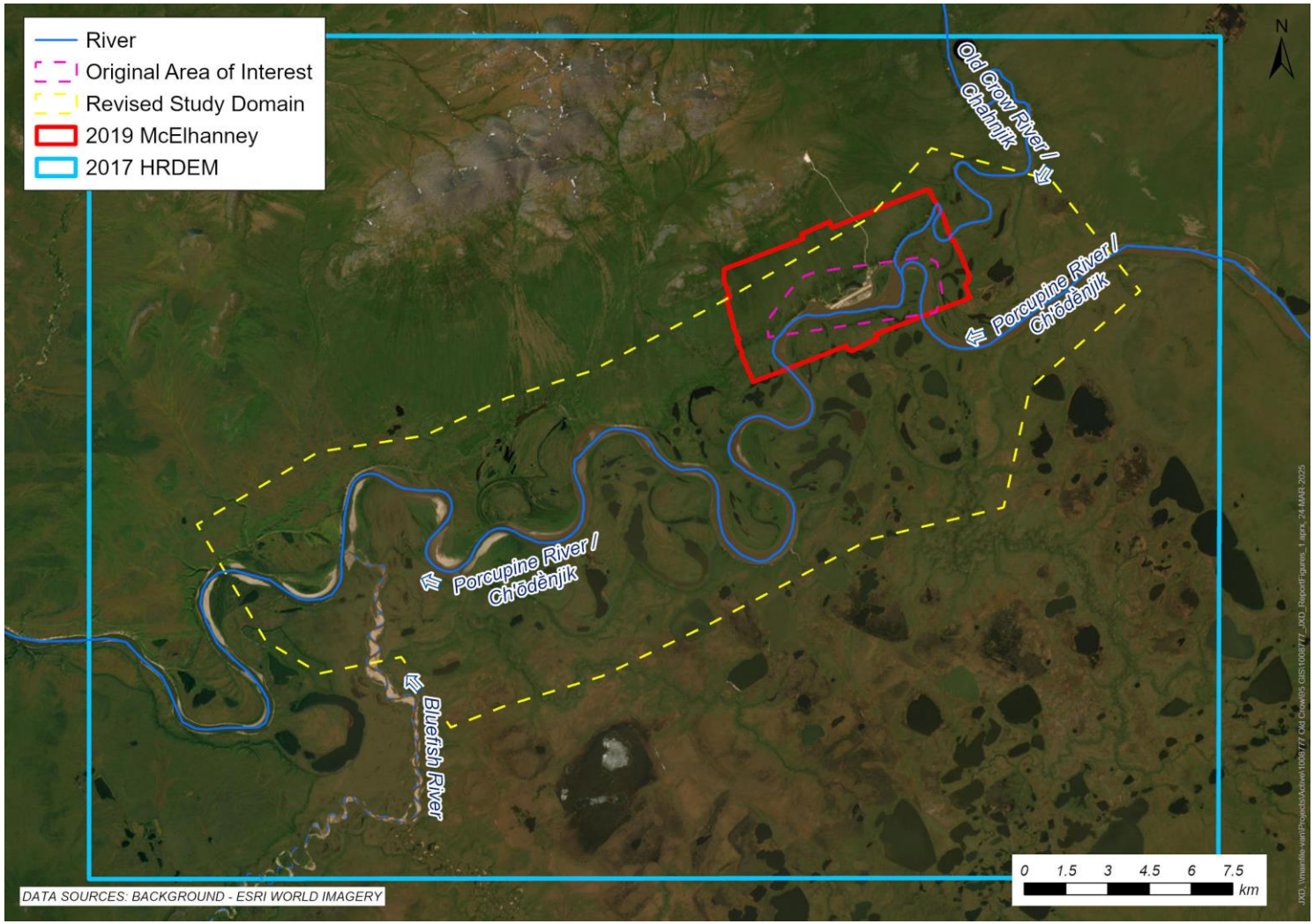


Figure 3.2 Study domain and LiDAR-based DEM and HRDEM data extent.

4 DATA COLLECTION

A variety of data spanning several decades is available for the Porcupine River and the Old Crow community area. The following subsections categorize this information by type and provide a summary of its relevance to the flood mapping project for Old Crow.

4.1 Archives, Analytical Reports and Scholarly Publications

To build a comprehensive understanding of the history of ice jam floods, data was collected and analyzed from several different sources. In particular, previous modelling efforts have provided important context for this project. The available documentation includes both qualitative and quantitative data. The qualitative data consists of observations made during breakup events and insights gained through firsthand experience at the site. The quantitative data includes high-water marks, discharge and water level estimates. Interpretations of archived data have extended the high-water mark dataset back to the early 1930s.

The data between these sources were cross-referenced to fill in missing gaps and to confirm the accuracy of the measurements.

The following list includes documents that provided essential background data for this study. Salient information from these sources will be referenced throughout the report.

Field Notes

- Field notes regarding 1991 ice jam flooding, Gregory (1991)

Memoranda

- Water level analysis for Yukon communities, Morrison Hershfield (2021)
- Conversation & Old Crow Tour with Elder, H Goulding (2024)
- Water Profile Level-logger Deployment, A Bier (2024)
- Estimation of Historical Peak Water Levels at Old Crow, BTurcotte (2024)

Breakup Monitoring and Summary Reports

- Old Crow Breakup Summary-1993, Water Resources Branch (1993)
- Old Crow Breakup Summary-2001, Water Resources Branch (2001)
- Old Crow Breakup Summary-2003 to 2007, Janowicz (2003-2007)
- Old Crow Breakup Summary-2009 to 2015, Janowicz (2009-2015)
- Old Crow Breakup Summary-2017 to 2018, Janowicz (2017b, 2018)

- Old Crow Breakup Summary-2023, Bercier and Bier (2023)
- 2024 Porcupine River Breakup Chronology, Water Resources Branch, (2024)

Technical Reports and Scholarly Articles

- Bank Erosion Protection on Porcupine River at Old Crow, Hollingshead (1973)
- Yukon Flood Study, Fenco Consultants (1974)
- Old Crow Erosion Study_1986, UMA Engineering Ltd. (1986)
- Historical Analysis of Ice Jamming at Old Crow, Yukon Territory, Janowicz, (1992)
- Ice Jam Flood Assessment Old Crow 1993, Jasek (1993)
- Ice Jam Flood Mechanism on the Porcupine River at Old Crow- Yukon Territory, Jasek (1997)
- River Ice Break-up and Flood Monitoring of the Porcupine River at Old Crow, Yukon Territory, INAC (1997)
- Porcupine River break-up Monitoring Program Using Enhanced Radarsat Satellite Imagery, Janowicz (2006b)
- Contemporary (1951–2001) Evolution of Lakes in the Old Crow Basin, Northern Yukon Canada, Labrecque et al. (2009)
- Old Crow landscape hazards - Geoscience mapping for climate. Yukon College, Benkert et al. (2016)
- Impacts of Climate Warming on River Ice Break-up and Snowmelt Freshet Processes on the Porcupine River in Northern Yukon, Janowicz (2017a)
- Flooding Processes and Recent Trends in Ice-Induced High Water Levels Along Rivers of Northwestern Canada, Turcotte (2021)
- Flooding in Old Crow - Exposure Analysis and Risk Reduction Recommendations. Yukon University for Yukon Govt, Turcotte and Saal (2022)
- Water level return period relationships 2022 update, Morrison Hershfield (2022)
- JGR Earth Surface - 2023 - Rowland - Scale-Dependent Influence of Permafrost on Riverbank Erosion Rates, Rowland et al., (2023)
- Yukon Regional Flow Frequency Analysis, NHC (2023b)
- Fluvial Morphology in Different Permafrost Environments - A Review, Vandenberghe (2024)
- Mitigation Recommendations-Mapping 2024, Stantec (2024)
- Improvement of river ice breakup forecasting tools in the Yukon - Porcupine River at Old Crow- Turcotte et al. (2024b)- Draft Report

Communications with local knowledge holders

- Conversations with community members, local knowledge holders, Danny Kassi, Peter Frost, Roger Kyikavichic, and C. O'Neill-Kizoff (2024) regarding the past flood events at the community and other sites of interest. We are grateful for Indigenous Knowledge contributed by community members to inform this study.

4.2 Hydrometeorological Data

4.2.1 Hydrometric Data

Hydrometric data facilitated the assessment of open water hydrology, interpretation of the ice breakup sequence, and analysis of flood chronology, in conjunction with the breakup monitoring reports.

Table 4.1 summarizes the Water Survey of Canada (WSC) gauges used in this analysis and Table 4.2 summarizes the WSC gauge physiographic characteristics. Figure 4.1 presents gauge locations.

The Porcupine River at Old Crow was first gauged by the Water Survey of Canada in 1961 (09FD001). However, over a decade later, the gauge was relocated 2.5 km downstream due to bank stability issues. This downstream gauge remained operational until 1995, after which it was discontinued. In 2006, a new gauge was established in the community (09FD003), recording water levels seasonally. As a result, there are major gaps in the recorded data for this period.

WSC data records were assessed for completeness and years with peak instantaneous flow (QPI) and peak daily flow (QPD) were noted. When appropriate, the QPI record was extended to the same length as the QPD record by calculating a peaking factor using a rank-rank linear regression. Records with missing data were infilled and/or extended if a strong correlation with a physiographically similar WSC gauge was apparent.

Table 4.1 Summary of WSC gauges used in the project.

WSC Gauge No.	WSC Gauge Name	Variable Measured	Period of Record	Missing QPI values, open water conditions	QPI record length after gap filling	Application
09FB001	Porcupine River below Bell River	Flow	1963-1965; 1968-1995	19	22	Derive open water boundary conditions
09FC001	Old Crow near the mouth	Flow, level	1976-2024	12	45 (34 if low outliers are removed)	Derive open water boundary conditions

WSC Gauge No.	WSC Gauge Name	Variable Measured	Period of Record	Missing QPI values, open water conditions	QPI record length after gap filling	Application
09FD001	Porcupine River at Old Crow	Flow	1961-1995	23	33	Derive open water boundary conditions
09FD002	Porcupine River near International Boundary	Flow	1986-2024	12	36	Extend flow time series for 09FD001 or 09FB001
09FD003	Porcupine River below Old Crow River	Level	2006-2024, seasonal	4	17	Used for breakup rating curve- Sections 6.4.1.2 and 6.4.2

Table 4.2 Overview of WSC gauge physiographic characteristics.

Watershed Property	09FB001 Porcupine River below Bell River	09FD002 Porcupine River near International Boundary	09FD001 Porcupine River at Old Crow & 09FD003 Porcupine River below Old Crow River	09FC001 Old Crow River near the Mouth
Drainage Area	34,174 km^2	58,927 km^2	54,845 km^2	13,865 km^2
Maximum Elevation	1,823 m	1,823 m	1,823 m	1,497 m
Average Elevation	619 m	559 m	555 m	414 m
Gauge Elevation	250 m	246 m	236 m	251 m
Mean Annual Precipitation	410 mm	364 mm	360 mm	272 mm
Lake % Area	1%	3%	3%	9%
Glacier % Area	0%	0%	0%	0%
Dominant Ecoprovince	Taiga Cordillera: 11.3	Taiga Cordillera: 11.2/11.3	Taiga Cordillera: 11.2/11.3	Taiga Cordillera: 11.2

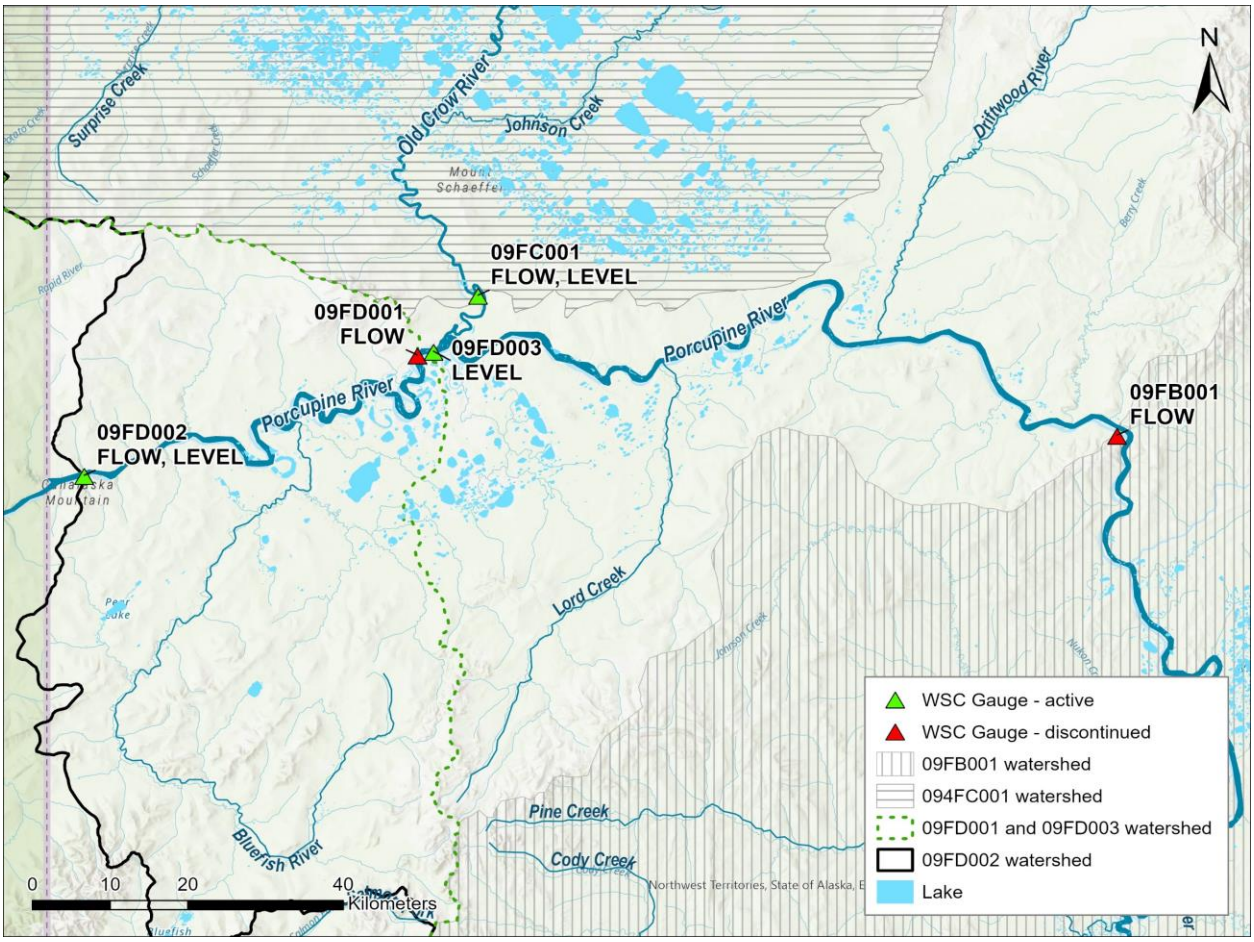


Figure 4.1 Overview of relevant WSC hydrometric gauges.

4.2.2 Datum Shift

Historical survey data for the Old Crow community was primarily collected using a local datum, including the benchmarks utilized for adjusting the WSC gauge. With the adoption of new geodetic systems for this project- horizontal datum NAD83 (CSRS) Yukon Albers and the vertical datum CGVD2013- datum conversions were required to standardize the water level data. Additionally, historical flood levels, whether measured or estimated during breakup events and documented in ice jam monitoring reports, were typically referenced to local topographic features (e.g., channel banks), introducing further uncertainty in the data interpretation.

The WSC gauge at Old Crow experienced several physical relocations and periods of inactivity. Prior to 1971, the gauge was positioned within the Old Crow community, approximately 200 metres upstream of its current location. In 1971, the gauge was moved approximately 2.5 km downstream from its original location within the community, due to concerns regarding channel bank stability. This relocation added a layer of complexity, as the recorded water levels downstream needed to be adjusted to reflect conditions near the community for accurate flood

risk assessments. In 1993, Jasek addressed this issue by developing a rating curve to translate downstream gauge readings back to the original location using a numerical model. The downstream gauge was decommissioned in 1995 then reinstated in 2006 near its initial site in the community, with recordings limited to seasonal water levels. Consequently, the Water Surface Elevation (WSE) data for Old Crow can be categorized into three distinct periods: pre-1971 (1961-1971), downstream recordings (1971-1995), and post-2006 to present, each corresponding to different local datums.

In 1993, Jasek established a benchmark (GSC 848163) at the windsock of the Old Crow airport, using it as a reference point for his survey data and High-Water Mark (HWM) measurements. This benchmark was, however, destroyed during airport renovations in 2006. Given that Jasek's analysis included the critical 1991 flood of record—the most significant ice jam event at the project site—his dataset was selected as the primary reference for translating historical water level data. Consequently, NHC first aligned pre-1971 recordings with the GSC 848163 benchmark before converting them to the project datum (CGVD2013). Due to the inherent variability in historical datum shifts, a comprehensive and robust conversion methodology was developed for each distinct recording period to enhance the accuracy of the data translation.

For the pre-1971 data conversion, common flood events documented by various sources (e.g., Janowicz's breakup monitoring reports) were identified and cross-verified. Janowicz's reports, extending across nearly six decades, were found to be the most comprehensive and consistent. However, discrepancies were observed between different sources such as Janowicz, UMA Engineering (for the years 1964, 1971, and 1973), Hollingshead (1964), and Jasek (1992), with differences sometimes spanning several metres. These inconsistencies were critically analyzed, and reliable events were selected for conversion to align with the GSC 848163 datum.

Subsequently, a datum conversion constant was established by determining the elevation of the historical windsock benchmark in CGVD2013. NHC, through historical documentation and archival reviews from Underhill Geomatics, estimated the benchmark's original location. Underhill's surveys in 2014 and 2020, alongside LiDAR data from 2019, confirmed the estimated elevation. The consistency between these recent measurements validated the identified elevation, which was then adopted as the windsock benchmark elevation in CGVD2013 for the conversion of historical data. The final datum conversion constants used to translate water level recordings from local datums to the project datum (CGVD2013) for various time periods are listed in Table 4.3.

Table 4.3 Datum conversions for various time periods.

Datum Information	Pre-1971	1971-1995	Post 2006
Estimated Difference Between the Local Datum and CGVD 2013	1.901	1.862	1.959
Suggested Constant to Convert to CGVD 2013 Datum	228.511 m	228.55 m	228.453 m

Finally, NHC and Underhill conducted surveys to locate the historical WSC benchmarks at both gauge locations. Ttwo active benchmarks at the current gauge site (BM2 and BM5) were successfully surveyed. The elevations obtained were closely matched with the historical records from the WSC benchmark history, providing additional validation for the conversion methodology used to standardize historical water level data to the current project datum. Although inactive benchmarks could not be identified, the historical gauge records from 1971 to 1995—associated with a site approximately 2 km downstream of the community mainly based on the missing benchmarks—had been referenced to the community location in Jasek's 1993 study. These adjusted records have been incorporated into the current analysis.

4.2.3 River Ice Data

River ice datasets for the Porcupine River at Old Crow primarily include water levels recorded at the new Porcupine River below Old Crow River WSC gauge (09FD003), breakup monitoring reports, technical memoranda, published papers, and publicly available data from the Canadian River Ice Database (CRID). Table 4.4 below presents the main source of ice datasets for different flood years reviewed in this project.

Data from 1993 to 2006 were sparse and characterized by high uncertainties due to the unknown measurement methodologies, calculation procedures, and reference datums used during this period. River ice classification maps, prepared by C-CORE[3] from Radarsat-2 and RCM satellite imagery in 2006- 2007, and 2010 to 2022 and prepared by DGI from RCM satellite imagery in 2023 and 2024 provided critical insights into the macro-scale sequence of events during breakup.

Table 4.4 Sources for ice datasets for the Porcupine River.

Year(s)	Source(s)
1932	Old Crow resident as described in Janowicz (1992)
1962 to 1963	Janowicz (1992)
1964	Janowicz (1992), UMA Engineering (1986), and Hollingshead (1973)
1965 to 1970	Janowicz (1992)
1971	Janowicz (1992) and UMA Engineering (1986)
1972	Janowicz (1992)
1973	Jasek (1993), Janowicz (1992), UMA Engineering (1986)
1975 to 1982	Janowicz (1992)
1983	Jasek (1993) and Janowicz (1992)
1984 to 1990	Janowicz (1992)

[3] https://c-core.ca/

Year(s)	Source(s)
1991 to 1992	Jasek (1993) and Janowicz (1992)
1993	Water Resources Branch (1993)
2001	Water Resources Branch (2001)
2003-2007	Janowicz (2003-2007)
2009-2015	Janowicz (2009-2015)
2017-2018	Janowicz (2017-2018)
2021-2022	Turcotte (2021), Turcotte and Saal (2022), Goulding (2022)
2023-2024	Bercier & Bier (2023), Water Resources Branch (2024), Turcotte (2024)

4.3 Geospatial Data

4.3.1 Base Data

CanVec datasets were utilized as base map data in this study. These datasets were partially provided by the Owner, with additional data gaps filled by NHC's inventory.

CanVec is a digital cartographic reference product developed by Natural Resources Canada (NRCan), derived from the highest quality, available geospatial data sources covering Canadian territory. It offers topographic information in vector format that adheres to international geomatics standards. CanVec includes over 60 topographic features organized into eight different themes. For this study, the accessed layers included Water Bodies, Watercourses, Municipal Boundaries, Land Authority, and Transportation Lines.

4.3.2 Digital Terrain / Digital Elevation Models

LiDAR data collected by McElhanney Ltd. on Sept. 10, 2019 (Figure 3.2). The 2019 LiDAR coverage provided by McElhanney is insufficient to cover the extended boundary, as such NHC supplemented the LiDAR coverage using High Resolution Digital Elevation Model (HRDEM) data (Natural Resources Canada, 2019). The HRDEM data is derived from optical digital images using photogrammetry and is available as a 2 metre geoTIFF raster for the northern portions of Canada.

Table 4.5 provides an overview of the LiDAR data and how the point density compares to the federal airborne LiDAR data acquisition guidelines (NRCan and Public Safety Canada, 2022).

NHC merged these datasets to create a seamless DEM covering both upstream areas of the Old Crow community, including the Old Crow and Porcupine Rivers, and downstream areas extending to the Bluefish River confluence. Figure 3.2 illustrates the extent of the original LiDAR dataset and the expanded domain covered by the HRDEM data. These data were utilized for hydraulic modelling and mapping purposes along the Porcupine River. Combined with field data

collected by NHC and Underhill Geomatics in the summer of 2024, this information formed the foundation of the hydraulic model used to generate flood maps for the Old Crow community.

The DEM created from the 2019 LiDAR data was used for mapping purposes while the combined DSM, consisting of the combined LiDAR and HRDEM data sets was used to simulate various flood scenarios to inform planning.

Table 4.5 Summary of LiDAR data and federal guideline specifications (NRCan and Public Safety Canada, 2022).

LiDAR Source	Point Density	Federal Guidelines (Medium Risk)	Federal Guidelines (Low Risk)	Format	Type
2019 McElhanney	7.9 pts/m^2	2-4 pts/m^2	2 pts/m^2	LAS	Digital terrain model (DTM, Bare Earth)

Federal Guideline Definitions:

High Flood Risk Category: All urban areas and rural areas that are protected by diking;
Medium Flood Risk Category: All other rural areas that include settlements and agricultural lands;
Low Flood Risk Category: Sparsely populated areas.

4.3.3 Land Use Land Cover Data

Esri Sentinel-2 10-metre Land Use/Land Cover Data was employed for this project to delineate various land cover types across the study domain. The land cover classifications provided by Esri were utilized to assign hydraulic resistance coefficients for the hydraulic modelling purposes. Where necessary, generalizations were applied to the extent and classification of the land cover data. Additionally, Esri's database includes temporal variations in land cover over a 6-year period, enabling the tracking of short-term land cover changes at the project site. Figure 4.2 presents the land cover dataset processed for the study domain. Further information on the use of this data is summarized in Section 6.1.2.2.

4.3.4 Orthoimagery

Orthorectified aerial imagery (15 cm resolution) of the Old Crow Community was supplied by the Government of Yukon. This dataset was utilized for the visual identification of project features within the community's vicinity and for the development of flood map layouts.

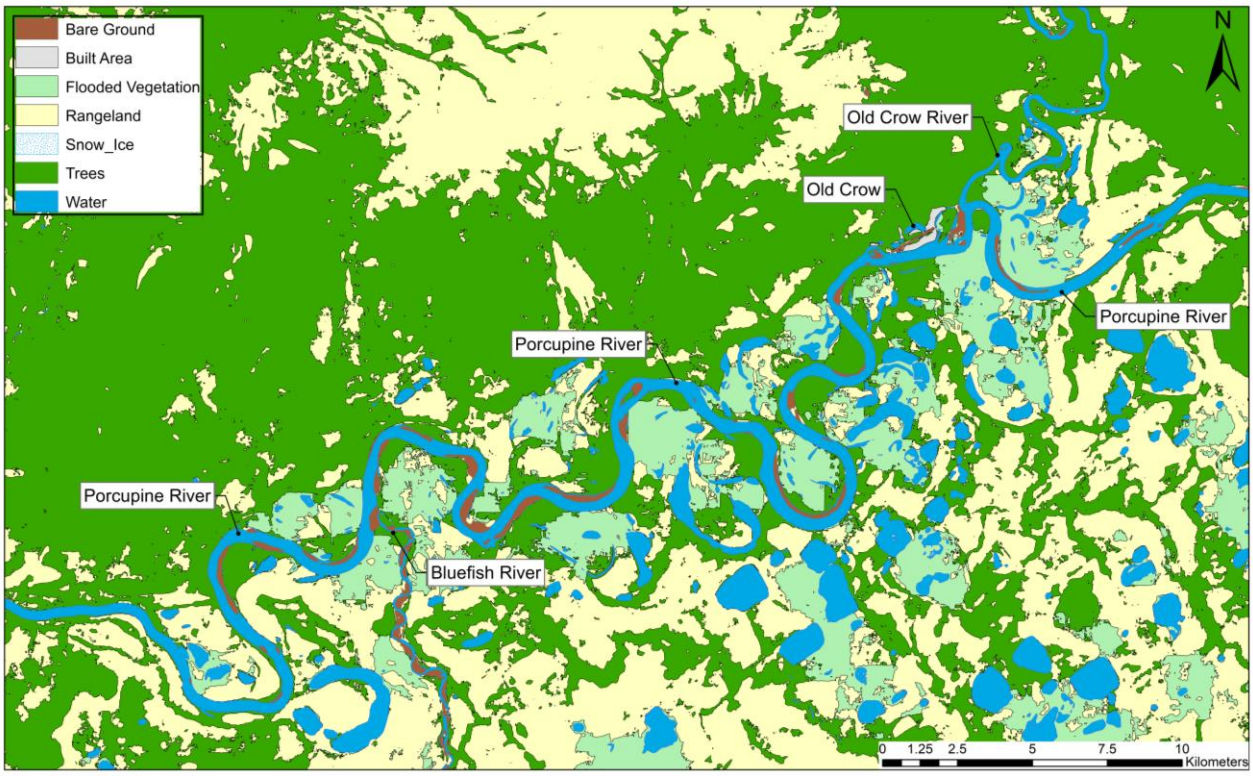


Figure 4.2 Land Cover classes for the study domain.

4.4 Field Investigations and Survey Data

4.4.1 Stream Geometry

Surveyed cross-section locations were strategically selected to ensure accurate representation of channel geometry within the hydraulic model and to facilitate historical comparisons by aligning with previously (1992) surveyed cross sections (Jasek, 1993). The cross-section data were acquired through a combination of ground-based topographic surveys and boat-based bathymetric surveys. The bathymetric data were collected using a single beam, 200 kHz CEE Hydro Systems CEE-LINE Echo Sounder, providing water depth measurements with an accuracy of 0.01 m ± 0.1% of depth (at 200 kHz), in conjunction with a Trimble R10 model 2 RTK GPS system, which recorded three-dimensional positional data with an accuracy of ±0.02 m.

The spatial extent of the surveyed cross-section data is illustrated in Figure 4.3. The average spacing between surveyed cross sections within the primary study domain was approximately 500 m, with intervals ranging from about 300 m to 1,100 m depending on the specific location and reach characteristics. Additional cross sections were surveyed at historical ice jam toe locations situated downstream of the main study reach along the Porcupine River.

Each surveyed cross section integrates boat-based bathymetric data from the wetted channel and ground-based topographic data collected at key locations: the water's edge, the bottom and top of banks, and a portion of the overbank areas. The overbank surveys extended a sufficient distance to ensure overlap with LiDAR elevation data. Ground survey data points were collected at major slope changes to accurately capture topographic variations.

The surveyed cross-section data are utilized to delineate the channel and bank portions of the model cross-sections, while the overbank areas are using the created DEM data. The methodology for integrating the DEM with the channel data in the cross-sections is elaborated in the Hydraulic Model setup and Calibration section of this document (Section 6.3.1).

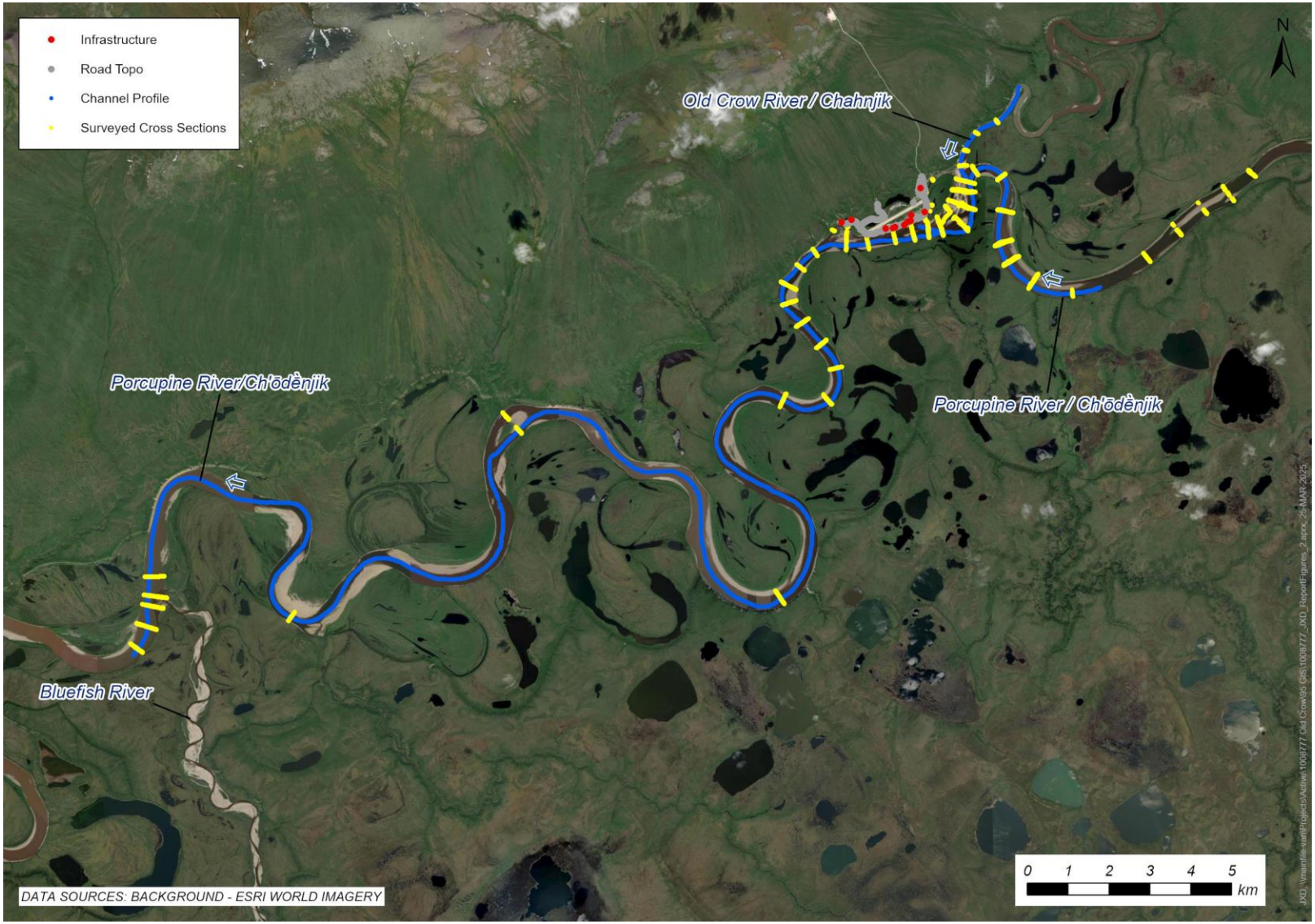


Figure 4.3 Channel profile and cross sections survey extent.

4.4.2 Horizontal Datum and Stationing Systems

Throughout this study, two horizontal datums are used to reference features, data, and study findings.

The first datum, referred to as the "River Monitoring Stationing," represents the chainage identification system used for monitoring and forecasting purposes. This datum begins at the Miner River confluence (Km 0) and extends to the Canada/U.S. border (Km 400). Past monitoring data is primarily referenced using this datum, as breakup monitoring campaigns have historically covered the entire Porcupine River.

The second datum, referred to as the "Hydraulic Modelling Stationing," corresponds to river stationing within the hydraulic analysis domain. This datum starts 1,350 m downstream of the Bluefish Confluence, marking the downstream boundary of the hydraulic model, and extends approximately 10 km upstream of the Porcupine/Old Crow Rivers confluence. This horizontal referencing system is primarily used to present hydraulic analysis and modelling results in this study. Figure 4.4 below illustrates both datums in relation to each other and the study domain defined for this project.

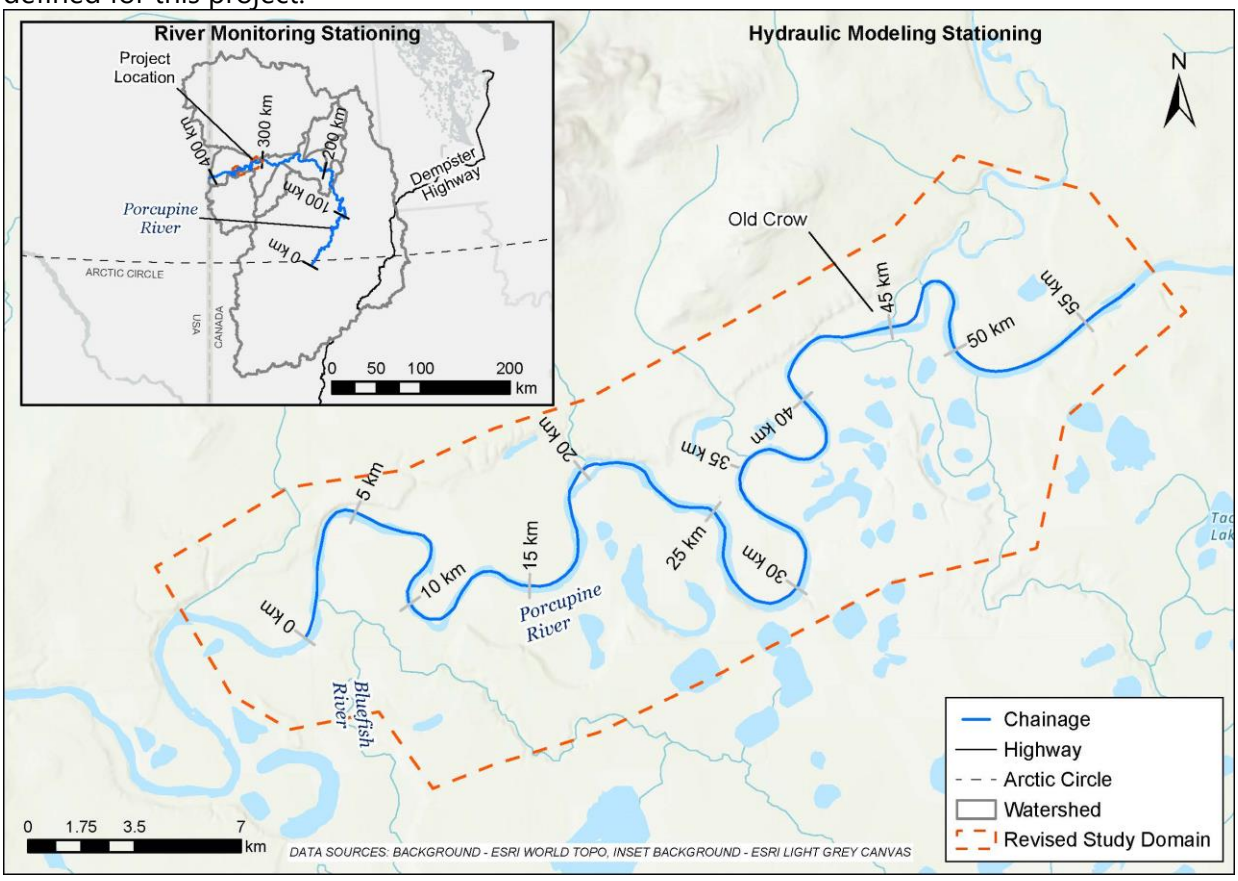


Figure 4.4 Horizontal datums and stationing systems.

4.4.3 Highwater Marks and Ice Scars

As previously detailed, earlier studies documented HWM data collected in proximity to the community. These observations were systematically made at specific locations, including: (1) the right bank of the river within the community boundaries, near the Old Mission, where both the former (09FD001: pre-1972) and current (09FD003: 2006- Present) WSC gauges are situated; and (2) approximately 2.5 km downstream of the community, at the site of the former Porcupine River at Old Crow WSC gauge (09FD001: 1973-1995). However, no ice jam profile, shear wall thickness, or top-of-ice elevation surveys are available for the reach. Limited ice survey data, specifically aufeis, is available at the Bluefish River confluence from a short-term monitoring program conducted in 1991 and from 1994 to 1997. Since 2016, aufeis elevation estimations have been referenced to the right bank of the channel at the Bluefish confluence. As part of this project, NHC/Underhill conducted HWM surveys for flooding events in 2011, 2015, 2023, and 2024. These data and ice scars have been critical for quantifying and ranking flooding events and informing the hydraulic modelling process.

Highwater marks and ice scars have been documented through multiple survey campaigns over the years (Table 4.6 and Table 4.7). The most extensive dataset related to ice jam-induced flooding comes from highwater and ice scar marks collected by Jasek in July 1992. This survey assignment, conducted for Indian and Northern Affairs Canada (INAC), specifically focused on the 1991 flood of record.

Table 4.6 Recorded ice scar elevations[1].

Measurement Information			Recorded Ice Scar Elevation
Year	**Relative Location**	**Station[2]**	**Elevation[3] (m)**
1973	2.44 km d/s of WSC gauge 09FD001	Km 322.44	246.66
1983	2.46 km d/s of WSC gauge 09FD001	Km 322.46	246.75
1991	At WSC gauge 09FD001	Km 320	246.194
	70 m d/s of WSC gauge 09FD001	Km 320.07	246.609
	1.82 km d/s of WSC gauge 09FD001	Km 321.82	247.306
	3.0 km d/s of WSC gauge 09FD001	Km 323	246.795
	3.05 km d/s of WSC gauge 09FD001	Km 323.05	246.422

Notes:
1. Adapted from Jasek (1993)
2. Monitoring/ Forecasting Horizontal Datum- Section 4.4.2- Figure 4.4
3. Elevations converted from *GSC 848163* to *CGVD2013*- Refer to Table 4.3 for details

Table 4.7 Historical highwater mark data.

Measurement Information				Recorded HWM Elevation [6]
Year[4]	**Description**		**Station[5]**	**Elevation (m)**
1991	2.5 km u/s of WSC gauge 09FD001		Km 317.5	246.927
	1.5 km u/s of WSC gauge 09FD001		Km 318.5	247.337
	At WSC gauge 09FD001		Km 320	246.817
1992	2.5 km u/s of WSC gauge 09FD001		Km 317.5	245.959
Year	**Description**	**Northing**	**Easting**	**Elevation (m)**
2011	HWM measured by NHC and UG on June 11, 2024	7494973.37	548794.27	242.491
2023	HWM measured by NHC and UG on June 11, 2024	7494971.92	548780.26	242.191
2024	HWM measured by NHC and UG on June 11, 2024	7494953.70	548715.56	241.061
	HWM measured by NHC and UG on June 11, 2024	7494964.92	548793.61	241.281
	HWM measured by NHC and UG on June 12, 2024	7495217.38	548484.23	242.901
	HWM measured by NHC and UG on June 12, 2024	7495186.73	548523.50	242.911

Notes:
4. 1991 and 1992 measurements are adapted from Jasek (1993)
5. Monitoring/ Forecasting Horizontal Datum- Section 4.4.2- Figure 4.4
6. Elevations are converted from *GSC 848163* to *CGVD2013*- Refer to Table 4.3 for details.

4.4.4 Field Observations, Photographic Records, and Video Documentation

Previous studies include detailed notes and photographic evidence from past flood events. The following field data have contributed to our understanding of flood dynamics along the Porcupine River and within the Old Crow community.

- Aerial reconnaissance reports documenting the status of ice cover along the upstream and downstream reaches of the Porcupine River during breakup.
- Photographs and videos of historical flood events captured by the Water Resources Branch breakup monitoring field crew and residents.

5 FLOOD HYDROLOGY

5.1 Flood History: Open Water and Ice Jam Flooding

Open Water Flooding

Old Crow has experienced minor open water flooding in the past. However, historical flood accounts indicate that open water flooding within the Porcupine River watershed in general and at the Old Crow community in particular, has been limited, with the most significant flood events being associated with ice jams during breakup.

Ice Jam Induced Flooding

The following section reviews the most significant ice jam-induced flooding events during breakup in the community of Old Crow. No major flooding events, except for one event (1997), were reported between 1995 and 2006. Information on ice events is summarized in Table 5.1.

In this study, two flood perception levels -corresponding to minor and significant flooding- were established based on observations over the period of record, set at 243.0 m and 246.5 m, respectively (~ 245 to 248.5 in local datum). At 243.04 m, Old Crow would experience minor flooding at the downstream end of the community. At approximately 244 m, the downstream end of the airport runway would be impacted. Before 245 m, the wastewater lagoon would be affected, potentially leading to water quality and contamination issues. At 246.5 m, the airport would become unusable, with flooding affecting the solar farm and residential areas north of the airport. Severe contamination from the lagoon would be expected, and facilities along the riverbank would likely be affected. Any level exceeding 246.5 m is considered significant flooding, with water depths surpassing 0.3 m (~1ft) across most of the community.

Considering the inadequacy of the ice related hydrometric data for the study, the ice jam flood characterization analysis was corroborated and extended with flood accounts presented in section 4.1. Review of the data confirmed that three notable flood events caused by river ice have occurred since 1991(246.9 m): in 1997 (244.9 m), 2011 (245.1 m), and 2015 (245.5 m).

Historical flooding refers to significant flood events that took place before the systematic collection of hydrometric data. In some instances, the magnitude of a historical flood can be estimated through historical documentations or anecdotal evidence. One of the most severe flooding events in the community, occurring before the initiation of systematic recordings, took place in 1932. This event was first documented in Fenco Consultants (1974), as cited by Janowicz (1992).

Historical accounts suggest that the 1932 flood was likely much more severe than the 1973 event, which was one of the significant floods documented during the period of systematic recording in the community. Table 5.1 summarizes the historical events at the community.

Table 5.1 Ice jam history.

Year	Description	Reference
1932	"[…] up to 4 feet of water in one house". The same house experienced 1.5 feet of water during the 1973 flood.	Old Crow resident originally from Fenco Consultants (1974) as described in Janowicz (1992)
1973	Confirmed ice scar found approximately 4.44 kilometres downstream of Old Crow.	Janowicz (1992) and Jasek (1993)
1983	Confirmed ice scar found approximately 4.46 kilometres downstream of Old Crow.	Janowicz (1992) and Jasek (1993)
1989	Documented ice jam flood caused by unusual meteorological conditions.	Janowicz (1992) and Jasek (1997)
1991	The entire town flooded except for the western end of the runway.	Gregory (1991)
1993	Heavy bank-to-bank ice flow observed at Old Crow.	Water Resources Branch (1993)
1997	"Some minor flooding occurred on low lying roads on the eastern and western ends of Old Crow." Previously anchored ice jams from upstream tributaries were released in the following days and several ice surges were observed.	Janowicz (1997)
2001	Heavy running ice jammed at Bluefish River with water levels rising until the Bluefish jam broke.	Water Resources Branch (2001)
2003	Heavy running ice jammed at Bluefish River and was released four hours later. An upstream jam was then formed and released resulting in a seven hour long heavy ice run.	Janowicz (2003)
2004	Heavy running ice moved past the community and jammed at Bluefish River. However, due to lower aufeis thicknesses, the confluence was not an effective anchor point. The jam released two hours after it was formed.	Janowicz (2004)
2009	The water level rose rapidly due to the formation of a downstream jam combined with rapid snowmelt. Low lying roads on both sides of Old Crow experienced minor flooding.	Janowicz (2009)
2010	Early and rapid snowmelt was observed prior to the event. A downstream jam increased water levels in Old Crow. The jam remained stable for around 7.5 hours, and it extended 5 km upstream of Old Crow.	(Janowicz, 2010a)
2011	Early and rapid snowmelt was observed prior to the event. Bank-to-bank ice runs initially jammed at Bluefish River. Continuous running ice and snowmelt runoff created two separate peaks.	(Janowicz, 2011a)
2015	Following break-up, significantly warmer weather led to a rapid melt of record-high snowpack, resulting in a sustained water level increase. This combination of break-up surge and snowmelt caused flooding near the downstream western end of the airport runway.	(Janowicz, 2015)

Year	Description	Reference
2022	Early observations of Bluefish River showed extensive bank-to-bank aufeis formation. The jam at the confluence grew close to 40 km long and extended to 5 km downstream of Old Crow.	Goulding (2022)
2024	Delayed, then rapid snowmelt of the record snowpack resulted in rapid progression of breakup. Ice jams upstream of Old Crow released, then an ice jam subsequently formed 35 km downstream of the community, raising water levels for 7 hours before releasing. The snowmelt peak followed breakup immediately, resulting in erosion of the road adjacent to the airport and additional flooding in the community because of localized snowmelt runoff.	Water Resources Branch (2024)

5.2 River Ice Processes

5.2.1 Freeze-Up

Freeze-up processes at Old Crow have not been linked to any significant flooding events. In general, water surface variations during the early winter months are typically associated with freeze-up processes, including the formation and consolidation of ice cover. However, these variations have not historically resulted in flooding in Old Crow. It was determined that ice-affected flooding was dominated by breakup and so an assessment of freeze-up water levels was not required.

5.2.2 Breakup

Breakup occurs when hydrodynamic forces are strong enough to dislodge and break up the ice cover. This process is controlled by both thermal and mechanical factors, which can affect the severity of the event.

When thermal processes dominate, hydrometeorological factors such as rising air temperatures lead to weakening, deterioration, and melting of the ice cover. The ice breaks down in place, redistributes, and flows downstream, resulting in a mild or uneventful breakup. On the Porcupine River, few breakup events have been primarily driven by thermal processes. Breakup on the Old Crow River is less comprehensively documented; however, it is also understood to have limited influence on the timing of initial breakup and associated flood risk at Old Crow.

In contrast, mechanical-dominated breakups are more dynamic and severe. These occur when significant hydrodynamic forces, caused by a large increase in discharge and water levels, break up the ice cover. In such events, the broken ice retains significant strength, and the breakup front progresses downstream as ice rubble drives through intact ice. If the advancing front is halted, the following ice rubble accumulates and thickens, forming a breakup jam. Most ice-related events in Old Crow have been dynamic breakups, and the community has also experienced multiple ice jam events.

The breakup processes have been extensively monitored and documented by Janowicz (1992, 1993-1999, 2006-2018, Turcotte (2019, 2020), Goulding (2021, 2022), Bercier and Bier (2023), and Bier and Goulding (2024). Jasek (1993,1997) also provided detailed descriptions of the breakup processes as well as some of the most severe ice jam-induced flooding events at the project site. The following sections summarize the findings from the above-mentioned sources.

The breakup of ice on the Porcupine River begins when the ice near Old Crow first starts to move. This section of the river, being steeper and straighter, requires only a modest increase in discharge to initiate ice movement. Typically, this movement leads to the formation of an ice jam downstream. This jam remains until a more forceful breakup front arrives, usually within a few hours.

Breakup on the Porcupine River does not follow a single, continuous front. Instead, multiple breakup fronts are triggered by various tributaries, complicating the process and potentially increasing the risk of flooding. The most active breakup fronts are generally initiated by tributaries like the Driftwood River and Lord Creek, which may merge or arrive separately at Old Crow, causing rapid rises in water levels.

Under normal conditions, the breakup front progresses downstream, with the risk of severe flooding decreasing as it moves further downstream of the community. However, in certain years, the breakup front may stall downstream, leading to the formation of an ice jam. If discharge continues to rise or if the ice jam advances upstream, this can result in significant flooding.

As breakup progresses, ice jams and solid ice upstream typically begin to release next. These jams can form in narrower sections of the river and, when they break, send surges of water and ice downstream. If no jams are present downstream, this may result in minor flooding, but if a jam is in place, the flooding can be severe. Observations suggest that this mechanism has contributed to past flooding events. Ice in the reaches upstream of the Bell River confluence typically mobilizes last, with its release occurring several days after the downstream sections have cleared. The breakup of the Old Crow River occurs primarily through thermal processes, often multiple days after the breakup in the Porcupine River, near the community. Its impact is minimal, as it contributes additional flow and potentially heat but does not generate significant dynamic effects on the Old Crow community (Turcotte, 2024).

Table 5.2 summarizes the historical breakups in the Porcupine River for the period of record.

Table 5.2 Breakup dates, type and characteristics history at the Old Crow.

Year	Breakup Date	Breakup Type
1932	Unknown	Unknown
1973	Wednesday, May 16, 1973	Dynamic
1989	Wednesday, May 3, 1989	Dynamic

Year	Breakup Date	Breakup Type
1991	Sunday, May 5, 1991	Dynamic
1993	Saturday, May 15, 1993	Dynamic
1994	Wednesday, May 4, 1994	Unknown
1995	Tuesday, May 2, 1995	Unknown
1997	Tuesday, May 6, 1997	Dynamic
2001	Thursday, May 24, 2001	Dynamic
2003	Wednesday, May 14, 2003	Dynamic
2004	Monday, May 17, 2004	Dynamic
2005	Saturday, May 7, 2005	Thermal
2006	Sunday, May 14, 2006	Dynamic
2007	Monday, May 21, 2007	Thermal
2009	Wednesday, May 6, 2009	Dynamic
2010	Sunday, May 2, 2010	Dynamic
2011	Friday, May 20, 2011	Dynamic
2012	Friday, May 18, 2012	Dynamic
2014	Wednesday, May 7, 2014	Dynamic
2015	Tuesday, May 12, 2015	Dynamic
2017	Saturday, May 13, 2017	Dynamic
2018	Saturday, May 12, 2018	Dynamic
2019	Wednesday, May 15, 2019	Dynamic
2020	Tuesday, May 12, 2020	Dynamic
2021	Saturday, May 15, 2021	Thermal
2022	Friday, May 13, 2022	Dynamic
2023	Saturday, May 13, 2023	Dynamic
2024	Friday, May 17, 2024	Dynamic

5.2.3 Ice Jam Formation Mechanisms

Jasek (1997) identified and summarized the ice jam formation mechanisms in the Porcupine River. NHC's review of additional data since 1997 confirmed that these mechanisms remain dominant at the site, though the extent of their contribution to ice jam formation appears to have shifted. The influence of climatic factors appears to be increasing, as they contribute to anachronous breakup events, leading to ice-induced high-water levels. The following sections provide a summary of the primary ice jam formation mechanisms.

Mechanism 1: Ice Jam formation due to aufeis

The severe flood of 1991 is believed to have resulted from the formation of substantial aufeis at the confluence of the Porcupine and Bluefish Rivers, approximately 40 km downstream of Old Crow. This condition was primarily caused by ice formation processes on the Bluefish River, where the river often freezes to the bed, blocking flow and forcing water to the surface through cracks and along the bank edges, creating overflow. This overflow quickly freezes, and the process can continue throughout the winter, leading to the development of an exceptionally thick aufeis deposit. Figure 5.1 shows the extent of aufeis growth at the Bluefish River confluence in 1997.

Severe aufeis formation significantly constricts flow at the confluence location, creating a stronghold for incoming ice floes to lodge and form ice bridges during breakup. Consequently, the altered stream geometry due to the aufeis provides a suitable location for the development of an ice jam toe. Under such conditions, combined with substantial incoming ice floes, extensive ice jam can potentially form and extends several kilometres upstream. Furthermore, the channel geometry upstream of the Bluefish River confluence offers sections where the ice jam can ground and form a secondary toe, as observed during the 1991 event. Even if the primary toe releases, the equilibrium section of the jam established at the secondary toe may persist, maintaining high water levels near the community and increasing the risk of flooding due to further jam development. This risk is exacerbated by the arrival of additional ice volumes that can extend the head of the jam upstream or extreme high-water levels due to the combination of waves generated by upstream jam releases, with the existing jam in the reach downstream of Old Crow.

Mechanism 2: Jave induced flooding

Ice jam releases from upstream reaches, such as the Salmon Cache and Driftwood River confluences, can generate significant surges of water and ice downstream toward the community. These ice jam release-induced waves, known as "Javes," have the potential to cause flooding or intensify the severity of the ongoing ice jam flooding, if they occur concurrently. Historically, these jams mobilized from upstream reaches after the initial ice clearance at the community, however they still have led to increased water levels due to the substantial volume of released ice and water.

Observations from the 1991 flood indicated that at least one such jave from upstream likely contributed to the flood's severity that year (Jasek, 1997). The volume of ice released from the upstream jam caused the existing one to advance upstream toward the community, while the additional water volume elevated flood levels.

Mechanism 3: Ice jam formation due to thermal processes

As previously noted, the northern and southern portions of the Porcupine River Basin can exhibit differing chronological behaviors during the breakup period due to differences in their

physiography. Significant temperature disparities between these portions of the basin can result in substantial freshet runoff in the southern reaches while the northern reaches remain covered by intact ice. Consequently, a freshet flood in the headwaters (southern portion) may encounter an undeteriorated ice cover in the northern regions, leading to mechanical breakup within that reach. The presence of robust ice sheets along the river increases the likelihood of jam toe formation at the intact ice edge. If ice and channel geometry conditions permit, multiple ice jams/ open water leads may form. The formation and release of multiple ice jams can elevate the risk of cascading effects, with the cumulative volume of ice from these jams potentially contributing to the formation of a significant jam downstream. Temperature differences between Old Crow and Eagle Plains are considered indicative of the thermal regimes in the northern and southern portions of the basin (Jasek, 1997). Historical observations have suggested that significant disparities in the cumulative Degree Days of Thaw (DDT) between these sites during breakup can increase the chance of ice jam formation in the Porcupine River, due to the mechanisms outlined above.

Table 5.3 below summarizes the jam characteristics for the years of record associated with flooding at the community due to ice jam formation.

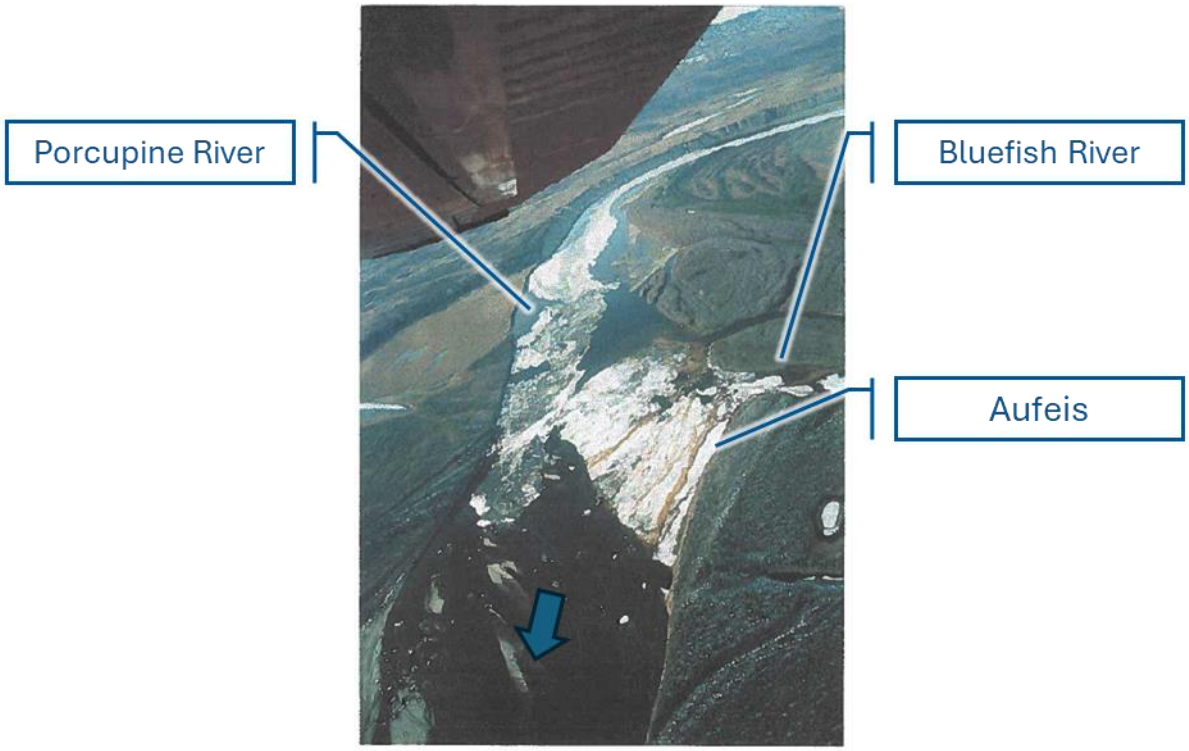


Figure 5.1 Aufeis extent at the Bluefish confluence, May 11, 1997. Photo: Water Resources Branch (1997).

Table 5.3 Ice jam characteristics in Porcupine River during the period of record.

Year	Ice Jam Date	Toe Location	Ice Jam Mechanism	Flooding
1973	unknown	unknown	unknown	Yes
1989	May 4, 9:30 AM	12 Mile Area	Mech. 3: Thermal	Yes
1991	May 8, 11:30 AM	Bluefish Confluence	Mech. 1: Aufeis	Yes
1993	May 14, 5:00 PM	Bluefish Confluence	unknown	Minor
1994	unknown	unknown	unknown	unknown
1997	May 7, 8:00 PM	Bluefish Confluence	Mech. 1: Aufeis	Yes
2001	May 24, 6:00 AM	Bluefish Confluence	Mech. 1: Aufeis	Minor
2003	May 14, 12:00 PM	Bluefish Confluence	Mech. 1: Aufeis	No
2004	May 17, 10:00 pm	Bluefish Confluence	unknown	Minor
2009	May 6, 10:45 PM	Location Unknown	unknown	Minor
2010	May 2, 12:15 AM	12 Mile Area- ~17 km DS of the community	unknown	Minor
2011	May 20, 2:15 PM	Bluefish Confluence	unknown	Yes
2014	Likely May 8, 1:20 AM	Bluefish Confluence	unknown	Minor
2022	14-May	Bluefish Confluence	Mech. 1: Aufeis	No
2024	May 17, 8:00 PM	Goose Camp	unknown	Minor

5.2.4 Factors Affecting Ice Jam Flooding Severity

Past research has identified several potential variables that can influence the severity of ice jam-induced flooding at the project site. The severity of such flooding is directly related to the water levels that the community will be exposed to during the event. These influencing variables can be categorized into two groups: those that directly impact water levels and those that indirectly influence water levels by affecting the severity of the ice jam. It is important to note that severe or extreme ice jam-induced flood events often result from a combination of these two groups.

Direct Influences:

- Breakup discharge: Discharge at the onset of breakup is highly dependent on hydrometeorological conditions during both the preceding winter and the freshet period. Key meteorological factors, such as winter precipitation (including high snow volumes) and intense rainfall during breakup, as well as temperature patterns (cold temperatures during

winter and warm conditions during breakup), can significantly influence the volume and peak of freshet discharge.

- Waves generated by the release of an upstream ice jam: As observed in the past, different reaches of the Porcupine River experience varying breakup patterns, which are influenced by the physiographical characteristics of the subbasins along the river. Some of these subbasins release freshet flows into the river through tributaries, initiating local breakup fronts, while other sub catchments may not yet have reached the breakup stage. Consequently, breakup can progress at different rates along the Porcupine River upstream of the community, potentially leading to the formation of local ice jams. If these jams release, depending on the breakup progress in the reach at or downstream of the community, they can either result in significant ice runs or exacerbate existing ice jams by increasing both the jam volume and channel flow.

Indirect Influences:

- Factors affecting ice jam toe formation: Some of the most severe ice jams have formed at the Bluefish River confluence, where aufeis alters the river's geometry and constricts channel width. Jasek (1997) identified factors influencing aufeis extent and severity, though no quantitative relationships were established. Empirical and qualitative insights were drawn from limited monitoring between 1991 and 1993-1996. The key factors are:
    - Winter Severity: Colder winters can affect aufeis formation, though no clear trend was noted.
    - Precipitation and Snow Depth at Breakup: Snow may insulate the river, preventing it from freezing to the bottom.
    - Previous Summer's Precipitation: Lower winter flows due to reduced summer precipitation may lead to freezing to the bottom.
    - Unusual Temperature Events: Mid-winter warm snaps followed by cold weather can increase over-ice flow, leading to more severe aufeis formation.
- Timing of breakup: Premature breakups- when the freshet occurs while the ice cover remains intact and undeteriorated- can lead to the formation of more severe ice jams.
- Volume of ice potentially contributing to the characteristics of the ice jam: In any ice jam event, the volume of ice mobilized from upstream that contributes to the bulk of the jam directly impacts its severity. As the equilibrium length of the jam extends- meaning the jam head progresses towards the community, or in extreme cases, passes the community and continues upstream- the severity of flooding at the community increases significantly.

The impact of each of these aggravating factors, whether individually or in combination, is reflected in the flood water surface elevation. Therefore, an adequate record of water surface elevations at the study site, if available, provides sufficient data for a comprehensive frequency analysis that accounts for these factors.

5.3 Open Water Flood Frequency Analysis

For the flood frequency analysis, the Old Crow River inflow to the hydraulic model was assumed the same as at the Old Crow near the mouth WSC gauge location (gauge number 09FC001,Figure 4.1). Porcupine River inflow was derived based on flow data from three WSC gauges: Porcupine River at Old Crow, Porcupine River near International Boundary, and Old Crow River near the mouth. The approach is outlined below:

1. Open water daily flows at the Porcupine River at Old Crow WSC gauge were extended using open water daily flows recorded at the Porcupine River near International Boundary WSC gauge. While javes can affect and alter the relationship between daily flows at these two locations during the ice-affected period, NHC assumes that by using only flow data during the open water period (i.e., not marked by "B" in WSC data) the effect of javes is minimized. While it is known that ice-affected period dates might be conservative and extend to open water periods (B. Turcotte, personal communications), no reassessment of "B" dates was performed. NHC believes that using "B" dates assigned by WSC helps filter any potentially ice-affected flows at both locations, and this was completed prior to deriving a correlation among the open water daily flows between these two gauges..
2. For each timestep, daily flows measured at Old Crow River near the mouth were subtracted from extended time series at Porcupine River at Old Crow to represent daily discharge upstream of the confluence with the Old Crow River. This approach assumes that the propagation time between inflow upstream of Old Crow and flow below is less than a day, which is fair considering the distance and based on daily peaks review.
3. Annual daily peaks extracted from the obtained time series and peaking ratio derived for Porcupine River at Old Crow were used to calculate instantaneous peaks.

Derived time series were checked for stationarity using the Mann-Kendall test (Kendall, 1975) (Table 5.4). A trend (tau) was considered significant when p-values were less then 0.05 (95% confidence level). If the p-value was greater than 0.05, then tau can indicate whether values were increasing or decreasing over time, but the change was not significant. While QPI time series at the Porcupine River at Old Crow WSC gauge exhibit a statistically significant declining trend, no statistically significant trend was detected for the extended QPI time series at the point of inflow for the Porcupine River (Table 5.4). This is most likely related to the fact that the derived record includes two decades of additional data. These results are consistent with the results for the Porcupine River near International Boundary WSC gauge which also covers recent years. Similarly, no statistically significant trend was detected for the Old Crow River near the mouth. NHC also performed the Multiple Grubbs–Beck Test to check for low outliers (Cohn et al., 2013). Low outliers were detected for the Old Crow River. To remove the influence of those smaller events on the upper end of the frequency estimates, detected outliers were removed from the analysis. Keeping low outliers results in 20-40% lower frequency estimates in this case, depending on the AEP.

Table 5.4 Mann-Kendall test results for raw and infilled peak annual instantaneous flow (QPI) and for peak annual daily flow (QPD).

Gauge #	Name	QPI, raw		QPI, infilled		QPD		Trend
		p-value	Tau	p-value	Tau	p-value	Tau	
09FB001	Porcupine River below Bell River	0.58	-0.12	0.11	-0.26	0.85	-0.05	Not statistically significant
09FC001	Old Crow near the mouth	0.80	-0.03	0.67	0.04	0.62	-0.06	Not statistically significant
09FD001	Porcupine River at Old Crow	0.04	-0.47	0.04	-0.25	0.01	-0.57	Statistically significant (with 0.05 level of significance)
09FD002	Porcupine River near International Boundary	0.56	-0.09	0.99	0.00	0.83	0.04	Not statistically significant
09FD003	Porcupine River below Old Crow River	0.91	0.03	0.23	0.22	0.85	0.05	Not statistically significant
	Porcupine River at the point of inflow into the model			0.81	0.03			Not statistically significant

FFA for stationary time series was then performed by fitting the Log-Pearson Type III distribution to peak instantaneous flow using the method of L-moments. NHC provided an uncertainty range by using a bootstrap resampling of 25,000 samples to determine the 5% and 95% confidence intervals of the fit (Headwater Analytics, 2015). Flood frequency results for the Porcupine River inflow are presented in Table 5.5. Flood frequency results for the Old Crow River inflow are presented in Table 5.6. Recommended flow estimates are based on the 50th quantile estimate.

Table 5.5 Flood frequency analysis results for Porcupine River point of inflow. Values are based on the peak instantaneous flow upstream of Old Crow River confluence including the uncertainty range (5% and 95% confidence interval limits).

AEP	Porcupine River at the point of inflow		
	5th quantile estimate, m^3/s	50th quantile estimate, m^3/s	95th quantile estimate, m^3/s
50%	2,651	3,024	3,436
20%	3,668	4,168	4,714
10%	4,226	4,859	5,567
5.0%	4,635	5,477	6,474
2.0%	5,026	6,220	7,810
1.0%	5,224	6,742	8,916
0.5%	5,379	7,236	10,132

Table 5.6 Flood frequency analysis results for the Old Crow River point of inflow. Values are based on the Old Crow River peak instantaneous flow including the uncertainty range (5% and 95% confidence interval limits).

AEP	09FC001 Old Crow River near the mouth		
	5% quantile estimate, m^3/s	50% quantile estimate, m^3/s	95% quantile estimate, m^3/s
50%	776	844	919
20%	940	1,038	1,152
10%	1,032	1,169	1,334
5.0%	1,107	1,296	1,543
2.0%	1,189	1,463	1,863
1.0%	1,242	1,592	2,148
0.5%	1,288	1,725	2,473

When compared to previously obtained flood frequency estimates (NHC, 2023b), the results at the Old Crow River points of inflow (Table 5.6) are generally higher; the percent difference varies between -2% and 12%. This difference is most likely due to the inclusion of additional years (2020-2023) in the current flood frequency analysis. The results for the Porcupine River point of inflow are on average 20% lower than the previous estimates for the Porcupine River at the Old Crow WSC gauge (NHC, 2023b). However, time series used for the current analysis were

extended using the downstream gauge, and flows supplied by the Old Crow River were removed. Therefore, the direct comparison is not possible.

6 HYDRAULIC MODEL DEVELOPMENT

6.1 HEC-RAS Program

In this study, flood level assessments for both open water and ice-covered flow conditions were conducted using the U.S. Army Corps of Engineers Hydrologic Engineering Center's River Analysis System (HEC-RAS), Version 6.5 (February 2024). The HEC-RAS model implementation requires key inputs including cross-sectional profiles of the river spaced at specified intervals, Manning's roughness coefficients for the main channel and overbank areas, and downstream boundary conditions defined by either a water surface elevation or channel slope. Upstream boundary conditions are set using discharge rates. For simulations involving supercritical or mixed flow regimes, additional upstream boundary specifications, such as water surface elevation or slope, are also required to ensure model stability and accurate flow characterization.

6.1.1 Theoretical Aspects

HEC-RAS utilizes the Energy Equation (derived from Bernoulli Equation) between consecutive cross sections to compute subcritical and supercritical water surface profiles. It is designed to evaluate hydraulic responses to modifications in the channel and floodplain, such as channel straightening, encroachments, enlargements, and the construction of flood control dikes. Additionally, it estimates energy losses caused by in-channel structures like culverts, bridges, weirs, and other obstructions. The analytical framework of HEC-RAS is based on the following assumptions and recognized limitations:

- The model assumes gradually varied flow, allowing boundary friction losses between cross sections to be estimated using Manning’s equation with section-average hydraulic parameters.
- The impact of geomorphological changes, such as erosion or mobile bed processes occurring during a flood, is not directly accounted for or simulated within HEC-RAS.
- It presumes a uniform water level across each cross section, utilizing three separate conveyance components for the main channel and the left and right overbank zones.
- The analysis is one-dimensional, considering only the velocity components in the principal flow direction for calculations.

The simulation of overbank floodplain flow upstream of the Old Crow and Porcupine Rivers confluence presents a challenge to the one-dimensional flow assumption of the HEC-RAS model. Special attention was given to address this limitation during the development of the model geometry, as detailed in Section 6.1.2.1 and 6.1.2.2.

6.1.2 General Model Setup

6.1.2.1 Geometric Layout

The general model setup encompassed defining the river centerline alignment, laying out cross-section cut lines, and configuring the flow pathways over the floodplains, including temporally and permanently ineffective flow areas. This process was carried out using ESRI ArcGIS and the RAS Mapper tool integrated within HEC-RAS. The total modelled reach of the Porcupine River extended approximately 57 km, based on the established river centerline. Additionally, a 1.7 km segment of the Old Crow River, upstream of its confluence with the Porcupine River, was incorporated into the model.

The cross-sectional geometry was developed by combining surveyed channel bathymetric profiles with LiDAR and the HRDEM as described in section 4.3.2. Each cross-section was extended across the floodplain to capture areas beyond the 500-year open water flood extent, which was delineated based on the initial two-dimensional (2D) open water model developed to inform the setup of the one-dimensional (1D) model. Near the confluence, where the Old Crow River intersects the Porcupine River floodplain, the extension of Old Crow River cross sections required selecting alignments that ensured a smooth transition between the simulated water levels of both rivers. However, in certain cases, particularly for the left overbank sections of the Old Crow River, where model cross-sections had to be oriented upstream relative to the Porcupine River, the adopted alignments could not always satisfy the assumption of perpendicular overbank flow.

Of note, the Old Crow River was not connected to the Porcupine River using a junction in HEC-RAS due to numerical assumptions in the model formulation, which are invalid for the case of this study. The junction formulation in HEC-RAS steady-state numerical calculation scheme assumes that the energy grade lines (and not the water surface elevations) are equal for upstream cross-sections linked at a combining flow junction. At the confluence, the energy of the Old Crow River is significantly different than that of the Porcupine River during flood conditions. Typically, this disparity would necessitate placing the most downstream cross-section of the Old Crow River farther upstream to avoid the backwater effects from the Porcupine River. However, for flood mapping purposes, cross-sections were required up to the confluence. Connecting these reaches via a junction would result in inaccurate water levels along the downstream portion of the Old Crow River. Consequently, the Old Crow River was not linked to the Porcupine River through a junction. Instead, the water level at the downstream boundary of the Old Crow River was manually set to match the corresponding water level in the Porcupine River for each simulation.

Furthermore, wide ice jam calculations through model junctions are not fully developed in HEC-RAS, rendering ice jam profile calculations at these junctions invalid. Additionally, dividing the Porcupine River into upstream and downstream reaches at the junction implies that the ice jam profile in the upstream reach would initiate at the first cross-section upstream the junction,

representing a static ice cover thickness. This effectively creates a new ice jam profile section i.e. an artificial "toe" location for the ice jam. The chosen approach of excluding the junction resolves these numerical issues and allows the model to simulate ice jam progression along the Porcupine River reach upstream of the Old Crow River confluence, if required.

In compliance with the bathymetric and topographic survey efforts, all cross-sectional and topographic data were geo-referenced using the 3TM NAD83 CSRS project coordinate system. For flood mapping purposes, all study findings and model outputs are projected to the defined study coordinate system, NAD83 Yukon Albers CSRS, Epoch 2002 coordinate system. Detailed information regarding model geometry setup is provided in Section 6.3.

6.1.2.2 Channel and Overbank Roughness

Manning's roughness coefficients were implemented across the modeled reaches, with horizontal variation at each cross section to reflect the heterogeneity of river and floodplain characteristics. The assignment of hydraulic resistance factors for the study area was guided by Esri Sentinel-2 Land Use/Land Cover data (2017-2023) at a 10 m resolution, which provided land cover classifications to assign the hydraulic resistance coefficient i.e. *n* value, accurately.

Each cross section utilized a minimum of three roughness zones (one for the main channel and two for the overbank areas) and up to five roughness zones for more complex sections, where distinct features like islands were present (such as at Gilligan Island- a large bar at the confluence of the Porcupine and Old Crow Rivers).

Manning's roughness coefficient is a well-established parameter used to represent a range of energy losses in open channel flow, which are not uniform with respect to discharge. As detailed in Section 6.4.1 roughness values were adjusted with discharge based on a calibrated series of roughness change factors. This approach was consistently applied across the entire model, particularly in low flow simulation scenarios where hydraulic resistance of channel boundaries is more influenced by mean flow fields. This methodology allowed for the development of a HEC-RAS model with a single geometric configuration that effectively represents the diverse range of flood discharges considered in the study.

6.2 Boundary Conditions

The following describes the boundary conditions for the hydraulic model:

- The inflows for the Porcupine River were defined based on the results of the flood frequency analysis (Section 5.3) and used as steady-state flow.
- The inflows for the Old Crow River were defined based on the results of the flood frequency analysis (Section 5.3) and used as steady-state flow.

- Bluefish River inflow was developed based on the difference in peak flows at Porcupine River at Old Crow (WSC gauge 09FD001) and Porcupine River near International Boundary (WSC gauge 09FD002). The average discharge difference between these two gauges is 9% and is assumed to represent the contribution from tributaries between the two locations. The Bluefish River watershed area is 70% of the area between the upstream and downstream Porcupine River gauges. Based upon Bluefish River watershed area relative to the entire contributing area, the Bluefish River inflow was 6% of the flow differential between the upstream and downstream gauge. Bluefish River inflows were steady state.
- A normal depth boundary condition was applied at the downstream end of the Porcupine River, utilizing a uniform flow approximation. The normal depth slope, S=0.0002, was selected based on the reach-average energy grade line slope. This approach provided simulated water surface elevations consistent with observed levels near the downstream boundary across a range of discharge scenarios, achieving a normal flow condition at the study area's downstream limit. Additionally, a specified water surface elevation boundary was assigned at the most downstream cross section of the Old Crow River. For each simulation, this value was determined as the average of the computed water levels at the Porcupine River cross sections bracketing the confluence with the Old Crow River.

6.3 Geometric Database

The geometric database contains all components of the HEC-RAS model geometry, constructed using geospatial analysis tools within ArcGIS and HEC-RAS. The RAS Mapper utility was employed to assist in the initial development of model geometry, with further refinement carried out through the HEC-RAS geometry editor. This section outlines the contents of the geometric database and the methodologies applied in developing the model geometry.

6.3.1 Cross-Section Data

Cross-section alignments were established in RAS Mapper, following the general trajectory of the topographic and hydrographic survey points for the 40 surveyed cross-sections along the Porcupine River (refer to Section 4.4). Additionally, 4 surveyed cross-sections were incorporated into the model for the Old Crow River. Each cross-section extends through the left and right overbank areas, reaching the valley walls.

The cross-section elevations were derived from a combination of DTM data, topographic survey data, and hydrographic survey data, as outlined below:

1. Alignment Definition: Cross-section alignments were set to intersect the surveyed point data, extending into the overbank regions.
2. Station-Elevation Data Sets Creation: Two station-elevation data sets were generated for each cross-section:
3. DTM-Based Data Set: Elevation data was extracted directly from the DTM.

4. Survey-Based Data Set: Elevation points from the topographic and hydrographic surveys were projected onto the cross-section line.
5. Data Export: Both the DTM-based and survey-based station-elevation data sets were exported from ArcGIS into HEC-RAS geometry format.
6. Cross-Section Combination and Simplification: In HEC-RAS, the DTM-based and survey-based cross-sections were merged using RAS Mapper. The total number of elevation points for each combined cross-section was then reduced to fewer than 500 points using the "Minimize Area Change Point Filter" option to optimize the data.
7. Measurement and Export: Distances between consecutive cross-sections, along the channel centerline, and along the primary flow paths of the left and right overbanks were measured in RAS Mapper. These measurements, along with the cross-section data, were exported to the HEC-RAS model.

Four strategically positioned, representative cross-sections were surveyed along the Porcupine River, extending from approximately 6.5 km downstream of the community to just upstream of the Bluefish confluence. These cross-sections were selected based on historical ice jam toe locations, including areas such as 12 Mile Bluff and Goose Camp. The purpose of these cross-sections was to capture channel geometry transitions along the river reach between the community and the Bluefish confluence. Additional cross sections, at shorter intervals, were surveyed in the Bluefish confluence area, as it has been a common location for ice jam toe formation in past events, including the 1991 ice jam event.

Numerically interpolated cross-sections were generated at appropriate intervals to depict this reach. The interpolation process follows the defined channel centerline and bank stations along the river and illustrate the channel width and shape transitions between the surveyed cross-sections; however, it generates a linear interpolation between the thalwegs of the upstream and downstream cross sections. To address this limitation, the underwater portion of each interpolated cross section—while preserving its geometric shape—was vertically adjusted (raised or lowered) based on the corresponding surveyed thalweg elevation along the longitudinal profile (refer to Section 4.4.1 -Figure 4.3), to more accurately represent the actual river gradient and thalweg variability. Additionally, the overbank areas of the interpolated cross-sections were updated based on the DTM data at the corresponding cross section location.

Consequently, a series of synthetic cross-sections were generated to represent the downstream reach of the Porcupine River up to the Bluefish confluence. These cross-sections consist of overbank areas derived from the DTM and channel areas based on the interpolated cross-sections, with thalweg elevations updated according to the surveyed profile of the river.

Figure 6.1 and Figure 6.2 provide the layout of the model cross-sections, where surveyed cross-sections are indicated by blue diamonds and the synthetic cross-sections, with updated thalweg elevations, are marked by red squares.

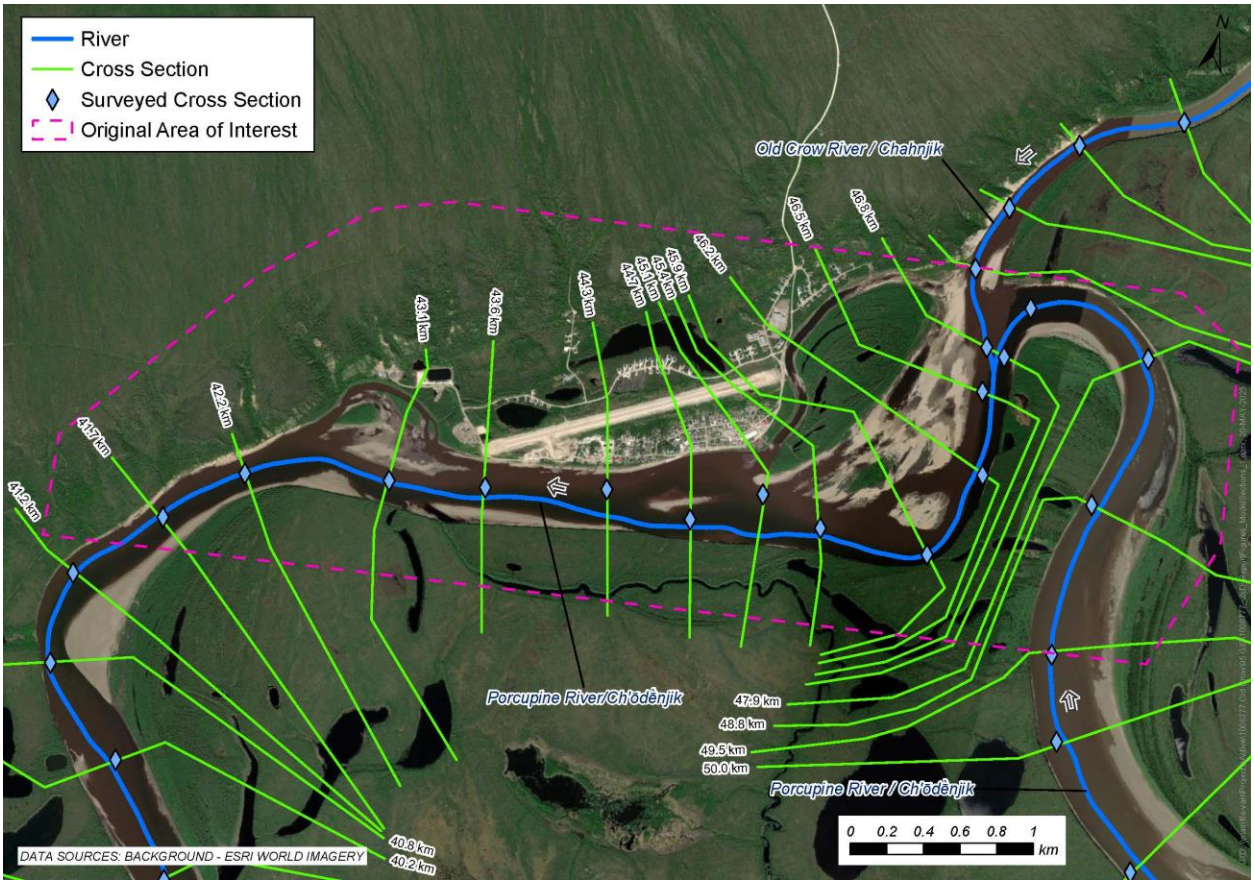


Figure 6.1 Hydraulic model layout illustrating the surveyed and synthetic cross sections over the study area.

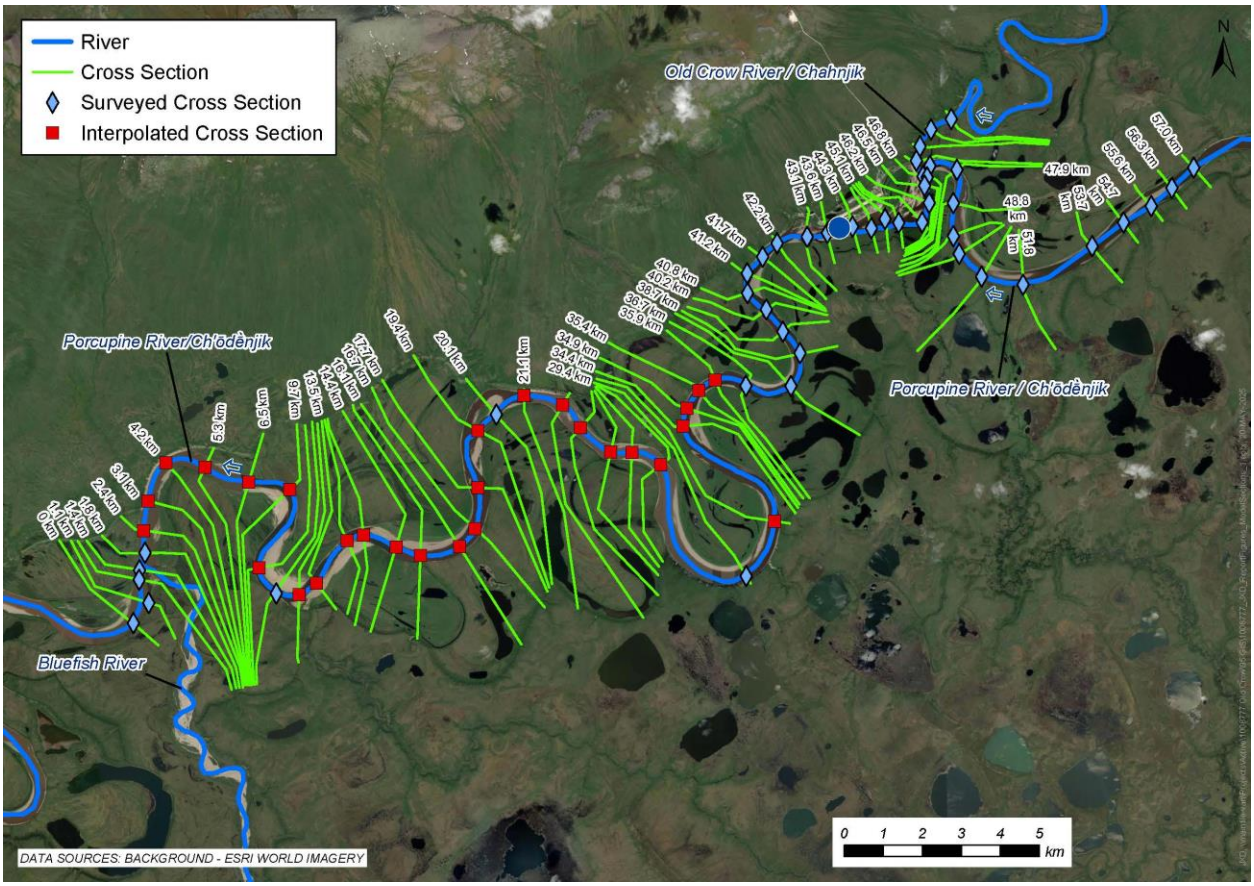


Figure 6.2 Hydraulic model layout illustrating the surveyed and interpolated cross sections over the community of Old Crow.

6.4 Model Calibration

Model calibration involved optimizing various parameters to accurately simulate observed water levels along the study reach under both high and low flow conditions. The calibrated parameters included:

- **Manning's roughness coefficients** for the channel, islands, and floodplain.
- **Discharge-dependent roughness adjustment factors**.
- **Friction slope** for the downstream normal depth boundary condition.
- **Ineffective flow areas** at each cross-section.
- **Expansion and contraction coefficients** between cross-sections.
- **Ice-specific model parameters**, such as ice roughness and jam stability factors, including internal friction angle, porosity, and the coefficient of lateral to longitudinal stress within the ice jam.

Additional case-specific ice jam characteristics, such as jam length, were also taken into account during the model calibration process.

6.4.1 Open Water Calibration

Among the parameters mentioned, the primary calibration factor for open water conditions was the Manning's roughness coefficient for the river channel. These coefficients were assigned to each cross-section by comparing simulated water surface elevations with observed water levels and recorded water marks. Roughness coefficients are presented in Table 6.1.

Table 6.1 Land Use Table and Assigned Manning's n Values.

Land Use Type	Assigned *n* Value
Trees	0.055
Rangeland	0.035
Flooded Vegetation	0.045
Streams	0.025
Bare Ground	0.03
Built Area	0.065

In the initial phase of model calibration, roughness within the model domain was defined in ArcGIS, informed by land cover types identified in aerial imagery. Lateral roughness variations for each land cover type were subsequently refined within the HEC-RAS geometry editor, guided by the Digital Terrain Model and survey data.

Calibration of Manning's roughness coefficients was performed from the downstream end of the model moving upstream. To maintain a physically representative model of the channel morphology, section-by-section adjustments to the Manning's roughness coefficient were avoided. Instead, channel roughness coefficients were varied on a reach basis —four reaches along the Porcupine River and one reach along the Old Crow River, totaling five reaches— while overbank roughness values were kept constant for each specific land cover type (refer to Figure 4.2). Adjustments to the Manning’s roughness coefficient were typically made to align shifts in flow or sediment regimes, which are often signaled by changes in channel planform observable in aerial imagery.

A significant challenge in the calibration process was the uncertainty in discharge and water level estimates, particularly regarding the timing and magnitude of flood peaks on the Porcupine and Old Crow Rivers. The approaches adopted and assumptions made to address this challenge are detailed in Section 5.3 and further elaborated in Section 6.5 of this document.

Flood events at Old Crow are predominantly driven by ice jam-induced flooding during the breakup period. As a result, flood monitoring programs have historically focused on capturing breakup-related flooding. While these programs provide a comprehensive overview of ice-induced flooding and relevant water levels, occasionally accompanied by surveyed high water marks, there is minimal information available regarding open water flooding events in Old Crow. Additionally, the WSC gauge at Old Crow has been subject to relocations, temporary deactivations, and changes in the type of recorded data, leading to inconsistencies in flow and HWM data for open water flood events at the project site.

Given these limitations, the open water model calibration was performed using two primary approaches:

1. **Low-flow calibration**: This was based on a water surface profile survey conducted in summer 2024 by Underhill Geomatics, as part of the channel thalweg profile survey (refer to Section 4.4).
2. **Reproduction of rating curves**: The calibration also involved reproducing rating curves developed for the WSC gauge at Old Crow, covering both low flow conditions (based on the survey profile and lower part of the rating curve) and high flow conditions (based on the upper parts of the rating curve).The process is described in Section 6.4.1.2 of this document.

The calibration procedures and results for these two scenarios are detailed in the subsequent sections.

6.4.1.1 Low-Flow Calibration

For the low-flow calibration, NHC primarily utilized surveyed water levels recorded in June 2024. The hydraulic model, as previously described, was employed to simulate water levels corresponding to the conditions during the thalweg survey, which were representative of low-flow conditions. This calibration effort aimed to evaluate whether the Manning's roughness coefficients assigned for high-flow scenarios were also appropriate for low-flow conditions.

The discharges corresponding to the observed water levels were estimated using real-time data from the WSC gauges at Porcupine River at the International Border (09FD002) and Old Crow River near the Mouth (09FC001). The estimated flows during the survey period ranged from approximately 1000 m^3/s to 1200 m^3/s, both of which are significantly lower than the 2-year flood peak.

Calibration results were evaluated by comparing computed water surface elevations with the observed water levels. Figure 6.3 illustrates the comparison between the simulated water surface profile and the observed levels during the survey period.

During the 2024 survey campaign, near the community of Old Crow, the computed water levels were, on average, 0.1 m higher than the observed levels. The average absolute difference between computed and observed water levels was 0.11 m, with the maximum positive difference being 0.24 m and the maximum negative difference being -0.14 m.

Discrepancies between surveyed and simulated water surface elevations—particularly between the 10 km and 20 km stations—were acknowledged and are attributed to temporal variations in river discharge during the survey day. Given the strong agreement near the community and the minimal expected influence of the mid-reach channel geometry on high-water levels during ice jam flooding, these differences are not anticipated to significantly affect flood estimates, and further model refinement was not pursued.

Overall, the low-flow calibration results indicate good agreement between the computed and observed water levels. The model generally underpredicts water levels under low-flow conditions. However, the low-flow calibration shows that computed water levels are, on average, slightly higher than the observed levels for low-flow scenarios. This suggests that the simulated water levels for the modeled flows are not highly sensitive to channel bed roughness. Instead, form roughness within the study reach has a more significant influence on the predicted water levels.

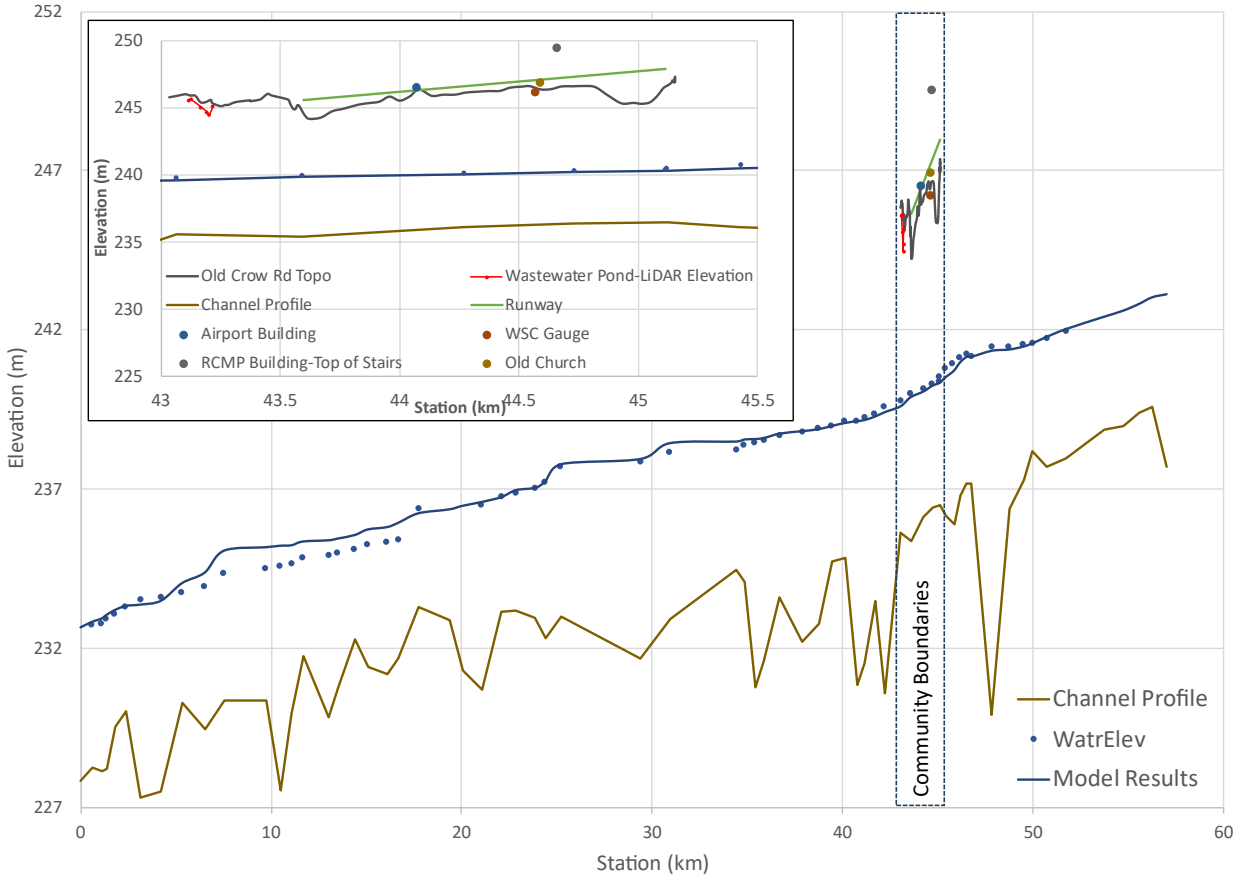


Figure 6.3 Low-flow calibration results along the Porcupine River- Community extent and significant community features are presented in the zoomed-in figure (top left).

6.4.1.2 WSC Rating Curve Reproduction

The high flow, open water model calibration was conducted using two datasets available for the Porcupine River at Old Crow: (1) a rating curve developed by Jasek (1993) and (2) WSE data plotted against derived flows at the gauge location using the methodology outlined in Section 5.3 .

To ensure consistency with the elevation reference framework used in this study, Jasek's rating curve was translated from the local datum to the CGVD2013 vertical datum. When plotted against the recorded flow-elevation data, the translated rating curve closely follows the trend of the observations at the WSC gauge for the post 2006 period. This consistency indicates that the datum translation process reliably converts water surface elevations from the local datum to CGVD2013, and hence, makes the translated Jasek's open water rating curve applicable for high-flow open water calibration.

The model's ability to replicate a comparable rating curve served as the basis for high-flow open water calibration. The model was executed for a range of representative flows, spanning from 1,000 m^3/s to 8,000 m^3/s, and the resulting water surface elevations were plotted against the updated Jasek curve. Model results aligned closely with the translated Jasek curve for flows below 7,000 m^3/s, though for higher discharges, the model exhibited a slight underestimation of water levels.

Annual extreme water surface elevation values from the gauge data were also plotted for comparison. Although the levels are not explicitly classified as open water or ice-affected levels in WSC data, their position relative to the developed open water rating curve suggests that, despite the gauge's seasonal operation, ice-affected levels are also captured. This hypothesis was tested using ice classification data from C-CORE for selected years and was confirmed to be plausible.

For further validation, three datasets—the updated Jasek curve, the flow-elevation data derived from post-2006 observations, and model-generated results—were superimposed for comparison, as illustrated in Figure 6.4. The agreement between these datasets enhances confidence in the reliability of the calibrated model for simulating a broad range of discharges under open water flood conditions.



Figure 6.4 Reproduction of the WSC rating curve using the open-water calibrated model, with comparison to the historical rating curve (Jasek, 1993) and post-2006 recorded data.

6.4.2 Ice Jam Calibration

6.4.2.1 Selection of Events

Since the mid-1980s, the Porcupine River has experienced several well-documented historical ice jam events. These events have been detailed in various reports, providing valuable insights. For a select number of these events, critical information required for ice jam flood modelling (e.g., water levels, toe locations, and flow rates) is available.

The strategy for model calibration and validation involved selecting events based on the following criteria: (i) availability of relatively detailed hydrometric data (e.g., flow and water surface profiles), (ii) representation of the full range of possible conditions, including ice jam toe locations, and resulting ice jam profiles, and (iii) duration long enough to achieve a quasi-steady state condition within the reach.

It is important to note that consistent parameter sets (including ice specific gravity, porosity, internal friction angle, and stress ratio) were applied across all years for both calibration and validation simulations. The 1991, 1993, and 2011 ice jam events were selected for model calibration, while the most recent 2024 event was used for verification and validation of the calibrated model.

1991 Ice Jam Event:

In 1991, ice breakup in front of Old Crow began on May 5, leading to the formation of an ice jam at the confluence of the Porcupine and Bluefish Rivers. This jam was likely caused by thicker-than-normal aufeis deposits at the mouth of the Bluefish River. By the evening of May 7, the head of the ice jam was positioned 9 km downstream of Old Crow, causing water levels to rise rapidly. At 19:10, the water level in Old Crow was recorded as approximately 246.3 m (CGVD 2013), with minor fluctuations likely due to the consolidation of the upstream section of the ice jam. As the night progressed, the concentration of surface ice increased, indicating an incoming surge. By 23:30, the water levels had risen dangerously, reaching depths over 1 m throughout the village and causing ice blocks to flow into the streets, posing significant threats to structures. The peak water level was recorded at 246.9 m (CGVD 2013) early on May 8. Aerial observations at 09:30 showed that the ice jam had advanced closer, with its head located within 5 km of Old Crow. The jam released around 11:30, leading to a rapid drop in water levels to 246.2 m (CGVD 2013) by noon, alleviating the immediate flood risk.





Figure 6.5 1991 ice jam flooding extent (a) (Photo Credit: Government of Yukon); ice remnants and flood impacts in the community, with the Old Church visible in the photo, taken the day after the ice jam (b) (Photo Credit: Martin Jasek – Provided through personal communication).

1993 Ice Jam Event:

On May 15, an ice breakup at Old Crow led to a rapid rise in water levels of 2.5 metres within 1.5 hours. Monitoring began in early May, with flood monitoring personnel flying in on May 14 to assess conditions. Initial observations indicated open water upstream with intermittent ice jams down to Old Crow, and a significant 30 km ice jam downstream of Bluefish River (Yukon Government, 1993). By 17:00, solid ice in front of Old Crow had shifted, causing localized jamming 2 km downstream at the hydrometric station, resulting in a steady water level increase of 15 cm/hour. By early morning on May 15, upstream ice movement intensified, leading to bank-to-bank ice flow through town and a peak water elevation rise of 2.5 metres by 03:20. Water levels then began to recede, with open water observed by 07:30 and ice coverage reducing to 60% by 09:00. Aerial observations at 11:00 revealed extensive ice jams extending 35 km to a point upstream of Bluefish River. Ice floe towards Old Crow from upstream was also observed. By May 16, ice coverage decreased significantly, with a brief increase in water level (0.5 metres) recorded, and an estimated peak discharge of 4,000 m^3/s [4] according to the breakup monitoring reports. Ice runs subsided by the afternoon, and open water extended upstream from the Bell River, minimizing the risk of further ice jamming.

2011 Ice Jam Event[5]:

On May 20, the ice breakup at Old Crow began at 09:15, initiated by rapid snowmelt due to significantly above-normal temperatures. Prior to this, the Porcupine River had risen 1.8 metres from its winter low observed on April 13. Following the onset of breakup, water levels rose by approximately 3.8 m over a five-hour period due to a bank-to-bank ice run that became obstructed behind a major ice jam at the Bluefish River confluence. This event occurred between May 20 and 21, resulting in water levels reaching approximately 15.5 m (CGVD2013: ~243.95 m). A second major ice run occurred at 04:00 on May 21, causing a slight increase in water levels. The release of the Bluefish ice jam temporarily lowered levels, but continuous ice movement combined with snowmelt contributions kept water levels elevated throughout the next 24 hours. The maximum ice-induced water level of 16.65 (water surface elevation of 245.1m- CGVD2013) metres was recorded at 05:00 on May 22 driven by the snowmelt runoff. An even higher peak of 16.69 metres occurred at 19:00 on May 23, also influenced by snowmelt runoff (water surface elevation of 245.14 m- CGVD2013). This maximum water level was noted as the highest since 1992, measuring 0.8 metres below the top of the bank at the local hydrometric station.

[4] NHC estimated the ice jam discharge to be approximately 1,200 m^3/s.

[5] Water level variations are referenced to the local datum.



Figure 6.6 Inundation of road at southwest corner of airport runway during the 2011 event (a); extent of flooding at the end of the road, near the airport boundaries during the same event (b).

6.4.2.2 Calibration Approach and Selection of Ice Jam Parameters

Calibration of the ice-enhanced HEC-RAS model involved selecting various ice-related parameters. Multiple parameter sets were tested, and a single set was identified that consistently provided the best agreement between the measured and simulated ice cover elevations, as well as the recorded water stages during ice jam events. Care was taken to ensure that the selected parameters remained within theoretically expected ranges.

After defining the internal strength of the ice jam- characterized by the friction angle and porosity, which typically take on universally constant values- the main challenges are to determine (i) the discharge at which the ice jam forms and (ii) the roughness of the ice cover. These two parameters are interdependent unless one is directly measured. During the breakup period, discharge is highly variable and estimates from the WSC gauge are often unreliable. The gauge frequently becomes inoperative, or the effects of ice on the rating curve are unknown. Additionally, since 1995, the gauge has only recorded water levels, meaning that discharges during breakup and ice jam events had to be estimated for calibration/validation purposes in some cases.

Flow estimation during breakup is associated with significant uncertainty. This uncertainty in discharge estimation over the breakup period can be primarily attributed to: (1) uncertainty in determining the timing of breakup initiation, and (2) uncertainty in estimating the discharge associated with breakup initiation. Discharge during breakup for the Porcupine River was estimated indirectly, as described in Section 5.3 of this report.

A review of the derived pre- and post-breakup flows for the project site, both in general and for the years selected for calibration, indicates a substantial difference between these stages. In the absence of reliable flow estimation/record during the breakup period, quantifying day-to-day discharge variability remains particularly challenging. Given the rapid changes in flow during breakup, errors in estimating breakup discharge could be as high as 200% to 300% in any given year.

The roughness of the ice jam also varies between events and years. However, observations on the Porcupine River downstream of Old Crow indicate that the ice jams in this reach are generally formed from floes of similar thickness and size (based on local knowledge), resulting in ice jams of consistent thickness. Therefore, the configuration of the underside of the jams is expected to be relatively uniform from year to year. Despite minor variations influenced by flow depth (and hence discharge), the year-to-year variability in ice jam roughness is likely low compared to the variability in formative discharge.

For years lacking direct flow estimates or recordings, such as 2011 and 2024, attempting to independently estimate discharge and then calculate roughness without referencing information from other years could yield subjective and potentially inaccurate estimates for both parameters. Instead, adopting a constant roughness value—derived from experience and within a relatively

narrow range—and then calculating discharge values that align with recordings from active upstream and downstream hydrometric gauges improves the reliability of discharge estimates. This approach preserves a degree of objectivity in estimating the overall ice jam characteristics.

The calibration process for the ice-enhanced HEC-RAS model followed these steps:

1. **Ice Jam Toe Location and Extent Identification:** Field data and breakup monitoring reports were reviewed to determine the toe location of each ice jam based on field observations and aerial reconnaissance conducted during the events. The chainage of the toe location was converted into relative model coordinates and applied to the corresponding cross sections. For the 2011 event, the head of the jam was not documented, and it was assumed to be approximately 4 km downstream of the community (~5.5 km downstream of the WSC gauge) based on ice classification images. As per the breakup monitoring report, significant ice runs were observed upstream during this event.
2. **Initial Ice Thickness Specification:** An initial sheet ice thickness of 1.3 m was adopted for all calibration years, based on historical ice cover thickness surveys (CRID surveys from 1976 to 1988) conducted at the Old Crow site. This thickness aligns with local knowledge, estimating the ice cover thickness to be around 1.2-1.5 m (4-5 ft, based on communication with local sources). This initial value was used as a starting point for ice jam calculations, but the model was iteratively adjusted to determine the stable ice thickness at each cross section. It is important to note that the initial thickness does not dictate the ultimate jam thickness. In all calibration and validation cases, the ice jam head did not extend beyond the confluence of the Old Crow and Porcupine Rivers, so no simulations were conducted past this junction.
3. **Specification of Ice Cover Properties:** The physical properties of the ice cover were set to typical breakup ice jam values found in the literature: ice specific gravity of 0.92, internal friction angle of 55°, and porosity of 0.35 (Beltaos, 1995). The ice erosion velocity was adopted as 1.25 m/s, based on a typical range of 1.2 to 2.4 m/s for breakup ice jams (Tuthill et al., 1998).
4. **Ice Jam Roughness Setting:** The roughness of the breakup ice jam, based on literature (Anders, 1980; Anders and Doyle, 1984), was found to vary between 0.05 and 0.072. Given the nature of the ice floes and the resulting similar jam thicknesses at this reach, a constant roughness value of 0.055 was adopted for consistency across all calibration and validation cases, reducing the degree of freedom in the final modelling parameters. Composite roughness values were calculated using the Belokon-Sabaneev method in HEC-RAS, varying between 0.03 and 0.07 depending on channel, floodplain, and under-ice conditions, consistent with values suggested for mechanically thickened ice covers (Nezhikhovskiy, 1964). Various roughness values (0.045–0.08) were tested to achieve a good fit with observed field water levels.
5. **Flow Selection for Calibration/Validation:** For each calibration/validation year, flows were selected based on the range of river discharge observed during the ice jam events (See

Section 6.5 for further details). This range was determined by examining recorded flows just before breakup and after the transition to open water conditions. The discharge was adjusted within this identified range until the simulated ice jam profiles and water levels matched historical observations.

- For the 2011 event, the estimated flow range was between 360 m^3/s and 2500 m^3/s, with a final simulated flow of 1050 m^3/s, within the middle of this range, close to the breakup average flow of 1150 m^3/s.
- The 2024 event had an estimated flow range of 130 m^3/s to ~3000 m^3/s, with a final simulated flow of 1250 m^3/s, near the midpoint of the range.
- For the 1991 event, Jasek's estimated flow of 3150 m^3/s was used for modelling.
- The 1993 event's estimated flow range was between 200 m^3/s and 3000 m^3/s, with a final simulated flow of 1200 m^3/s, close to the average flow (1366 m^3/s) during the breakup and ice jam formation period.

6. **Internal Strength Parameter (μ):** The internal strength of the ice jam is represented by the dimensionless coefficient μ, which scales with the internal friction angle (φ) and the longitudinal to lateral stress ratio within the jam. An internal friction angle of 55° resulted in μ values between 0.96 and 1.0. These values are within the typical range (0.8-2.0) suggested for this parameter.

The final adopted ice jam calibration parameters can be found in Table 6.2 .

Table 6.2 Final ice parameter values adopted for ice jam calibration.

Manning's *n* (Solid Cover)	Manning's *n* (Ice Jam)	Ice Jam Specific Gravity	Friction Angle	Porosity	Internal Strength Parameter (μ)	Critical Erosion Velocity (m/s)	Manning's *n* (Solid Cover)
0.022	0.055	0.92	55°	0.35	0.99	1.25	0.022

6.4.2.3 Calibration Results

The calibration results for the years 1991, 1993, and 2011 are illustrated in Figure 6.7, Figure 6.8 and Figure 6.9 respectively. Table 6.3 provides a summary of the differences between the simulated water surface elevations and the recorded water levels along the reach for each calibration years.

Table 6.3 Comparison of Simulated and Observed Water Levels for calibration years.

Ice Jam Event-HWM	Chainage (m)	Observed/ Estimated Level (m)	Simulated Level (m)	Difference (m)	Ice Jam Event-HWM
1991- 1	44903.5	246.888	246.97	0.08	1991- 1

Ice Jam Event- HWM	Chainage (m)	Observed/ Estimated Level (m)	Simulated Level (m)	Difference (m)	Ice Jam Event- HWM
1991- 2	42403.5	246.778	246.9	0.12	1991- 2
1993	44578	243.84	243.89	0.05	1993
2011	44481	243.95	243.92	0.03	2011

For the 1991 event, the discrepancies between simulated and observed water levels were minimal, with differences of 0.08 m and 0.12 m at chainages 44.9 Km (44,903.5 m) and 42.4 km (42,403.5 m), respectively. As a reference, the Old Crow Community is situated approximately between stations 43.5 Km and 45.5 Km. Figure 6.7 illustrates the simulated ice jam profile, including the top and bottom of the ice cover, as well as the water surface profile along the study reach. As shown in the figure, the simulated water surface profile aligns well with the HWMs, and there is a good agreement between the surveyed ice scars and the simulated ice cover profile, with surveyed points falling within the calculated top and bottom ice lines. Between stations 20 km and 25 km, although the majority of ice scars align with the middle of the calculated profile, there is a notable match between the top of the ice profile and the highest surveyed ice scars. It is important to note that some of these ice scars may have formed while the ice was still in the staging phase. Additionally, ice scars found upstream of the documented ice jam head were likely the result of ice runs.

The 1993 and 2011 events exhibited minor deviations within ±0.1 m at some locations along the channel. These small variations indicate an acceptable level of model calibration, demonstrating the model's capability to reliably reproduce flood profiles for ice jam events Simulated ice jam profiles for the 1993 and 2011 events are presented in Figure 6.8 and Figure 6.9, respectively.

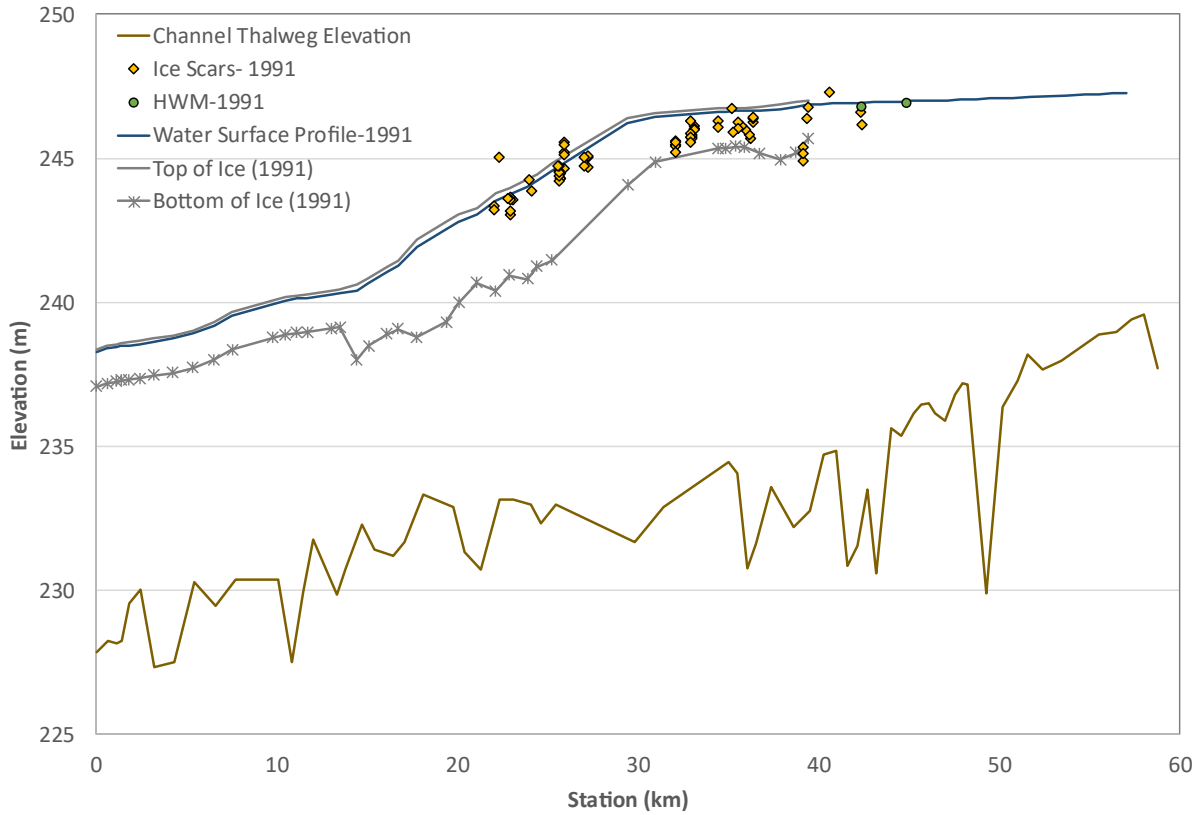


Figure 6.7 Calibration results for the 1991 ice jam.

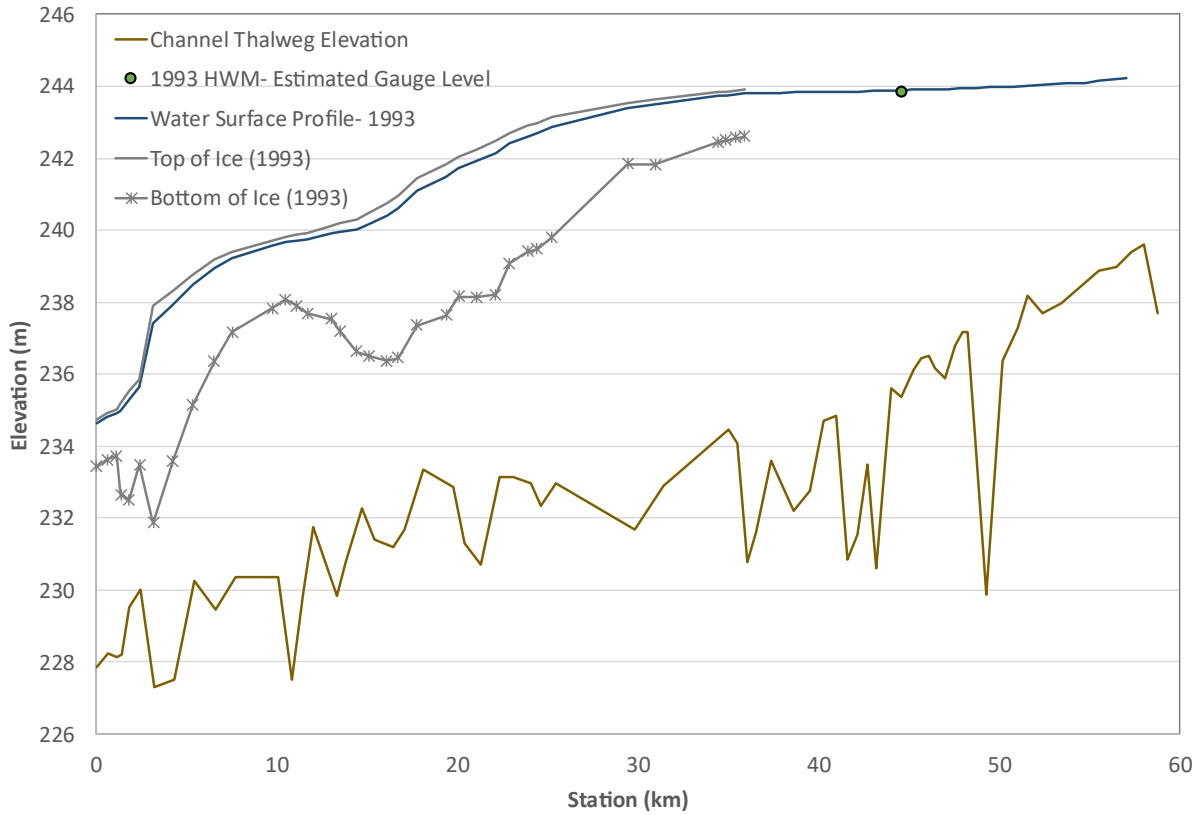


Figure 6.8 Calibration Results for the 1993 ice jam.

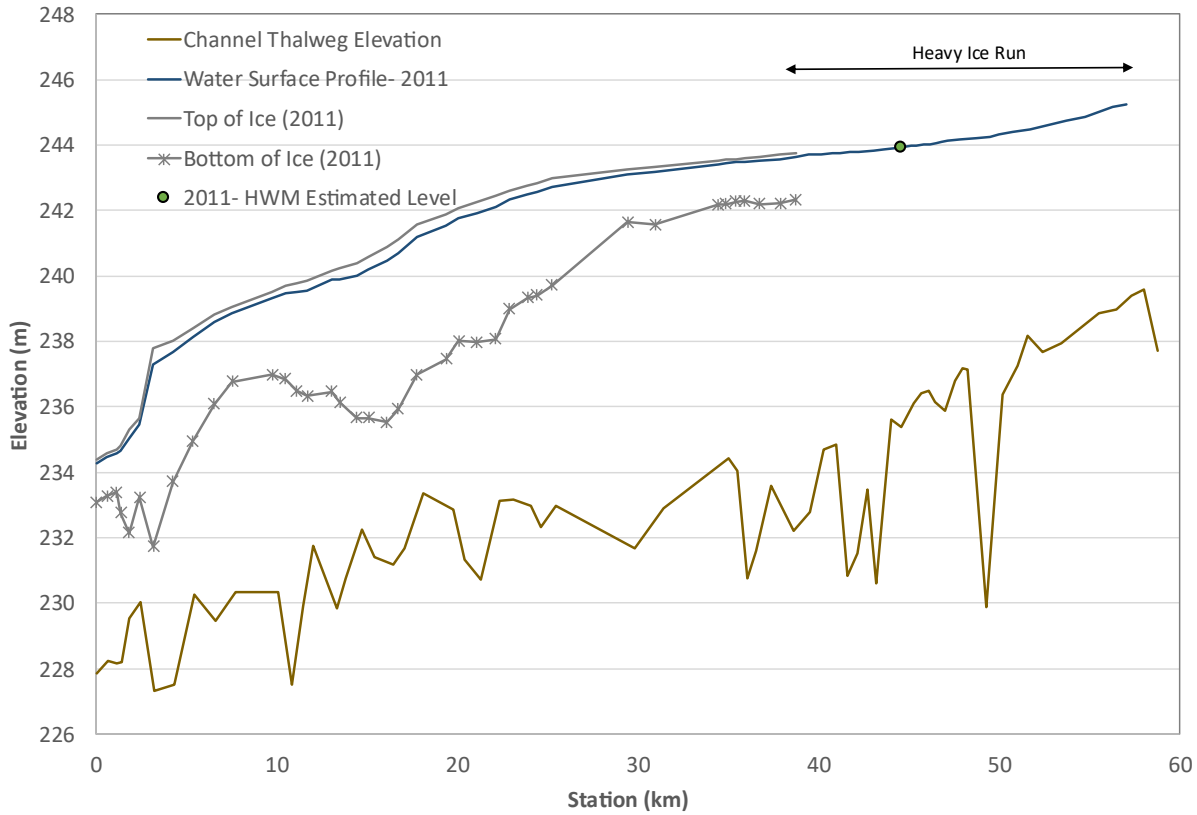


Figure 6.9 Calibration Results for the 2011 ice jam.

6.4.3 Model Validation

As previously discussed, the 2024 ice jam event was selected for validating the model calibration due to its comprehensive documentation. The breakup and ice jam characteristics were well captured through direct observations during the event, along with a HWM survey conducted by NHC. The ice jam features, including the toe and head locations, are consistent with historically observed ice jam formations on the Porcupine River.

The 2024 ice jam exhibited a steep, single-channel planform with a clearly defined channel. The toe of the jam was located near Goose Camp, extending upstream to the 12 Mile Bluff area, another common location for ice jam formations. The breakup chronology for this event is presented in the following sections.

On May 13, 2024, a High Water Advisory was issued for Old Crow due to increasing snowmelt response in the Porcupine River headwaters, with visible ice darkening and open leads forming along the riverbanks. By May 16, an observation flight noted a 5 km ice jam at Anik Island (220

km upstream of the community) and another jam between km 145-175[6]. Water was observed flowing on top of ice from km 265 down to Old Crow.

By May 17, breakup had commenced at Old Crow with two significant upstream ice jams: a 9 km jam at Billy Net Stretch (100 km upstream of the community) and a 24 km jam near Caribou Lookout (13 km upstream of the community). The warm weather and lack of freezing accelerated upstream flows, contributing to rising water levels. By late evening, an ice jam below Old Crow formed with the toe at Goose Camp (35 km downstream of the community) and the head at 12 Mile Bluff (12 km downstream of the community).

On May 18, remote camera observations confirmed the downstream ice jam had released by morning, allowing ice to flow past the Bluefish River confluence. Despite the release, water levels remained high with continued rising flows from upstream tributaries. Observation flights noted ice runs moving downstream, including a full-concentration 30 km ice run. By May 19, increasing upstream flows combined with ice runs resulted in a peak water level that rose 84 cm above the breakup peak.

For the validation, the model parameters- such as ice density, porosity, erosion velocity, internal friction angle, and lateral stress coefficients- remained consistent with those used in the calibration phase. The discharge range for the 2024 ice jam event was estimated to be between 130 m^3/s and 3000 m^3/s. A discharge of 1,250 m^3/s was selected for the simulation, which provided the best match with the recorded water level data during the event.

In addition to real-time water surface elevation recordings, several HWMs were identified using post-event photographs. The locations of these HWMs, primarily consisting of ice remnants on the channel banks, were later surveyed. It should be noted that these ice remnants represent only the ice debris left behind, so the actual water levels during peak stages were likely higher. Moreover, the remnants may have melted or shifted slightly down toward the channel as the water receded.

Table 6.4 summarizes the differences between the simulated and recorded water surface elevations, as well as the identified HWMs for the 2024 validation year. The comparison of the model simulation results with the recorded ice cover information is presented in Figure 6.10.

[6] River monitoring horizontal datum.

Table 6.4 Comparison of the simulated and observed water levels for the 2024 event.

Ice Jam Event- HWM- WSE	Chainage (m)	Observed/ Estimated Level (m)	Simulated Level (m)	Difference (m)
HWM 1	43607	243.022	243.62	0.6
HWM 2	43686	243.243	243.64	0.4
HWM 3	44208	242.61	243.6	0.99
HWM 4	44247	243.15	243.64	0.49
Gauge WSE	44578	243.6	243.65	0.05
Data Logger[7]	43066	243.5	243.63	0.13

Notes:
7. Data recorded on May 18, 2024, within hours of the ice jam removal.

The performance of the ice-enhanced HEC-RAS model was deemed satisfactory for the validation case. Notably, the toe locations of the ice jams and the channel planform within the equilibrium segments of the jams differed significantly between the calibration and validation years, leading to distinctly varied ice jam profiles. Despite these variations, the adopted parameter set effectively captured the key characteristics, including the location of the jam toe, as well as the length and thickness profile of the jam within its equilibrium section. Overall, the model demonstrated a reliable capability to simulate the equilibrium portion of the ice jam across both validation and calibration years.

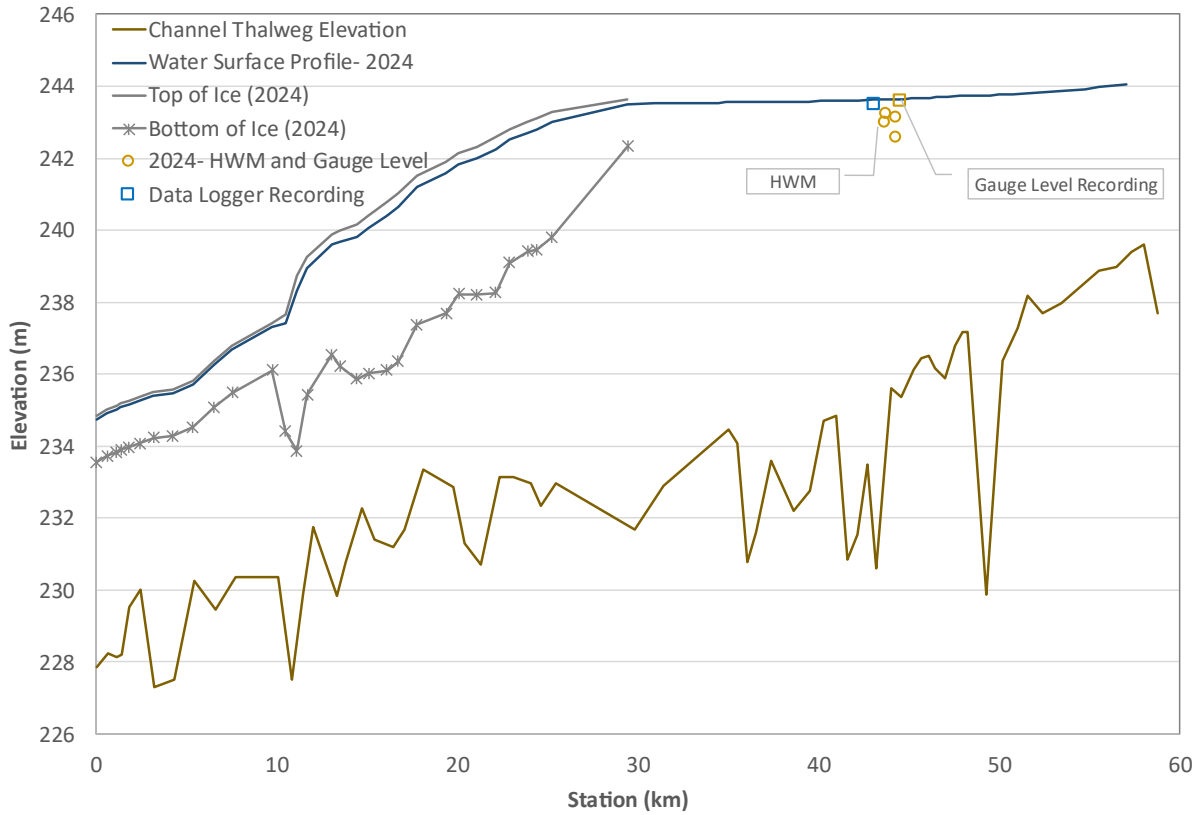


Figure 6.10 Model validation results- 2024 event.

6.5 Ice Cover Flood Frequency Analysis

This section outlines the methodology developed for the frequency analysis of ice jam-induced flood levels for the project. Peak water levels from ice cover are a result of complex river ice processes. The complexity warrants exploring non-standard statistical approaches to produce flood frequency estimates. There is a wide range of possible ice jam scenarios that might lead to maximum water levels; as such, to produce ice jam induced flood levels a Monte Carlo analysis is used to model the probability of various ice jam scenarios that result in maximum water levels.

Monte Carlo analysis employs statistical techniques to evaluate the collective influence of causative factors on the characteristics of an entire dataset, rather than focusing on individual events. This approach is particularly advantageous as it accommodates potential variations in influencing factors when assessing the effects of their impact on ice-related water levels.

Instead of analyzing individual events explicitly, the method aggregates data to develop statistical distributions of independent variables (input distributions), which are subsequently transformed into statistical distributions of dependent variables (output distributions). Kuczera (1999) provides a comprehensive explanation of the application of Monte Carlo analysis for joint frequency analysis, particularly relevant in flood hydrology studies.

The following steps summarize the approach undertaken to develop design ice jam induced flood levels. Figure 6.11 provides a visual representation of the analytical approach described.

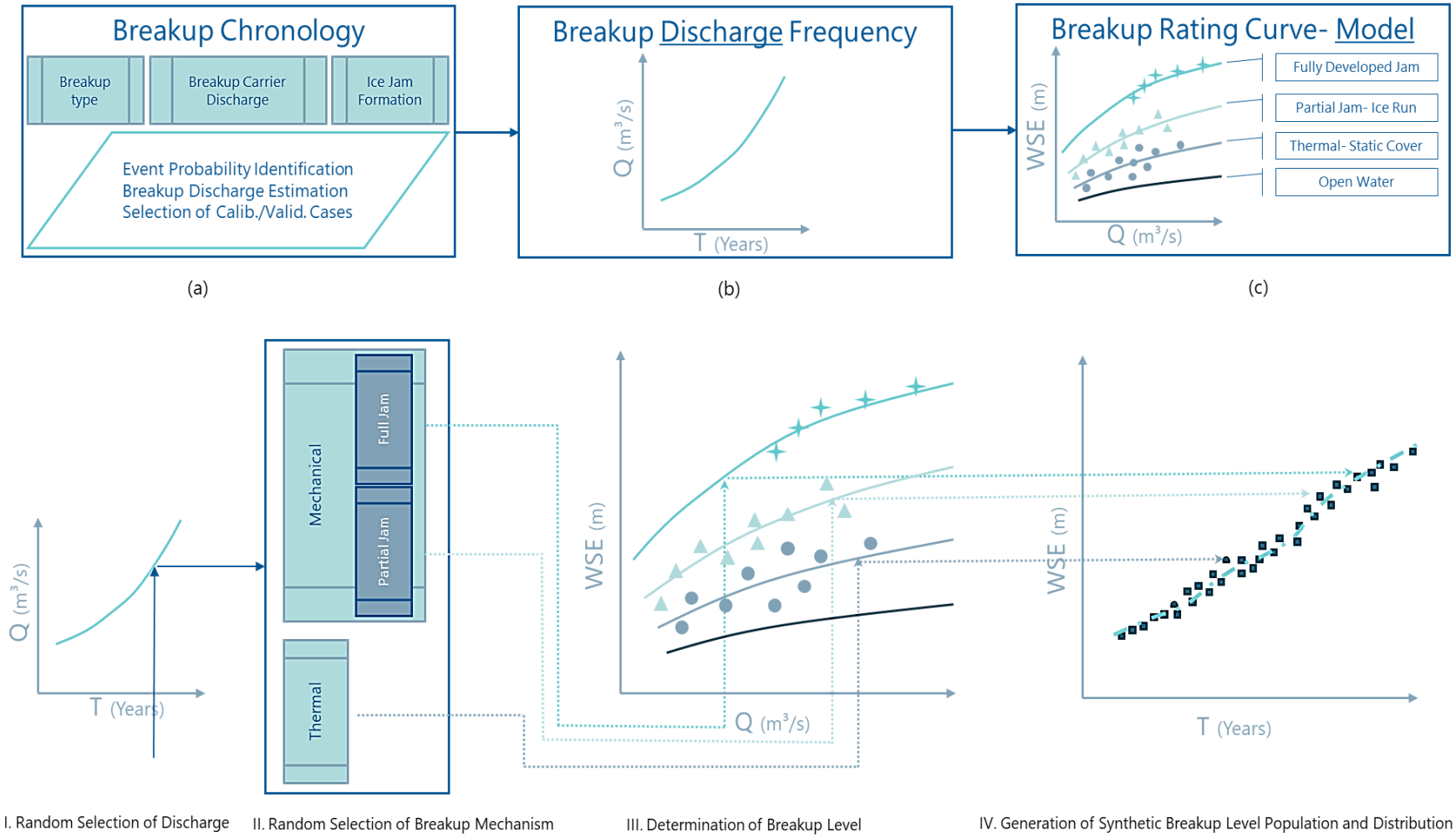


Figure 6.11 Ice jam induced flood level frequency analysis steps; deterministic and statistical analyses (a, b, c) and Monte Carlo simulations steps (I to IV).

Step 1: Breakup Discharge and Frequency Analysis:

Breakup discharge refers to the flow rate corresponding to the peak water level. This flow can occur at any point between the onset of breakup, when ice cover is still present, and the period after breakup, when open water conditions prevail.

Determination of this flow is challenging. Even if the exact timing of the breakup initiation is known, estimating the magnitude of this flow is difficult due to the uncertain relationship between water level and flow as the channel transitions from a stable, solid, floating ice cover to fully open water conditions.

There is a significant gap in hydrometric records at Old Crow, adding further challenge to the estimation of breakup flow. No flow recordings are available at the community after 1995. Flow data exists at the WSC gauge (09FD001) from 1961 to 1995, with ice-affected records denoted in the dataset (coded as "B" for ice-affected values). The currently operating hydrometric gauge, established in 2006, records only seasonal water levels and does not indicate whether the measurements are ice-affected.

Instead, a relatively detailed breakup monitoring program has been in place since 1992 (refer to Section 4.2.3 for details). As a result, data from the breakup monitoring reports formed the primary basis for estimating breakup discharge in this project. Where ice-period information was available in gauge records, it was used in conjunction with the monitoring reports.

A review of breakup monitoring reports and gauge data indicates that breakup predominantly occurs during the rising limb of the flow hydrograph at Old Crow. Therefore, the breakup period was defined based on the monitoring reports, and breakup flow was estimated for this period using available gauge recordings when flow measurements were present. When gauge data was unavailable due to non-operation or conversion to a seasonal water level recording format, flow estimates were made using derived flow data for the breakup period.

A breakup discharge database was developed for this project summarizing the required information for breakup discharge frequency analysis. This database provides the essential information required to perform an ice jam-induced flood level frequency analysis using a Monte Carlo analysis.

The breakup discharges utilized in the Monte Carlo analysis were generated by randomly sampling discharge values from the frequency distribution derived from recorded breakup events. The resulting frequency curve of breakup discharges is illustrated in Figure 6.12. Among the tested distributions, both the Pearson Type III (P3) and Log-Pearson Type III (LP3) ranked as the best fits to the data. However, the Pearson Type III distribution was selected based on a visual "goodness of fit", particularly for flows with higher return periods.

The distribution (P3) more accurately represents the largest recorded events, specifically those near the 1 % AEP. For comparison, the Log-Pearson III, Normal, and Log-Normal distributions are also plotted, providing additional context for evaluating the dataset.

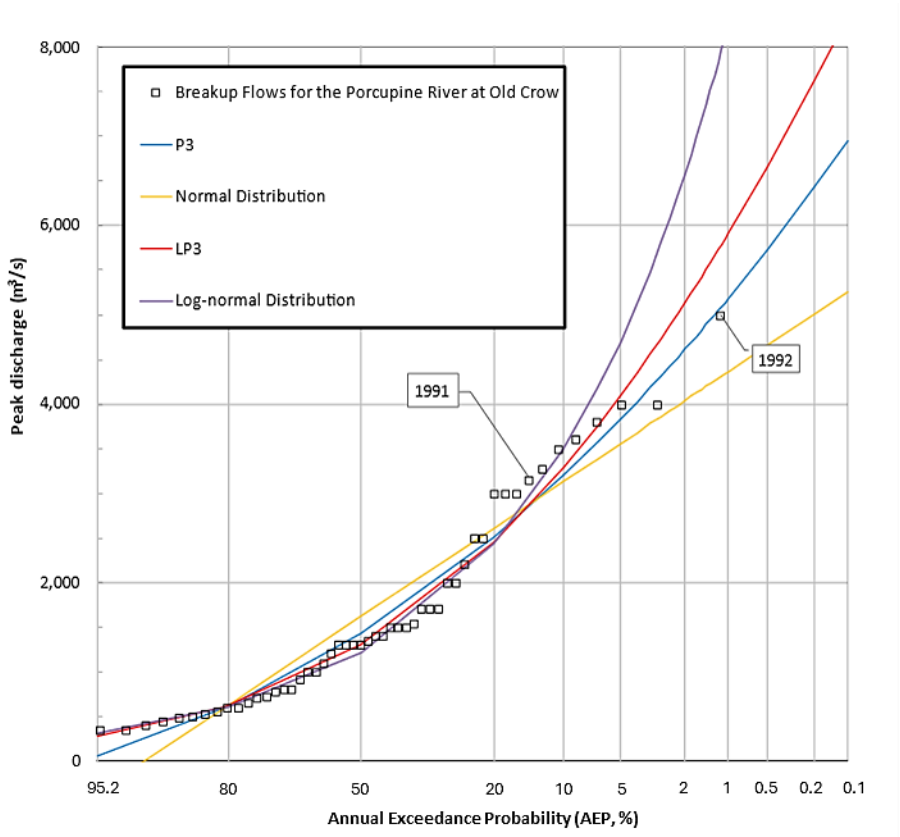


Figure 6.12 Frequency curve for breakup discharges.

In addition to associating the estimated breakup discharges with recorded events, the characteristics of each historical event were defined using the developed breakup chronology (refer to Section 4.2.3 for details). Based on these historical events, various scenarios were formulated to represent ice jam conditions for modelling purposes in this study. These scenarios were constructed by combining observations of historical ice jam characteristics with hypothetical yet plausible conditions targeting the creation of framework for simulations.

The scenarios are categorized as follows:

1. **Thermal Breakup Condition**: Events controlled primarily by thermal processes.
2. **Dynamic Breakup Leading to Heavy Ice Runs**: Scenarios involving heavy ice runs without the formation of ice jams.

3. **Dynamic Breakup Leading to Ice Jam Formation**:
    - **Partial Jams**: Ice jams with the equilibrium section located downstream of the community.
    - **Full Jams**: Ice jams where the equilibrium length extends to or beyond the community.

For the full ice jam development scenarios, it is assumed that contributions from upstream ice release play a critical role. These upstream contributions include the release of ice from prior jams, adding to the ice volume and supporting the growth of an existing jam downstream. This process allows the head of the jam to reach or pass the community without necessarily causing a release of the jam toe at the downstream end.

Following the definition of simulation scenarios and platform development, the probability of each event was estimated based on historical observations, as summarized in Table 6.5 below.

Notably, historical records indicate that upstream ice javes have not significantly contributed to extensive ice jam growth that severely impacted the community. However, instances have occurred where partial upstream ice releases, or javes, contributed to jam development downstream. In these cases, the released ice volumes were either insufficient to result in extensive ice jams or the downstream jams released before achieving full growth.

Although such a phenomenon has not been observed to result in catastrophic impacts, it remains a significant risk. Previous studies, such as Jasek (1993), have highlighted this risk during past events. For instance, in the 1991 event, Jasek noted that if the upstream ice jams had released before the downstream jam was cleared, the additional ice volume could have exacerbated the jam's growth, potentially extending beyond the community and worsening the flood conditions.

Table 6.5 Summary of historic ice conditions at breakup.

Breakup Type		Number of Historic Events	Probability
Breakup mode	Thermal	4	0.15
	Dynamic	22	0.85
Jam formation (Downstream of Old Crow)	Jam formation	17	0.31
	No jam formation	37	0.69
Jam induced flooding	Major (full jam)	4	0.24
	Minor/No flooding (partial jam)	13	0.76
Toe location	Bluefish confluence	10	0.75
	Goose Camp	1	0.10

Breakup Type		Number of Historic Events	Probability
	12 Mile Bluff	2	0.15
Jave contribution	Jave occurrence during breakup and caused further growth to the jam	1	0.05
	No Jave occurred during breakup, or had no impact on the existing jam	21	0.95

Step 2: Ice-affected Rating Curves for Breakup:

Using the calibrated model, each predefined breakup scenario was simulated across a range of flood discharges derived from the frequency analysis of breakup flows (Figure 6.12). This process resulted in the development of unique rating curves for each scenario at the community location, representing the floodwater level associated with a specific discharge under the prevailing breakup conditions. These sets of rating curves are directly utilized in the Monte Carlo analysis to translate the randomly selected discharge into the corresponding water level, based on the assigned breakup scenario.

Figure 6.13 below illustrates the rating curves developed for the various scenarios analyzed in this study. For the partial and full ice jam scenarios, simulations were conducted with the ice jam toe positioned at three locations: the Bluefish River Confluence, Goose Camp, and the 12 Mile Bluff area. Each location is associated with a distinct probability of occurrence in the event of a dynamic breakup resulting in ice jam formation (as outlined in Table 6.5). However, for clarity in the figure, only the rating curves corresponding to the Bluefish Confluence toe location are presented for the partial and full jam scenarios.

A curve was fitted to each of the rating curves, and the corresponding equation that best replicates the fitted curve was derived. These equations are utilized to convert flow discharges into water levels under the specified breakup scenarios.

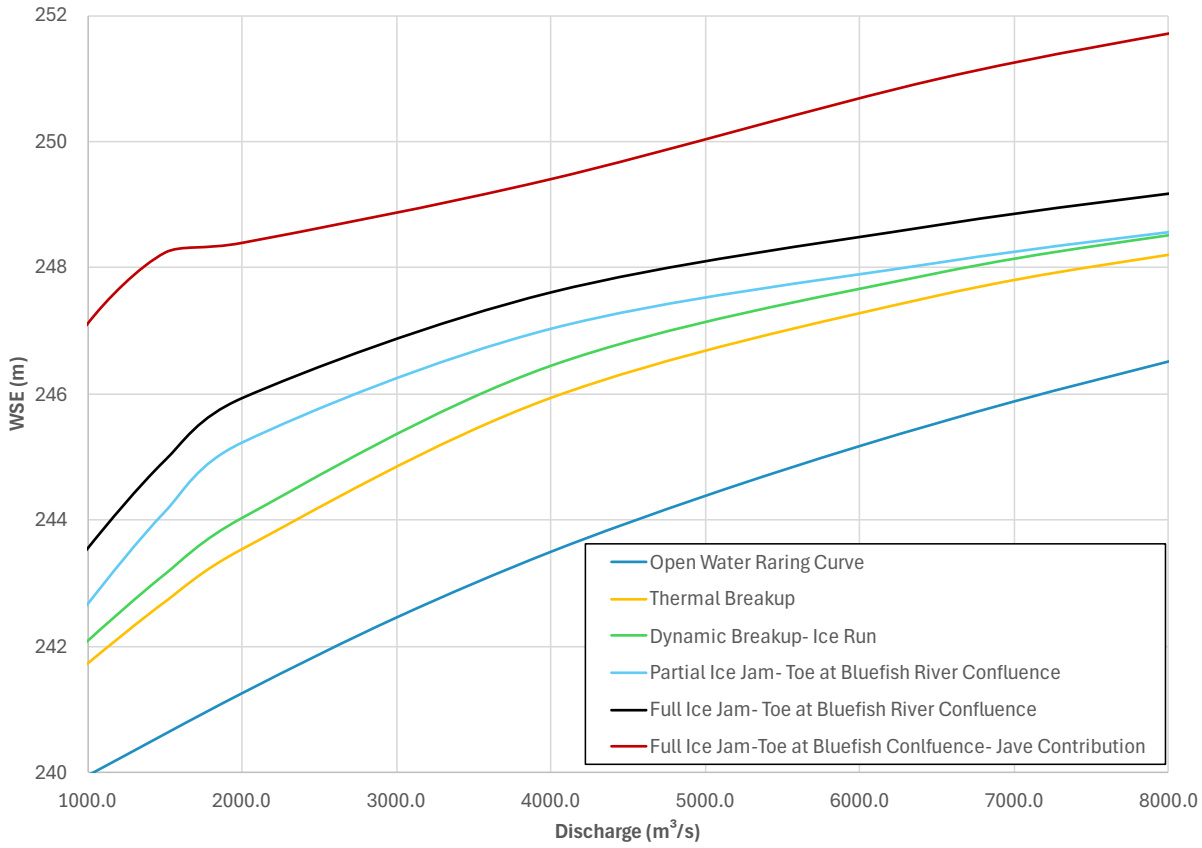


Figure 6.13 Ice affected rating curve for breakup.

Step 3: Monte Carlo Analysis of Ice-Induced Flood Levels:

The goal of the Monte Carlo simulation is to present resulting water surface levels that will result from an infinite number of breakup discharges under various ice cover scenarios. This allows for an assessment of the maximum water surface level that could result from an unknown combination of ice cover scenarios.

The Monte Carlo analysis generates an extended series of peak breakup water levels (10,000 events) based on the probabilities of occurrence for the following three ice conditions: (i) a thermal breakup; (ii) a mechanical breakup that does not produce an ice jam but leads to an ice run; and (iii) a mechanical breakup resulting in the formation of an ice jam, either fully or partially. The probabilities associated with each of these conditions were determined based on the breakup types inferred from historical records (refer to Table 6.5).

The following steps, referred to as the Monte Carlo analysis, were employed to determine the breakup flood level frequency:

1. A synthetic series of breakup events (10,000 events, or "years") was generated. For each simulated year, a breakup type was assigned, along with a corresponding scenario code, based on the assigned probabilities for each breakup type. The synthetically generated scenarios within each category (as defined by the scenario code) were reviewed to ensure that the generated population adequately represents physically plausible conditions prior to generating the corresponding water levels.
2. Using the assigned code, the appropriate equation was selected and applied to calculate the water level corresponding to the flow, based on the defined scenario code. This process generated a large, synthesized dataset of water levels for subsequent frequency analysis.
3. The synthesized data were ranked and plotted as a frequency curve of peak breakup levels.

All of the aforementioned steps are presented schematically in subfigures I-IV of Figure 6.11.

Step 4: Ice Jam Flood Level Frequency Curve Development

The peak annual ice-affected flood level frequency analysis was conducted by combining the water level data sets for various breakup scenarios. The resulting series were ranked and plotted as a frequency curve of peak annual ice-affected breakup levels and compared to the recorded peak annual ice-affect breakup levels (Figure 6.14). In addition to the ice jam flood frequency curve, three hypothetical flood frequency curves have been included to define the upper and lower bounds of flood levels induced by ice-related processes. These curves represent distinct breakup mechanisms: the **Ice Jam Only Curve**, which assumes breakup is governed solely by ice jam formation; the **Ice Run Curve**, representing dynamic breakup scenarios without significant ice jamming; and the **Thermal Only Curve**, which assumes breakup is exclusively driven by thermal processes with no ice jam/ ice run influence.

As observed, the flood level frequency curve converges with the hypothetical curves at the upper and lower ends. It is important to note that water levels associated with larger events, such as the AEP of %0.1(1,000-year), are based on scenarios involving combinations of less probable events. Consequently, the values for these cases should be interpreted with caution, as they resulted from a more limited population of synthetic values.

The 1% and 0.5% AEPs, along with the two highest recorded water levels at the community, are also listed on the figure to facilitate a comparison between the historically recorded levels and the estimated levels for the 1% and 0.5% AEPs. Table 6.6 lists the peak annual ice-affected flood levels for a range of AEPs. The open water level frequency values are listed for comparison.

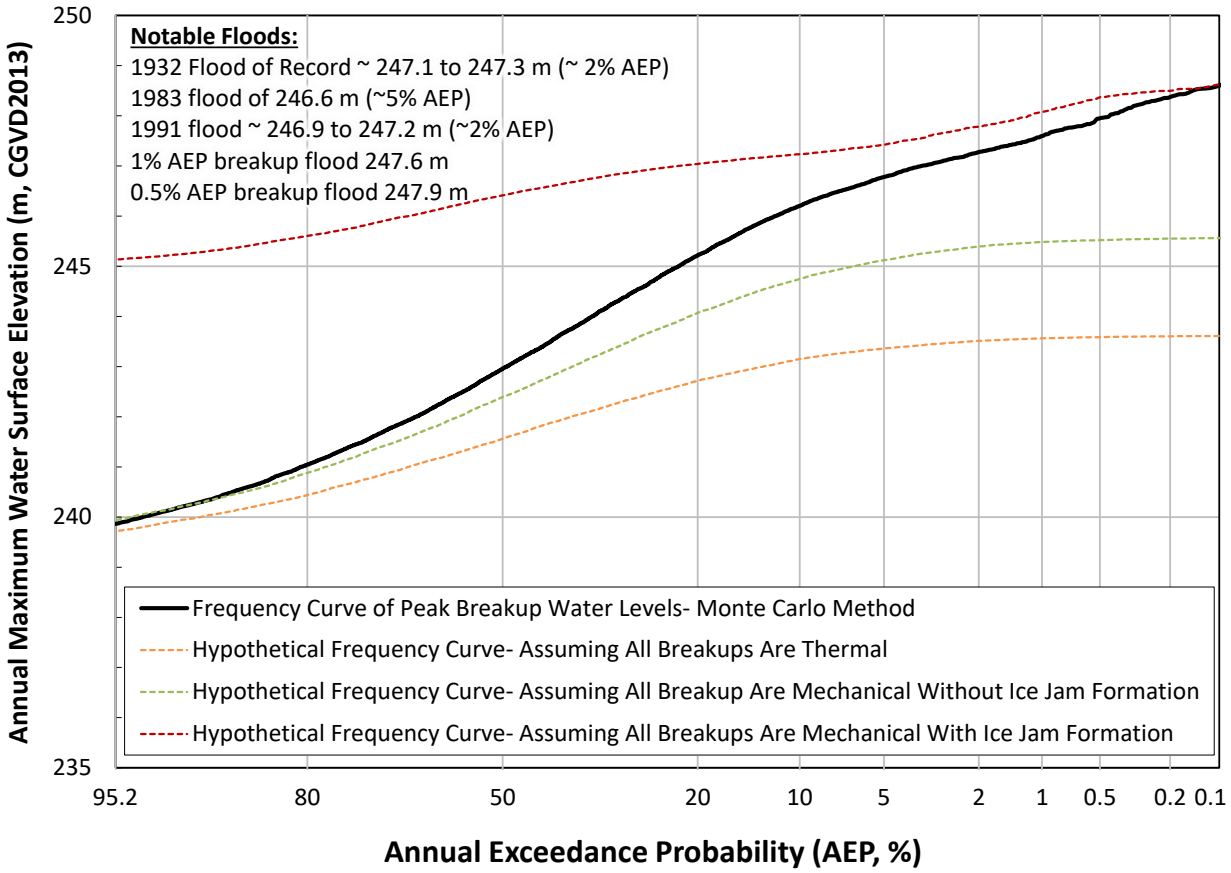


Figure 6.14 Frequency curve of peak annual ice-affected water level at Old Crow at the WSC gauge location.

Table 6.6 Peak annual ice-affected flood level frequency values at WSC Gauge Location. Values in CGVD2013 datum.

Return Period	Annual Exceedance Probability	Peak Annual Ice-affected Flood Level	Open Water Flood Level
2-year	% 50	242.9 m	243.4 m
10-year	% 10	246.2 m	245.3 m
20-year	% 5	246.7 m	245.7 m
50-year	% 2	247.2 m	246.3 m
100-year	% 1	247.6 m	246.7 m
200-year	% 0.5	247.9 m	247.0 m
500-year	% 0.2	248.5 m	247.3 m
1991	~ % 2	246.9 – 247.2[8] m	
1932	~ % 2	247.1 – 247.3[9] m	

Notes:

8. 246.9 m was reported by Jasek (1992) based upon a high-water mark survey and used as assumed value for this study; 247.2 m was reported by Janowicz (1992) as an estimated high-water level
9. 247.1 m as reported by Janowicz, (1992); 247.3 as reported by Fenco Consultants (1974).

7 FUTURE CONDITIONS

There are no established standards or guidelines for outlining how potential climate and land cover change impacts should be assessed and applied for floodplain mapping in the Yukon Territory. NHC reviewed the Federal Flood Mapping Guidelines Series (FFMGS) (Government of Canada, 2023, NRCan and Public Safety Canada, 2018) and the Northwest Territories Ice Jam Flood Mapping Guidelines V1.0 (NHC, 2023a) and developed the following approach for assessing future conditions:

1. Review of guidelines and standards. In the absence of flood mapping guidelines for the Yukon Territory, NHC will rely on FFMGS when selecting a design flow. The climate change assessment will be based on Northwest Territories Ice Jam Flood Mapping Guidelines V1.0.
2. Complete a background review of climate change studies that highlight interaction between different cold region hydrological processes, and their response to changing climatic forcing, studies that report observed trends in relevant hydro meteorological variables and physiographical conditions, studies that investigate past and future changes in cold region hydrological processes using hydrological models and future climate projections.

3. Identify the potential impacts of different hydrometeorological variables as well as physiographical conditions on the critical flood mechanisms. During this step NHC checked available data for each of the selected variables and conditions and identified if quantitative analysis of the change was appropriate. The results of this step are summarized in Sections 7.2 through 7.7.
4. Assess how the dominant flood hydrology may change under a changing climate. This step is summarized in Section 7.8.
5. Identify a flood mapping scenario that reflects potential changes in dominant flood mechanisms.

7.1 Potential Impacts of Climate Change

Both, open water and ice-impacted flooding are affected by climate change. Among many variables that characterize changing climatic conditions, data for temperature and precipitation are more commonly available. Changes in temperature and precipitation are anticipated across Canada, with greater changes observed and projected for its northern regions (e.g., Northern Climate Exchange, 2015). These changes might impact the hydrologic and ice regimes in the study area. Currently, the hydrologic regime is driven by snowmelt. Under climate change, increased precipitation in late fall coupled with temperatures still below zero may lead to an increase in local snowpack and higher freshet flows. Higher temperatures during winter could also promote rain-on-snow events which could affect snowpack properties and might generate runoff. Eventually, with ongoing temperature increases, the freezing season will become shorter. Coupled with precipitation increases, this may lead to more extreme rainfall events in spring and summer, thus eventually shifting towards a mixed hydrological regime (e.g., Champagne et al., 2023).

Air temperature is a strong driving factor for ice cover formation, and it affects breakup timing. An increase in temperature shifts those two events closer to each other and results in a shorter ice cover duration. Shorter ice cover duration and winter temperature increase lead, in turn, to a thinner ice cover and, as a result, to a reduced severity of ice jams (Das and Lindenschmidt, 2021; Turcotte et al., 2019; Beltaos and Burrel, 2002). Das and Lindenschmidt (2021) note that a longer pre-breakup ablation period might increase the probability of a thermal breakup versus a mechanical one. . However, the relationship between the different factors is complex and they might counteract each other. For example, earlier snowmelt and resulting earlier river ice exposure coupled with higher winter discharge might lead to a higher probability of a mechanical breakup, since incoming shortwave radiation earlier in the season might not be enough to trigger ice cover ablation (Turcotte et al., 2019). This might be counteracted by increasing snowpack thickness. An increase in snow can provide more insulation for the ice-cover and can reduce its thinning (Das and Lindenschmidt, 2021). Snowpack increase will result

in a larger freshet which increases the probability of mechanical breakup (Turcotte et al., 2019). Increased fall rain will mean that ice freeze-up will take place during higher flows, and thus higher flows will be required to initiate its breakup, which can potentially lead to a reduced probability of significant ice jams (Das and Lindenschmidt, 2021). These processes are complex, and rivers may not respond the same way to a dynamic freeze-up. Higher temperature also means more rainfall events in winter. An increase in winter rainfall can enhance mid-winter breakup events due to ice-cover ablation and increased flows.

In addition to changes in hydrometeorological variables, changes in physiographical conditions have the potential to affect hydrologic and ice regimes. Processes such as permafrost thaw and land cover change will affect precipitation interception, redistribution, and infiltration, thus changing the overall water availability for runoff in the system.

Table 7.1 summarizes the potential impact of change on the flood mechanism variables that have been discussed. Based on data availability and project scope, it also summarizes the proposed analysis for each variable. The following sections provide the analysis for each of the groups.

Table 7.1 Summary of potential drivers of change to future flood mechanisms.

Group	Variable	Potential Impact on Flood Mechanism	Proposed Analysis
Hydrometeorological	Air temperature	• ice cover duration • ice volume • ice breakup regime (mechanical vs thermal) • freshet discharge timing	• Trend analysis on historical average, minimum, and maximum daily temperature • Projected changes in monthly cumulative degree-days above °C
	Rainfall	• number of mid-winter breakups • freeze-up water levels and discharge and, therefore, breakup thresholds	• Trend analysis on rainfall • Projected changes in monthly precipitation
	Snowfall	• ice cover thickness and degradation • ice breakup regime (mechanical vs thermal) • freshet discharge magnitude and timing	• Trend analysis on historical snowfall, historical snow water equivalent and snow depth • Projected changes in monthly precipitation
River Ice	Thickness	• ice cover resistance	• Literature review

	Duration	• ice breakup regime (mechanical vs thermal)	• Literature review
Permafrost	extent	• channel morphology and bank stability	• Literature review
	Active layer thickness	• Surface and groundwater discharge magnitudes and temperature • Surface elevation	• Literature review
Aufeis	Thickness, extent, location	• Surface runoff upstream • Ice cover resistance	• Literature review
Land cover	Forest cover Shrub cover	• Surface and groundwater discharge magnitudes and timing	• Literature review
Geomorphological Changes		• Channel morphology and bank stability • Surface elevation • Surface and groundwater discharge velocities • Ice cover formation • Aufeis location • Ice jam location	• Literature review • Conceptual model

7.2 Hydrometeorological Variables

To characterize changes in hydrometeorological variables, NHC analysed trends in observed temperature and precipitation (rain and snow) data as well as analysed projected changes in both variables.

7.2.1 Historical Data

NHC used Adjusted and Homogenized Canadian Climate Data (AHCCD) to explore trends in historical meteorological variables. AHCCD accounts for potential inhomogeneities and systematic biases in temperature and precipitation records and is available from 1951 through 2022 at the Old Crow Airport location (climate stations Old Crow A and Old Crow RCS, station IDs 1582 and 26894). The dataset includes mean, maximum, and minimum daily temperature, total precipitation, rainfall, and snowfall. NHC also analysed snow survey data from the Yukon Snow Survey network for Old Crow (09FD-SC01). This dataset has both snow depth and snow water equivalent (SWE) available from 1977 through to 2024.

NHC applied the nonparametric Mann-Kendall test to detect statistically significant changes (with the level of significance of 0.05) in monthly average temperature and monthly total

precipitation. Only years with at least 85% of record complete were used for trend analysis. The results are summarized in Table 7.2.

Historical trends show that:

- Average, minimum, and maximum temperatures have been increasing during November, January, and February.
- Average daily temperature increases in January, February, May, October, and November. No increase in temperature is detected for March and April.
- Minimum temperature has also been increasing during summer months.
- Winter snowfall has increased significantly over the last few decades.
- SWE has been increasing for February-April.
- Statistically significant increasing trends for rainfall were only detected for July and September.

Table 7.2 Mann-Kendall test results for monthly average temperature and total monthly precipitation. Significant increasing trends are highlighted in grey.

Month	Average daily temperature		Minimum daily temperature		Maximum daily temperature		Rainfall		Snowfall		Snow water equivalent	
	p-value	Tau	p-value	Tau	p-value	Tau	p-value	Tau	p-value	Tau	p-value	Tau
Jan	0.010	0.26	0.000	0.35	0.037	0.21	0.310	-0.17	0.268	0.15		
Feb	0.007	0.27	0.010	0.26	0.006	0.28	0.511	0.11	0.011	0.33	0.005[10]	0.606
Mar	0.097	0.17	0.505	0.07	0.053	0.19	0.511	0.11	0.001	0.46	0.001	0.314
Apr	0.093	0.17	0.058	0.19	0.188	0.13	0.136	0.22	0.069	0.24	0.049	0.240
May	0.001	0.33	0.000	0.36	0.007	0.27	0.523	0.09	0.881	0.02		
Jun	0.053	0.19	0.004	0.28	0.307	0.10	0.420	0.11	0.265	0.16		
Jul	0.073	0.18	0.002	0.31	0.894	0.01	0.011	0.33	0.209	0.21		
Aug	0.346	0.09	0.011	0.25	0.950	-0.01	0.666	0.06	0.549	0.09		
Sep	0.046	0.20	0.000	0.35	0.324	0.10	0.031	0.29	0.409	0.11		
Oct	0.025	0.23	0.004	0.29	0.095	0.17	0.938	0.01	0.111	0.21		
Nov	0.011	0.26	0.005	0.28	0.038	0.21	0.135	-0.24	0.000	0.52		
Dec	0.716	0.04	0.324	0.10	0.824	0.02	0.886	-0.03	0.001	0.44		

Notes:

10. Only 13 observations were available for February from Yukon Snow Survey network at Old Crow, therefore the results for February should be treated with caution

7.2.2 Future Projections

Temperature differences between northern and southern portions of the Porcupine River watershed can lead to ice induced floods at Old Crow (Section 5.2.3, Mechanism 3: Thermal regime driven jams). To investigate potential changes in this flood mechanism, NHC looked into projected changes in temperature. Projected changes in monthly DDT were downloaded for Coupled Model Intercomparison Project Phase 6 (CMIP6) from climatedata.ca[7] for Old Crow (represents northern portion of the watershed) and for Eagle Plains (represents southern portion of the watershed). The data was previously downscaled by the Pacific Climate Impact Consortium (PCIC) to a resolution of approximately 10 km using the BCCAQv2 method developed by PCIC (Cannon et al., 2015). NHC analyzed a median model response from 9 Global Climate Models (GCMs) for two Shared Socio-Economic Pathways (SSPs): 2-4.5 and 5-8.5, where SSP 5-8.5 represents a high emission scenario and SSP 2-4.5 represents a moderate scenario. The results were summarized for mid-century (2041-2070) and end- century (2071-2100) time horizons and compared to two historical periods: 1962-2000 and 2000-2024 (Figure 7.1 and Figure 7.2). Two historical periods were chosen to represent periods with available records. The results are shown in Figure 7.1 for Old Crow and Figure 7.2 for Eagle Plains. Note that for the two historical horizons, Figure 7.1 and Figure 7.2 show modelled results and not observations. This is done to account for potential biases in GCMs: when comparing modelled future results to modelled historic results with the same bias, it can be assumed that the bias is not affecting relative changes.

[7] https://climatedata.ca/download/

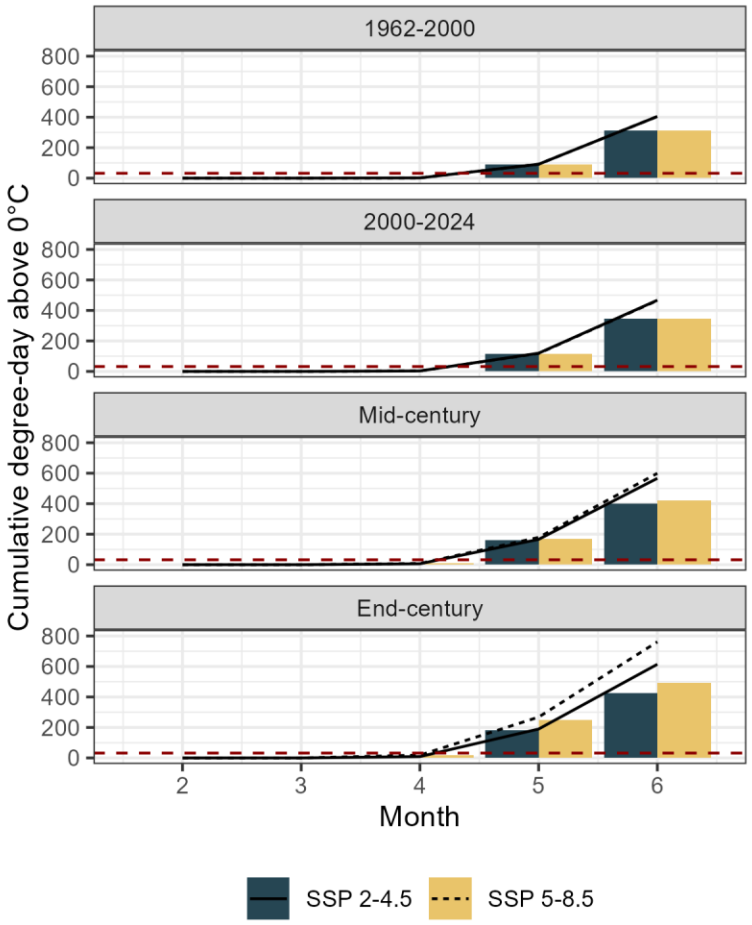


Figure 7.1 Projected changes in monthly cumulative degree-day above 0°C at Old Crow for 1962-2000, 2000-2024, mid-century (2041-2070), and end-century (2071-2100) time horizons. Black lines show cumulative degree-day above 0°C for entire January-June period. Red dashed line shows 32°C mark.

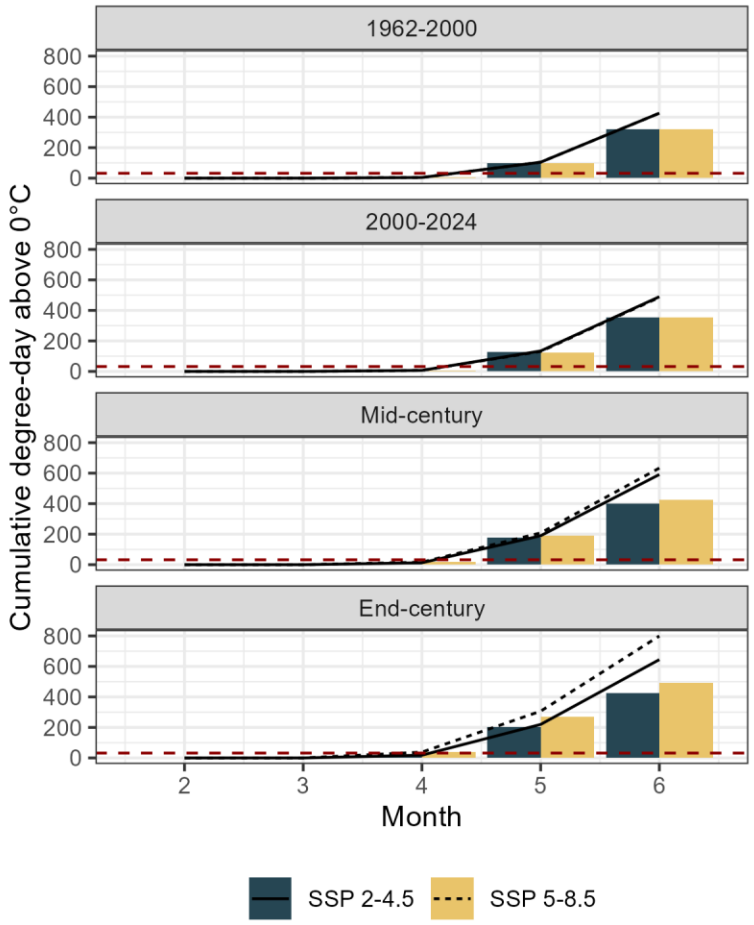


Figure 7.2 Projected changes in monthly cumulative degree-day above 0°C at Eagle Plains for 1962-2000, 2000-2024, mid-century (2041-2070), and end-century (2071-2100) time horizons. Lines show cumulative degree-day above 0°C for entire January-June period. Red dashed line shows 36°C mark.

Both scenarios project an increase in DDT for the April-June period at Old Crow and at Eagle Plains. In April, DDT is projected to increase from 3°C to a range of 9° to 18°C for Old Crow, depending on the SSP. At Eagle Plains, April DDT are projected to reach 18°- 38°C by the end of century, depending on the SSP. This means that the difference in April DDT between the southern and northern portions can be 20°C by the end of the century according to SSP 5-8.5. DDT of 36°C was previously reported as a typical value for a breakup to occur at Eagle Plains (Jasek, 1997). Thus, it is possible that, by the end of the century, southern portion of the Porcupine River watershed will potentially experience breakup in April, whereas the northern part will not.

Projected changes in precipitation were downloaded for the Porcupine River watershed from PCIC Climate Explorer tool[8] (PCEX) for the CanESM5 model. This model was selected for the analysis because its projected response across different indices is the closest to the mean response obtained using an entire CMIP6 ensemble (Curry et al., 2023). Similar to temperature, precipitation data is downscaled by PCIC using BCCAQv2. Projected changes in precipitation were analyzed for mid-century (2041-2070) and end of century (2071-2100) in comparison to the historic baseline (1981-2010) for entire study area. Precipitation is projected to increase for almost all months. The largest increase is projected for April-May, September, and January (Figure 7.3).



Figure 7.3 Projected changes in precipitation over study area for mid-century (2041-2070) and end-century (2071-2100) time horizons in comparison with 1981-2010 baseline.

[8] https://www.pacificclimate.org/analysis-tools/pcic-climate-explorer

To summarize, the analysis of future projections in cumulative degree-day above 0°C and precipitation shows that:

- DDT is projected to increase for April at both Old Crow and Eagle Plains from almost zero to at least 10°C and 20°C respectively
- For April, the difference between DDT at the two locations is projected to increase from 2-3°C up to 20°C
- For May, the difference between monthly average DDT at the two locations is projected to increase from 12-13°C (average for the baseline time horizon) up to 38°C (average for the end-of-century time horizon)
- Precipitation is projected to increase for almost all months.
- The largest increase in precipitation is projected for April-May, September, and January.

7.3 River Ice

Ice cover thickening between freeze-up and breakup is governed by air temperature. Winter and spring temperatures have been increasing in the past (Table 7.2) and are projected to keep increasing. Several studies report a decrease in ice cover thickness with a rate of 0.8-1.8 cm per year (e.g., Turcotte et al., 2019) as an apparent response to this increase. Ice cover ablation at the end of the winter season will depend on the snow cover thickness, incoming shortwave radiation flux, and the rate of temperature increase. The results of trend analysis suggest that snowpack has been increasing during the last decades (Table 7.2). Depending on the SSP scenario, winter precipitation is projected to increase between 20% and 75% (Figure 7.3). However, not all of it will fall as snow, and mid-winter rain-on-snow events might reduce the resulting snowpack. In general, an observed trend towards earlier, shorter, and a steeper freshet hydrograph on the Porcupine River illustrates the effect of an increase in air temperature and precipitation and might be more likely to cause large ice jams (Janowicz, 2017a).

7.4 Permafrost

Research indicates that the active layer may deepen in response to climate change. This will increase groundwater storage and the depth and length of infiltrated groundwater pathways. This, in turn, may lead to a decrease in groundwater contribution to runoff in the upstream reaches and an increase runoff in the downstream reaches (Bense et al., 2012, Lamontagne-Hallé et al., 2018). In addition, studies suggest that, due to permafrost thaw, the magnitude and spatial extent of groundwater contributions to streamflow will undergo an overall increase (Ge et al., 2011, Bense et al., 2012, Evans and Ge, 2017). This can partly explain an observed increase in regional winter flows (Brabets and Walvoord, 2009, Jacques and Sauchyn, 2009, Walvoord and Striegl, 2007). For example, in the Yukon River headwaters, the rate of permafrost-thaw-induced increase in groundwater contribution to the runoff is estimated to range between 0.7 and 0.9%

per year (Walvoord and Striegl, 2007). Possible subsidence due to permafrost degradation is further discussed in Appendix C.

7.5 Aufeis

Currently, no trends in the volume of aufeis and their spatial distribution are observed in permafrost-underlain terrains (Morse and Wolfe, 2016). There is no consensus about aufeis response to a changing climate (Turcotte et al., 2024a). However, while there might be more sub- and supra-permafrost discharge in cold months, it is possible that with rising winter temperatures, water refreezing will become more limited, which might decrease the thickness of both ground and stream aufeis. Additionally, expected permafrost degradation and changes in watershed connectivity might affect ground aufeis locations and their extent.

7.6 Land Cover Changes

The watersheds of interest may also be susceptible to land use change over both the medium- and long-term time horizons. Given the landscape of the watersheds, the most significant changes may occur from forest disturbances such as forest fires and infestations as well as from shrubification.

Forest fires in the region are projected to intensify in the future (Kim et al., 2024; McCoy and Burn, 2005; Wang et al., 2015), and can impact watershed hydrological response and peak flows in several ways:

- Fire may destroy forest canopy, leading to changes in several important components of the hydrologic cycle, including precipitation interception, snow accumulation and melt, and evapotranspiration.
- Fire may reduce or destroy the organic layer and thus impact soil insulation and the thermal regime and moisture content. In permafrost underlain terrains, this affects the seasonal thaw layer and the active layer thickness.
- Fire may modify the structure of surface and near-surface soils, reducing infiltration rates and, in some cases (depending on soil type, the severity of the fire and other factors), inducing water repellency.

A decrease in canopy cover will lead to increased amounts of precipitation reaching the ground, which will normally result in thicker snowpack. Being exposed to direct shortwave radiation, snow in those open areas could melt earlier, typically resulting in higher peak flows in snowmelt dominated watersheds in North America (e.g., Seibert et al., 2010; Pomeroy et al., 2012; Smith et al., 2023). A recent modelling study in a mountainous catchment in southern BC highlighted that the change in peak flow in response to forest fire will depend more on the spatial distribution of burnt areas than the affected area. Disturbances at higher elevations will lead to higher (and

earlier) peak flow because snowmelt from those areas will coincide with the snowmelt at lower and intermediate elevations, thus increasing watershed synchronization. In contrast, post-fire, advanced timing in snowmelt within intermediate and lower elevations leads to a watershed desynchronization and a smaller increase in peak flow (Smith et al., 2023).

Forest removal will also affect forest evaporation. Several studies highlighted the reduction in open area evaporation compared to forests (e.g., Zhao et al., 2021). This reduction, together with a decrease in intercepted precipitation, would increase soil moisture and the amount of water available for streamflow (Winkler et al., 2010), which could lead to faster runoff and larger flows. Observations in the Yukon showed that, on average, it takes about 5-10 years for a canopy to recover to a 10% forest cover after disturbance (Bartels et al., 2016).

In permafrost underlain regions, active layer thickening and developments of taliks were related to postfire conditions and change in soil thermal regime (Yoshikawa et al., 2002; Larsen et al., 2023). Depending on the site conditions, talik development might take 3-5 years after fire (Yoshikawa et al., 2002). This can result in enhanced winter streamflow caused by additional groundwater flow paths. In the Northwest Territories, this potentially led to an aufeis formation (Spence et al., 2020), and in Alaska, even after 10 years post-fire, burnt soils are less structured and can produce higher runoff due to multiple preferential pathways (Koch et al., 2014). In addition to changes in soil structure, forest fire might lead to the formation of a hydrophobic layer. This layer can act as a water barrier, thus decreasing infiltration and increasing surface runoff (DeBano, 2000; Kettridge et al., 2014). The effect, however, is temporary and runoff may return to pre-fire rates within a few years.

Several components of the hydrologic cycle, such as snow accumulation and melt as well as evapotranspiration, are also affected by ongoing shrubification. Shrub cover and density are increasing over the Canadian subarctic (Zhang et al., 2013), and it changes precipitation interception and affects snow accumulation and melt. Shrubs impact snow redistribution and promote preferential accumulation of snow due to increased roughness. During warm spells and in spring, protruding shrub branches decrease surface albedo and enhance snowmelt around them thus affecting snowmelt rate and timing (Belke-Brea et al., 2020). Resulting changes in snow cover can change soil thermal regime and active layer thickness. An increase in shrub cover and density is also projected to increase evapotranspiration (Krogh and Pomeroy, 2019) which in turn will change the soil moisture regime.

There is no straightforward relationship between land cover changes and peak flows. It is even more difficult to hypothesize what future land cover changes may be for the study area. As such, we are not recommending a specific adjustment to design conditions to account for future landcover changes. However, this is a limitation of the study results.

7.7 Geomorphological Changes

The Old Crow region is located in a complex, periglacial environment that includes previously unglaciated terrain, a continuous permafrost zone, and active fluvial and river ice processes. Each of these facets contribute to the geomorphic complexity and character of the region. The morphologies of the Porcupine and Old Crow Rivers are expected to respond to changes in climatic and environmental conditions, including changes to permafrost, flow, and precipitation regimes. Changes to the morphology and behavior of these river systems may alter the flood regime and associated geomorphic hazards along the river corridors.

Potential morphological responses of the Old Crow River and Porcupine River to changes in climate are described in Appendix C. However, it is important to note that there is considerable uncertainty in how the fluvial system may respond to changes in environmental conditions due to both inherent variability in natural systems and the complexity of feedbacks (both positive and negative) between climatic drivers and systems responses. Thus, potential net geomorphic responses may be indeterminate, as there may be multiple (and even opposing) responses to climatic drivers that vary spatially and temporally. Acknowledging the inherent level of uncertainty in predicting channel response to changing environmental variables, general geomorphic responses to climate change in the Old Crow region may include the following:

- Increasing temperature and precipitation may increase peak flow frequency and magnitude, which could increase bank erosion, channel migration, sediment transport, and risk of avulsions.
- Permafrost and ground-ice decay are likely to lead to increased bank instability, resulting in increased erosion and channel widening or migration. Permafrost decay may also cause floodplain subsidence, potentially increasing flood risk and the occurrence of channel avulsions.
- Changes to ice jam frequency and magnitude in the Porcupine River are uncertain owing to multiple drivers that can produce contrasting effects; Turcotte and Saal (2022a) found similar results.
- Ice jams will likely continue to form in reaches where there is increased resistance to ice flow as channel geometry changes, such as sharp bends, channel constrictions, and slope or flow velocity reductions.

More information regarding existing and potential future geomorphic conditions is provided in Appendix C.

7.8 Effect of Climate Change on Dominant Ice Jam Formation Mechanisms

Three dominant ice jam mechanisms were identified in Section 5.2.3. The first is related to aufeis formation at the confluence of the Porcupine and Bluefish rivers. This aufeis either directly blocks streamflow or acts as a dam and leads to a formation of a deep slow-moving reach upstream, favoring ice jam formation. Due to a lack of information about the impacts of climate change on aufeis formation, it is impossible to say how climate change will affect the mechanism. Therefore, no recommendation can be provided about an adjustment to design conditions for this mechanism.

The second mechanism is related to javes. Javes often occur following the local breakup at Old Crow due to the release of jams at the Salmon Cache and Driftwood confluence, or upstream of the confluence of the Old Crow and Porcupine Rivers. In addition, ice jams just upstream of Old Crow can produce javes upon breaking when releasing large amounts of built-up water. With increasing temperatures and extreme precipitation events, this mechanism can potentially be amplified under a changing climate due to an increase in rain-on-snow and mid-winter snowmelt events. However, increased groundwater storage resulting from permafrost thaw as well as thinner ice cover might counter these effects, and thus the overall changes to the second mechanism are highly uncertain.

Finally, a third mechanism is related to a differential temperature regime between southern and northern parts of the Porcupine River watershed. An ice jam flood in this case results from rapidly increasing discharge upstream due to higher temperatures at the southern part of the watershed with a strong ice cover downstream due to lower temperatures at the northern part. Trend analysis showed that while May temperature has been increasing, April-March temperature has not been changing significantly (Section 7.2.1), thus resulting in a higher temperature gradient between the end of winter and spring. The difference in DDT between Eagle Plains and Old Crow is projected to increase by the end of century, and thus this mechanism may be amplified under climate change. The amplification due to temperature difference alone might be counteracted by an existence of an ice cover mobilization threshold for both locations. If threshold DDT starts occurring earlier in the season for both locations simultaneously, the breakup mechanism might not be affected. The mobilization threshold is likely to change due to changes in physiographic setting and changes in ice cover characteristic. In this case, the third mechanism might be amplified if the mobilization threshold change rate is different between the southern and the northern parts of the watershed.

7.9 Recommended Changes to Present Day Conditions to Account for Climate and Land Cover Change

The qualitative and quantitative analyses above highlight that numerous variables and physiographic settings will be affected by projected changes in climatic forcing. Changes in future temperature and precipitation might contribute to both a decrease and an increase in ice jam flood severities and will also affect breakup mechanisms in different ways (Section 7.1, 7.8). Moreover, under the SSP 5-8.5 scenario, some models in the Canadian subarctic show that peak flows in snowmelt-dominated watersheds might start occurring outside of the freshet (e.g., Champagne et al., 2023). It is impossible to say, however, whether open-water flood events will become a dominant flood mechanism. Among all the outcomes mentioned in the sections above, there exists a combination of events caused by a changing climate that may generate the most critical and severe ice breakup, which may lead to higher flood levels:

- Occurrence of mid-winter breakups, followed by the re-freezing of the ice cover. This may increase overall ice production in the watershed and increase ice resistance at the end of the winter season. Based on the current conditions and observations, however, this outcome is unlikely, as no mid-winter breakups have been observed.
- Increase in winter snow accumulation which will also increase ice cover resistance at the time of breakup as well as increase the freshet discharge.
- Both a) increased winter groundwater discharge due to increase active layer thickness and b) changes in river morphology due changes in sediment transport (Appendix C) contribute to larger aufeis formation at the confluence of Porcupine and Bluefish rivers.
- Larger temperature differences between the southern and northern parts of watershed might lead to higher flows generated in headwaters earlier in spring. This larger flow generated by the southern part then encounters undeteriorated ice cover in the northern part of the watershed.

The current standard of practice for applying climate and land cover change adjustments to open water flood mapping is to adjust the design discharge by a percentage to represent future conditions. The resulting water surface elevations output from the hydraulic model are then mapped.

The same approach cannot be adopted for ice jam flood mapping due to the complexity of factors that may lead to ice jam induced flooding.

Unlike open water conditions, it is not possible to ascribe a unique flood level to each flood frequency discharge. Whereas flood *discharge* is the parameter to assess magnitude of open water floods, flood *level* is the key parameter to assess ice jam floods. For an ice jam flood condition, there are a range of flood levels that could be associated with a single discharge because the flood level magnitude resulting from an ice jam depends on factors other than

discharge – for example (as discussed in sections above): ice thickness, ice jam extent (with head and toe locations), toe location, and under ice roughness. There is no standard of practice for applying climate and land cover change adjustments to ice jam flood mapping.

A practical approach was adopted to incorporate climate change adjustments into the ice jam flood frequency analysis by systematically varying the ice jam parameters employed in the Monte Carlo simulations. Ice jam induced AEPs under future conditions were developed by adjusting causal factors used in the Monte Carlo analysis. The causal factors adjusted were two key flood-driving factors: breakup discharge and the probability of the dominant breakup type. The Monte Carlo analysis was then re-executed to generate an updated frequency curve for ice jam-induced flood levels at the WSC gauge location (09FD001) under a future conditions scenario.

The following rationale was developed for adjustment of the causal and probability factors to account for future climate and land cover conditions.

- The breakup discharge was increased by 15%. As outlined in the assessment of future conditions in Section 7.2.2, climate change is expected to drive increasing trends in temperature and precipitation during the breakup season (April and May) potentially influencing both the timing and dynamics of ice breakup. Increases in temperature and precipitation during April and May may result in increased breakup flow discharge. While this study does not directly assess flow increases, guidelines across Western Canada suggest that a 10–20% increase in discharge is a reasonable adjustment to account for future climate and land cover change[9,10]. The precise quantification of these impacts remains challenging due to complex interactions with watershed characteristics and other environmental factors.
- Climate projections indicate that the combined effects of multiple climatic and river ice factors may alter the probability of the dominant breakup mechanism. It is not possible to quantify the direction or magnitude of this change. The incremental increase of 5% for the probability of a dynamic breakup provides a somewhat conservatively high estimate on the potential increase in ice jam flood levels attributed to a potential increase in dynamic breakups.

The reconstructed ice jam induced flood level frequency curve and associated water levels represents a future climate condition at the WSC gauge and is presented in Figure 7.4 and Table 7.3 below.

[9] Legislated flood assessments in a changing climate in BC, https://www.egbc.ca/getmedia/f5c2d7e9-26ad-4cb3-b528-940b3aaa9069/Legislated-Flood-Assessments-in-BC.pdf

[10] Alberta flood hazard identification program, flood study technical guidelines, 2022. https://www.alberta.ca/flood-hazard-identification-program

The future climate condition was not applied to flood mapping. Instead, it was incorporated into the community flood threshold analysis. The community flood threshold analysis provides information for flood risk management and community resilience planning and it described further in Section 9.

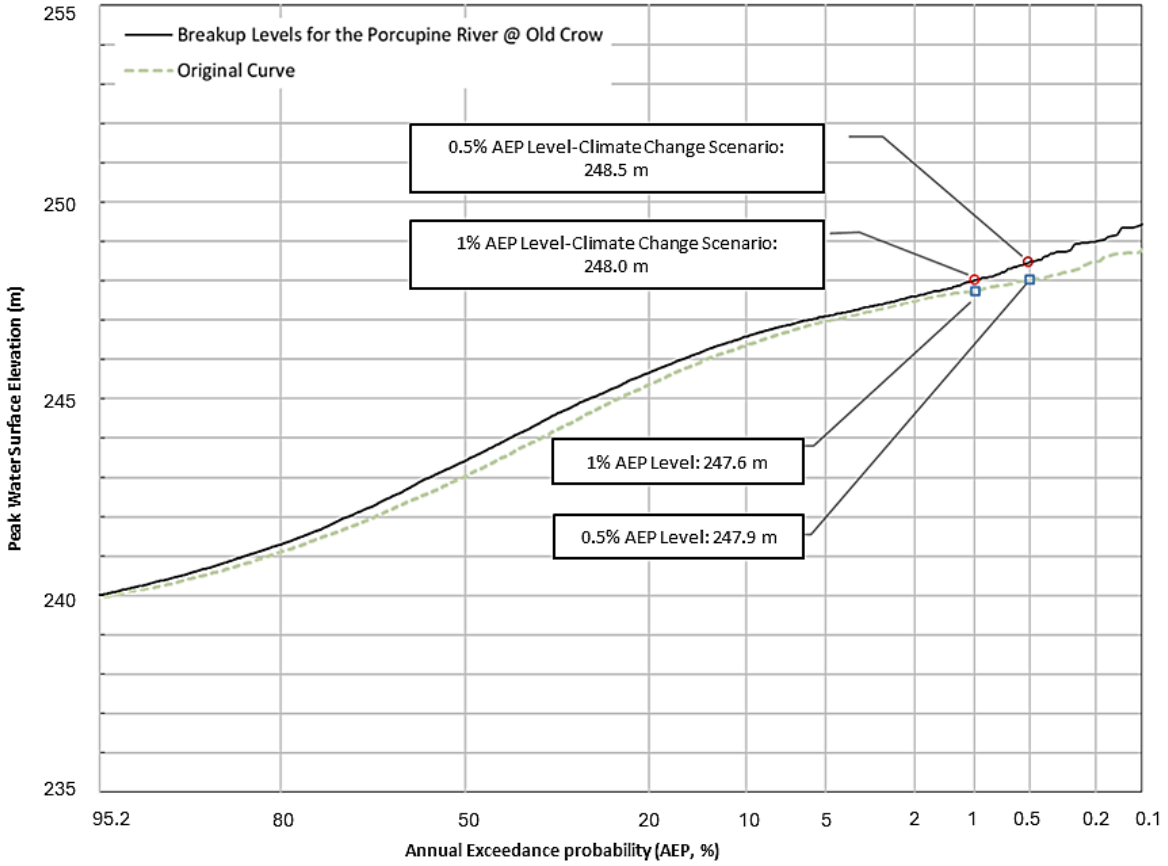


Figure 7.4 Revised flood level frequency curve representing the climate change scenario in comparison to existing conditions. Extreme AEPs less than 0.5% (e.g., 0.2 and 0.1), are shown for illustration only and not to be relied upon.

Table 7.3 Present and future ice jam induced water levels for different AEPs (CGVD 2013).

AEP	Present ice jam scenario	Future ice jam scenario	Difference
20%	245.2 m	245.7 m	0.5 m
10%	246.2 m	246.6 m	0.4 m
5%	246.7 m	247.1 m	0.4 m
2%	247.2 m	247.6 m	0.4 m

AEP	Present ice jam scenario	Future ice jam scenario	Difference
1%	247.6 m	248.0 m	0.4 m
0.5%	247.9 m	248.5 m	0.6 m

7.10 Limitations and Uncertainties of Climate and Land Cover Change Analysis

NHC recommends recognizing the following limitations and uncertainties when interpreting results of climate change and land cover change analysis:

1. NHC's approach assumes that the existing ice-induced flood regime will continue to be the dominant governing regime in the future. While some modelling studies have shown that peak flows in a similar environment may start occurring outside of the spring freshet in the future under a high-emission scenario, it is impossible to say whether open-water flood events will become the dominant flood mechanism for the Porcupine River.
2. The accuracy of historical data analysis is limited by data availability, accuracy, and completeness.
3. When it comes to future projections of climate, there are three primary sources of uncertainty:
    - Emission scenario uncertainty - It is not possible to determine the future emission of greenhouse gases. Two different trajectories of emissions have been assessed as part of this study, but the future will likely differ from these scenarios. Typically, SSP 5-8.5 is selected as a precautionary emission scenario. Emission uncertainty represents the dominant source of uncertainty for more distant time horizons, such as the end of the 21st century.
    - Climate model uncertainty - GCMs are unique models which can differ from their representation of physical processes due to their level or approach of simplification. As a result, different GCMs will generate different projections under the same emission scenario.
    - Internal climate variability[11] - Earth's climate is inherently variable. Internal climate variability has been shown to be the dominant source of uncertainty in the simulated climate response of a single GCM for relatively proximal projected time horizons, such as the mid 21st century (Deser et al., 2012).

[11] Internal climate refers to local or regional climate and the unique characteristics and variations within the region, such as the local temporal and spatial patterns in temperature, precipitation, humidity, and wind. This is in contrast to external climate which refers to continental or global climate.

4. When it comes to future projections of land cover change the following are limitations:
    - There is no straightforward relationship between land cover changes and peak flows.
    - The impacts of land cover and land use changes on watershed hydrological response and peak flows are conjectured for a current climate forcing. It is unknown what future changes in landcover may be.

8 FLOOD MAP PRODUCTION

8.1 Base Map

The base map layout is presented in Figure 8.1. The 1:2,500 scale map sheets cover areas of Old Crow that have buildings and allow for sufficient resolution for individual building recognition. The 1:7,500 scale map sheets provide an overall overview of flood inundation extents for the project area, encompassing both left and right overbank floodplain zones.

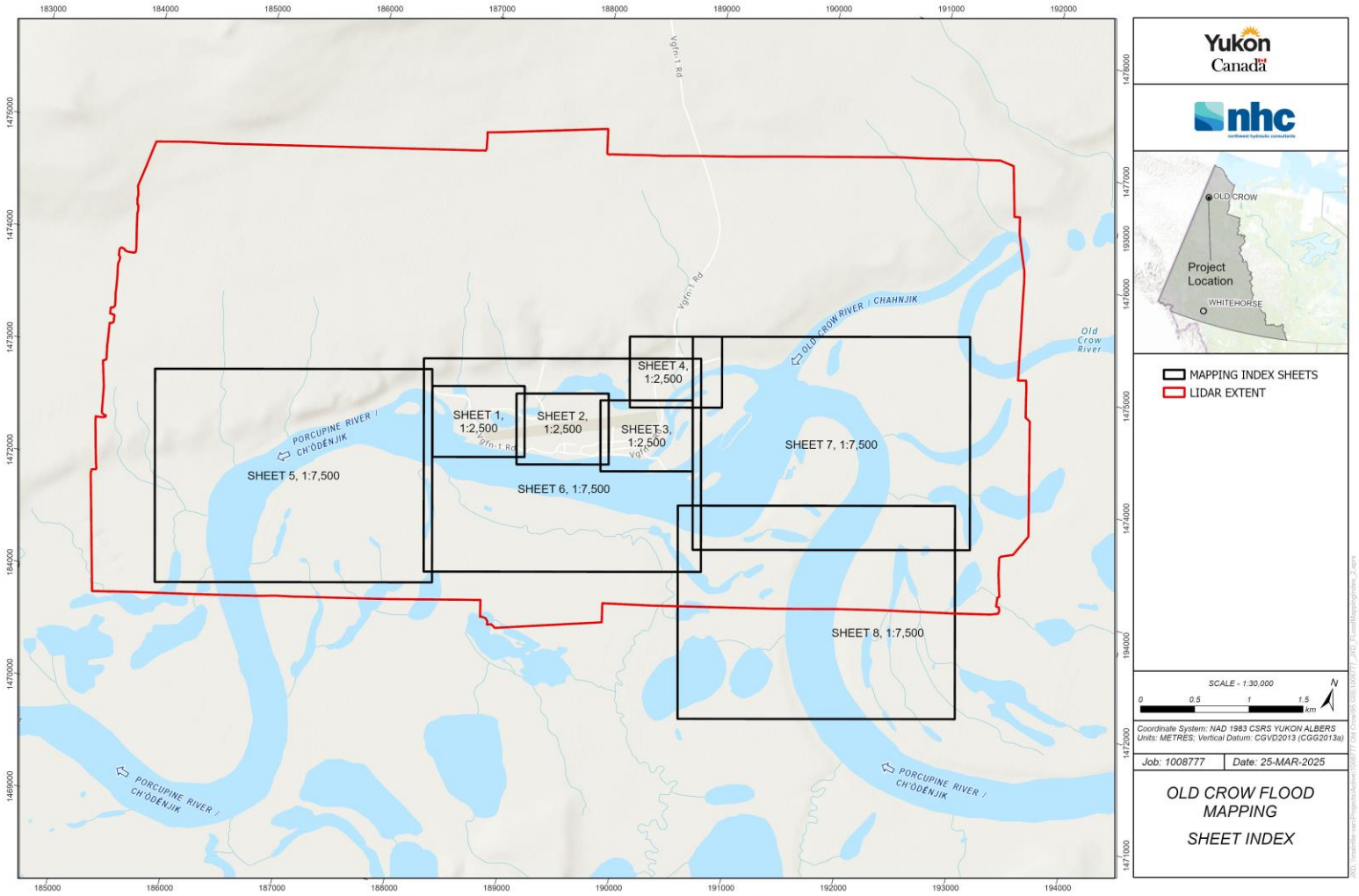


Figure 8.1 Map sheet layout.

8.2 Events Mapped

The Government of Yukon typically undertakes mapping of the 5%, 1% and 0.5% AEP events. The exception to this is if the flood of record exceeds the 0.5% AEP. For this study, the 5%, 1% and 0.5% ice-cover AEP events were mapped. The associated water surface elevations for the events mapped were determined based upon the ice-cover frequency analysis resulting from the Monte Carlo analysis. To represent an approximation of open water bankfull conditions, the 50% open water AEP was also shown on the maps.

The flood maps are presented in Appendix D. The community of Old Crow is relatively flat, which makes it susceptible to flooding even at lower AEPs. The difference in flood inundation extent between the 1% and 0.5% AEP events is minor, however the depth of water under the 0.5% AEP event is greater. Several buildings in the community of Old Crow are constructed on stilts. This results in various buildings appearing to be inundated in the flood maps, when in fact the building floor may not be inundated. Further information about specific infrastructure flooded under various AEPs is summarized in Section 9.

In Canada, the design flood commonly adopted for engineering purposes is the 1.0% AEP flood as per the federal guidelines (NRCan and Public Safety Canada, 2018). During the preparation of this report, Public Safety Canada announced that, effective April 2025, the 0.5% AEP flood extent will be designated as the "High Risk Area."[12]

8.3 Simulation of Flood Events at Two Culturally Significant Locations

Two sites frequently used by the community were identified during the initial phases of the study. These two sites were cabin locations at Tl'oo K'at just north of Old Crow and cabins at the Porcupine/Bluefish confluence. To support community planning, ice-cover flood extent shapefiles were produced at these two community sites for the 5%, 1% and 0.5% AEPs. Flood mapping was not completed for these two community sites. The relative ice-cover AEP flood levels compared to the cabin elevations are summarized in a separate report available from the Government of Yukon upon request.

The flood extent shapefiles are part of the digital deliverables for this project.

[12] https://www.publicsafety.gc.ca/cnt/mrgnc-mngmnt/rcvr-dsstrs/dsstr-fnncl-ssstnc-rrngmnts/index-en.aspx
https://www.publicsafety.gc.ca/cnt/mrgnc-mngmnt/rcvr-dsstrs/dsstr-fnncl-ssstnc-rrngmnts/2025/dfaa-gdlns-en.aspx

9 COMMUNITY FLOOD THRESHOLDS FOR KEY INFRASTRUCTURE

To support future planning for the community of Old Crow, 14 key infrastructure facilities were identified, and their potential exposure to flooding was assessed under a range of AEP scenarios for both current and projected future conditions. Several buildings in the community are elevated on stilts, which may cause them to appear inundated in flood maps even when the floor level remains above floodwaters. To address this, both ground and floor elevations of the selected infrastructure facilities were surveyed and compared against estimated water levels for various AEPs. This allowed for a more accurate assessment of potential inundation at each location. The results of the flood threshold analysis for the community's key infrastructure facilities are provided in a separate report, available from the Government of Yukon upon request.

10 SUMMARY AND RECOMMENDATIONS

This study provides an assessment of hydrology, ice processes, and potential impacts of climate change on ice jam flooding in the Old Crow region. Historical data analysis, combined with numerical modelling, was conducted to evaluate ice jam formation mechanisms, flood extent, and potential future changes in ice dynamics.

A HEC-RAS hydraulic model was developed for the Porcupine and Old Crow Rivers, to assess potential flood hazards at the community of Old Crow, located at their confluence, as well as two culturally significant locations situated along the reach. The model was enhanced for ice jam simulations and used to develop an ice jam-induced flood level frequency curve for the Old Crow community using the Monte Carlo method. Flood maps were generated based on the analysis results for sections of the Porcupine and Old Crow Rivers adjacent to the community. For this study, the 5%, 1%, and 0.5% ice-covered AEP events were mapped.

The following is a summary of key observations and recommendations:

- Ice-induced flooding is the dominant flood mechanism in the Porcupine River. Sudden changes in the hydrologic regime in the southern part of the watershed often trigger dynamic ice breakups along the Porcupine River in the northern reaches.
- Dynamic breakups are sometimes associated with ice jam formation along multiple sections of the Porcupine River, both upstream and downstream of Old Crow.
- Three primary mechanisms of ice jam formation have been identified and discussed for the Porcupine River downstream of Old Crow. Historical observations indicate three main ice jam toe locations. Among these, ice jamming at the Bluefish River confluence, exacerbated by

aufeis formation, has led to some of the most severe flood events, including the 1991 flood of record at Old Crow.

- Based on historical records, ice jams formed in the lower reaches typically release before those in the upper reaches. However, this trend may change in the future.
- The community is situated on a flat floodplain along the right bank of the Porcupine River, just downstream of the Old Crow River confluence. Upstream of the confluence, the Porcupine River makes a sharp bend, where a significant change in stream gradient is observed. The channel geometry and physiographic conditions near the community make it susceptible to flooding, even during moderate ice-related events.
- The coincidence of spring breakup with local runoff events often exacerbates flooding severity within the community.
- The lower-lying areas toward the downstream end of the community are the first to be impacted by backwater and surface runoff. Critical infrastructure, such as the wastewater treatment plant, is located in this flood-prone area. Flooding in this region could lead to the release of contaminated water through the low-lying zone north of the runway and solar panels, potentially affecting residential areas in the community center.
- The community benefits from a detailed annual flood monitoring program during the breakup period. It is recommended that this program continue and be enhanced by incorporating technologically advanced apparatus and new monitoring techniques.
- Flood forecasting programs and studies are ongoing and under development. It is recommended that these efforts continue. When combined with improved flood monitoring programs, they can facilitate the establishment of an early flood warning system to support emergency planning. This system could integrate monitoring data with stochastic and deterministic analyses to produce short- and medium-term flooding scenarios, enhancing the community's resilience to breakup flooding.
- Flood thresholds have been established for critical community facilities. These thresholds should be used for flood planning and preparedness efforts.
- Climate change impacts on the hydrologic regime and breakup mechanisms within the Porcupine watershed are critical considerations. These impacts have the potential to alter flooding patterns at the community, increasing the likelihood of more severe and dynamic flood events. This underscores the necessity for robust and comprehensive emergency planning. The heightened risk of rapid and extreme flooding may necessitate the development of new mitigation measures and community evacuation procedures. It is recommended that these procedures be reviewed and updated regularly to ensure their effectiveness.
- Detailed analyses, including the assessment of climate change impacts, should be undertaken before the development of new infrastructure or the upgrading of existing facilities within the community.

The results presented in this report offer insights into the complex interactions between river ice dynamics, river morphology and climate variability. The analysis is based on the best available data, current scientific understanding, and industry-standard methodologies at the time of this study. However, the accuracy of the results is subject to the quality and completeness of the input data. As climate conditions, regulatory frameworks, and flood management policies evolve, periodic reassessment of the findings and recommendations outlined in this report is advised to ensure their continued relevance and effectiveness in flood risk management and emergency planning.

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APPENDIX C

Geomorphic and Erosion Hazard Assessment

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ABBREVIATIONS

Acronym / Abbreviation	Definition
DEM	Digital elevation model
DSM	Digital surface model
HRDEM	High resolution digital elevation model
LiDAR	Light detection and ranging
REM	Relative elevation model
RPAS	Remotely piloted aircraft system

GLOSSARY

Term	Definition
Active layer	The layer of ground above permafrost that freezes and thaws seasonally.
Aggradation	A net raising of the riverbed elevation due to sediment deposition.
Aufeis	Successive overflow layers freezing, forming a sheet like ice accumulation.
Avulsion	The process of a creek or river abruptly changing its course, often as a result of a natural event like flooding or erosion, leading to a rapid rerouting of water flow.
Bank hardening	Material placed along a channel bank with the intent of reducing erosion.
Bar	Relatively coarse sediment deposits within the channel, generally deposited as high flow periods wane and exposed during low flow periods.
Bathymetry	Underwater topographic mapping of waterbodies floors and beds.
Breakup	The period where solid river ice cover breaks apart.
Channel	A physical feature consisting of a bed and banks that conveys water and sediment.
Confluence	The point where two or more streams meet and merge flows.
Cutoff channel/ meander cutoff	A channel that forms short circuiting the primary channel, dissecting the convex bend of a meander loop.
Deposition	The process in which sediment is dropped, settled, or added to the riverbed and its surroundings.
Erosion	Breakdown and transport of sediment by water, wind, or ice.
Floodplain	The relatively flat area adjacent to an alluvial river that is prone to flooding and which has evolved through the deposition of alluvial materials.
Fluvial	Pertaining to a river system.
Freeze-up	The period where a solid ice cover forms across a river.
Geomorphology	The study of landforms and the processes that cause and alter landforms.
Ground-ice	Ice within freezing and frozen ground.
Ice jam	An accumulation of ice impeding the flow of a river.

Term	Definition
Jave	Waves that propagate from an ice jam breach.
Meandering (channel)	A type of river pattern characterized by a single, sinuous channel that winds across the landscape.
Permafrost	Ground that remains below 0°C for two or more consecutive years.
Sedimentation	The process of sediment depositing.
Scarp	Steep bank or slope.
Scour	Erosion of a river's bed or bank material by the movement of flowing water.
Terrace	A flat or gently sloping elevated landform typically located adjacent to a river or floodplain.
Watershed	The total land surface area that drains to a point in a stream.

1 INTRODUCTION

The purpose of the fluvial geomorphic and erosion hazard assessment is to gain a better understanding of river morphodynamic processes to supplement the development of floodplain mapping. Specifically, the assessment seeks to characterize historical changes along the Porcupine and Old Crow Rivers near the Village of Old Crow, qualitatively evaluate erosion vulnerability within the study area, identify key hydrologic and meteorologic factors that result in erosion and geomorphic change, and improve the current understanding of past, present, and potential future changes in the river channels.

Incorporating geomorphology into floodplain mapping is important because it provides context regarding how the landscape has and continues to evolve. A sound understanding of geomorphological processes is critical for floodplain mapping because changes in channel form can directly impact flood risk; for example, flood conveyance capacity may decrease over time in *aggrading* rivers, where sediment deposition is raising the elevation of the riverbed, causing overbank areas to be inundated more frequently and at lower flows. Geomorphic assessments also consider potential hazards associated with, or in addition to, those caused by flooding; examples of geomorphological hazards include bank erosion and rapid changes in channel alignment, termed *avulsions*. Ultimately, incorporating geomorphology into floodplain mapping can prolong the utility of the maps and allow for preventative or proactive hazard mitigation.

The fluvial geomorphic and erosion hazard assessment completed as part of this study is primarily based on desktop analyses and supplemented with field data collected by third parties. The work includes a review of publicly available datasets, reports, and geohazard assessments; a review of field data collected by others to identify erosion and sediment transport indicators along the Porcupine and Old Crow Rivers; historical bankline mapping and assessment of channel migration; and qualitative evaluation of how potential future changes in channel morphology may impact flooding and erosional processes, including those driven by climatic changes.

1.1 Scope

The scope of this geomorphic assessment is to qualitatively identify and investigate key fluvial processes occurring within the Porcupine River and the Old Crow River floodplains that may affect flooding and erosion hazards. The study includes an overview-level assessment of landscape processes occurring along the Old Crow and Porcupine Rivers in the general region of the study (Figure 1.1), as well as a more detailed assessment near the Village of Old Crow (Figure 1.2). The following points summarize key differences between the two levels of assessment:

1. The overview-level assessment covers a broad area extending from upstream of the Village of Old Crow on the Porcupine and Old Crow Rivers, downstream to the Bluefish River confluence (Figure 1.1). The overview-level assessment considers large-scale watershed

processes occurring in the region that can affect the geomorphology and behavior of the river system (e.g., changes in permafrost). Specific tasks of the overview-level assessment include:

- background information review
- aerial imagery interpretation
- qualitative evaluation of potential effects of climate change.

2. The more detailed assessment covers approximately 8.5 km of the Porcupine River at the confluence with the Old Crow River, adjacent to the Village of Old Crow (Figure 1.2). Tasks of the detailed study area assessment include:
    - field data review to identify erosion and sediment transport indicators
    - historical bankline mapping and channel migration analyses
    - cursory assessment of sediment transport processes using hydraulic model outputs to investigate spatial patterns of erosion and deposition
    - qualitative evaluation of how potential future changes in channel morphology may impact flooding and erosional processes, including those driven by climatic changes.

These tasks are described in greater detail in Section 2.

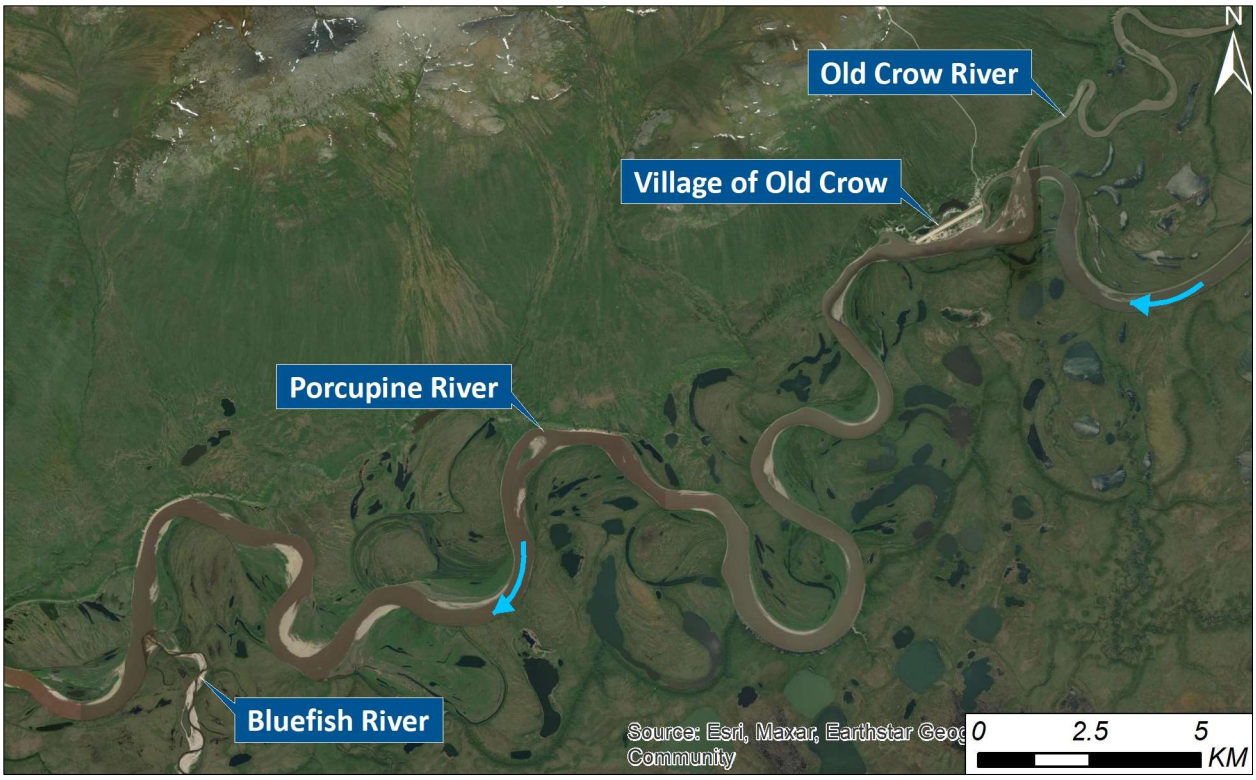


Figure 1.1 Overview-level study area along the Porcupine and Old Crow Rivers. Blue arrows indicate flow direction. Imagery from 2023 ESRI World Imagery.

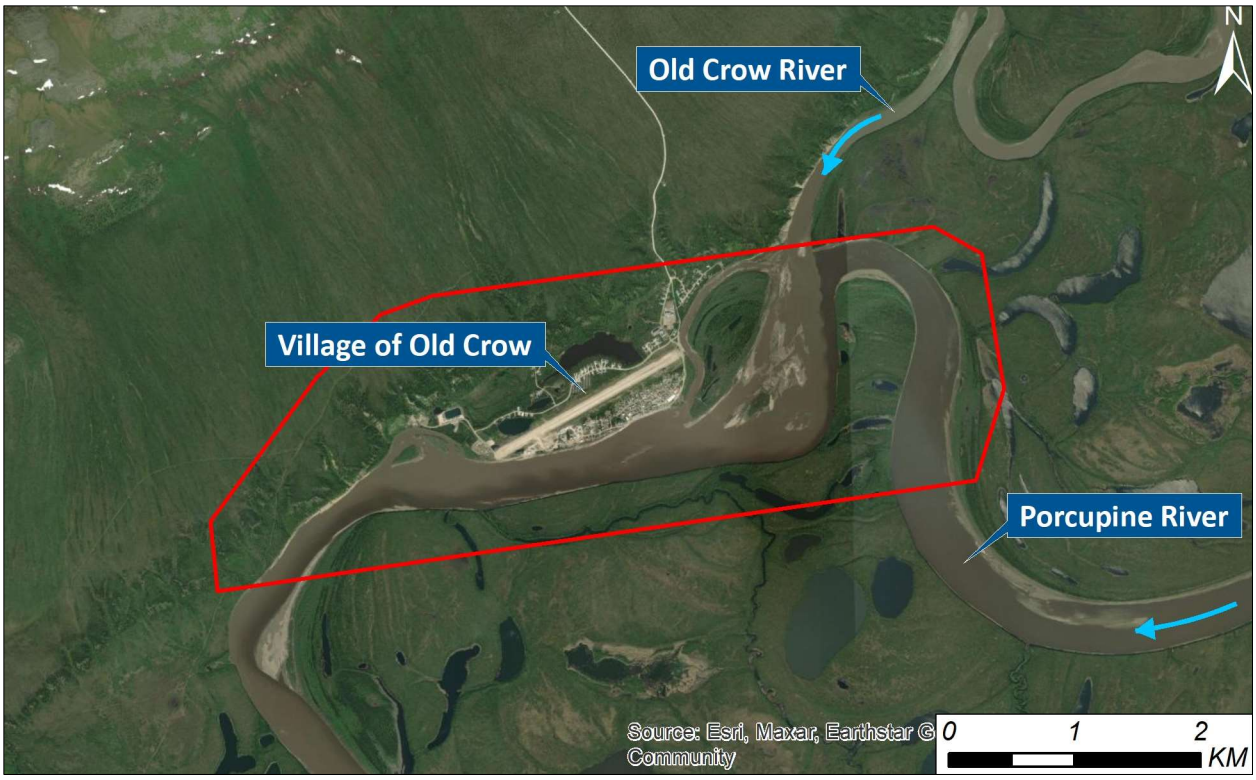


Figure 1.2 Detailed study area near the Village of Old Crow outlined in red. Blue arrows indicate flow direction. Imagery from 2023 ESRI World Imagery.

1.2 Data Sources

This study makes use of both publicly available and project-specific data. Publicly available data used to gain a better understanding of the regional physiographic context include:

- historical air photos obtained from the Yukon Government
- 2019 LiDAR digital elevation model data (DEM) (1 m) for the Old Crow Village site
- high resolution digital elevation model (HRDEM) polarstereo digital surface model (DSM) data acquired between 2007 and 2022 for the study area outside of LiDAR coverage
- previous reports and documents for the physiographic region (Section 2).

Field data at specified locations were collected in 2024 by Underhill Geomatics Ltd. (Underhill) on behalf of NHC to inform the geomorphic assessment (more detail provided in Section 3). Data collection included the following:

- topographic and bathymetric survey data
- aerial imagery and video using a Remotely Piloted Aircraft System (RPAS)

- geotagged photographs of channel bed and bank conditions.

Further description of how these data were used in the assessment is provided in Section 3.

1.3 Assumptions and Limitations

This study is a desktop-based geomorphic assessment, supplemented by field data collected by third parties; field information for the geomorphic desktop assessment, was acquired during the survey and general field inspection, which did not include NHC geomorphology staff. Therefore, geomorphic interpretations are qualitative in nature and reliant upon remote observations and data. The findings of the assessment are also limited to the availability, accuracy, and completeness of data sources.

It is important to acknowledge that fluvial systems in permafrost and periglacial landscapes are dynamic environments that should not be expected to remain static; physical changes to the Porcupine and Old Crow Rivers may occur progressively or rapidly, potentially resulting in substantial changes to channel morphology adjacent to the Village of Old Crow.

2 BACKGROUND INFORMATION REVIEW

Available information and reports were reviewed to inform the geomorphic assessment, including information about the hydrological and geomorphological character of the Old Crow River and the Porcupine River basins, as well as information about the history of flooding, erosion, and ice jams affecting the Village of Old Crow. The review provides geologic, hydrologic, and geomorphic context for the study. Key documents reviewed include:

- Benkert et al., 2016 - Old Crow landscape hazards: Geoscience mapping for climate change adaptation planning.
- Janowicz, 2017 - Impacts of Climate Warming on River Ice Breakup and Snowmelt Freshet Processes on the Porcupine River in Northern Yukon.
- NHC, 2023 - Yukon Regional Flow Frequency Analysis and Empirical Equation Development Final Report.
- Turcotte and Saal, 2022 - Flooding in Old Crow: Exposure analysis and risk reduction recommendations.
- Turcotte, 2021 - Flooding processes and recent trends in ice-induced high-water levels along rivers of Northwestern Canada.

Sharing knowledge and information with Community members is paramount to gaining a better understanding of past and present river conditions at Old Crow and viewing the results of the analyses within the context of local perspectives on erosion and flooding is of critical

importance. The main concern conveyed to NHC by local Community members is that the Porcupine River is widening. This perspective is greatly appreciated and provides useful information on processes occurring in the study area affecting the morphology of the channels.

2.1 Geology

The geology surrounding Old Crow has been influenced by the processes of orogeny, faulting, and the deposition and reworking of paleo fluvial and lacustrine sediment. Neoproterozoic quartzites underlie the high ridges to the north of Old Crow, transported from the east along the Porcupine shear zone. Devonian and pre-Devonian limestone lie to the south of the shear zone. Late Devonian granites intruded into the fault region post-displacement. South of Old Crow, orogenesis of the Ogilvie Mountains in the Mesozoic formed a sedimentary basin of Jurassic shale and siltstone, and Cretaceous sandstone. Later orogenesis of the British Mountains north of Old Crow in the Paleogene led to deposition of Eocene and Oligocene sedimentary rocks. Neogene sedimentary rocks were deposited due to primarily fluvial and lacustrine processes (Benkert et al., 2016).

Bedrock in the Old Crow region is overall characterized as clastic and carbonaceous sedimentary rock, with much in the uplands being mapped as 'weathered bedrock' (Benkert et al., 2016).

Colluvial and fluvial processes dominated the Pleistocene, along with eolian processes depositing fine layers of loess. Periglacial wasting mechanisms likely drove colluvial processes during this period. Active Holocene fluvial and lacustrine deposits are present in the region. Surficial deposits across the Old Crow region include in-situ weathered, fluvial, lacustrine, colluvial, eolian, organic, and anthropogenic sediments (Benkert et al., 2016).

2.2 Glacial History

The Old Crow region is part of Beringia, a large unglaciated landmass. Old Crow remained exposed during the maximum extent of the Cordilleran and Laurentide ice sheets, approximately 17,000 to 18,000 years ago (Clague, 2009; Kennedy et al., 2010). Glacier flow has not scoured unconsolidated sediments, therefore much of this region's sediments were derived from erosion and deposition that date further back in geologic time than glaciated regions (Benkert et al., 2016).

At the Laurentide Ice Sheet's furthest extent, it backed up drainage in the Richardson Mountains and formed a glacial Lake in the Old Crow, Bell, Driftwood and Bluefish basins. In the late Pleistocene, overflowing glacial lakes into Old Crow basin incised a western outlet to the Yukon River, changing the Porcupine River's course from its previous eastward drainage into the Paleo-Mackenzie River. The Porcupine River drained glacial Old Crow lake, incising into the lacustrine sediment below (Benkert et al., 2016).

2.3 Permafrost

The Permafrost Map of Canada indicates that Old Crow is underlain by continuous permafrost (National Atlas Information Service et al., 1995). However, research in the Dawson region determined treeline areas are annually warmer than valley bottoms where cold air pools (Lewkowicz et al., 2011, 2012). Since the air temperature and boreholes that were used to classify Old Crow as an area of continuous permafrost were collected from the valley bottom, it is possible some areas in the broader Old Crow region are not continuous permafrost (Benkert et al., 2016). NHC (2024) describes discontinuous permafrost in the southern part of the Porcupine River watershed.

2.4 Wildfire

Since 1985, an average of 137 fires have started in Yukon every year, burning an average of 171,841 ha annually (AECOM, 2021). The total area burned per year has increased over the past 50 years, with 2004 representing the most extreme year for wildfires in the Yukon in terms of the number of fires and burned area (Streicker, 2016). Areas immediately south of the Old Crow Basin (North Ogilvie Mountains and Eagle Plains) show statistically significant trends of increasing annual escaped wildfires (> 200 ha) between 1946 and 2018 (AECOM, 2021), while neighboring jurisdictions (Northwest Territories, British Columbia and Alaska) have also recently experienced extreme fire seasons.

Wildfires in the region are projected to intensify in the future (Kim et al., 2024; McCoy and Burn, 2005; Wang et al., 2015). Some of the main climatic and environmental changes that are anticipated to impact the number and severity of fires include (AECOM, 2021):

- longer fire seasons
- changes in precipitation and temperature
- additional stresses to forest and vegetation (e.g. drought, flooding, insects and disease).

Potential impacts of increasing wildfires on watershed hydrology, flood and ice regimes, and geomorphic processes (e.g., sediment production) are further discussed in Sections 4.8 and 4.9, as well as in NHC (2024).

2.5 Hydrologic and Climatic Regime

Changing climatic conditions in the Old Crow region are discussed in several reports (Janowicz, 2017; NHC, 2023, 2024; Turcotte, 2021; Turcotte and Saal, 2022). These environmental changes are expected to influence the flooding and ice regimes of the Old Crow and Porcupine Rivers; an increasing trend in the mean flow of the Porcupine River and a decreasing trend in cumulated degree-days of freezing (indicating a milder winter) have already been detected for the Old Crow region (Turcotte, 2021). Potential morphological responses of the Old Crow and Porcupine

Rivers to changes in climate are summarized in Section 4.9. This section summarizes the hydrologic and climatic regimes for the Old Crow region; more detailed information is provided in NHC (2024).

The hydrologic regime of Porcupine and Old Crow rivers is nival and is characterized by snowmelt-driven peak flows. Freshet typically occurs in May-June and often coincides with ice breakup. Due to a number of physiographical characteristics (e.g., northward watershed orientation and related difference in snowmelt onset date, presence of permafrost and channel morphology, winter and early-spring temperature, and precipitation patterns), ice breakup in the area often leads to ice jam-induced flooding events. By July, freshet flows typically subside. A slight rise in flow in August is often observed due to late-summer precipitation. In fall, flow decreases as air temperature goes down, and river ice begins to form. Usually, by December, rivers are characterized by low flows and are ice-covered.

A changing climate is projected to impact both hydrologic and ice regimes in the area. The magnitude and timing of snow accumulation and melt will be impacted by the projected increases in precipitation and temperature and might initially lead to an increase in local snowpack and higher freshet flows. While rainfall events in winter are currently quite uncommon in the Porcupine River watershed, climate change may initiate a new winter regime that will promote rain-on-snow events that can generate runoff. Eventually, more extreme rainfall events might be happening in spring and summer, thus eventually shifting hydrologic regime to a mixed one.

Aspects of the hydrological cycle, such as evapotranspiration, infiltration, and subsurface flow, will also be affected by changes in land cover and permafrost thaw. These changes in hydrologic regime will, in turn, influence river ice cover thickness and duration, freeze-up and breakup conditions, permafrost thaw, and may increase the prevalence of wildfires, shrubification of tundra areas, and landslide hazards (Turcotte and Saal, 2022). The severity of ice jam-induced flooding may also change in the future in response to changing environmental conditions; however, changes to ice jam frequency and magnitude in the Porcupine River are uncertain owing to multiple drivers that can produce contrasting effects (Turcotte and Saal, 2022).

2.6 Historical Flood and Ice Jam Events

This section provides a brief overview of historical ice jam events and associated flooding in Old Crow; a more detailed description of events is provided in NHC (2024).

A significant ice jam flood occurred in 1973, when water backed up in the Porcupine River due to an ice jam downstream of the Village of Old Crow. In 1991, another ice jam flood occurred due to warm weather in the headwaters contrasting with cool conditions in Old Crow. This resulted in less ice breakup downstream than in the headwaters (Jasek, 1997). The ice jam was located downstream of Old Crow at the Bluefish River confluence and caused significant flooding in the village (Turcotte and Saal, 2022).

Ice jams form on the Porcupine River channel most years, including immediately upstream and downstream of Old Crow. Ice jamming at the Bluefish River confluence occurs with less regularity than in the vicinity of Old Crow, and icing does not seem to consistently intercept ice runs or initiate ice jams. When ice jamming does occur at the Bluefish River confluence, the toe of the jam is located approximately 42 km downstream of Old Crow. While this makes the Bluefish River ice jams generally less of a concern to flooding in Old Crow, large ice jams at the Bluefish River confluence have caused flooding of Old Crow in the past, and as recently as 1991 (Turcotte and Saal, 2022).

3 FIELD DATA

Field data were collected by Underhill from June 6 to 18, 2024. Data included the collection of geotagged photographs and RPAS aerial imagery to document existing riverbed, bank and channel conditions, and to identify erosion and sediment transport indicators, including: presence of undercut banks and erosional scarps, presence and condition of permafrost and ground-ice in channel banks, presence of depositional and floodplain features, presence and condition of existing riverbank protection works, and information on human activities that may contribute to erosion hazard.

The data collected by Underhill were used to inform the geomorphic assessment in the context of historical and potential future changes in channel morphology. However, flow conditions during the data collection period in June 2024 were high, between 677 and 2,704 m^3/s, as measured at Water Survey of Canada (WSC) gauge 09FD002 Porcupine River near International Boundary (Figure 3.1). The high-water conditions limited what could be directly observed; for example, data on substrate composition is very limited as much of the bed was submerged and obscured by turbid water.

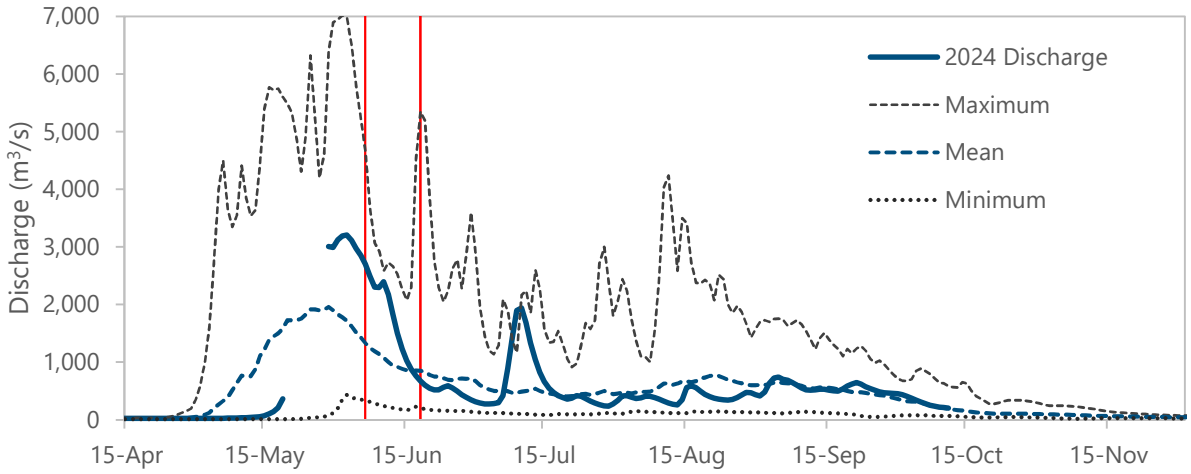


Figure 3.1 Hydrograph at Water Survey of Canada (WSC) gauge 09FD002 Porcupine River near International Boundary showing annual mean, minimum, and maximum flows with discharge from April 15 to October 11, 2024 overlain. Field work in 2024 occurred during the period shown between the red lines. Period of record for statistics is between 1986 to 2024.

4 GEOMORPHIC ASSESSMENT

Changes in channel morphology can be used to investigate potential changes in flood conveyance and identify potential erosional hazards within the floodplain. The following subsections describe the existing channel morphology and floodplain characteristics. Patterns of sediment transport are subsequently investigated using a 1-D hydraulic model to identify zones of erosion and deposition, as spatial and temporal changes in the ability of a river to transport sediment can result in changes to channel pattern and form, which in turn may affect flood conveyance and create erosional hazards. These findings are viewed in conjunction with historical changes in channel morphology detected using aerial imagery to better understand past, present, and potential future channel behavior and to identify potential areas of concern, including possible avulsion locations. Finally, spatial and temporal trends in bank erosion are compared to available climatic and hydrologic data to interpret how these rates may change given projected future changes in climate.

4.1 Existing Channel Condition

4.1.1 Channel Description

Within the study area, the Porcupine River and the Old Crow River are characterized as relatively low-gradient, sand- and gravel-bedded rivers with a meandering channel morphology (Figure 4.1; Figure 4.2). The rivers typically have a single dominant channel, with secondary

channels bifurcating around semi-stable, vegetated mid-channel bars and islands. Oxbow lakes and relict channels are common throughout the floodplain, indicating the extent of channel migration and reworking of the valley floor throughout the Holocene (Benkert et al., 2016).

As mentioned in Section 3, high and turbid water conditions obscured much of the bed during the field investigations completed by Underhill, including mid-channel and point bars; field crews were therefore only able to capture photos of bed material at a few locations exposed above the water surface. Using the provided photos, it is inferred that the bed is primarily composed of sand and gravel, with fine sand and silt deposits in more quiescent areas sheltered from the flow (Figure 4.1; Figure 4.2). The field crews observed that size variations of channel substrate seemed to correlate with the channel bank material, where the substrate below peat banks typically contained gravels 1 to 3 cm in diameter, whereas stones below sand cliffs were typically greater than 4 cm in diameter; however, coarser material may have originated directly from the hillslopes above and not represent fluvially deposited material.



Figure 4.1 Mid-channel bar deposition at confluence of the Old Crow River and the Porcupine River. View looking upstream in the Old Crow River. Silt, sand, and gravel deposits visible with field notebook for scale. Photo taken by Underhill.



Figure 4.2 The Porcupine River left bank showing sand deposition along an inside bend at approximately 16+500 (see Figure 4.13 for river stationing). View looking upstream. Photo taken by Underhill.

4.1.2 Bank Composition

The following observations of bank composition were recorded by Underhill during the fieldwork to inform the geomorphic assessment (Underhill Geomatics Ltd, 2024):

> *Channel banks in the study area typically consist of peat, silts, sands, and gravels. Banks along the outside of river bends are generally steep with heavily undercut peat or sloughing sand cliffs. The inner banks of riverbends are gradually sloped and made of peat, sand, or mud that is mixed peat and sand. Undercuts of peat banks are typically 0.5 to 1.5 m in depth and were actively collapsing at the time of fieldwork. The peat banks on the outside of bends are typically 1 to 4 m in height, some were as tall as 6 to 8 m. They were particularly tall at the Bluefish confluence.*

The sand cliffs were actively sloughing at the time of fieldwork. Cross-sections measured at sandy cliffs do not include GPS measurements at the tops of the cliffs because they were not safe to climb, but they are significantly taller than the peat banks. Some of the sand cliffs have ash and fine silt layers near the water level and appear to be spilling out of the cliff face. In particular, many sections of the sand cliffs on the Old Crow River had layers of ash and fine silt near water level.

Figure 4.3 shows an example of a typical undercut, eroding bank composed of fine-grained sediment on the Porcupine River observed by Underhill during the fieldwork, while Figure 4.4 shows a typical eroding sand bluff on the Old Crow River.



Figure 4.3 Typical undercut, eroding bank composed of fine-grained sediment on the left bank of the Porcupine River upstream of the Old Crow River confluence at approximately 7+500 (see Figure 4.13 for river stationing). Photo taken by Underhill.



Figure 4.4 Typical eroding sand bluff along the left bank of the Old Crow River upstream of the Porcupine River confluence at approximately 2+000 (see Figure 4.14 for river stationing). Photo taken by Underhill.

4.1.3 Permafrost

As part of the field data collection, NHC requested that Underhill observe and record the presence of permafrost or ground-ice in the bank. The area along the right bank of the Porcupine River, downstream of Old Crow at approximately 17+000 (see Figure 4.13 for river stationing), was noted as having a significant amount of exposed ice wedges in the bank (Underhill Geomatics Ltd, 2024). The ice wedges were found exposed in a subsiding peat bank with a shallow (approximately 0.5 m thick) soil cover (Figure 4.5). The ice wedges were reported to be typically 0.5 to 1 m in width and 1 to 2 m in depth. Underhill further noted that the absence of visible trees on the overlying bank and floodplain suggests wide-spread permafrost presence at this location.

Larger-scale bank collapses, including potential detachment failures and thaw slumping, were also noted by Underhill during the field investigation (Underhill Geomatics Ltd, 2024). Figure 4.6 shows an example of bank degradation and collapse at the ice wedge site described above.

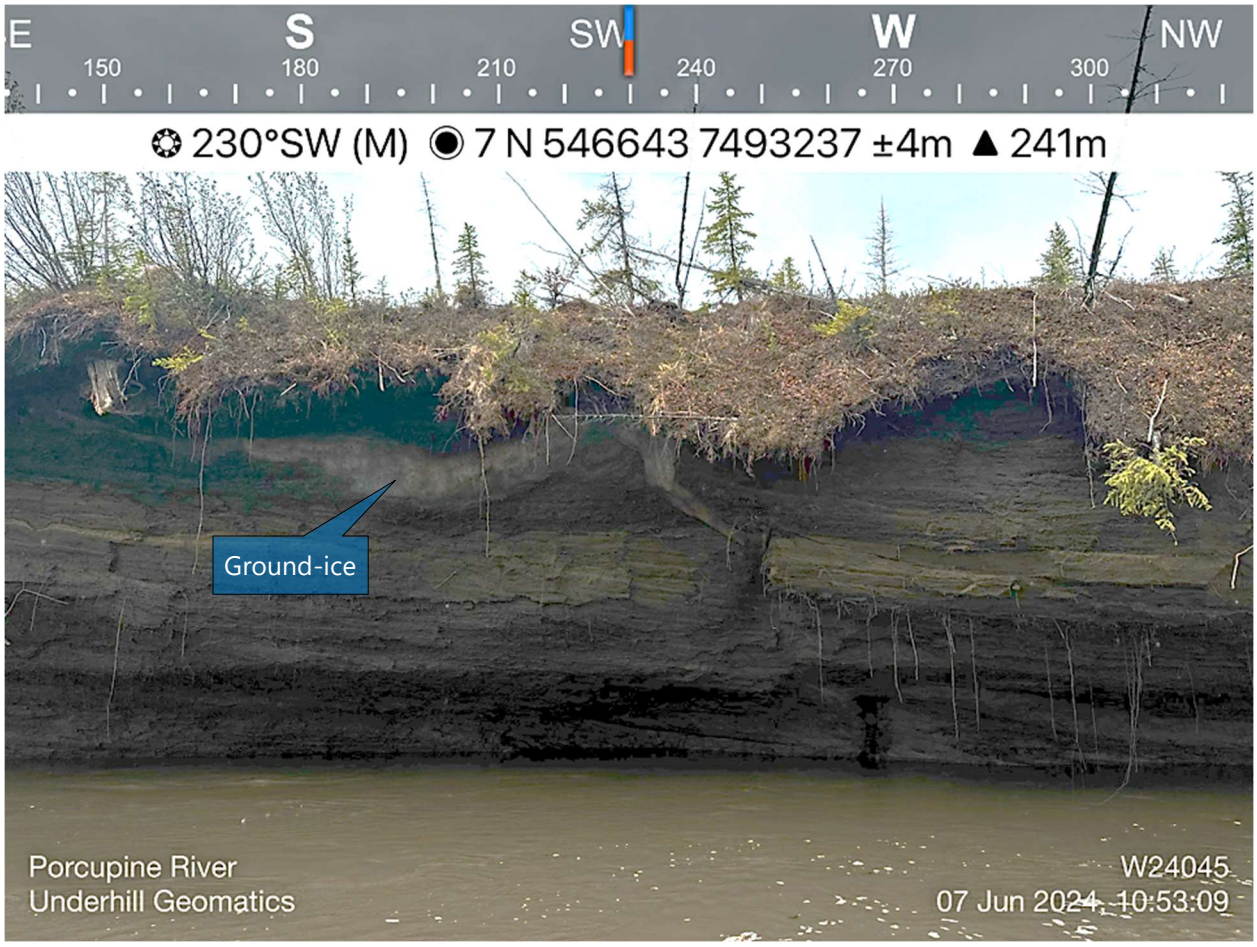


Figure 4.5 Ground-ice observed in the right bank of the Porcupine River, downstream of Old Crow at approximately 17+100 (see Figure 4.13 for river stationing). Photo taken by Underhill.



Figure 4.6 Example of bank degradation and collapse at the ice wedge site. Photo taken by Underhill.

4.1.4 Bank Protection

Fluvial and ice processes are both causing the banks to erode within the study area; ice flows in particular represent a substantial cause of bank erosion and sediment mobilization. Figure 4.7 illustrates high abrasion conditions and ice entrained sediment transport caused by the flow of ice along the Porcupine River banks adjacent to the Village of Old Crow.

Rock has been placed to harden the channel banks adjacent to the Village of Old Crow with the intention of reducing erosion that may impact infrastructure. As shown on Figure 4.8, two bank hardening sites were noted during the field assessment: the *southern bank hardening location*, located along the right bank of the Porcupine River near the southern extent of the Village; and the *eastern bank hardening location*, located on the right bank of the Old Crow River side channel near the eastern extent of the Village near the airport runway. An additional area of concern was noted adjacent to the western end of the airport runway, which currently lacks bank protection and is actively eroding. These sites are further described below.



Figure 4.7 Still image from a video provided by Benoit Turcotte (Technical Advisory Committee) dated May 17, 2024, during high abrasion conditions and ice entrained sediment transport due to ice movement. View looking upstream.

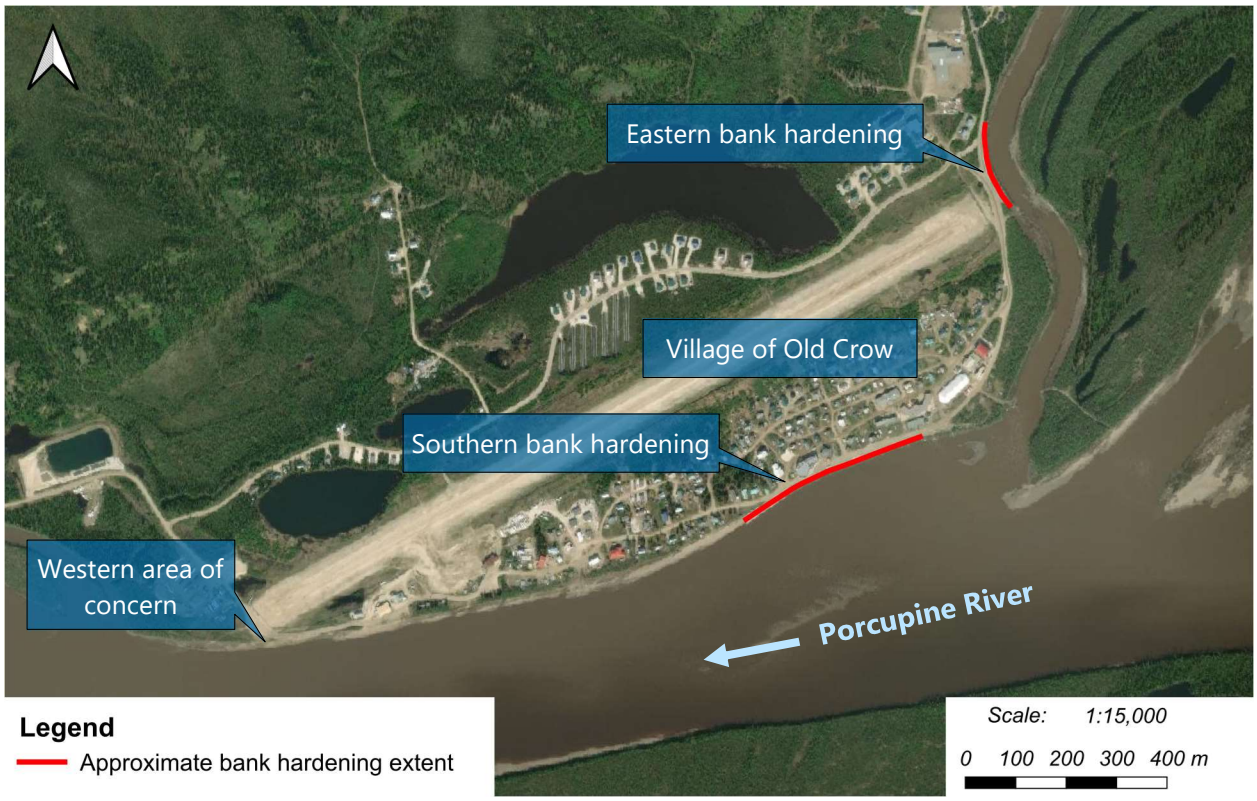


Figure 4.8 Approximate extent of bank hardening sites adjacent to the Village of Old Crow. Bank hardening was identified in photos from Underhill and the extent was mapped using ESRI 2023 imagery. Background imagery is ESRI 2023. Blue arrow indicates flow direction.

Bank hardening near the southern extent of Old Crow, shown in Figure 4.9 and Figure 4.10, has likely reduced erosion compared to banks consisting of only natural channel bank material to some degree; however, erosion of natural banklines may have been exacerbated adjacent to the rock revetments due to end-effects (e.g., recirculating flow) (Figure 4.10). In general, the placed material appears to be heterogeneous in size and distribution, and it has been observed that ice pieces from the Porcupine River easily displace the rocks (generally smaller than 200 mm) during dynamic breakup (Turcotte and Saal, 2022). Turcotte and Saal (2022) further note that the alignment and downstream extent of the erosion protection may be suboptimal, especially as the channel orientation continues to evolve. Overall, the existing bank protection at this site does not appear to provide adequate bank protection under all conditions; thus, the bankline likely remains susceptible to erosion during high flows or breakup when ice is flowing along the bank.



Figure 4.9 Bank hardening along the Porcupine River adjacent to the Village of Old Crow waterfront. Blue arrow indicates flow direction.

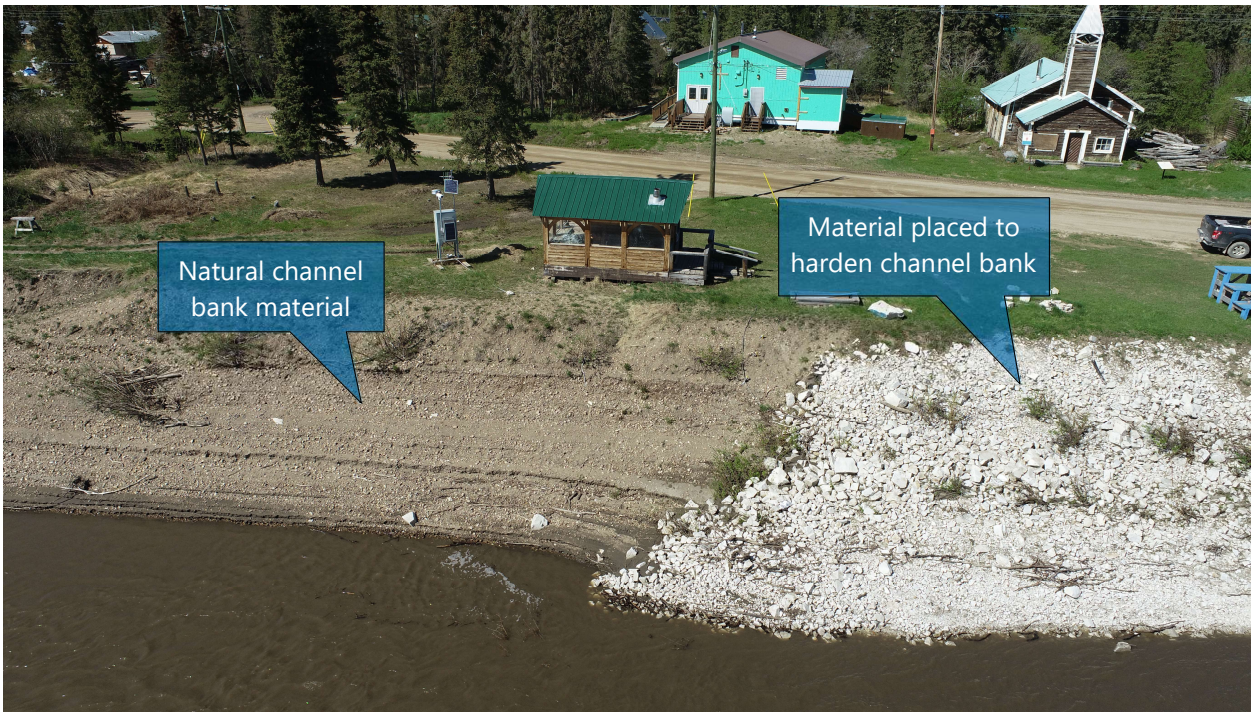


Figure 4.10 Western limit of southern bank hardening transitioning to natural channel bank material on the right bank of the Porcupine River. Flow direction from right to left.

The eastern bank hardening site shown (Figure 4.8) is located at the northeast end of the airport runway adjacent to a side channel of the Old Crow River. While the placed material may increase the channel bank strength relative to the natural bank material, it does not appear to be providing adequate nor functional bank protection, as erosional scarps are visible along the toe of the placed material, indicative of recent and ongoing erosion (Figure 4.11).

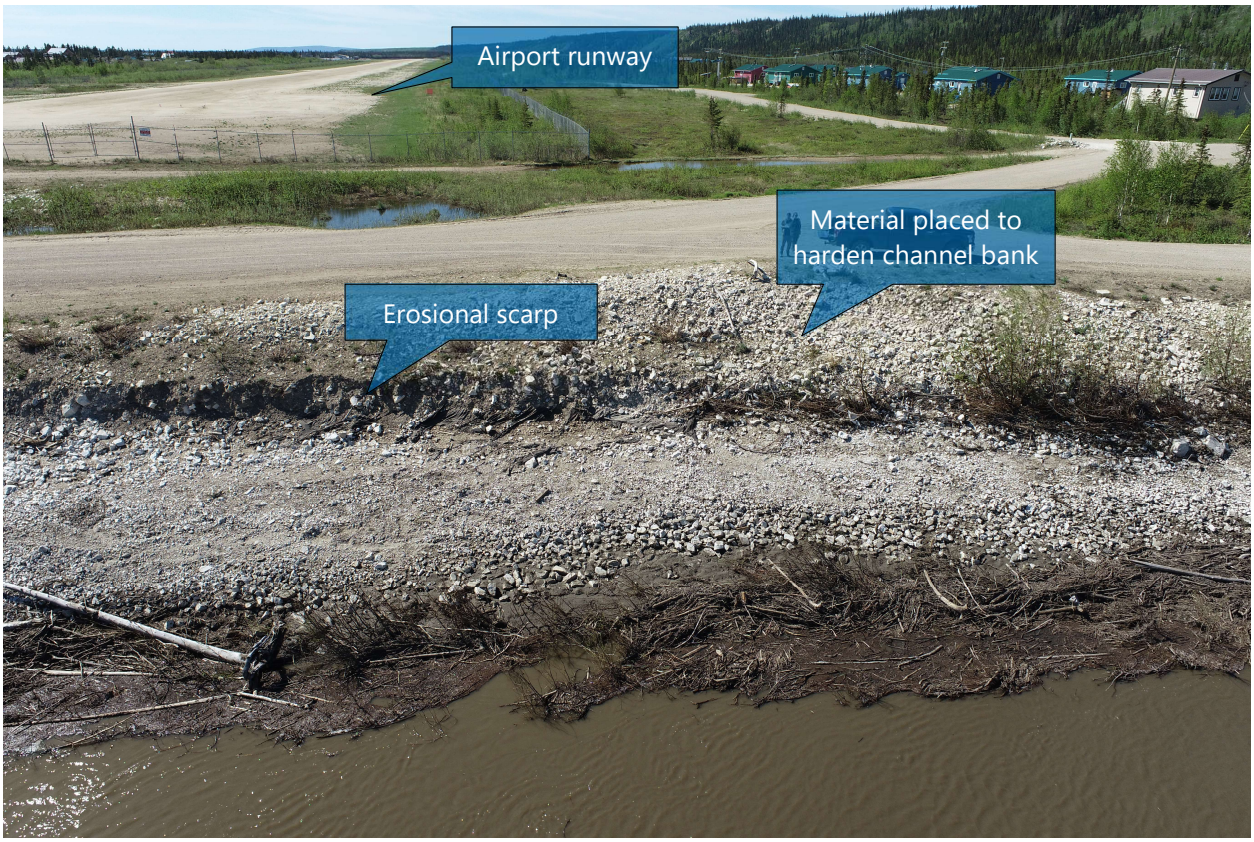


Figure 4.11 Eastern bank hardening located along the Old Crow River side channel at northeast end of airport runway. Flow direction is from right to left.

The western area of concern (Figure 4.8) was identified during discussions with the Technical Advisory Committee for this project. This site is located near the western end of the airport runway. The road next to the runway is also located immediately adjacent to the riverbank, which is actively eroding (Figure 4.12). The bank currently lacks erosion protection, and the existing channel bank material is likely to continue eroding during high flows and ice breakup, particularly when exposed to flowing ice (Figure 4.7).



Figure 4.12 Western area of concern along the Porcupine River. Recent erosion is visible as the presence of erosional scarps. Flow direction is from right to left.

Note that the observations discussed in this section are based on photographs and RPAS imagery provided by others in June 2024, and available aerial imagery. No NHC geomorphology staff were present on site during this assessment. Underhill provided photographs, imagery, and field observations under direction from NHC to assist with the geomorphic assessment.

4.2 Longitudinal Profile and Relative Elevation Model

Longitudinal channel profiles extracted along the approximate thalweg of the Porcupine and Old Crow Rivers are shown in Figure 4.13 and Figure 4.14, respectively. Note that the water surface and channel bed elevations shown in the longitudinal profiles reflect conditions at the time the rivers were surveyed in June 2024. Figure 4.13 also shows the approximate locations of historic ice jam initiation points for reference.

The longitudinal profiles are accompanied by relative elevation models (REM), showing the elevation of the channel and floodplain relative to the water surface elevation of a DEM constructed from HRDEM polarstereo DSM data tiles acquired between 2007 and 2022 (Natural Resources Canada, 2019; Porter et al., 2023). The REM is generated by detrending the

downstream gradient from the DEM to display elevations relative to the water surface along the length of the channel. REMs are useful to help visualize fluvial landforms such as active and relict floodplains, terraces, relict channels and flow paths, and oxbow meanders.

Within the study area, the Porcupine River water surface profile (Figure 4.13) has a gradient generally between 0.01 to 0.03%. The water surface gradient is notably low at, and upstream of the confluence with the Old Crow River, at approximately 0.01%, after which it locally increases to approximately 0.04% as the Porcupine River flows past the Village of Old Crow. The reach of the Porcupine River located near the confluence with the Old Crow River is prone to sediment deposition due to influx of sediment from the Old Crow River, combined with the low gradient of the Porcupine River. Sediment deposition at this site is expected to continue causing morphological instability, including channel widening, bed aggradation, and active channel migration (further discussed in Sections 4.3 and 4.4).

Downstream of Old Crow Village, at a distance of approximately 15+000 on Figure 4.13, the channel is primarily single-threaded with a consistent gradient and meanders across the full width of the active floodplain. There is additional sediment input from the Bluefish River, the confluence of which corresponds to the location of the 1991 ice jam. This is discussed in greater detail in Section 4.6.

The longitudinal profile of the Old Crow River extends from the confluence with the Porcupine River, upstream for approximately 3.1 km (Figure 4.14). The channel gradient is notably steeper along the Old Crow River than the Porcupine River, which is likely a cause of the increased sediment deposition in the Porcupine River. The bathymetric profile shows a trend of increasing bed elevation from approximately 1+600 to the confluence with the Porcupine River located at approximately 3+000, likely reflecting sediment deposition and bed aggradation at the confluence.

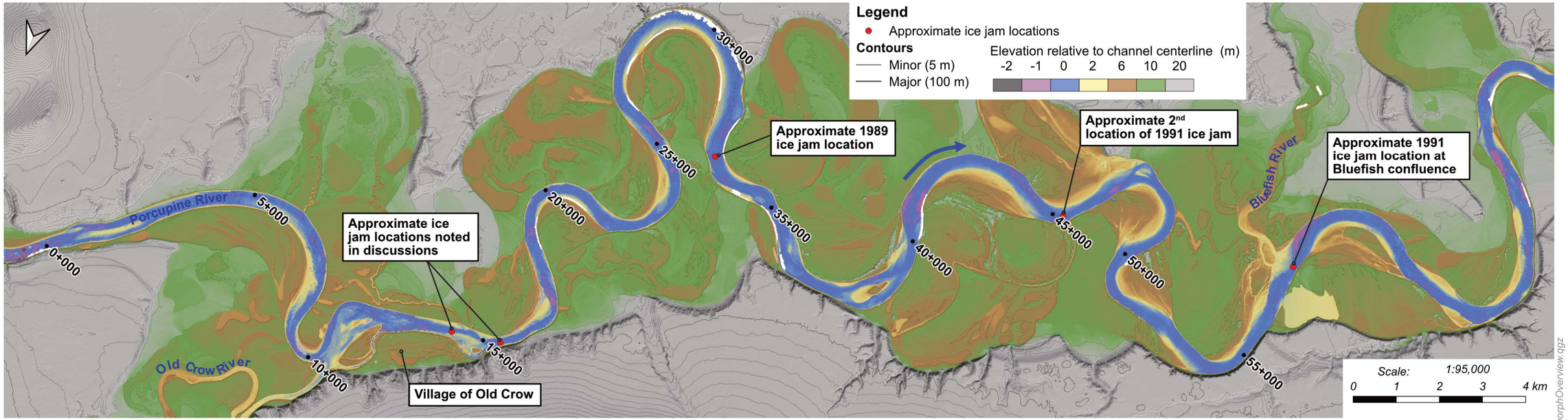
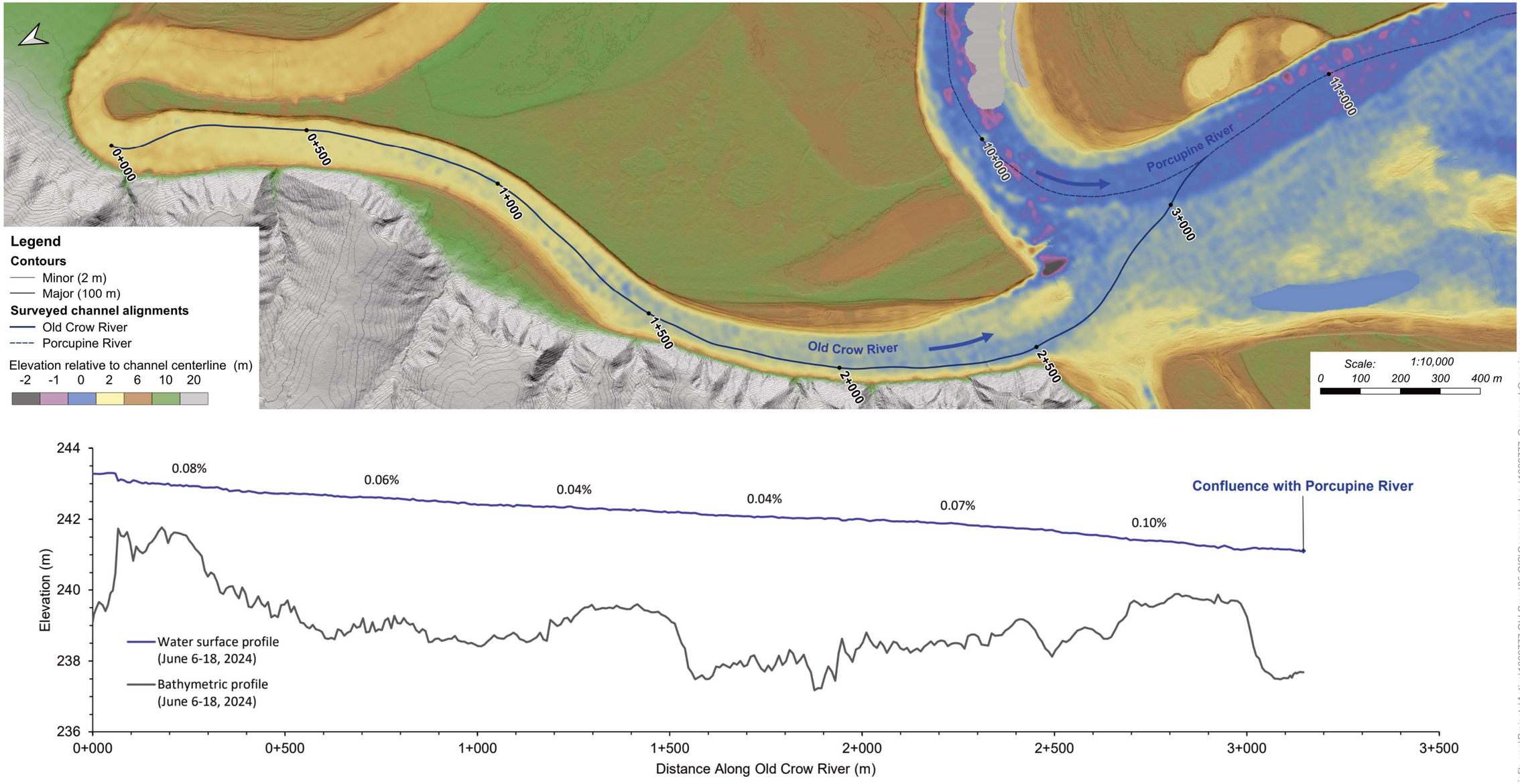


Figure 4.13 Longitudinal plan and profile of the Porcupine River. Blue arrow indicates flow direction. REM shading is relative to the Porcupine River water surface elevation in DEM generated from HRDEM polarstereo DSM data. The REM is overlayed on the hillshade. The longitudinal profile displays water and bed elevations collected between June 6 and 18, 2024.



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Figure 4.14 Plan and longitudinal profile of the Old Crow River at confluence with the Porcupine River. Blue arrows indicate flow direction. REM shading is relative to the Porcupine River water surface elevation in DEM generated from HRDEM polarstereo DSM data. The REM is overlayed on the hillshade. The longitudinal profile displays water and bed elevations collected between June 6 and 18, 2024.

4.3 Sediment Transport

Sediment transport refers to the movement of organic and inorganic particles by water; in this study, sediment transport is focussed specifically on the ability of the river to mobilize and transport inorganic sediment downstream (e.g., sand and gravel). Sediment that is mobilized and entrained by the flow can produce morphological changes in river systems, including patterns of erosion and deposition. Spatial and temporal changes in the ability of a river to transport sediment can therefore result in changes to channel pattern and form, which in turn may affect flood conveyance and create erosional hazards.

4.3.1 Sediment Supply

The existing terrain within the Old Crow region appears to contain a substantial amount of sediment that may be eroded from the landscape through fluvial and periglacial processes and made available for fluvial transport. As described in Section 2, the surficial geology of the study area includes lacustrine sediment, Pleistocene and older alluvial sediments, colluvium, and Holocene alluvial deposits. Tributary channels flowing through easily erodible sediment, such as lacustrine deposits, appear to be conveying substantial volumes of sediment to the mainstem Porcupine River (Figure 4.15). Similarly, streams in the mountainous headwaters of the Porcupine River have a wide, braided morphology, indicative of streams carrying high sediment loads to the mainstem river channels.

Larger river systems, such as the Old Crow and Porcupine Rivers, are also directly recruiting sediment through active bank erosion (Figure 4.3). Sediment is also being input to the channels through exogeneous periglacial and hillslope processes, including rilling and gullying of erodible, fine sediment deposits along the channel margins (Figure 4.4). Additional mass wasting processes, including landslides, debris-falls, and thaw-flow slides (active layer detachment), have been reported around the Old Crow area in permafrost-affected fluvial and colluvial materials (Benkert et al., 2016). These ice-affected environments are sensitive to climatic factors, such as heat and precipitation, which diminish permafrost and may contribute to slope instability; thus, the amount of sediment input to the river system may increase in the future as a result of an increase in mass wasting processes along the channel margins and in ice-affected fluvial material driven by climatic change.

Overall, the relatively fine bed material texture and low gradient slopes of the Porcupine and Old Crow Rivers (Section 4.1), combined with the prevalence of sediment sources across the landscape and changing climatic conditions that may increase sediment delivery in the future (see Section 4.9), suggest that these river systems are unlikely to be sediment-starved and may be functioning in a *transport-limited regime*, where the amount of sediment moved by the rivers is limited by the hydraulic conditions (i.e., flows), as opposed to the supply of sediment to the channel.

The amount of sediment being supplied to the rivers may increase in response to climate change; Turcotte et al. (2011) provide a summary of how ice-related processes may influence bank erosion and sediment input rates. Additional study of sediment sources, and how they have changed across the Porcupine River watershed, would be required to further assess how changes to sediment regimes may impact flood hazard; however, it is important to note that even with additional study, the potential net geomorphic responses to changes in sediment supply may be indeterminate given the complexity and interrelatedness between climatic drivers, ice-related processes, and fluvial responses (further discussed in Section 4.9).

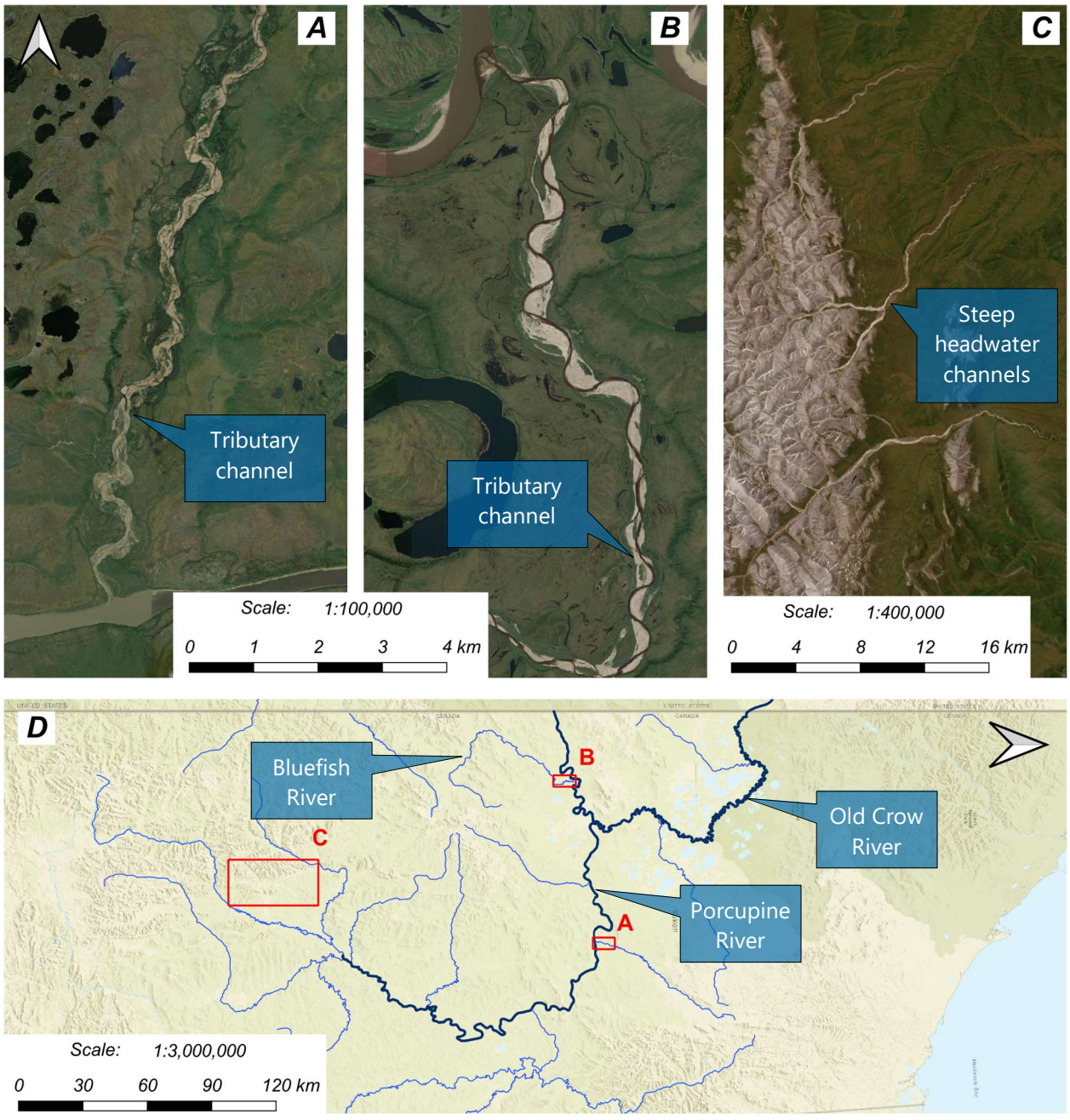


Figure 4.15 Examples of sediment sources in the Porcupine River watershed; A and B illustrate tributary channels flowing through easily erodible sediment that appear to be conveying substantial volumes of sediment to the mainstem Porcupine River, whereas C illustrates sediment delivery from steep slopes in the upper extents of the Porcupine River watershed. D provides overview map of region with locations of A, B, and C shown in red. Background imagery in A, B, and C, ESRI satellite 2023. Background map in D is ESRI World Street map.

4.3.2 Stream Competence

Sediment transport is generally a function of the shear stress exerted by moving water on the channel bed, where grains (i.e., sand, gravel, cobble) begin to move once the amount of stress exerted by the flow exceeds the resisting forces holding the particles in place. Shear stress can therefore be interpreted as an indicator for bed mobility; areas exposed to higher shear stresses likely experience higher bed mobility and erosion, while areas exposed to lower shear stresses likely represent depositional zones.

Sediment mobility was assessed through an analysis of *stream competence*, referring to the maximum grain size that the river can entrain and transport at a given flow. This differs from the *transport capacity* of the river, which represents the total volume of sediment that can be transported by the flow. This assessment of sediment mobility pertains to *open-water flow conditions*; Sections 4.3.3 and 4.3.4 discuss how ice-related processes can influence sediment transport and be key morphological drivers in ice-affected rivers (Turcotte et al., 2011).

The initiation of particle motion was estimated using the following relation:

$$\tau_c = \tau_{*c}(\gamma_s - \gamma_f)D_i$$

where τ_c is the critical shear stress for the initiation of motion, τ_{*c} is the dimensionless critical shear stress (Shields parameter), γ_s and γ_f are the specific weight of sediment and fluid, respectively, and D_i is the diameter of the sediment. The critical shear stress refers to the threshold condition above which sediment is mobilized; sediment is assumed to be mobile when the modelled shear stress exceeds the estimated critical shear stress for that grain size, or in other words, when the ratio of shear stress to critical shear stress exceeds one ($\tau/\tau_c > 1$). This assumption does not account for differences in sediment mobility produced by particle shape and density, nor does it consider potential shielding and protruding effects of relatively large particles on relatively small particles (e.g., Einstein, 1950; Wilcock and Crowe, 2003). Further, it is important to note that competence represents the ability of the flow to entrain particles but does not explicitly account for the presence of these particles on the bed (i.e., while the flow may be able to transport gravel, there may not be any gravels on the bed available for transport). This analysis provides high-level insights into the general patterns of sediment entrainment and transport within a reach, which can be used to interpret and understand geomorphic changes at a relatively coarse scale.

Crucial to accurately mapping stream competence is the selection of τ_{*c}, which has been studied extensively (e.g., Andrews, 1983; Buffington and Montgomery, 1997; Hodge et al., 2024; Lamb et al., 2008; Miller et al., 1977; Neill, 1967; Parker, 1990; Shields, 1936; Shvidchenko et al., 2001). Reviewing many of the prediction equations, diagrams, and overall history of what is commonly used, there really is no one value that is perfect for a reach of river, as τ_{*c} varies by grain size, shape and protrusion, channel slope, and relative roughness. For this analysis, a single value of

0.04 was selected for τ_{*c} and shear stress values were computed for the upper and lower breaks for grain sizes presented in Table 4.1.

Table 4.1 Grain size and breaks in shear stress used to estimate sediment mobility using the HEC-RAS shear stress results.

Grain size	Grain diameter	Shear stress (Pa)
Silt and sand	< 2 mm	< 1.3
Fine gravel	2 – 8 mm	1.3 – 5.2
Medium gravel	8 – 16 mm	5.2 – 10.4
Coarse gravel	16 – 32 mm	10.4 – 20.7
Very coarse gravel	32 – 64 mm	20.7 – 41.4
Small cobble	64 – 128 mm	41.4 – 82.9

The shear stress values used to estimate stream competence were output from a 1-D hydraulic model developed for this study; further detail regarding the hydraulic model is provided in NHC (2024). It is important to note that the shear stress values obtained from the model are approximate and only intended for cursory assessment of sediment mobility due to several limitations associated with the 1-D simulation approach, including but not limited to:

- computed shear stresses are influenced by the selection of hydraulic roughness, which is often used as a calibration parameter for the model (this limitation is not specific to 1-D models)
- the average shear stress is estimated at each simulated model cross-section, and subsequently adjusted (or distributed) across the section based on the simulated velocity distribution
- the resulting adjusted shear stresses are interpolated between the model cross-sections based on the simulated mean flow fields; therefore, shear stresses between the simulated cross-sections may not accurately represent local channel geometry or hydraulic conditions.

The following competence maps (Figure 4.16; Figure 4.17; Figure 4.18) were developed by classifying the simulated (and spatially interpolated) shear stresses obtained from the 1-D hydraulic model based on the shear stress intervals presented in Table 4.1. The resulting maps show the estimated maximum grain size mobilized during the 2-year, 10-year, and 200-year return period open-water floods; it is important to note that these maps are not intended to accurately predict grain mobility during these flood events due to the inherent uncertainties, limitations, and assumptions in the analysis. Rather, the value of these figures is in providing insight into relative changes in the patterns and spatial distribution of stream competence, where relative changes in stream competence can indicate whether a reach is prone to erosional or depositional processes.

The following key points can be gleaned from the competence maps presented below:

- A marked decrease in stream competence in the Porcupine River occurs immediately downstream of the confluence with the Old Crow River. This area is prone to sediment deposition (particularly of medium to coarse gravels) due to the influx of sediment from the Old Crow River, combined with the low gradient of the Porcupine River (Section 4.2) and decrease in stream competence. Spatially, the decrease in stream competence aligns well with the development of mid-channel bars (see figures below), corroborating the depositional nature of this reach. Deposition is expected to continue within this reach, causing morphological instability including channel widening, bed aggradation, and active channel migration (see Section 4.4).
- The decrease in stream competence downstream of the Old Crow River confluence persists across the entire range of simulated flows (up to the 200-year flood). As flows increase, coarse gravels are transported throughout the channel upstream, suggesting a high potential for deposition at this location during high flow events (e.g., above the 10-year flow). Deposition is anticipated to continue into the future as a result of the persistent decrease in competence across a wide range of flows; this may lead to increased flood hazard over time.
- The patterns of deposition near the confluence may also be amplified by differences in the timing, magnitude, and frequency of peak flows on the Porcupine and Old Crow Rivers; for example, the peak flow of the Old Crow River typically occurs later than the peak flow in the Porcupine River, potentially resulting in increased sediment accumulation earlier in the year.
- A second decrease in stream competence occurs immediately downstream of the Village of Old Crow, particularly at low to moderate flows (e.g., 2-year flood). This area corresponds to a local expansion in the channel width and associated reduction in depth, where there is a northern secondary channel flowing around densely vegetated mid-channel bars and islands. Similar to the reach immediately upstream of the Old Crow, this area is prone to continued sediment deposition, particularly due to the higher stream competence immediately upstream. The reduction in stream competence, expansion in channel width, and reduction in channel depth also aligns with the breakup and formation of ice jams and ice runs, reported to be causing erosion adjacent to the airport runway along the western area of concern (Section 4.1.4).
- Two areas appear to have relatively high stream competence, especially during moderate to high flows (e.g., above the 5-year flow): adjacent to the Village of Old Crow near the western area of concern (Section 4.1.4), and further downstream where there is a constriction in the channel width. These two areas may be particularly prone to erosion

and scour during high flow events. These areas also have the highest stream power[1] within the study area, suggesting that bank erosion is likely to occur at high flows.

- Overall, the pattern and spatial distribution of stream competence does not change substantially once flows exceed about the 5- to 10-year flood, but the patterns become intensified. This suggests that the patterns of erosion and deposition described above are likely to remain consistent with increasing flows, but the overall magnitude of change (i.e., amount of erosion or deposition) is likely to be amplified with increasing flow and sediment transport rates.

[1] Stream power provides an estimate of the amount of energy expended along the channel, which can be used to infer how much geomorphic change is possible at a given flow.

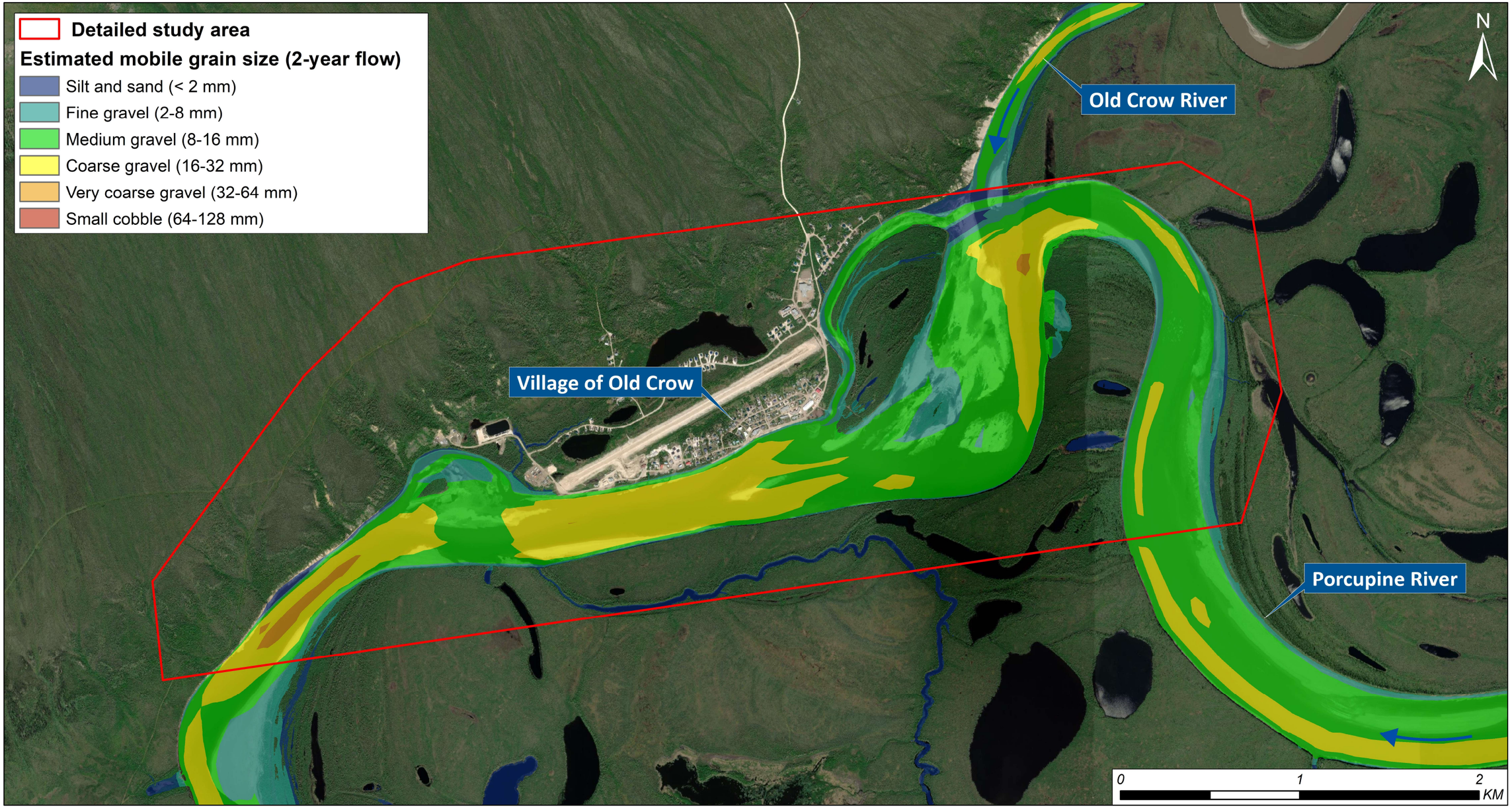


Figure 4.16 Estimated stream competence for a 2-year return period flood (Old Crow River: 844 m^3/s; Porcupine River: 3,024 m^3/s); shear stress values were obtained (and interpolated) from the 1-D hydraulic model and classified based on the shear stress bins presented in Table 4.1. Detailed study area outlined in red, flow direction shown by blue arrows. Imagery is 2023 ESRI World Imagery.

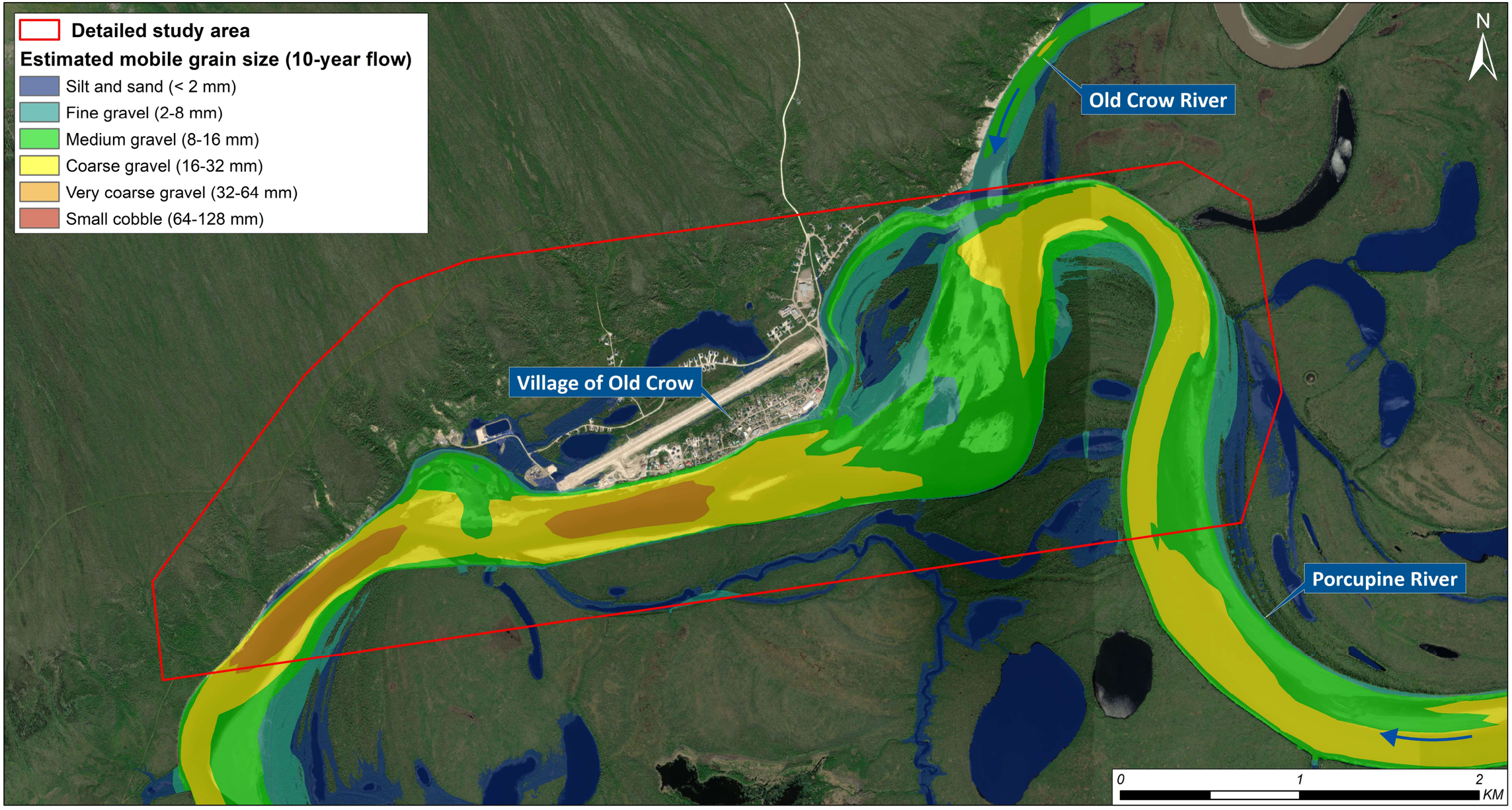


Figure 4.17 Estimated stream competence for a 10-year return period flood (Old Crow River: 1,169 m^3/s; Porcupine River: 4,859 m^3/s); shear stress values were obtained (and interpolated) from the 1-D hydraulic model and classified based on the shear stress bins presented in Table 4.1. Detailed study area outlined in red, flow direction shown by blue arrows. Imagery is 2023 ESRI World Imagery.

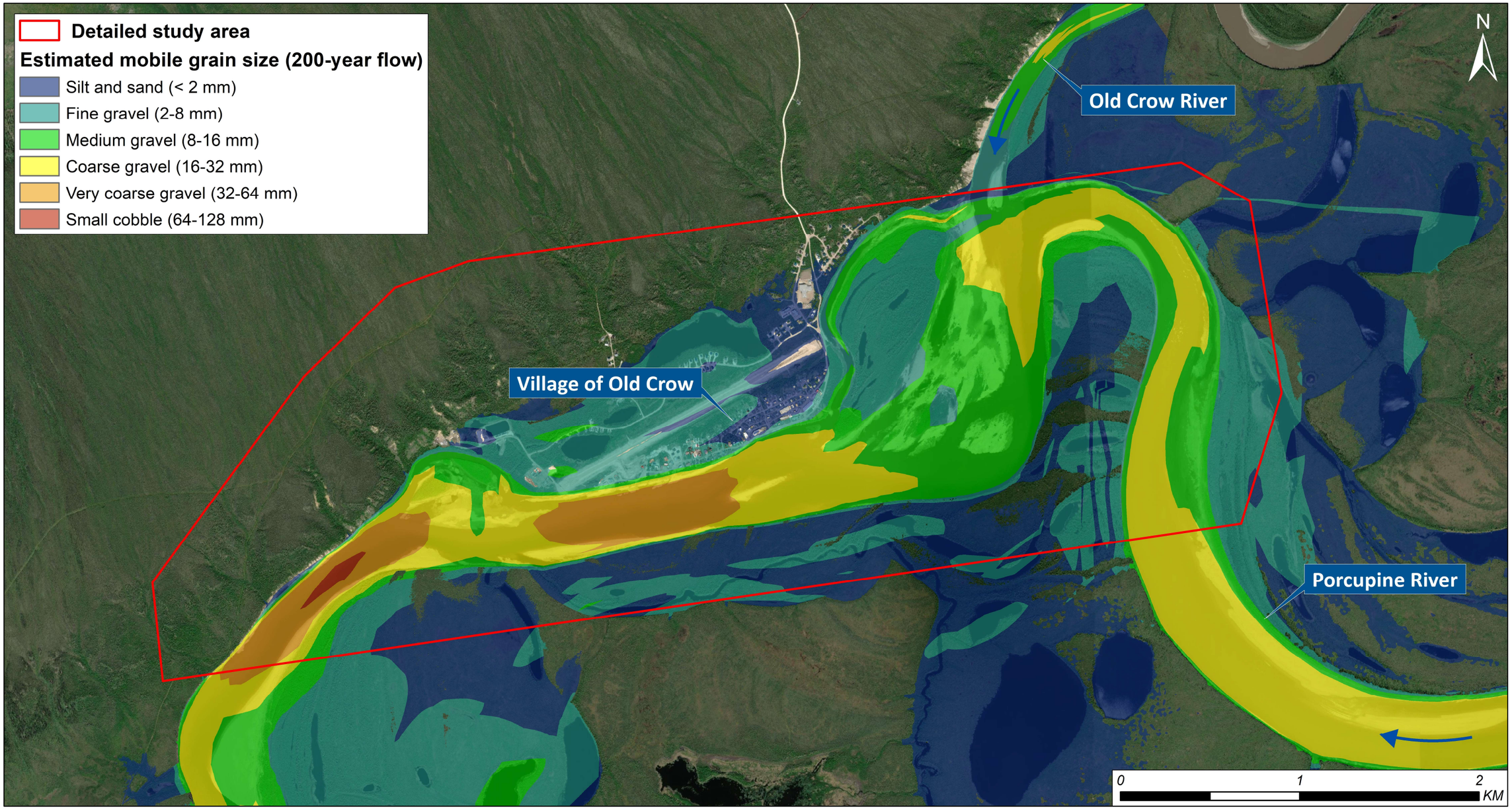


Figure 4.18 Estimated stream competence for a 200-year return period flood (Old Crow River: 1,725 m^3/s; Porcupine River: 7,236 m^3/s); shear stress values were obtained (and interpolated) from the 1-D hydraulic model and classified based on the shear stress bins presented in Table 4.1. Detailed study area outlined in red, flow direction shown by blue arrows. Imagery is 2023 ESRI World Imagery.

4.3.3 Influence of River Ice

The formation, growth, and breakup of ice in rivers can have a variety of effects on flooding and sediment transport, where ice breakup processes can contribute substantial sediment to the annual sediment budget (Beltaos and Burrell, 2021; Ettema, 2008; Turcotte et al., 2011). NHC (2024) provides a summary on how river ice processes affect flooding. The interactions between river ice and sediment transport processes have also been described in detail in previous studies (e.g., Hirshfield and Sui, 2011; Turcotte et al., 2011; Zabilansky et al., 2002). While river ice processes undoubtably affect sediment transport in the Old Crow and Porcupine Rivers, it was beyond the scope of the current study to quantitatively assess sediment transport processes driven by river ice conditions. A qualitative review of prominent river ice processes, and how they may affect sediment transport in the Old Crow River and the Porcupine River, is presented in Table 4.2.

Table 4.2 Summary of river ice processes that could affect sediment transport in the Old Crow River and the Porcupine River.

River Ice Process	Description	Geomorphic Response
Freeze-thaw cycles	Channel bank strength and stability can be affected by freeze-thaw cycles.	Freeze-thaw cycles can reduce the stability and structural integrity of the channel banks, thereby increasing the erodibility of the bank material and susceptibility of the bank to failure and collapse (Turcotte et al., 2011).
Bankfast ice	Ice forms along the bank in low velocity water.	Bankfast ice can both limit or promote sediment transport. When the river is partially open, bankfast ice can reduce flow velocities along the bank and provide erosion protection along the toe, reducing sediment transport along the channel margins. However, bankfast ice can also concentrate flows through the center of the channel, potentially increasing sediment transport mid-channel. During break up, bankfast ice that becomes dislodged from the channel bank may also directly dislodge or pluck sediment frozen to the ice (Ettema, 2008; Turcotte et al., 2011). Any sediment deposited onto the ice surface from slope processes above, may also be transported downstream.
Stable floating ice cover	Floating ice cover can form across large channels (>100 m width).	A floating ice cover can increase hydraulic roughness compared to open-water conditions. Flow velocities and bed shear stresses may consequently decrease, reducing sediment mobility compared to similar discharges in open-water conditions (Lau and Krishnappan, 1985; Prowse and Gridley, 1993).

River Ice Process	Description	Geomorphic Response
Anchor ice	Ice forms attached to the bed. During ice break up or with increasing flows, anchor ice separates from the bed and moves downstream.	Sediment directly frozen to anchor ice can be entrained as the ice separates from bed and moves downstream. The volume of sediment is likely a minor component of overall sediment budget. However, ice-rafted particles can be much larger than those transported hydraulically under similar flow conditions (Beltaos and Burrell, 2021).
Moving or flowing river ice	Moving ice can scour, gouge, and abrade bank sediment. Sediment eroded by moving ice is directly input to the channel and made available for fluvial sediment transport.	Flowing ice can cause substantial channel bed and bank erosion through scouring, gouging, and abrasion. The moving ice can rapidly erode the channel margins, resulting in immediate sediment input to the channel. Erosion caused by flowing ice can also over-steepen the channel banks, increasing susceptibility to future bank failure (Beltaos and Burrell, 2021; Ettema, 2008; Turcotte et al., 2011).
Ice congestion	Rafted ice accumulates in portions of the channel, which can redirect or divert flow patterns.	Ice congestion may redirect, divert, or concentrate flows in parts of the channel that are not typically exposed to high velocity flows, including along bars and the channel banks. Increased flows to these areas may cause local erosion and scour (Beltaos and Burrell, 2021; Ettema, 2008).
Pressurized flow	Floating ice cover fuses to channel banks restricting vertical movement of ice cover. If flow increases in the channel, the fluid pressure under the ice cover may increase, which can induce sediment transport.	If pressure increases sufficiently to induce sediment transport, scour at the bed may occur. However, this may be a relatively local or brief phenomenon, as scouring of the channel bed would help relieve uplift pressure applied to the ice cover, suggesting that the greater the effect of a pressurized flow on sediment transport, the shorter the sediment transport event will last (Turcotte et al., 2011; Zabilansky et al., 2002).

4.3.4 Ice Jams

Ice jamming is a prominent process in river ice systems that can have numerous effects on channel morphology and sediment transport (Beltaos and Burrell, 2021; Ettema, 2008; Turcotte et al., 2011). NHC (2024) provides a detailed summary of historical ice jams that have occurred in the Old Crow area, including documented formation mechanisms. This section broadly describes ice jams within a geomorphic context, including how channel morphology can influence ice jam formation and how ice jam mechanisms can influence sediment transport. It was beyond the scope of the current study to quantitatively assess sediment transport processes driven by ice jam formation and release.

Ice jams commonly form where there is a change in the channel geometry that increases resistance to ice flow, such as sharp bends, channel constrictions, and slope or flow velocity reductions (Beltaos, 1997; De Munck et al., 2017; Shen and Liu, 2003). Morphologic features that often cause a reduction in ice transport capacity include meanders, braided channels, and shoals

or islands in the channel (De Munck et al., 2017). Ice jams and associated *javes*, referring to the waves that propagate from a jam breach, can cause large amounts of erosion, deposition, and sediment transport (Beltaos and Burrell, 2021). A summary of ice jam processes affecting sediment transport are provided in Table 4.3.

Table 4.3 Summary of ice jam processes that may occur in the Old Crow River and the Porcupine River.

Ice Jam Process	Description	Geomorphic Response
Localized reduction in channel cross-sectional area	As an ice jam forms, the available cross-sectional area for flow to pass through in the channel is reduced.	Flow velocity and bed shear stress is increased in the vicinity of the ice jam due to the reduction in cross-sectional area and flow conveyance. This can result in local scour and erosion of the bed and banks (Ettema, 2008). The reduction in flow conveyance can also lead to overbank flows and associated erosion of floodplain channels.
Reduced flow velocity upstream of jam	Flow velocity upstream of the jam is reduced as flow downstream is blocked or constricted.	Sediment transport capacity is reduced resulting in temporary deposition. Sediment in the channel is likely to be remobilized once ice jam is released (Turcotte et al., 2011).
Ice jam formation in a meander	Ice jams that form along the outside corner of meander bends.	Flow will be redirected along the inside corner which can cause scour and erosion, potentially resulting in local channel deepening. Ice jams that form in tight meander bends may induce overbank flows and avulsions through the formation of a meander cutoff (Ettema, 2008).
Ice jam formation in multi-thread channels	If an ice jam forms in one channel, flow may be diverted into a secondary channel.	Sediment transport in secondary channels can increase with increasing flow conveyance, causing channel widening, shifts in the dominant flow path, or channel avulsions (Ettema, 2008).
Jave	Wave that propagates from ice jam breach	A surge in flow can cause rapid erosion of the channel bed and banks. Unstable banks in particular may collapse. Ice blocks in the flow may gouge, scour and abrade the channel banks, potentially oversteepening the channel banks and increasing susceptibility to bank failure (Ettema, 2008).
Overbank flow from ice jam	Flow is forced overbank and onto the floodplain due to the reduction in flow conveyance caused by ice in the main channel.	Overbank flows may cause both erosional and depositional processes depending on the conditions. Rapid or large overbank flows may cause erosion of floodplain soils, widening or incision of floodplain channels, or avulsions through the formation of meander cutoffs. More moderate or progressive overbank flooding may contribute to natural formation of the floodplain through increased deposition of fine sediment (Ettema, 2008).

Ice Jam Process	Description	Geomorphic Response
Increased turbulence	Following breakup or a jam breach, flow turbulence is increased due to both the release of large volumes of water and ice pieces mixing with the flow.	Higher localized flow velocities associated with turbulent fluctuations can mobilize sediment from the channel bed and banks (Turcotte et al., 2011). This can cause considerable local scour and can destabilize banks. Turbulent fluctuations can also destabilize the bed by mobilizing larger particles that, under typical flow conditions, would remain stable and provide structural stability to the bed surface.

4.4 Historical Channel Migration

Delineation and comparison of historical channel banklines can be used to investigate the pattern, rate, and propensity of the river channel to migrate (or move) laterally across the floodplain over time. Channel banklines were mapped using available historical aerial imagery from 1962, 1997, and 2019 (Figure 4.19; Figure 4.20).

Interpretation of the historical aerial imagery and channel banklines suggests that sediment deposition in the Porcupine River is a prominent factor driving channel migration. As seen on Figure 4.19 and Figure 4.20, the development and growth of mid-channel and point bars between 1962 and 2019 has produced compensating erosion on the opposite bank. Mid-channel bar development also appears to have resulted in an increase in the overall channel width, which is consistent with local observations (Section 2).

Bank erosion appears to be primarily occurring along the outside bends of the channel, as illustrated in Figure 4.19 and Figure 4.20. Erosion rates vary between sites with no distinct trend; however, the study area where channel migration was assessed is relatively small, making it difficult to establish trends in erosion rates. Additional bankline delineation over the broader study area could increase the understanding of broader trends in channel bank erosion and channel migration (Section 5.2). Diminishing bank strength due to permafrost degradation may also be contributing to accelerated bank erosion and channel migration rates (Rowland et al., 2023); however, without further field studies, it is difficult to determine the existing and potential future impacts of ice decay on bank stability.

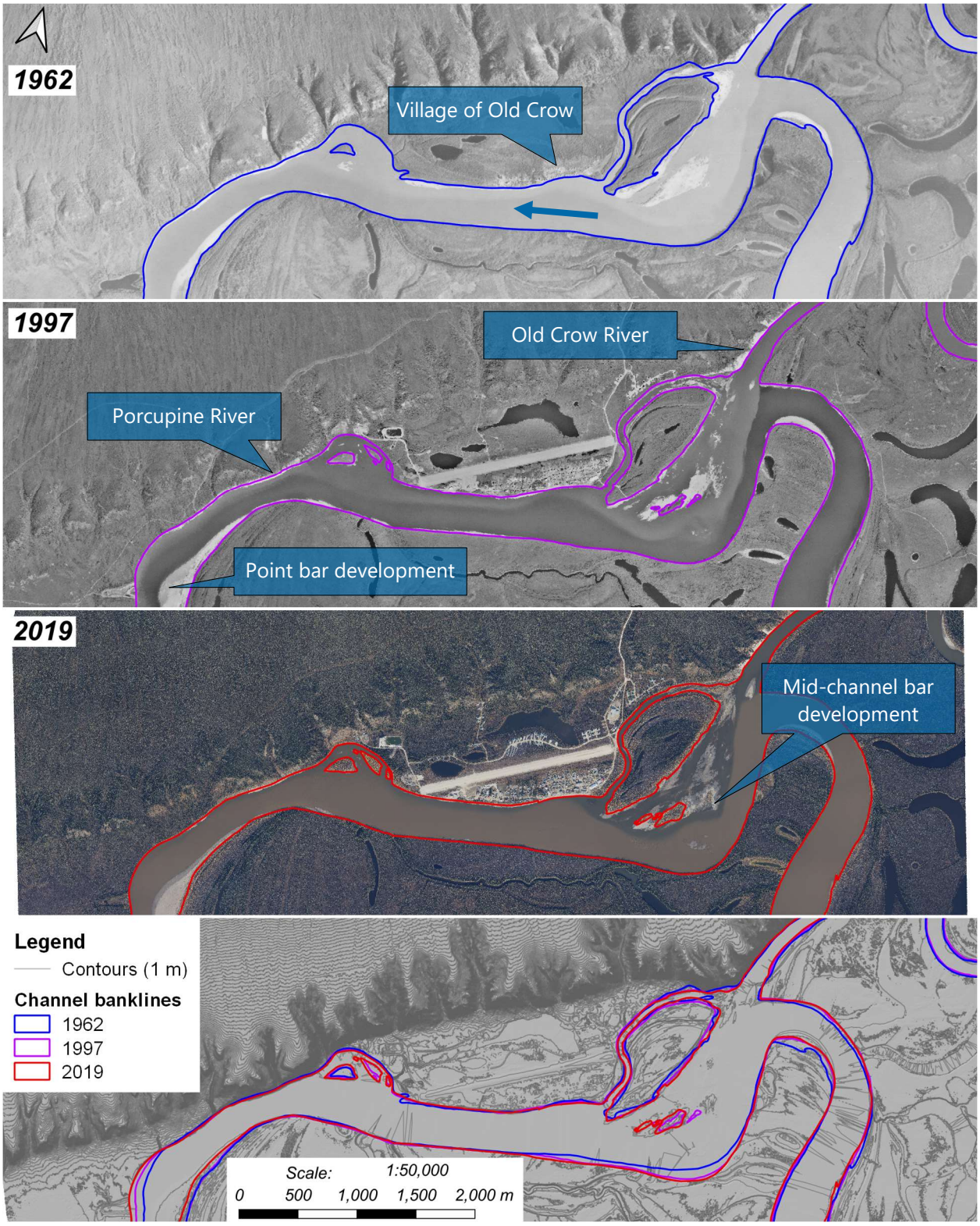
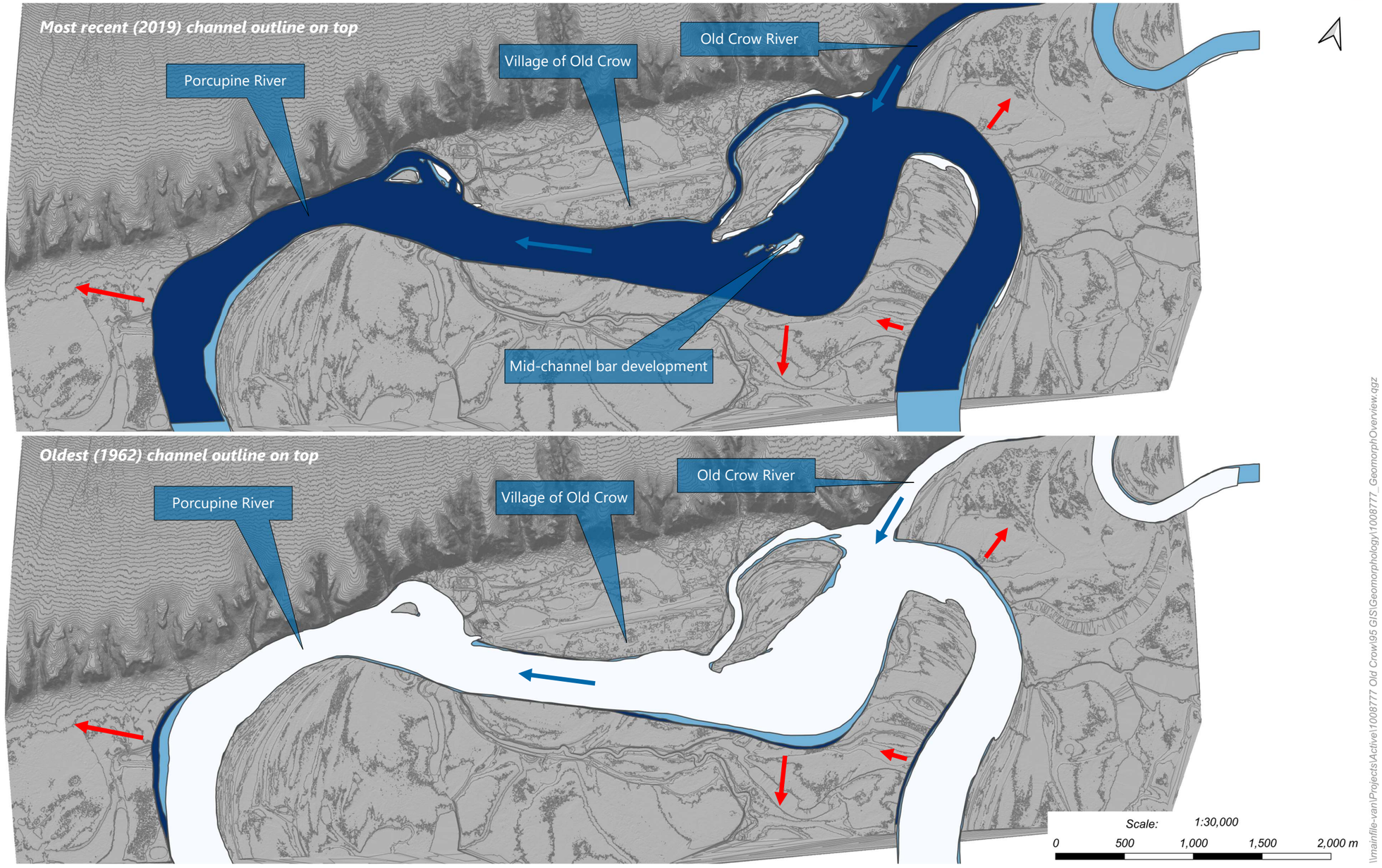


Figure 4.19 Channel banklines overlaid on historical aerial imagery and hillshade. Contours and hillshade derived from LiDAR DEM. Blue arrow indicates flow direction.



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Figure 4.20 Channel banklines from 1962 to 2019 illustrating historical channel migration adjacent to the Village of Old Crow. Hillshade and contours derived from LiDAR DEM. Blue arrows indicate flow direction. Red arrows indicate directions of channel migration.

4.5 Potential Avulsion Locations

A potential avulsion location on the Porcupine River was identified upstream of the Village of Old Crow by Turcotte and Saal (2022) (Figure 4.21; Figure 4.22), located at a distance of 8+000 on Figure 4.13. As further discussed in Section 4.9, the effects of climate change may increase the potential for an avulsion to occur at this location through a combination of effects, including: increased bank erosion in response to increasing magnitude of peak flows (NHC, 2024); destabilization of the channel banks due to changes in the river ice regime and melting of permafrost and ground-ice along the channel margins (Rowland et al., 2023); floodplain subsidence caused by thawing permafrost within the floodplain; and potential occurrence of overbank flooding caused by ice jams.

In the event that an ice jam forms immediately upstream of the confluence of the Old Crow River and the Porcupine River, overbank flows may occupy relict channels, indicated by red arrows in Figure 4.21 and Figure 4.22. Incision into the floodplain may result in an avulsion if the hydraulic gradient becomes steeper along these new flow paths than along the present channel alignment. Downstream impacts of a channel avulsion at this location may be diverse and widespread, including: potential increases in bank erosion due to change in flow alignment; channel incision and bed scour in response to the steepened hydraulic gradient at the avulsion point; compensating sediment deposition and bed aggradation downstream of the avulsion point; destabilization of the channel banks; and reorganization of in-channel bars. These morphological changes may impact the flood risk (e.g., bed aggradation) and result in increased geomorphological hazards along the Village of Old Crow.

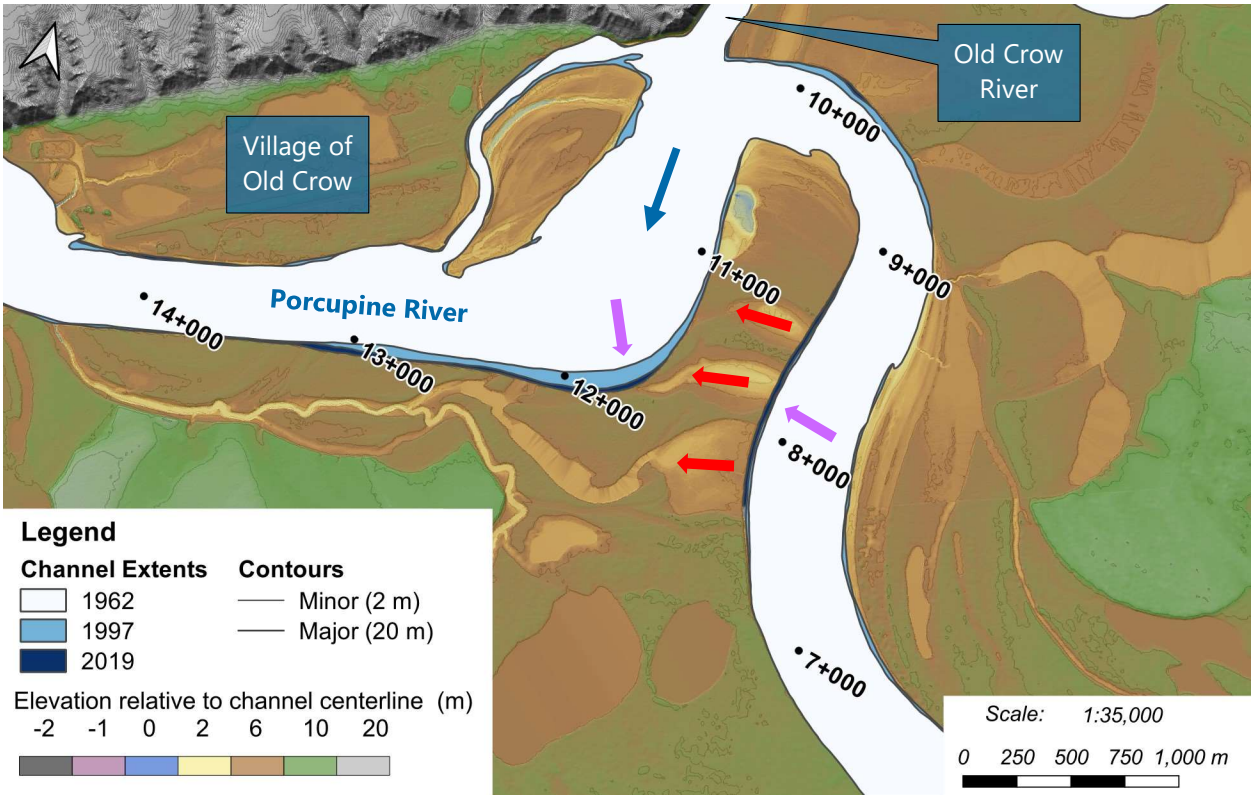


Figure 4.21 Possible avulsion location upstream of the Village of Old Crow. Possible avulsion paths shown as red arrows that would occupy relict channels. Historical channel migration direction shown as purple arrows. Blue arrow indicates flow direction.

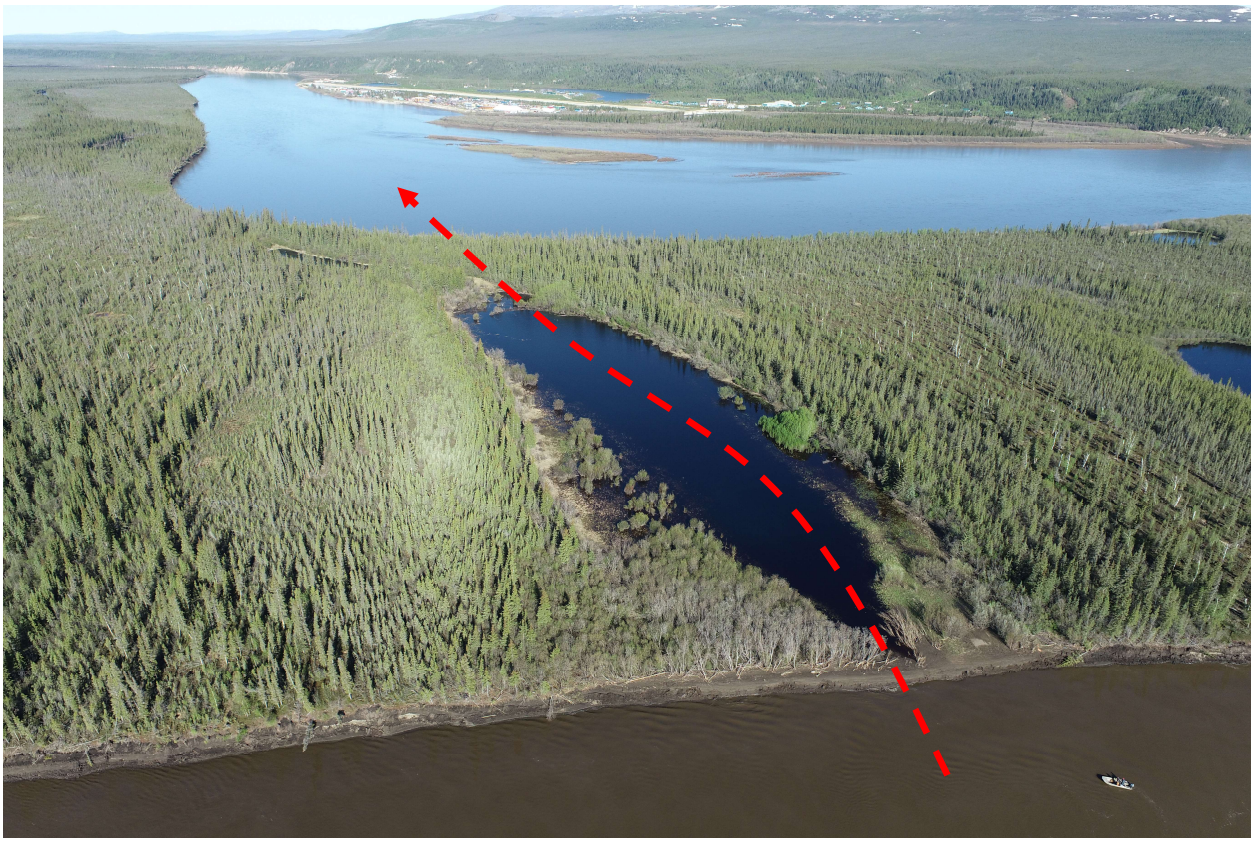


Figure 4.22 Possible avulsion location upstream of the Village of Old Crow at a distance of 8+000 on Figure 4.13; possible avulsion path shown by red dashed arrow. Photo facing downstream with the Village of Old Crow in the background. Photo taken by Underhill.

A second potential avulsion location was identified at a tight meander bend on the Old Crow River (Figure 4.23), located upstream of the confluence with the Porcupine River at a distance of 0+500 on Figure 4.14. At this site, a cutoff channel avulsion may occur if erosion increases along the left bank, breaching the thin neck of land separating the upstream and downstream channel segments. As described above, an avulsion at this location may produce a variety of downstream impacts as the channel morphology will adjust to the rapid change in alignment and hydraulic gradient, including increased channel migration and lateral instability, as well as increased sediment mobilization near the avulsion point and associated downstream deposition. While historical bankline mapping (Figure 4.23) suggests that only very limited erosion has occurred along the left bank over the historical imagery record (1962 to 2023), erosion may be exacerbated in the future due to the evolution of the meander geometry (note elongation that occurred between 1962 and 2023), different environmental conditions (e.g., an ice jam in the meander bend) and climate change, the potential effects of which are discussed in greater detail in Section 4.9.

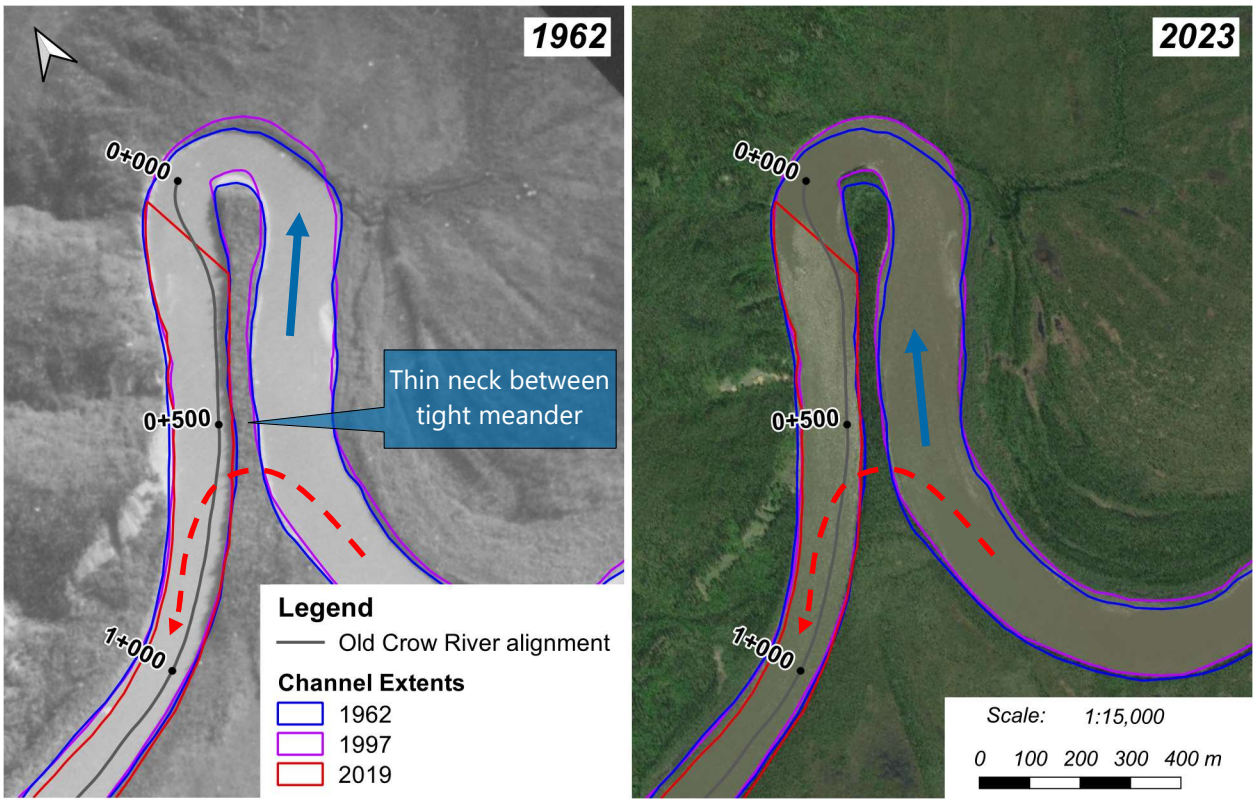


Figure 4.23 Tight meander in the Old Crow River upstream of the Porcupine River confluence. Channel extents from 1962 to 2019 illustrate that little change has occurred; however, this remains a possible location for a cutoff avulsion under future conditions. Possible avulsion path shown by red dashed arrow, blue arrow indicates flow direction.

4.6 Bluefish River Confluence

The confluence of the Bluefish River and the Porcupine River was the initiation point of an ice jam in 1991 (Jasek, 1997). The formation of *aufeis*, defined as a sheet like ice accumulation formed by the freezing of successive overflow layers, was suggested as part of the cause for the jam formation at the confluence (Jasek, 1997). However, the specific environmental conditions leading to extensive aufeis formation at the Bluefish River delta are not well understood.

Landsat satellite imagery from 1985 to 2021 was visually inspected to qualitatively assess the potential for an ice jam to reform at this location based on morphological changes at the confluence of the Porcupine and Bluefish Rivers. As shown in Figure 4.24, the fan formed at the confluence appears to have undergone only minor changes in morphology and extent over this period. While the overall extents of the fan appear relatively stable, the Porcupine River channel is migrating westward, likely responding to sediment input from the Bluefish River. Photos taken during field investigations in June 2024 show evidence of channel bank erosion on the right

bank of the Porcupine River, opposite the Bluefish River fan (Figure 4.25). Channel bank erosion will likely continue along this reach as the Porcupine River is directed against the right bank by flow and sediment input from the Bluefish River.

Overall, the cursory and qualitative review of aerial imagery suggests that the confluence of the Porcupine and Bluefish Rivers likely remains prone to ice jam formation for two main reasons: the existing confluence morphology resembles that which existed during the 1991 ice jam, and continued sediment input from the Bluefish River appears to be partially constricting the flow of the Porcupine River as it is deposited at the confluence, resulting in compensating erosion along the opposing (right) bank, that could presumably constrict ice flows as well.

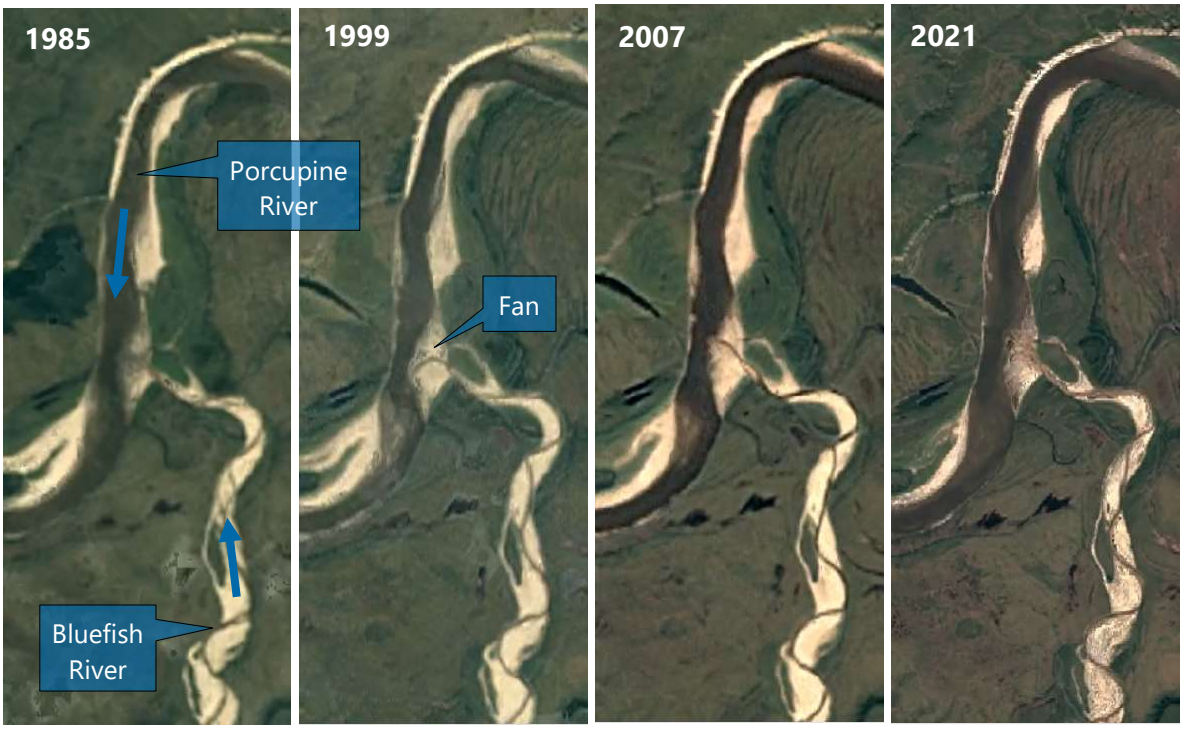


Figure 4.24 The Porcupine River and the Bluefish River confluence shown in Landsat satellite imagery from 1985, 1999, 2007, and 2021. Blue arrows indicate flow directions.



Figure 4.25 Recent erosion visible along right bank of the Porcupine River opposite to the Bluefish River confluence on June 11, 2024. Flow direction is from right to left.

4.7 Permafrost

As discussed in Section 2.3, the Permafrost Map of Canada indicates that the study region falls within the zone of continuous permafrost (National Atlas Information Service et al., 1995). Permafrost has been identified within the study area in previous studies (Benkert et al., 2016) and was observed in areas of channel bank erosion along the Porcupine River (Section 4.1.3).

The presence of permafrost in the floodplain and along the channel margins can influence river morphology and behavior in several ways. Intact permafrost and ground-ice can provide stability to the channel banks, in turn reducing erosion and channel migration rates. However, melting and decay of this ice can have the opposite effect by destabilizing soils and bank materials and promoting increased fluvial erosion (Rowland et al., 2023). Channel incision can be reduced due to the presence of permafrost as frozen ground is relatively resistant to erosion compared to unfrozen ground. Overland flow, therefore, generally results in decreased sediment transport in permafrost terrain compared to similar terrain consisting of unfrozen ground (Rowland et al., 2023). The ability of frozen ground to store water and attenuate flows is also reduced compared to similar, unfrozen ground, which can result in higher runoff response delivering increased flow to mainstem channels in permafrost terrain (Vandenberghe, 2024; Walvoord et al., 2012). The potential effects of a reduction in permafrost, or an increase in the active layer depth, on the geomorphic character of the Porcupine River and the Old Crow River are discussed in Section 4.9.

4.8 Land Cover Changes

Changes in land cover within the Old Crow and Porcupine River watersheds can impact watershed hydrology, flood and ice regimes, and landscape-level geomorphic processes (e.g., sediment production). Given the general landscape characteristics of the watersheds, the most significant changes may occur from forest disturbances, including wildfires and infestations, as well as from shrubification. The impacts of land cover change may also vary by region; for example, potential impacts of increased wildfires may disproportionately affect remote areas with limited (or no) fire suppression.

Potential impacts of land cover change to the hydrological response and peak flows of the Old Crow and Porcupine Rivers are discussed in NHC (2024). In brief, wildfires and shrubification are projected to intensify over the Canadian subarctic in the future (Kim et al., 2024; McCoy and Burn, 2005; Wang et al., 2015; Zhang et al., 2013), which can have a multitude of impacts on ground temperature, active layer thickness, permafrost, precipitation interception, infiltration rates, snow accumulation and melt. Some of the main climatic and environmental changes that are anticipated to impact the number and severity of fires include (AECOM, 2021):

- longer fire seasons
- changes in precipitation and temperature
- additional stresses to forest and vegetation (e.g. drought, flooding, insects and disease).

These changes can impact watershed hydrological response and peak flows in numerous ways, including:

- altering the forest canopy and vegetation cover, thereby impacting several important components of the hydrologic cycle, including precipitation interception, snow accumulation and melt, and evapotranspiration
- altering the properties of the organic soil horizon, thereby impacting soil insulation and the thermal regime and moisture content; in permafrost underlain terrains, this affects the seasonal thaw layer and the active layer thickness
- modifying the structure of surface and near-surface soils, thereby impacting infiltration rates and, in some cases (depending on soil type, the severity of the fire and other factors), inducing water repellency.

Overall, there is no straightforward relationship between land cover changes and peak flows. It is even more difficult to hypothesize what future land cover changes may be for the study area, and how these could drive geomorphic responses in the Old Crow and Porcupine Rivers. Potential morphological responses associated with changes in climate and land cover are further discussed below (Section 4.9).

4.9 Effects of Climate Change

Predicted changes in climate for the Old Crow region are discussed in detail in NHC (2024). To summarize, precipitation within the study area is predicted to increase in all months with the greatest increase predicted to occur in January, April, May, and September. Precipitation during winter is predicted to increase 20 to 75%, which could lead to an increase in local snowpack and higher freshet flows. While rainfall events in winter are currently quite uncommon in the Porcupine River watershed, climate change may initiate a new winter regime that will promote rain-on-snow events that can generate runoff. Eventually, more extreme rainfall events might be happening in spring and summer, thus eventually shifting hydrologic regime to a mixed one.

Mean annual air temperature and cumulative degree-days above 0°C for the period of April to June are also predicted to increase, which may result in changes to peak flow response, permafrost decay, and an increase in depth of the active permafrost layer (NHC, 2023, 2024). An increasing trend in the mean flow of the Porcupine River and a decreasing trend in cumulated degree-days of freezing (indicating a milder winter) have already been detected for the Old Crow region (Turcotte, 2021).

Appendix E in NHC (2023) also discusses projected changes in permafrost distribution due to climate change. Although modelling presented in the report doesn't account for changes in precipitation or vegetation cover, the increase in temperature will likely result in decreasing presence of permafrost (NHC, 2023).

Potential morphological responses of the Old Crow River and the Porcupine River to changes in climate are described in Table 4.4. It is important to note that there is considerable uncertainty in how the fluvial system may respond to changes in environmental conditions due to both inherent variability in natural systems and the complexity of feedbacks (both positive and negative) between climatic drivers and systems responses. Thus, potential net geomorphic responses described in Table 4.4 may be indeterminate, as there may be multiple (and even opposing) responses to climatic drivers that vary spatially and temporally. There is also uncertainty around which climatic drivers and processes may end up being more dominant than the others.

Each line item of Table 4.4 reflects an independent potential response. The list is not exhaustive nor cumulative; the intent of Table 4.4 is to highlight more prominent processes that could elicit a geomorphic response. Widespread changes in land cover, such as those which may arise due to wildfires or beetle infestations, are not explicitly considered, as the extents of future disturbances are difficult to predict; however, any widespread change in land cover will likely result in a hydrologic response that may affect sediment load, sediment transport, channel migration, erosion, and deposition.

Table 4.4 Summary of climate change drivers that may cause morphological changes in the Old Crow River and the Porcupine River adjacent to the Village of Old Crow.

Process/Trend	Driver	Resulting Effects	Geomorphic Response
Fluvial Processes			
F1 - Increasing precipitation	Precipitation is predicted to increase across all months. Increased summer/spring precipitation can contribute to increased peak flows as rain or rain-on-snow events. Increased winter precipitation as snow is anticipated to increase the snowpack, which in turn can result in greater freshet flows.	• Increased erosion • Increased sediment transport capacity • Increased channel migration • Increased avulsion risk	Increased peak flows may cause increased bank erosion, channel migration, and risk of avulsions. Sediment transport capacity may also increase, where the rivers may be able to transport a greater volume and calibre of sediment with the increase in flows; however, the actual amount of sediment transported by the rivers, and associated morphological response, depends on several factors, including the amount of sediment supplied to the channel.
F2 - Increasing air temperature	Increasing air temperature may increase the duration of the snow- and ice-free period.	• Increased erosion • Increased sediment transport capacity	Stable ice cover has been shown to result in a reduction of sediment transport compared to similar open-water flow conditions (Ettema, 2008; Turcotte et al., 2011). Increasing the duration of ice-free periods may increase the capacity for the river to transport sediment resulting in an increased sediment yield. Also, the greater duration of when the contributing landscape is unfrozen may increase the amount of sediment supplied to the channel through surface erosion (Ettema, 2008). These effects, coupled with increased precipitation expected in the Porcupine River watershed (NHC, 2024), may result in increased sediment transport. The increase in air temperature, coupled with an increase in snowpack, may also result in increased runoff during freshet. This may result in higher peak flows, increased sediment transport and erosion. Increasing air temperature may also cause decay of ground-ice and permafrost along the channel margins; as stated below in P1, melting ice can destabilize and reduce bank strength, resulting in increased bank erosion and channel widening (Rowland et al., 2023).

(continued below)

Process/Trend	Driver	Resulting Effects	Geomorphic Response
Permafrost Processes			
P1 - Increasing air temperature	Increasing air temperatures can lead to increased ground temperatures and an increase in active layer depth. Increasing air temperatures can result in decay of ground-ice and permafrost along the channel margins and within the floodplain.	• Increased active layer depth • Increased subsidence • Increased/Decreased erosion • Increased/Decreased sediment transport capacity • Increased/Decreased rate of channel migration • Increased risk of channel bank slope failures	Increased air temperature can lead to increased active layer depth and loss of permafrost. Environmental changes associated with increased air temperatures, such as increased wildfires and shrubification of tundra areas, can further exacerbate permafrost thaw. This may in turn result in increased groundwater storage capacity when the active layer is above 0°C, which may partially attenuate the magnitude of peak flows, and hence, magnitude of channel forming events. Channels may reduce in width if the frequency of high flow conditions that promote channel bank erosion is reduced. Rates of channel migration may also therefore decrease. Conversely, an increase in active layer depth may also increase the potential for overbank flows to erode or entrain floodplain sediments during periods when the active layer is above 0°C. Thawed sediment is more readily transported than frozen sediment as the ice boundary restricts sediment mobilization. This likely applies to smaller, tributary channels that flow over permafrost terrain. Larger channels, such as the Old Crow River and the Porcupine River, likely already have unfrozen ground beneath the active channel (Wankiewicz, 1984). Decaying ground-ice and permafrost along the channel margins may reduce bank strength, causing the channel banks to become destabilized and susceptible to erosion. This may result in channel widening and increased rates of channel migration (Rowland et al., 2023). Increased subsidence within the floodplain due to a reduction in permafrost may cause a heterogeneous reduction in land elevation. This may result in changes to overland flow pathways and an increase in the frequency that flow inundates the floodplain. This may increase the likelihood of avulsions due to increased frequency of overbank flows or greater concentration along certain flow pathways. A decrease in channel bank strength as a result of thawing permafrost may result in slope failures, such as slumping (Turcotte et al., 2011). Failures such as these may exacerbate channel bank erosion and can add sediment directly into the channel.
P2 - Increasing winter precipitation	Increased winter precipitation as snow, particularly in fall or early winter, may increase the capacity of the snow to insulate the ground from air temperatures. This may result in increased ground temperatures and increased active layer depth (Johansson et al., 2013; Park et al., 2015).	• Increased active layer depth • Increased subsidence • Increased/Decreased erosion • Increased/Decreased sediment transport capacity • Increased/Decreased rate of channel migration • Increased risk of channel bank slope failures	The geomorphic response of increased active layer depth will be similar to those stated above in P1; however, changes in precipitation may have a less pronounced effect on permafrost processes compared to changes in air temperature.
P3 - Increasing summer precipitation	Increased precipitation as rain and resulting runoff may increase thermal erosion where channels are overlying permafrost.	• Increased active layer depth • Increased erosion • Increased sediment transport capacity	The increase in precipitation will increase the erosive power of the flow over the landscape. Overland flow or flow concentrated in channels overlying permafrost may erode into permafrost, which may impact the active layer depth. While the magnitude of erosion and sediment mobilization will not likely be as pronounced compared to flow over non-frozen terrain, the increase in flow will likely mobilize additional sediment compared to what has historically occurred on the landscape. As the permafrost is thermally eroded by the flow, the active layer may also increase in depth, the implications of which are discussed above in P1.

(continued below)

Process/Trend	Driver	Resulting Effects	Geomorphic Response
River Ice Processes			
R1 - Increased temperature gradient from southern to northern extents of the watershed	Upstream of the Village of Old Crow, the Porcupine River flows from the southern extents of the watershed. Warmer air temperatures in the south may result in earlier breakup compared to the northern portion of the watershed.	• Increased risk of ice jam formation • Increased flood hazard • Increased erosion • Increased avulsion risk	Differential warming patterns may increase the likelihood of ice jam formation as ice flows originating from the south (upper watershed) may jam into stationary river ice further north along the river's course; this assumes that a threshold discharge is not required for ice jam mobilization. Increased ice jam formation, or ice jam formation at new locations, can increase the frequency of overbank flooding and ice-related morphological changes, such as those described in Table 4.3. This can result in increased risk of channel avulsions, increased sedimentation of the floodplain, and increased erosion both within side channels during the ice jam event and along all flow paths subsequent to the jam breach.
R2 - Increasing air and water temperature	Breakup occurs earlier and freeze-up occurs later, resulting in increased duration available for sediment transport and erosion (Prowse and Beltaos, 2002; Turcotte et al., 2011). Increased air and water temperatures may result in a decrease in overall ice thickness, reducing the risk of breakup ice jamming (Das and Lindenschmidt, 2021). It may also increase the frequency of rain-on-snow events during freeze-up, breakup and winter periods (Das and Lindenschmidt, 2021).	• Decreased risk of ice jam formation • Increased/Decreased erosion • Increased sediment transport capacity • Increased rate of channel migration	An increased length of the ice-free period may increase the duration of when shear stresses and flow velocities are high enough to convey sediment (Turcotte et al., 2011); see description in F2. This may increase the duration of when the river is actively transporting sediment, and hence may increase the total volume of the transported sediment load. Increased temperatures resulting in more frequent rain events during freeze-up, breakup, mid-winter periods may result in degradation of river ice. Mid-winter breakup events may occur more frequently, which may increase rates of erosion and channel migration. Conversely, degradation of river ice cover may result in a decreased likelihood or severity of ice jam formation. As flows released from ice jams can cause substantial geomorphic change in the channel, a reduction in ice jam severity during breakup may result in reduced erosion and sediment transport in the channel (Das and Lindenschmidt, 2021).
R3 - Increasing precipitation	Increased snowpack may lead to increased thermal insulation of the ice as well as increased snow available for melt in spring. Increased precipitation as rain may also increase the magnitude of high flow events and reduce ice thickness during rain-on-ice precipitation events (Das and Lindenschmidt, 2021).	• Increased/Decreased erosion • Increased/Decreased sediment transport capacity • Increased/Decreased rate of channel migration • Increased/Decreased risk of ice jam formation	Increased runoff and streamflow, driven by increased snowpack depth and increased precipitation as rain, may cause increased bank erosion, channel migration, sediment transport, and risk of avulsions; see description in F1. Deeper snowpacks may insulate the ice resulting in thicker river ice, which would increase the likelihood of mechanical breakup initiating instead of thermal breakup. Mechanical breakup has a greater tendency to cause geomorphic change due to the effects of flowing ice (bed scouring, gouging, and abrasion), increased flow turbulence, and ice jamming (Prowse and Beltaos, 2002; Turcotte et al., 2011). Conversely, a reduction in ice thickness due to precipitation as rain may promote thermal breakup, potentially reducing the geomorphic responses described above.

5 CONCLUSION

The Old Crow region is a complex environment that includes unglaciated terrain, a continuous permafrost zone, active river ice processes, and a river system with the headwaters flowing from south to north in a periglacial landscape that is susceptible to a changing climate. Each of these facets contribute to the complex geomorphic character of the region and have the potential to influence the flood and ice regimes.

The following synthesis of the preceding sections highlights attempts to provide inferences regarding the dominant fluvial and ice processes in the Old Crow study area and associated potential responses to climate change. However, the exact geomorphic response of climate change remains uncertain due to both inherent variability in natural systems and the complexity of feedbacks between climatic drivers and systems, where multiple (and opposing) responses to climatic drivers may be occurring, resulting in an indeterminate outcome.

5.1 Synthesis of Potential Geomorphic Hazards

General geomorphic responses to climate change in the Old Crow region may include the following:

- Increasing temperature and precipitation may increase peak flow frequency and magnitude, which could increase bank erosion, channel migration, sediment transport, and risk of avulsions.
- Land cover changes, especially those associated with forest disturbances (e.g., wildfires and infestations) and shrubification, are anticipated to impact hydrology, flood and ice regimes, permafrost, and geomorphic processes within the study area; however, potential hydrological and geomorphological responses to land cover changes are not direct nor straightforward, limiting the ability to predict how the rivers may respond.
- Loss of permafrost and ground-ice within the floodplain and along the channel margins is likely to increase bank instability, potentially resulting in increased erosion and sediment delivery to the channel, channel widening, and increased lateral migration (Rowland et al., 2023). Permafrost decay may also cause floodplain subsidence, potentially increasing flood risk and the occurrence of channel avulsions.
- Ice jams will likely continue to form at locations where there is increased resistance to ice flow, including tight meander bends, channel constrictions, and slope or flow velocity reductions.
- Changes to ice jam frequency and magnitude in the Porcupine River are uncertain owing to multiple drivers that can produce contrasting effects; Turcotte and Saal (2022) found similar results.

Although morphological response of the Porcupine and Old Crow Rivers to climate change is uncertain due to multiple drivers, often with contrasting effects, the detailed study area assessment identified several morphological changes that may occur in the vicinity of Old Crow in response to changing climatic and environmental conditions:

- Predicted increases in temperature and precipitation, coupled with their effects on permafrost and slope stability (Section 4.3.1), are likely to increase the amount of sediment supplied to the rivers. Increased sediment loads in the Old Crow and Porcupine Rivers would likely result in increased deposition at the confluence of the two river systems due to the reduction in stream competence that persists across a wide range of flows (Section 4.1); assuming the reduction in competence will persist into the future (i.e., barring any large morphological changes), future increases in discharge are likely to exacerbate sediment deposition within this reach. Increased deposition in this reach is likely to promote channel instability (e.g., channel migration, bank erosion, bed aggradation) and may impact flood levels of the Porcupine River adjacent to the Village of Old Crow.
- Climate change may increase the potential for an avulsion to occur on the Porcupine River, upstream of the confluence with the Old Crow River (Section 4.5), through a combination of effects, including: increased bank erosion in response to increasing magnitude of peak flows (NHC, 2024); destabilization of the channel banks due to changes in the river ice regime and melting of permafrost and ground-ice along the channel margins (Rowland et al., 2023); floodplain subsidence caused by thawing permafrost within the floodplain; and potential occurrence of overbank flooding caused by ice jams. Downstream impacts of a channel avulsion at this location may be diverse and widespread, including: potential increases in bank erosion due to change in flow alignment; channel incision and bed scour in response to the steepened hydraulic gradient at the avulsion point; compensating sediment deposition and bed aggradation downstream of the avulsion point; destabilization of the channel banks; and reorganization of in-channel bars. These morphological changes may impact the flood risk (e.g., bed aggradation) and result in increased geomorphological hazards along the Village of Old Crow.
- A meander cutoff avulsion is also possible along a tight meander bend on the Old Crow River (Section 4.5). While historical bankline mapping suggests that only very limited erosion has occurred since 1962, erosion may be exacerbated in the future due to the evolution of the meander geometry or changes in environmental and climatic conditions. Again, an avulsion at this location may cause extensive channel rearrangement downstream, which may include substantial impacts to the channel bed and banks adjacent to the Village of Old Crow.
- Increases in the magnitude or duration of peak flows may promote increased erosion and scour along two particular reaches adjacent to the Village of Old Crow that have relatively high competence and stream power (Section 4.3.2); near the western area of

concern (Section 4.1.4), and further downstream where there is a constriction in the channel width.

- The condition and extent of existing bank protection adjacent to the Village of Old Crow is generally inadequate to provide erosion protection against existing, and potential future, high flow and ice breakup events (Section 4.1). NHC recommends further assessment and upgrades to existing bank protection (see Section 5.2).
- The Bluefish River confluence with the Porcupine River will likely continue to be prone to the development of ice jams and aufeis formation due to its morphology and associated constriction of the Porcupine River; however, the specific environmental conditions leading to extensive aufeis formation at the Bluefish River delta are not well understood.

5.2 Setbacks

Two types of setbacks are typically considered in floodplain mapping: a hydraulic setback and a geomorphic setback. A hydraulic setback is applied to prevent encroachment into the floodway that can restrict flood conveyance and transfer flood risk to other properties. A geomorphic setback refers to a designated buffer, or horizontal distance, applied to the margins of a river, stream, or shoreline to account for potential erosion that could impact existing or future infrastructure. Typically, the professional of record determines the setback for the floodplain maps as the greater of the floodway and the geomorphic setbacks.

Several guidance documents are available for mapping geomorphic process corridors and establishing geomorphic setbacks (CWCB, 2020; Gouvernement du Québec, 2024; Natural Resources Canada, 2024; Nelson et al., 2024; Olson et al., 2014; Rapp and Abbe, 2003). A study to determine geomorphic setbacks can include the following components: identifying the active area around a river, characterizing erosion magnitude to define a setback distance or hazard severity, and accounting for uncertainty or access requirements by adding an additional setback. The preferred study approach, level of detail, and which components a study includes, will depend on the study objectives, geomorphic setting, and potential consequences. Simple approaches, like defining a standard setback distance, have been used in the past but are typically only recommended when there is low likelihood of geomorphic impacts and low potential consequences (Natural Resources Canada, 2024).

High-level guidance documents for flood hazard mapping in British Columbia state that a minimum 30 m setback should be applied to all major watercourses (APEGBC, 2017; MFLNRORD, 2018). At the time of writing, there are no equivalent guidelines published for Yukon that NHC is aware of. While this does provide initial guidance, APEGBC (2017) also state that if there is active bank erosion, setbacks should be informed by fluvial geomorphic analysis. Values or assets potentially exposed to erosion hazard should also be considered.

Establishing geomorphic setbacks is beyond the scope of this overview-level assessment. A more comprehensive assessment would be required to define setbacks given the complexity of

geomorphic processes driving landscape evolution within the Old Crow region and their susceptibility to climate change. In the absence of such studies, a generalized minimum setback of 30 m from the top of bank is suggested for planning of infrastructure and development (APEGBC, 2017; MFLNRORD, 2018); *this setback should be applied from the position of the bank at the time of development planning*. Land within the setback should be designated as unsuitable for further development. Where exemptions to the setback are applied for, potential geomorphic hazards should be further assessed, understood, and mitigated (if and where applicable).

While further analysis would likely improve the overall understanding of key environmental drivers and potential pathways of change, NHC is aware that additional study can be costly and may not necessarily result in greater certainty in terms of predicting how the landscape will respond in the future. Therefore, the recommendations put forth in Section 5.3 are primarily focussed on data collection and monitoring. NHC recommends that the information gained through data collection and monitoring be used to directly inform an adaptive management strategy aimed at mitigating or responding to flood and erosion hazards.

5.3 Recommendations

This study relied on information and data provided remotely as well as available literature and previous studies regarding river ice, permafrost, and ice jam processes. While this study highlighted some of the more prominent processes that could elicit a geomorphic response, potential geomorphic responses to changing climatic and environmental drivers, and associated impacts to flood risk, remain uncertain due to inherent variability in natural systems and the complexity of feedbacks between climatic drivers and fluvial systems.

While additional research into environmental and geomorphic processes in the region would improve the overall understanding of key environmental drivers and potential pathways of change, NHC is aware that these programs may be costly and logistically difficult to implement, especially given the remote nature of the area. As such, NHC focussed on providing recommendations that may provide a more rapid and direct benefit to the Community and be more easily implemented.

NHC recommends that the flood mapping study would benefit from the following supplemental analyses and monitoring programs in the Old Crow region:

- **Permafrost**: the condition of permafrost in the Old Crow study area will influence channel migration rates, sediment transport, erosion, avulsion potential, and flooding. Monitoring the condition of the permafrost near Old Crow, including the potential for related floodplain subsidence, will provide useful information regarding potential changes in morphology and flood or erosion risk.
    - For example, a seasonal thaw depth assessment could be completed following the procedures used by the Circumpolar Active Layer Monitoring (CALM)

program[2]. This generally requires designating an area of undisturbed tundra that the seasonal thaw depths can be measured using hand tools. The thaw depths at predetermined measurement points are recorded and processed, hopefully assisted by schoolteachers and students they assign to the effort. If repeated on an annual basis by the Community, the thaw depth trends will support technical confirmation of continued permafrost threats. In addition, the teachers and students can share their findings with a global research community conducting similar assessments throughout the circumpolar region. Appropriate guidance from a permafrost expert should be sought when establishing such a monitoring program.

- **Floodplain**: mapping and photo monitoring of permafrost and ground-ice features within the floodplains of the Old Crow and Porcupine Rivers in the vicinity of the Village of Old Crow is recommended. This information will help inform the geomorphic character of the floodplain and provide useful information regarding how the morphology of the channel and floodplain may change due to climate change effects on permafrost (e.g., floodplain subsidence or bank erosion due to ground-ice decay).
- **Bank erosion**: annual and event-specific monitoring (e.g., after breakup, ice jams, and large floods) of bank erosion is recommended to build baseline information and help establish trends of morphological change (e.g., channel migration rates). This monitoring may be done using photographs, RPAS collected imagery, or simple survey techniques (e.g., measure the distance between the top of bank and a fixed point). Recommended sites to monitor include the channel banks along the Village of Old Crow, particularly in areas where erosion has previously been noted by the Community and areas composed of natural bank material adjacent to hardened banks (Section 4.1.4). Monitoring of bank erosion should also be undertaken at the two potential avulsion sites described in Section 4.5. If a notable increase in bank erosion is detected over time, additional studies are recommended to further assess the potential impacts of erosion or avulsions at these locations, including potential erosion mitigation and risk reduction measures.
    - It is further recommended that the condition of existing bank protection in Old Crow (Section 4.1.4) be assessed by a Qualified Professional in terms of its design, installation, and functionality. Particular attention should be given to the effectiveness of the bank hardening to withstand erosion from ice forces (e.g., ice runs). Should the existing bank hardening be deemed inadequate to provide the Community with appropriate erosion protection, the extent and design of the bank protection works should be improved to provide suitable erosion protection against hydraulic and ice forces. It is recommended to obtain professional advice about potential improvements to existing erosion protection, especially where new assets have been built along the riverbank.

[2] https://arcticdata.io/catalog/portals/CALM

- **Bank ice**: photo monitoring of locations where visible ground-ice features and permafrost indicators are present along the banks would be useful to correlate changes in ground-ice with changes in bank instability over time.

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APPENDIX D

FLOOD MAPS

General Notes:

1. The associated report should be read and understood prior to use of these flood maps: Northwest Hydraulic Consultants Ltd. (NHC) 2025. *Old Crow Flood Mapping Study.* NHC project 1008777.

2. Flood extents were delineated for the following flood scenarios: 5%, 1%, and 0.5% Annual Exceedance Probability (AEP, 1-in-20, 1-in-100, and 1-in-200 year events). The inundation extents for each AEP represent results for ice induced flood events. All breakup scenarios were considered.

3. Flood levels were calculated using a 1D numerical flow model developed by NHC within HEC-RAS software.

4. All elevations are referenced to Canadian Geodetic Vertical Datum 2013 (CGVD2013). Water surface elevations do not include freeboard.

5. The asset ID number corresponds to asset ID numbers assigned by Underhill Geomatics during the June 2024 survey.

A generalized minimum setback of 30 m from the top of bank is suggested for planning of infrastructure and development. This setback is in general agreement with published guidelines (APEGBC, 2017; FLNRORD, 2018). Land within the setback area should be designated as unsuitable for further development; where exemptions to the setback are applied for, potential geomorphic hazards should be further assessed, understood, and mitigated (if and where applicable). For further information on areas of erosion vulnerability, see Appendix C of the associated project report.

Data Sources:

1. The digital elevation model (DEM) used to develop the flood mapping and terrain contours was pre- and post-processed using Esri ArcGIS Pro software. The data sources for the DEM are listed below.

   a. LiDAR flown by McElhanney, acquired September 10, 2019.

   b. The study area outside the LiDAR boundary was supplemented using high resolution digital elevation model (HRDEM) data from Natural Resources Canada.

2. River channel bathymetry on Porcupine and Old Crow Rivers was surveyed by Underhill Geomatics in June 2024.

3. Mapping background - Orthophotos from McElhanney, acquired September 10, 2019 and Esri World Imagery where needed. Inset map and Index backgrounds - Esri World Topo.

Use and Limitations of Flood Maps:

1. The maps delineate flood inundation areas for flood scenarios based on available survey data and water level records.

2. Future changes to the river channels, floodplain, and future climate will render the maps obsolete. The information on the maps should be reviewed after 5 years have elapsed since publication or after any extreme flood occurrence.

3. Flood mapping delineates flood inundation areas, showing the extent of one or more flood scenarios under existing conditions. Flood mapping is typically used for near real-time emergency response planning and operations.

4. The intent of the field survey, data collected, analyses, and results was for the purposes of flood mapping. The flood maps are not intended for engineering design or construction.

5. Underlying hydraulic analysis assumes channel and shoreline geometry is stationary. Erosion, deposition, degradation, and aggradation are expected to occur and may alter actual observed flood levels and extents. Roads, bridges, new dikes, and future developments on the floodplain can restrict water flow and increase local water levels. Obstructions, such as log-jams, blockages, local storm water inflows, groundwater, other land drainage or tributary flows beyond those indicated were not modelled and may cause flood levels to exceed those indicated on the maps. Additionally, flooding may occur outside of the designated boundaries caused by ponding from rainwater or snowmelt on the floodplain, groundwater seepage, local snowmelt, or local drainage courses.

6. The flood extents for modelled scenarios have not been established on the ground by legal survey. The accuracy of the flood boundaries is limited by the LiDAR base mapping and orthophotography.

7. Isolated areas of inundation smaller than 100 m^2 and some manually flagged areas larger than 100m^2 were removed from the maps. Holes in the inundation extents with areas less than 100 m^2 were also removed.

8. The flood maps do not represent hazards due to erosion, avulsion, or channel migration. An overview assessment of geomorphic hazards can be found in Appendix C of the associated project report.

9. Industry best practices were followed to generate the flood maps. However, actual flood levels and extents may vary from those shown. Residual flood risk beyond that mapped exists for flood events more extreme than the design events. Northwest Hydraulic Consultants Ltd. and the Government of Yukon do not assume any liability for such variations.

DISCLAIMER

This report has been prepared by Northwest Hydraulic Consultants Ltd. for the Government of Yukon Department of Environment – Water Resources Branch for specific application to the Old Crow Flood Mapping Study (Porcupine River and Old Crow River), a project funded through the Flood Hazard Identfcation and Mapping Program. The information and data contained herein represent Northwest Hydraulic Consultants Ltd.'s professional judgment in light of the knowledge and information available to Northwest Hydraulic Consultants Ltd. at the time of preparation and was prepared in accordance with generally accepted engineering and geoscience practices.
This study and associated project deliverables may be used and relied upon by Government of Yukon Department of Environment – Water Resources Branch, its officers, and employees, as well as all orders of government and other public and private sector organizations, to understand clearwater and ice jam flood hazards for the specific flood scenarios and water bodies assessed in the study. The report and flood maps produced as part of this project are intended to inform decision-making support of land use planning, flood mitgation, emergency preparedness and response, and adaptation to a changing climate. Northwest Hydraulic Consultants Ltd. is not liable in any way whatsoever to any party for any injury, loss, or damages suffered by such parties arising from the misuse, misinterpretation, or reliance upon this report or any of its contents.

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Engineer	GIS	Reviewer
SGZ	JXD	FMH/PKK

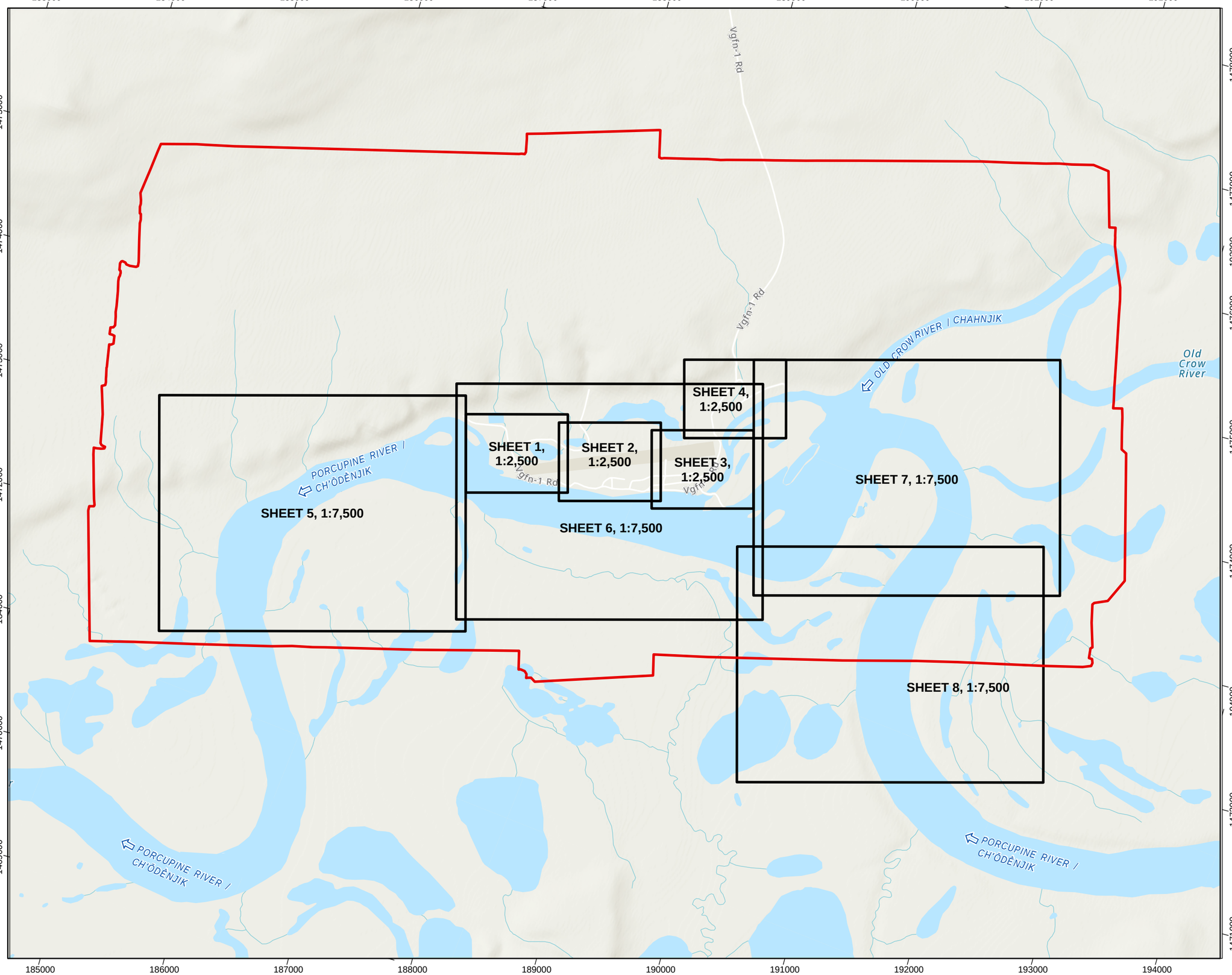
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OLD CROW FLOOD MAPPING

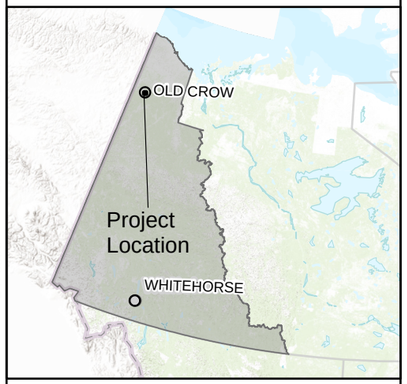
MAP NOTES

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MAPPING INDEX SHEETS
LIDAR EXTENT

Engineer	GIS	Reviewer
SGZ	JXD	FMH/PKK

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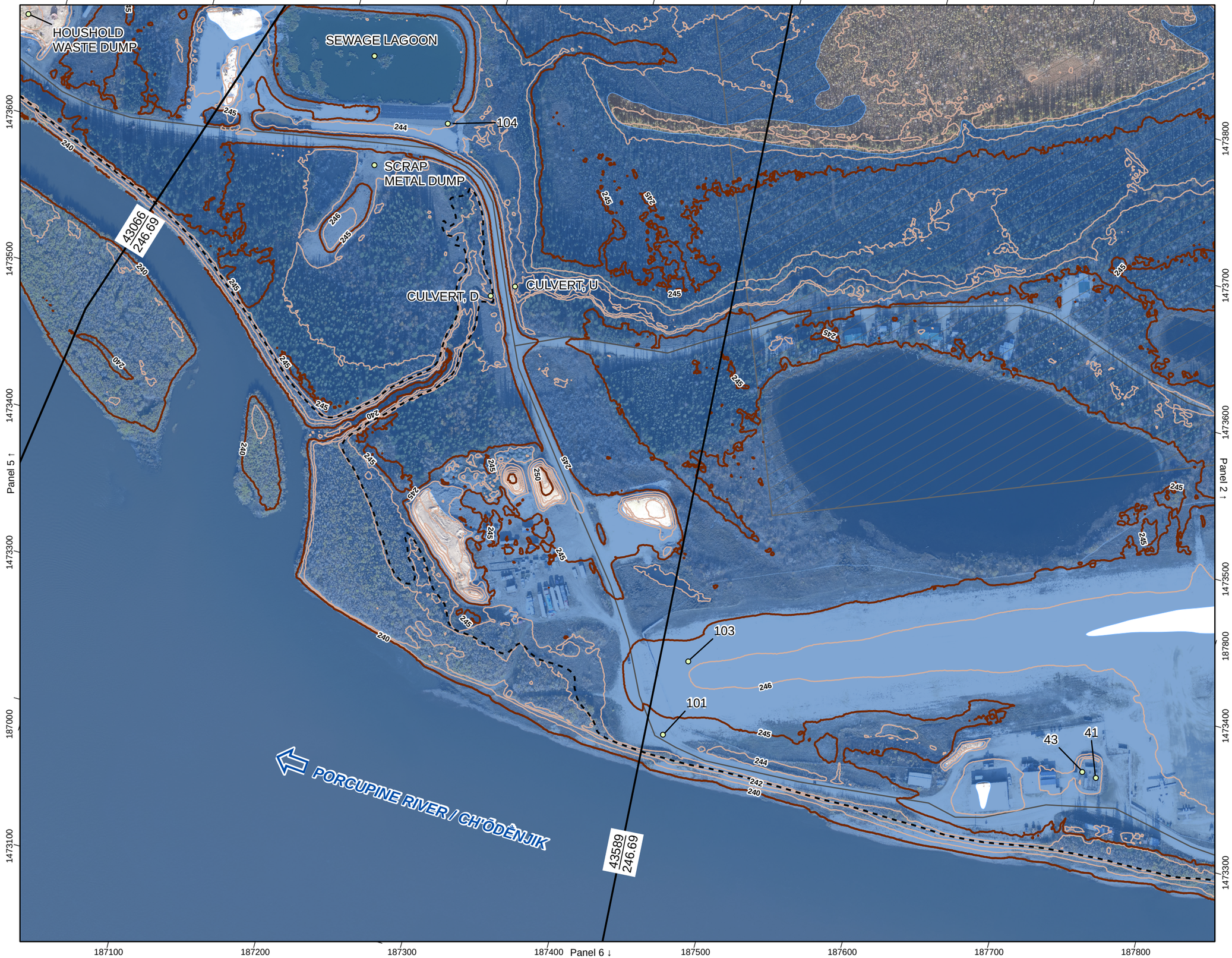
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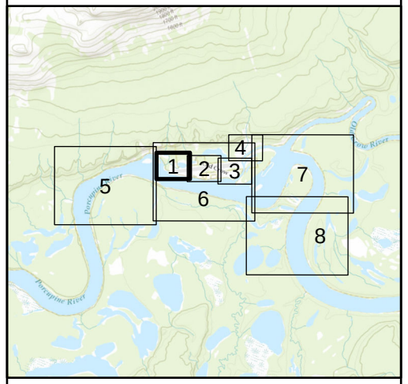
SHEET INDEX

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- POINT OF INTEREST
  Asset ID number (see General Notes)
- ROAD
- MAJOR CONTOUR AT 5M INTERVAL
  Labelled with elevation in metres
- MINOR CONTOUR AT 1M INTERVAL
  Labelled with elevation in metres
- MODELLED CROSS-SECTION
- 40757 STATIONING *(Labelled in metres)*
  246.43 WATER SURFACE ELEVATION *(Labelled in metres)*
- 50% AEP OPEN WATER EXTENT
- INUNDATION EXTENT
- VUNTUT GWITCHIN FIRST NATION SETTLEMENT LAND
- FLOW DIRECTION

DATA SOURCES: REFER TO NOTES ON INDEX MAP

Engineer	GIS	Reviewer
SGZ	JXD	FMH/PKK

SCALE - 1:2,500

0 25 50 75 100 M

N

Coordinate System: NAD 1983 CSRS YUKON ALBERS
Units: METRES; Vertical Datum: CGVD2013 (CGG2013a)

Job: 1008777	Date: 15-MAY-2025

OLD CROW FLOOD MAPPING

5.0% ICE INDUCED ANNUAL EXCEEDANCE PROBABILITY

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53A - SOLAR FARM
E-BUILDING

45122
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44725
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37 - AIRPORT
TERMINAL

28A

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AIRPORT
CULVERT, U

AIRPORT
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23 - NURSING
STATION

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18 - OLD CHURCH

17 - RCMP
BUILDING

20 - WATER SURVEY OF
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11 - NEW
COMMUNITY
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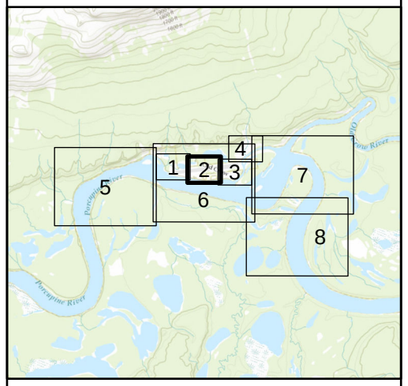
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PORCUPINE RIVER / CH'ŌDÈNJIK

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- POINT OF INTEREST
  Asset ID number (see General Notes)
- ROAD
- MAJOR CONTOUR AT 5M INTERVAL
  Labelled with elevation in metres
- MINOR CONTOUR AT 1M INTERVAL
  Labelled with elevation in metres
- MODELLED CROSS-SECTION
- 40757 / 246.43 STATIONING *(Labelled in metres)* / WATER SURFACE ELEVATION *(Labelled in metres)*
- 50% AEP OPEN WATER EXTENT
- INUNDATION EXTENT
- VUNTUT GWITCHIN FIRST NATION SETTLEMENT LAND
- FLOW DIRECTION

DATA SOURCES: REFER TO NOTES ON INDEX MAP

Engineer	GIS	Reviewer
SGZ	JXD	FMH/PKK

SCALE - 1:2,500

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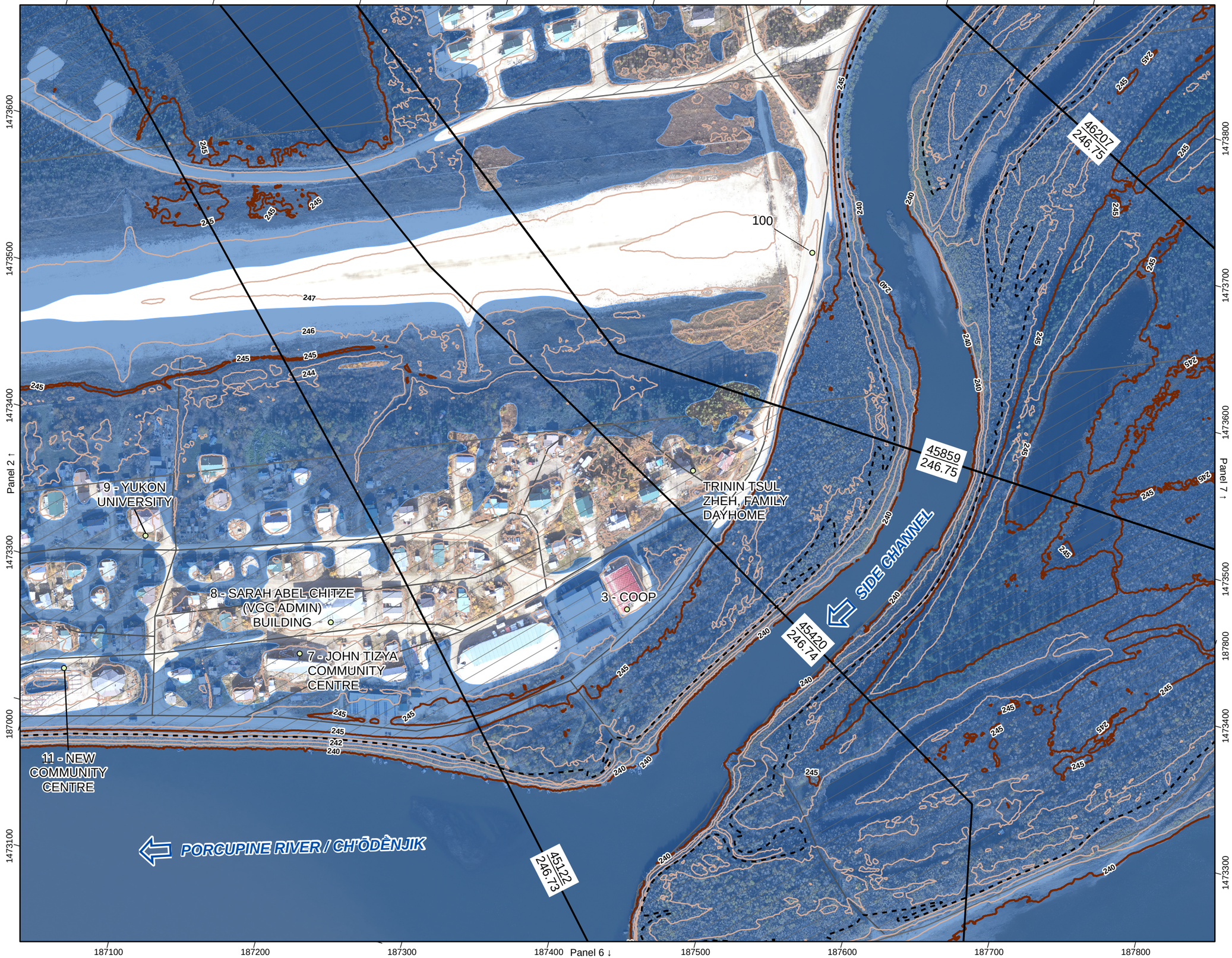
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OLD CROW FLOOD MAPPING

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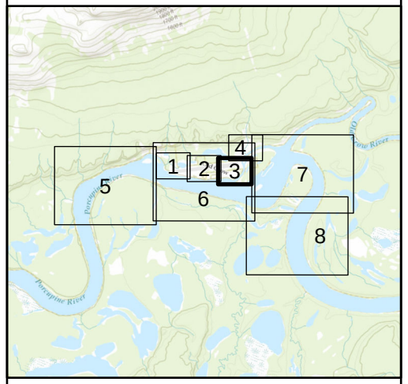
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- POINT OF INTEREST
  Asset ID number (see General Notes)
- ROAD
- MAJOR CONTOUR AT 5M INTERVAL
  Labelled with elevation in metres
- MINOR CONTOUR AT 1M INTERVAL
  Labelled with elevation in metres
- MODELLED CROSS-SECTION
- 40757 / 246.43 STATIONING *(Labelled in metres)* WATER SURFACE ELEVATION *(Labelled in metres)*
- 50% AEP OPEN WATER EXTENT
- INUNDATION EXTENT
- VUNTUT GWITCHIN FIRST NATION SETTLEMENT LAND
- FLOW DIRECTION

DATA SOURCES: REFER TO NOTES ON INDEX MAP

Engineer	GIS	Reviewer
SGZ	JXD	FMH/PKK

SCALE - 1:2,500

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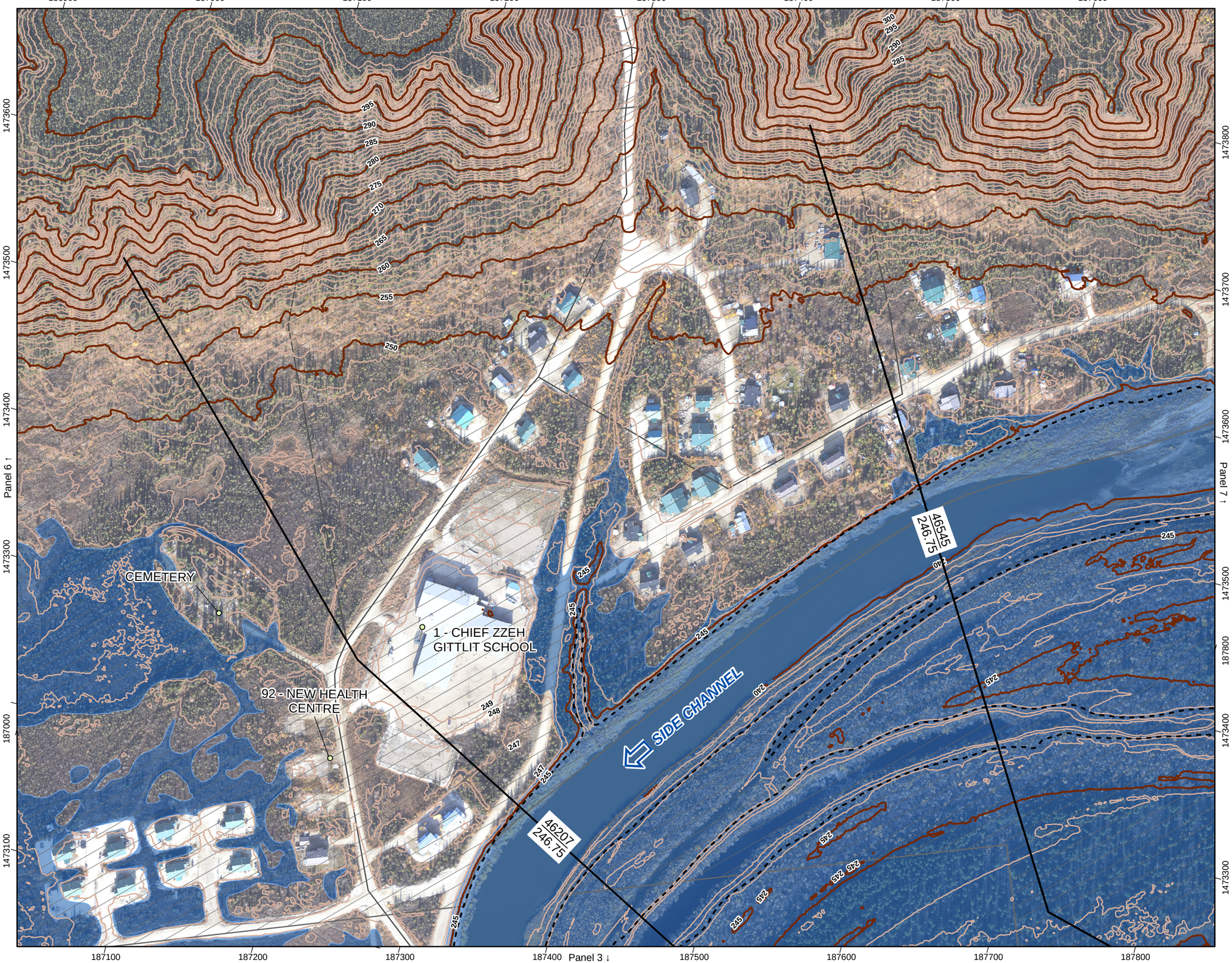
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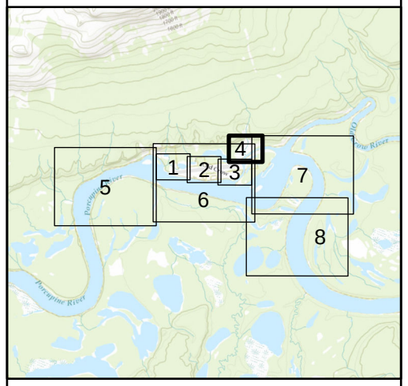
OLD CROW FLOOD MAPPING

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- POINT OF INTEREST
  Asset ID number (see General Notes)
- ROAD
- MAJOR CONTOUR AT 5M INTERVAL
  Labelled with elevation in metres
- MINOR CONTOUR AT 1M INTERVAL
  Labelled with elevation in metres
- MODELLED CROSS-SECTION
- 40757 / 246.43 STATIONING *(Labelled in metres)* / WATER SURFACE ELEVATION *(Labelled in metres)*
- 50% AEP OPEN WATER EXTENT
- INUNDATION EXTENT
- VUNTUT GWITCHIN FIRST NATION SETTLEMENT LAND
- FLOW DIRECTION

DATA SOURCES: REFER TO NOTES ON INDEX MAP

Engineer	GIS	Reviewer
SGZ	JXD	FMH/PKK

SCALE - 1:2,500

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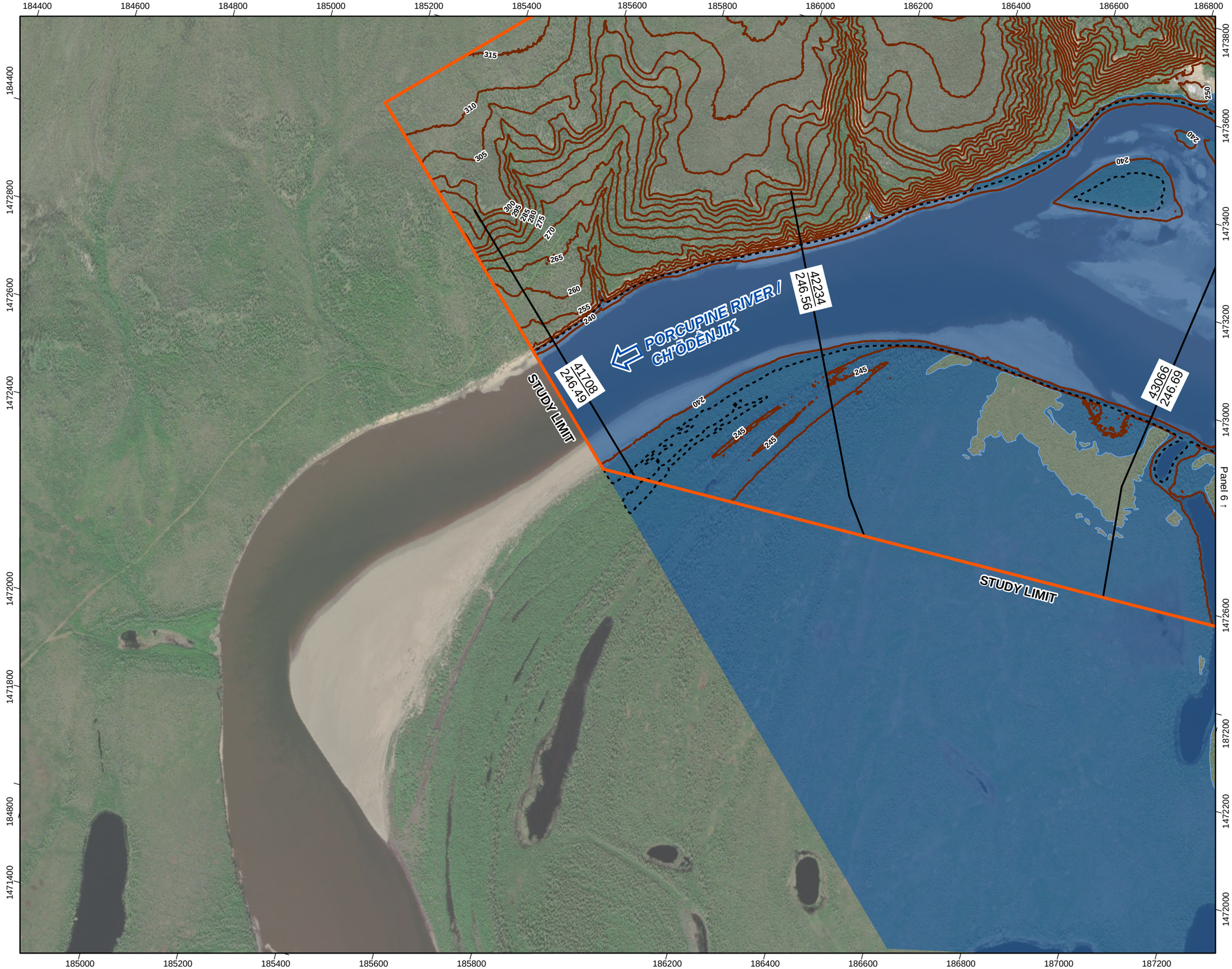
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OLD CROW FLOOD MAPPING

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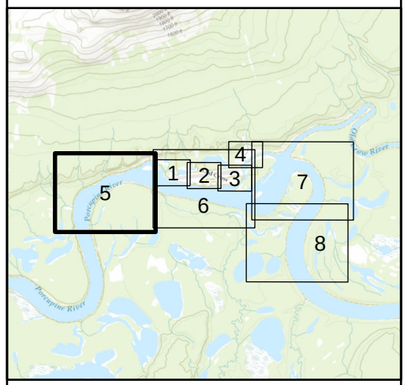
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Panel 6 →

- ROAD
- STUDY LIMIT
- MAJOR CONTOUR AT 5M INTERVAL
  Labelled with elevation in metres
- MODELLED CROSS-SECTION
- 40757 / 246.43 STATIONING *(Labelled in metres)* / WATER SURFACE ELEVATION *(Labelled in metres)*
- 50% AEP OPEN WATER EXTENT
- INUNDATION EXTENT
- FLOW DIRECTION

DATA SOURCES: REFER TO NOTES ON INDEX MAP

Engineer	GIS	Reviewer
SGZ	JXD	FMH/PKK

SCALE - 1:7,500

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N

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Units: METRES; Vertical Datum: CGVD2013 (CGG2013a)

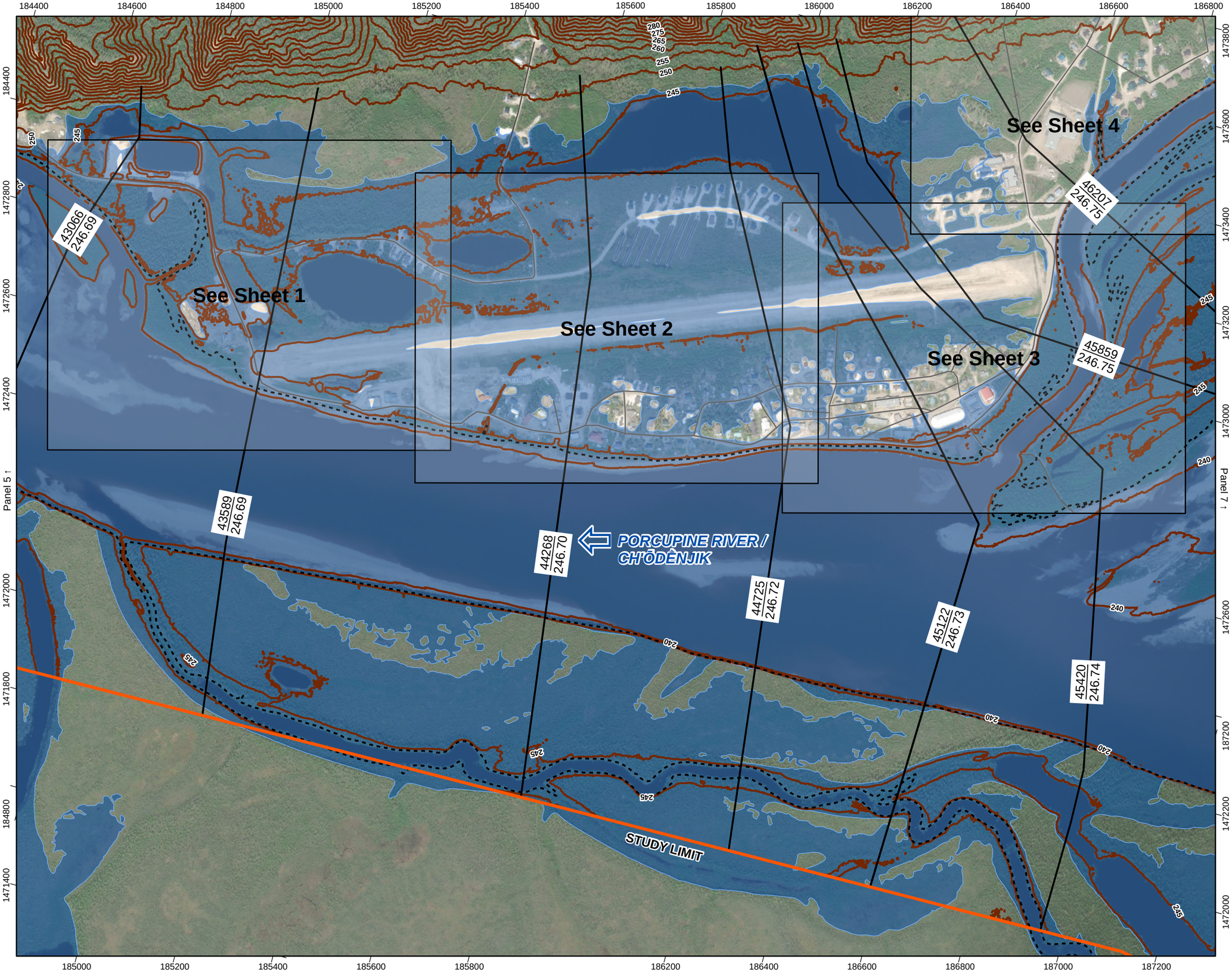
Job: 1008777	Date: 15-MAY-2025

OLD CROW FLOOD MAPPING

5.0% ICE INDUCED ANNUAL EXCEEDANCE PROBABILITY

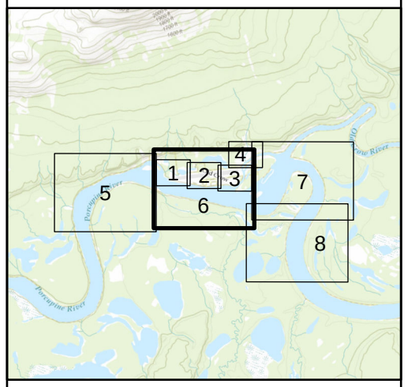
SHEET 5 of 8

JXD, \\mainfile-van\Projects\Active\1008777 Old Crow\9S GIS\1008777_JXD_FLoodMapping_7p5k_2.aprx



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- ROAD
- STUDY LIMIT
- MAJOR CONTOUR AT 5M INTERVAL *Labelled with elevation in metres*
- MODELLED CROSS-SECTION
- 40757 STATIONING *(Labelled in metres)*
- 246.43 WATER SURFACE ELEVATION *(Labelled in metres)*
- 50% AEP OPEN WATER EXTENT
- INUNDATION EXTENT
- FLOW DIRECTION

DATA SOURCES: REFER TO NOTES ON INDEX MAP

Engineer	GIS	Reviewer
SGZ	JXD	FMH/PKK

SCALE - 1:7,500

0 50 100 150 200 250 300 M

N

Coordinate System: NAD 1983 CSRS YUKON ALBERS
Units: METRES; Vertical Datum: CGVD2013 (CGG2013a)

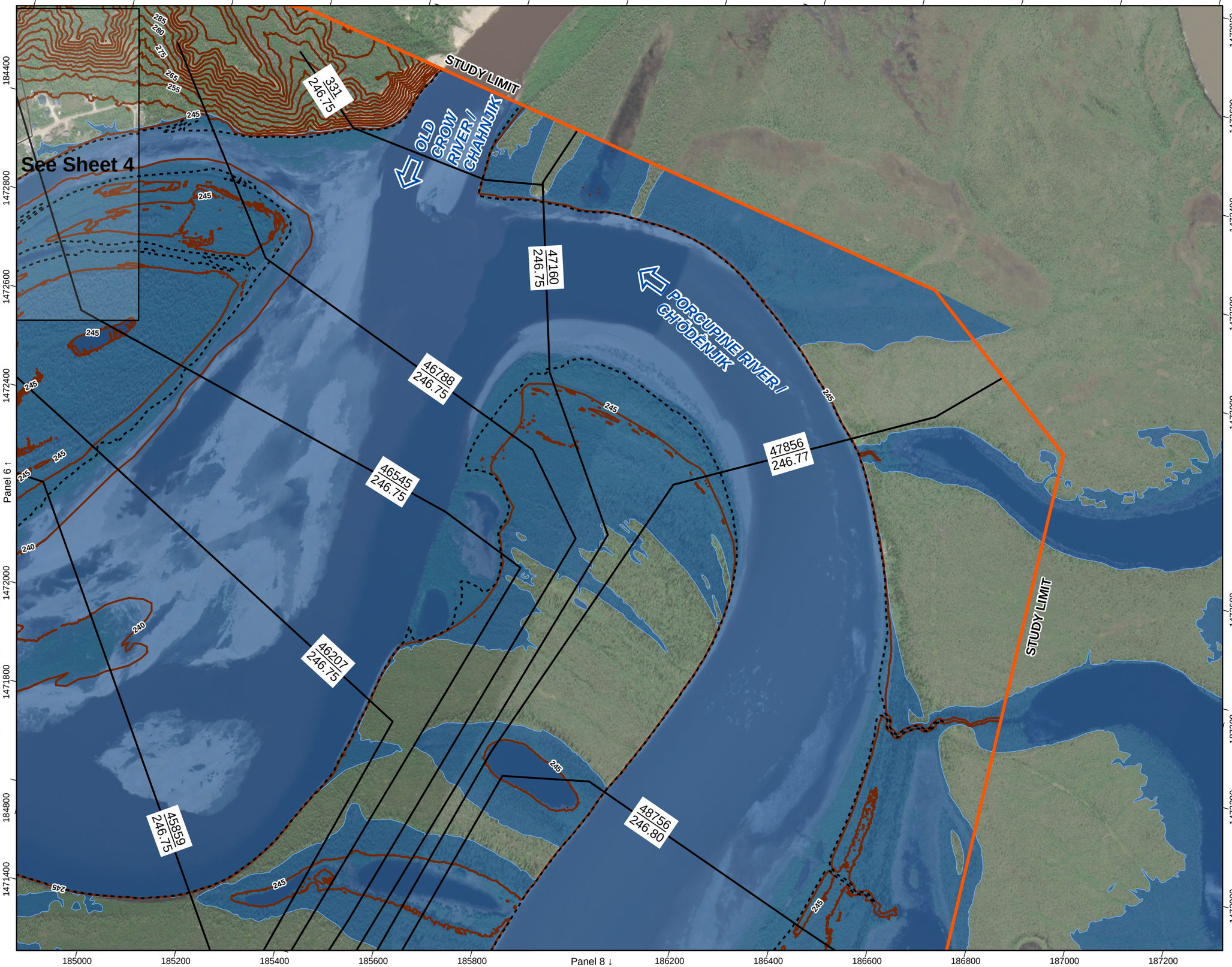
Job: 1008777	Date: 15-MAY-2025

OLD CROW FLOOD MAPPING

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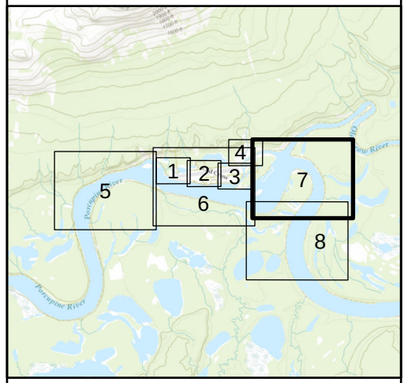
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JXD, \\mainfile-van\Projects\Active\1008777 Old Crow\95 GIS\1008777_JXD_FLoodMapping_7p5k_2.aprx



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- ROAD
- STUDY LIMIT
- MAJOR CONTOUR AT 5M INTERVAL *Labelled with elevation in metres*
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Engineer	GIS	Reviewer
SGZ	JXD	FMH/PKK

SCALE - 1:7,500

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Coordinate System: NAD 1983 CSRS YUKON ALBERS
Units: METRES; Vertical Datum: CGVD2013 (CGG2013a)

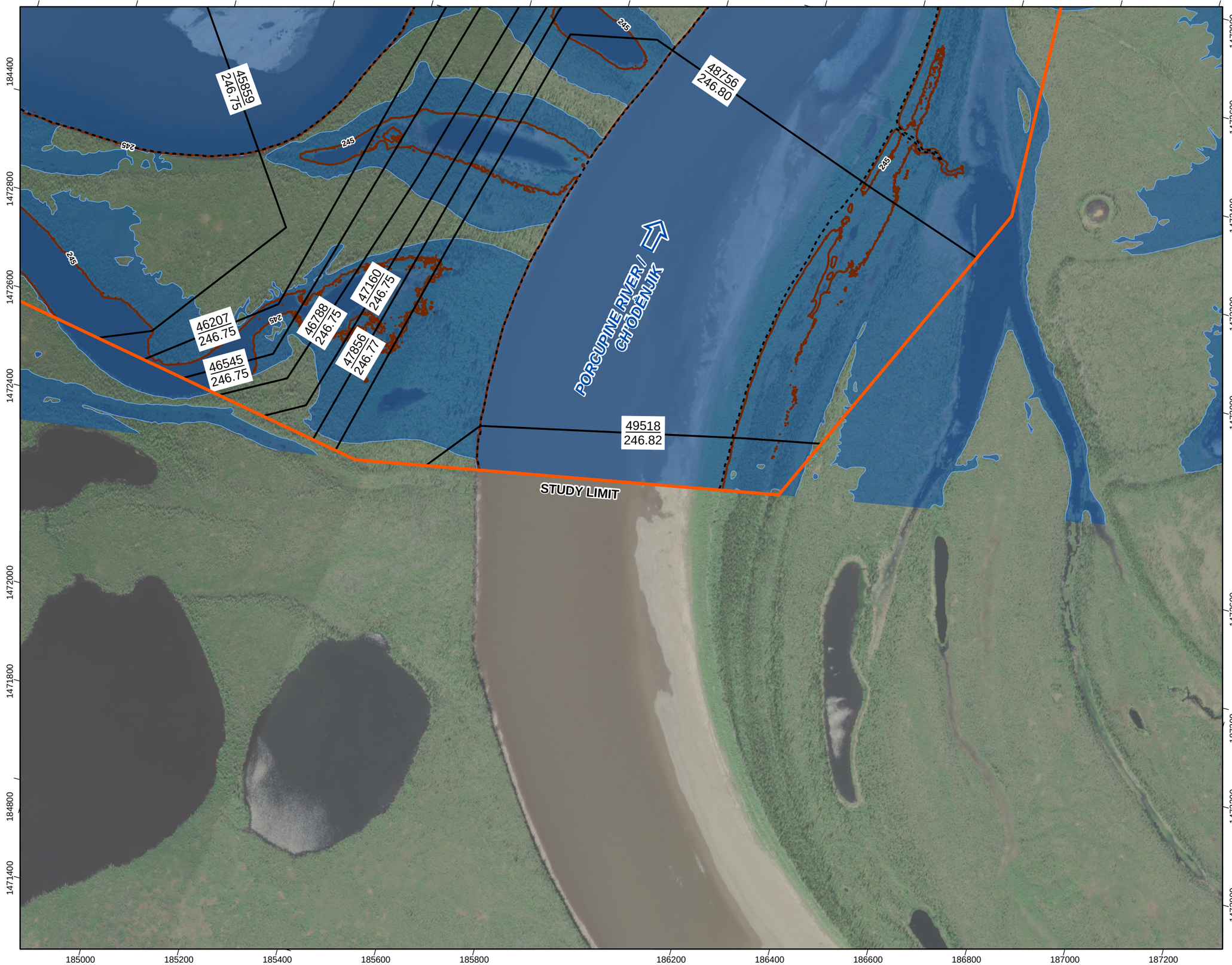
Job: 1008777 | *Date: 15-MAY-2025*

OLD CROW FLOOD MAPPING

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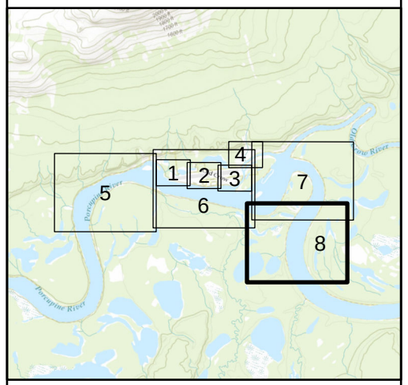
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- ROAD
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DATA SOURCES: REFER TO NOTES ON INDEX MAP

Engineer	GIS	Reviewer
SGZ	JXD	FMH/PKK

SCALE - 1:7,500

0 50 100 150 200 250 300 M

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Coordinate System: NAD 1983 CSRS YUKON ALBERS
Units: METRES; Vertical Datum: CGVD2013 (CGG2013a)

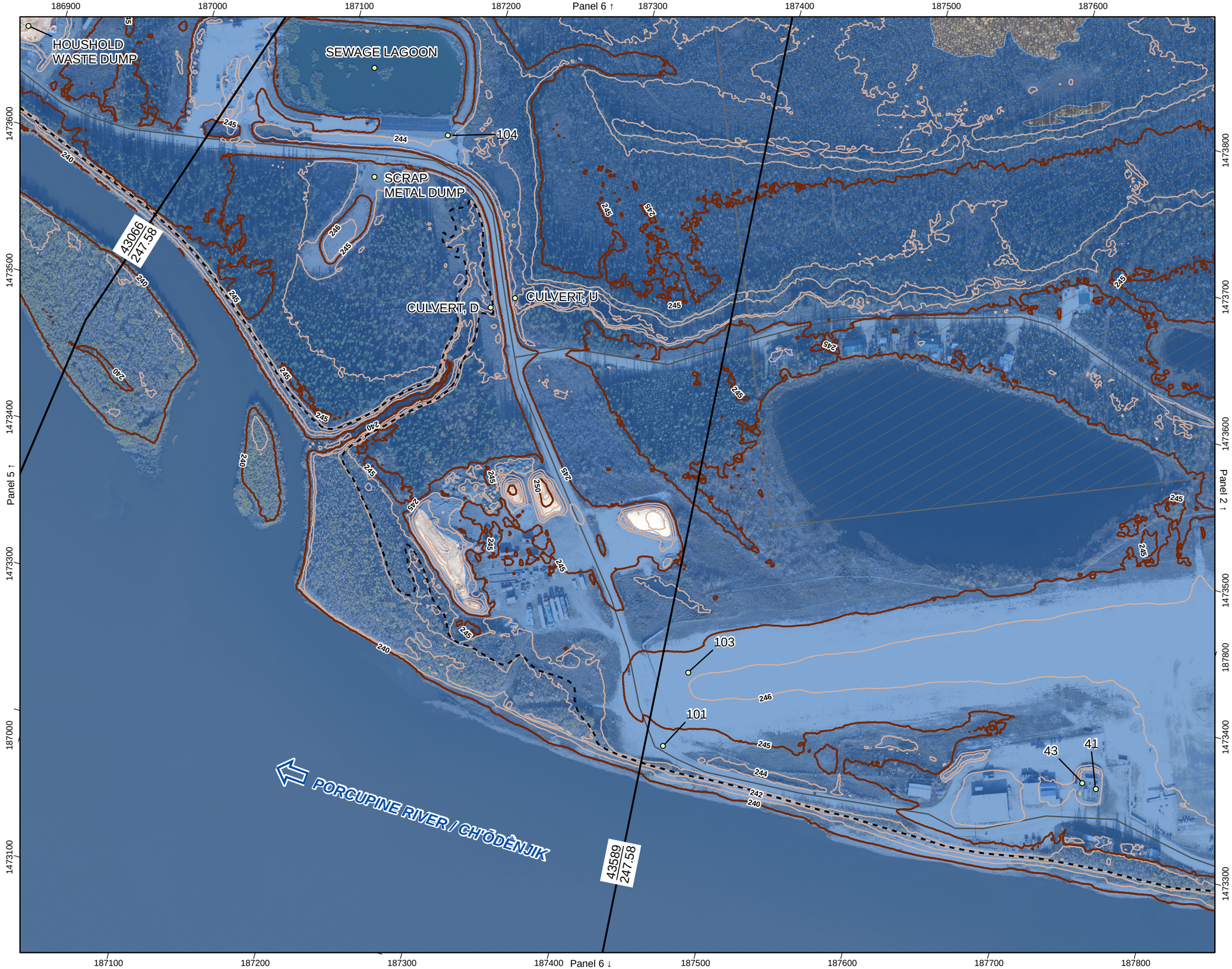
Job: 1008777 | *Date: 15-MAY-2025*

OLD CROW FLOOD MAPPING

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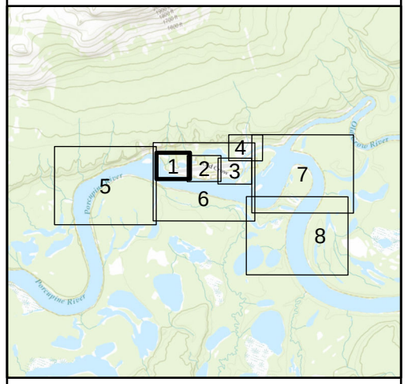
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JXD, \\mainfile-van\Projects\Active\1008777 Old Crow\95 GIS\1008777_JXD_FLoodMapping_7p5k_2.aprx



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- POINT OF INTEREST
  Asset ID number (see General Notes)
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  Labelled with elevation in metres
- MINOR CONTOUR AT 1M INTERVAL
  Labelled with elevation in metres
- MODELLED CROSS-SECTION
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- FLOW DIRECTION

DATA SOURCES: REFER TO NOTES ON INDEX MAP

Engineer	GIS	Reviewer
SGZ	JXD	FMH/PKK

SCALE - 1:2,500

0 25 50 75 100 M

N

Coordinate System: NAD 1983 CSRS YUKON ALBERS
Units: METRES; Vertical Datum: CGVD2013 (CGG2013a)

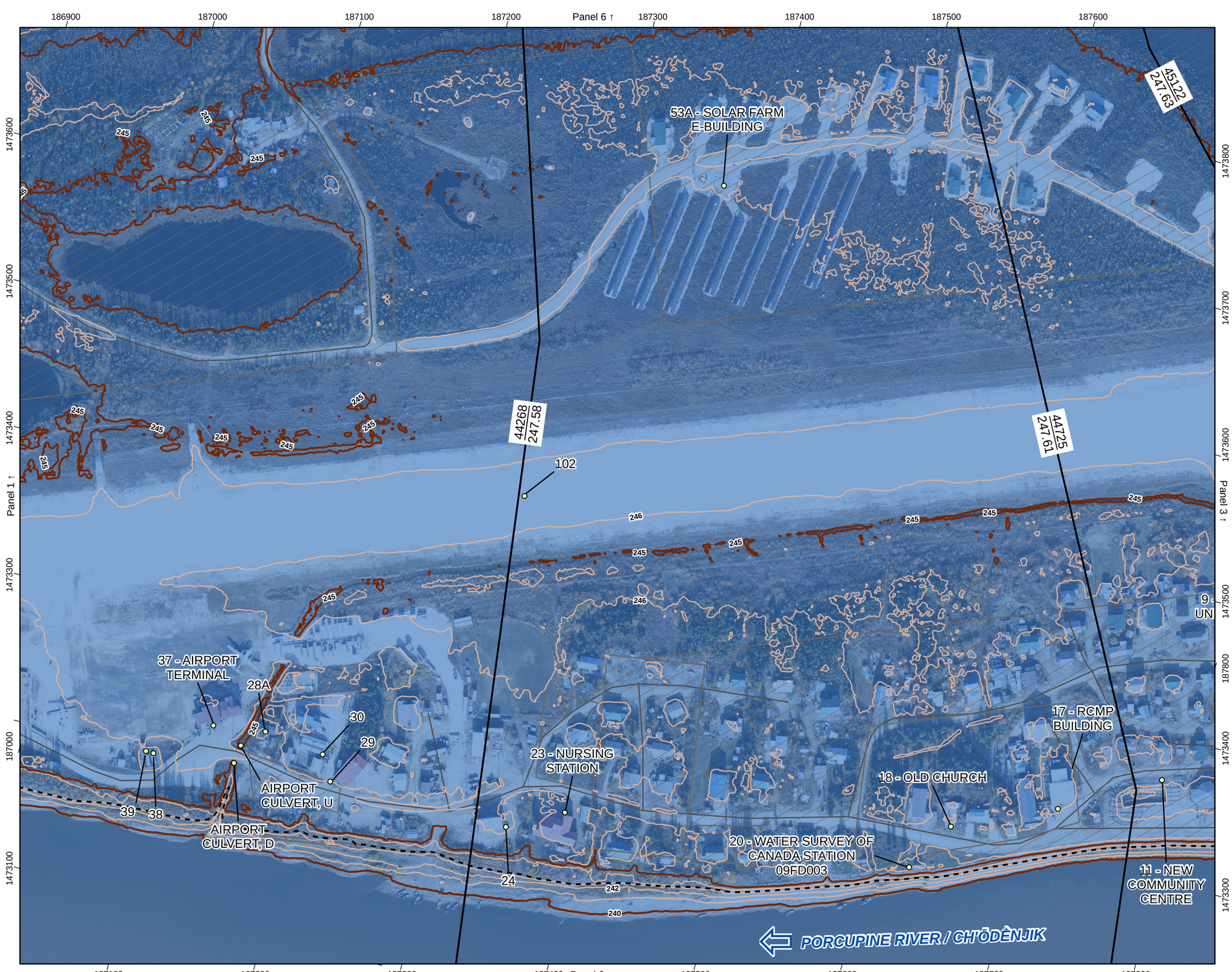
Job: 1008777	Date: 15-MAY-2025

OLD CROW FLOOD MAPPING

1.0% ICE INDUCED ANNUAL EXCEEDANCE PROBABILITY

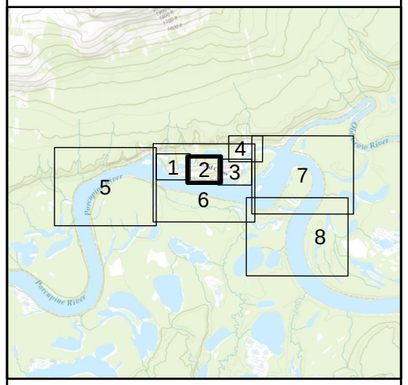
SHEET 1 of 8

JXD, \\mainfile-van\Projects\Active\1008777 Old Crow\95 GIS\1008777_JXD_FLoodMapping_2p5k_2.aprx



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- MAJOR CONTOUR AT 5M INTERVAL
  Labelled with elevation in metres
- MINOR CONTOUR AT 1M INTERVAL
  Labelled with elevation in metres
- MODELLED CROSS-SECTION
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DATA SOURCES: REFER TO NOTES ON INDEX MAP

Engineer	GIS	Reviewer
SGZ	JXD	FMH/PKK

SCALE - 1:2,500

0 25 50 75 100 M

N

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Units: METRES; Vertical Datum: CGVD2013 (CGG2013a)

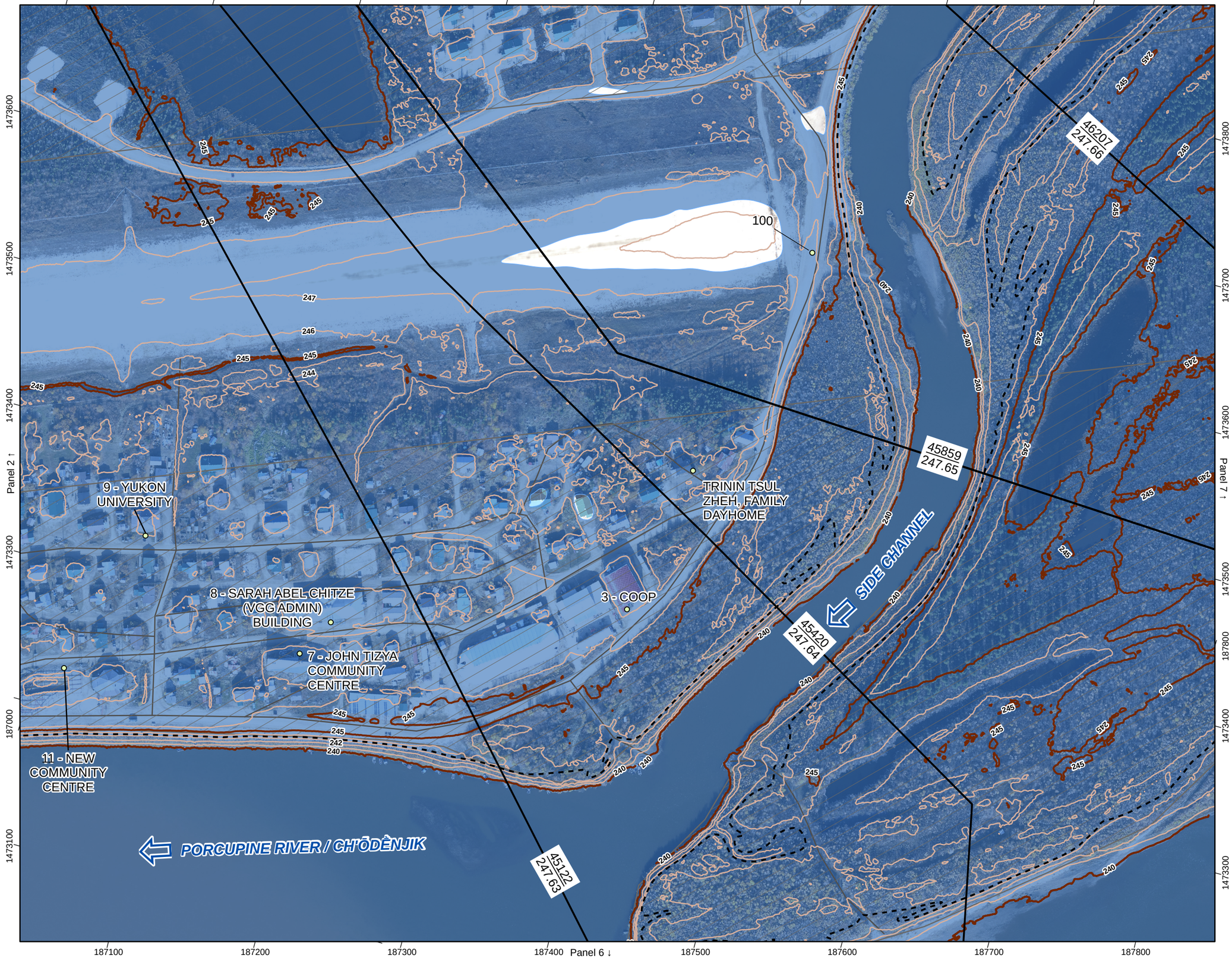
Job: 1008777	Date: 15-MAY-2025

OLD CROW FLOOD MAPPING

1.0% ICE INDUCED ANNUAL EXCEEDANCE PROBABILITY

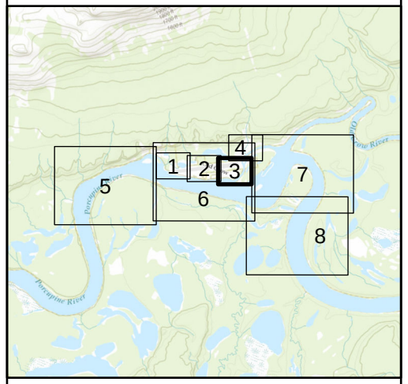
SHEET 2 of 8

JXD, \\mainfile-van\Projects\Active\1008777 Old Crow\95 GIS\1008777_JXD_FLoodMapping_295k_2.aprx



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- POINT OF INTEREST
  Asset ID number (see General Notes)
- ROAD
- MAJOR CONTOUR AT 5M INTERVAL
  Labelled with elevation in metres
- MINOR CONTOUR AT 1M INTERVAL
  Labelled with elevation in metres
- MODELLED CROSS-SECTION
- 40757 STATIONING *(Labelled in metres)*
  246.43 WATER SURFACE ELEVATION *(Labelled in metres)*
- 50% AEP OPEN WATER EXTENT
- INUNDATION EXTENT
- VUNTUT GWITCHIN FIRST NATION SETTLEMENT LAND
- FLOW DIRECTION

DATA SOURCES: REFER TO NOTES ON INDEX MAP

Engineer	GIS	Reviewer
SGZ	JXD	FMH/PKK

SCALE - 1:2,500

0 25 50 75 100 M

N

Coordinate System: NAD 1983 CSRS YUKON ALBERS
Units: METRES; Vertical Datum: CGVD2013 (CGG2013a)

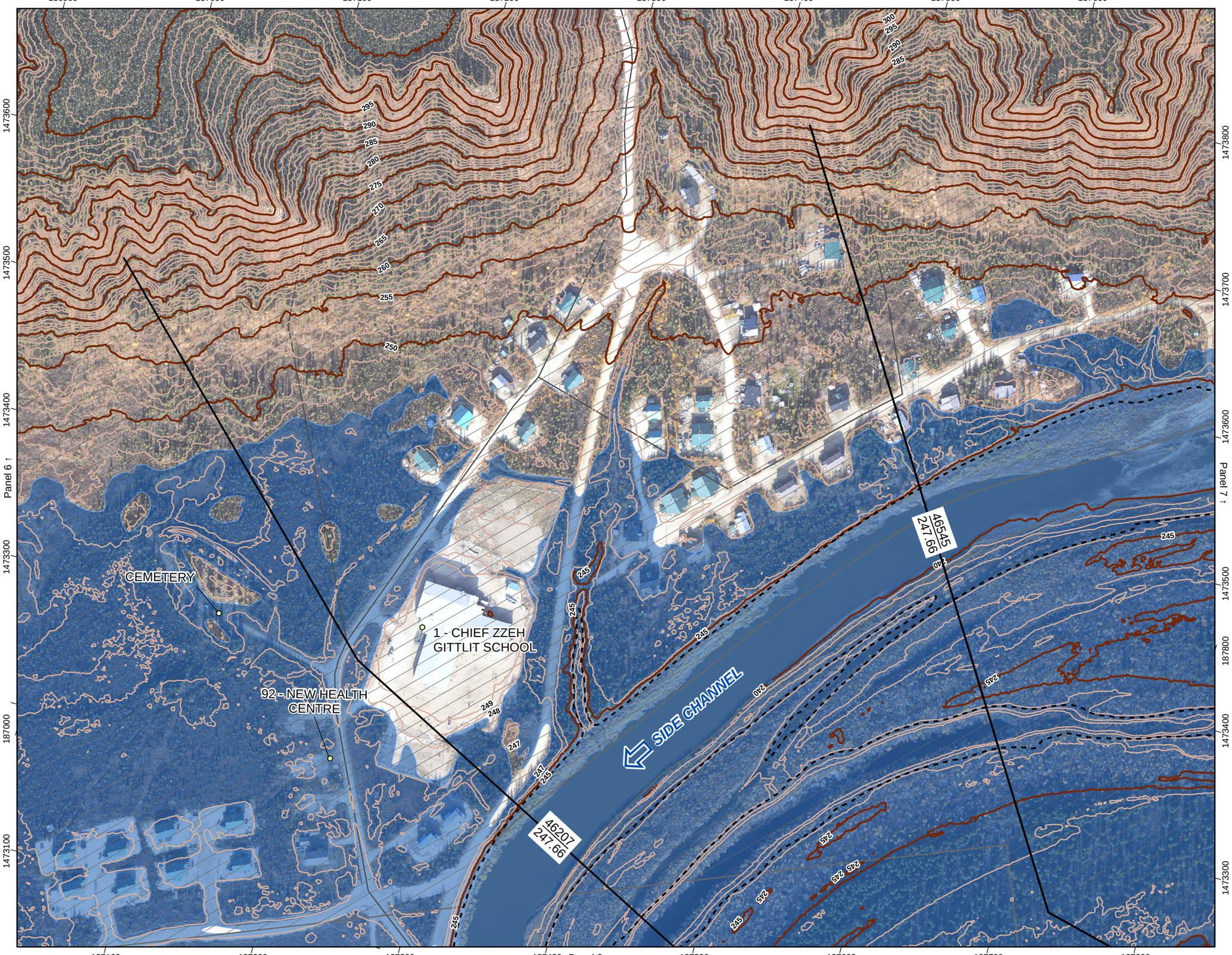
Job: 1008777	Date: 15-MAY-2025

OLD CROW FLOOD MAPPING

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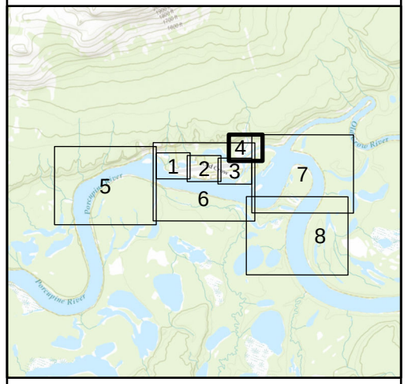
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- POINT OF INTEREST
  Asset ID number (see General Notes)
- ROAD
- MAJOR CONTOUR AT 5M INTERVAL
  Labelled with elevation in metres
- MINOR CONTOUR AT 1M INTERVAL
  Labelled with elevation in metres
- MODELLED CROSS-SECTION
- 40757 / 246.43 STATIONING *(Labelled in metres)* / WATER SURFACE ELEVATION *(Labelled in metres)*
- 50% AEP OPEN WATER EXTENT
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- VUNTUT GWITCHIN FIRST NATION SETTLEMENT LAND
- FLOW DIRECTION

DATA SOURCES: REFER TO NOTES ON INDEX MAP

Engineer	GIS	Reviewer
SGZ	JXD	FMH/PKK

SCALE - 1:2,500

0 25 50 75 100 M

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Units: METRES; Vertical Datum: CGVD2013 (CGG2013a)

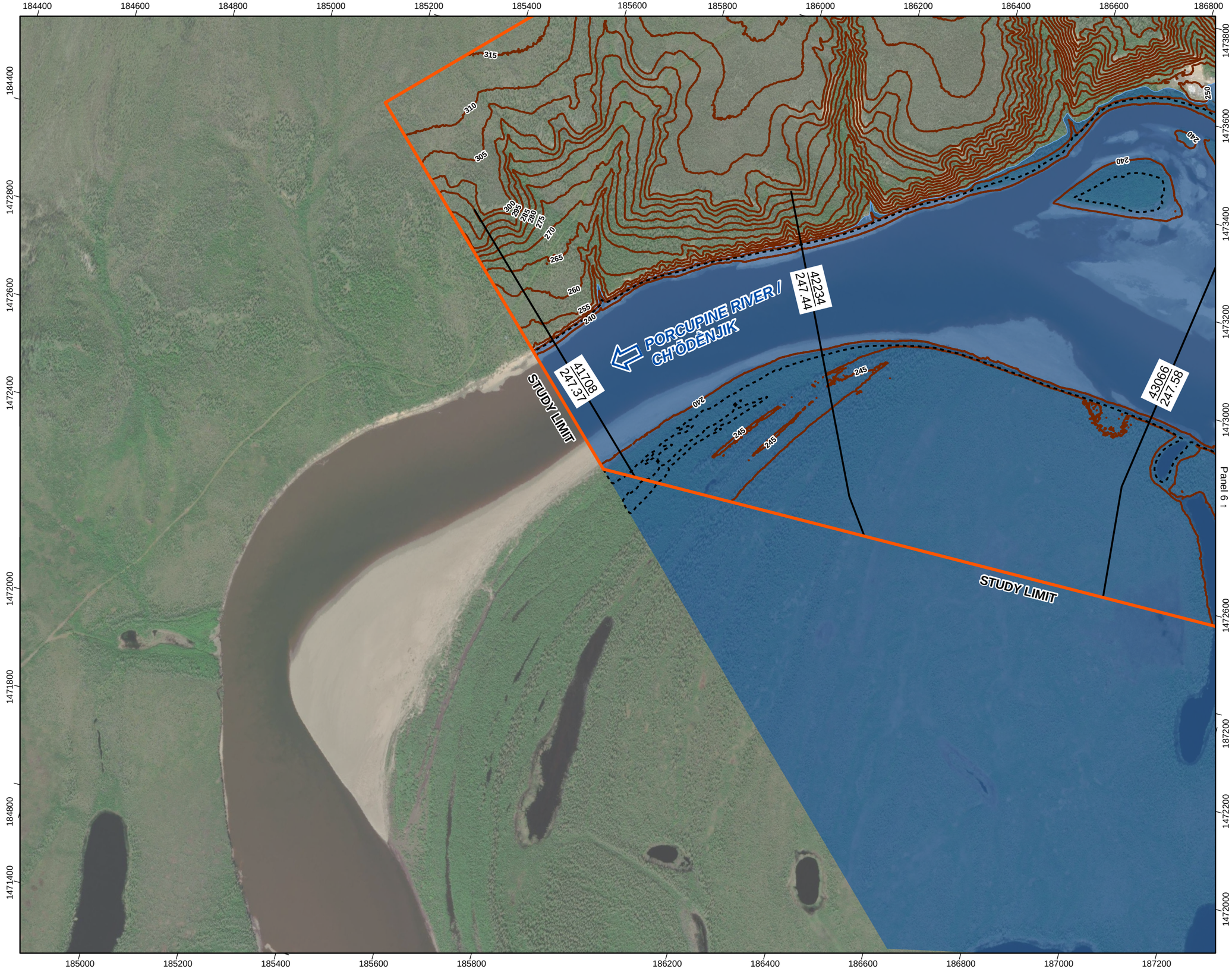
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OLD CROW FLOOD MAPPING

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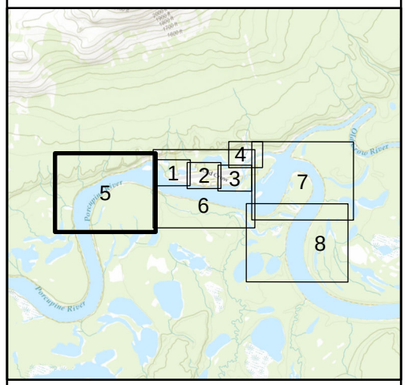
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JXD, \\mainfile-van\Projects\Active\1008777 Old Crow\95 GIS\1008777_JXD_FLoodMapping_2p5k_2.aprx



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- ROAD
- STUDY LIMIT
- MAJOR CONTOUR AT 5M INTERVAL
  Labelled with elevation in metres
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- 40757 / 246.43 STATIONING *(Labelled in metres)* / WATER SURFACE ELEVATION *(Labelled in metres)*
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DATA SOURCES: REFER TO NOTES ON INDEX MAP

Engineer	GIS	Reviewer
SGZ	JXD	FMH/PKK

SCALE - 1:7,500

0 50 100 150 200 250 300 M

N

Coordinate System: NAD 1983 CSRS YUKON ALBERS
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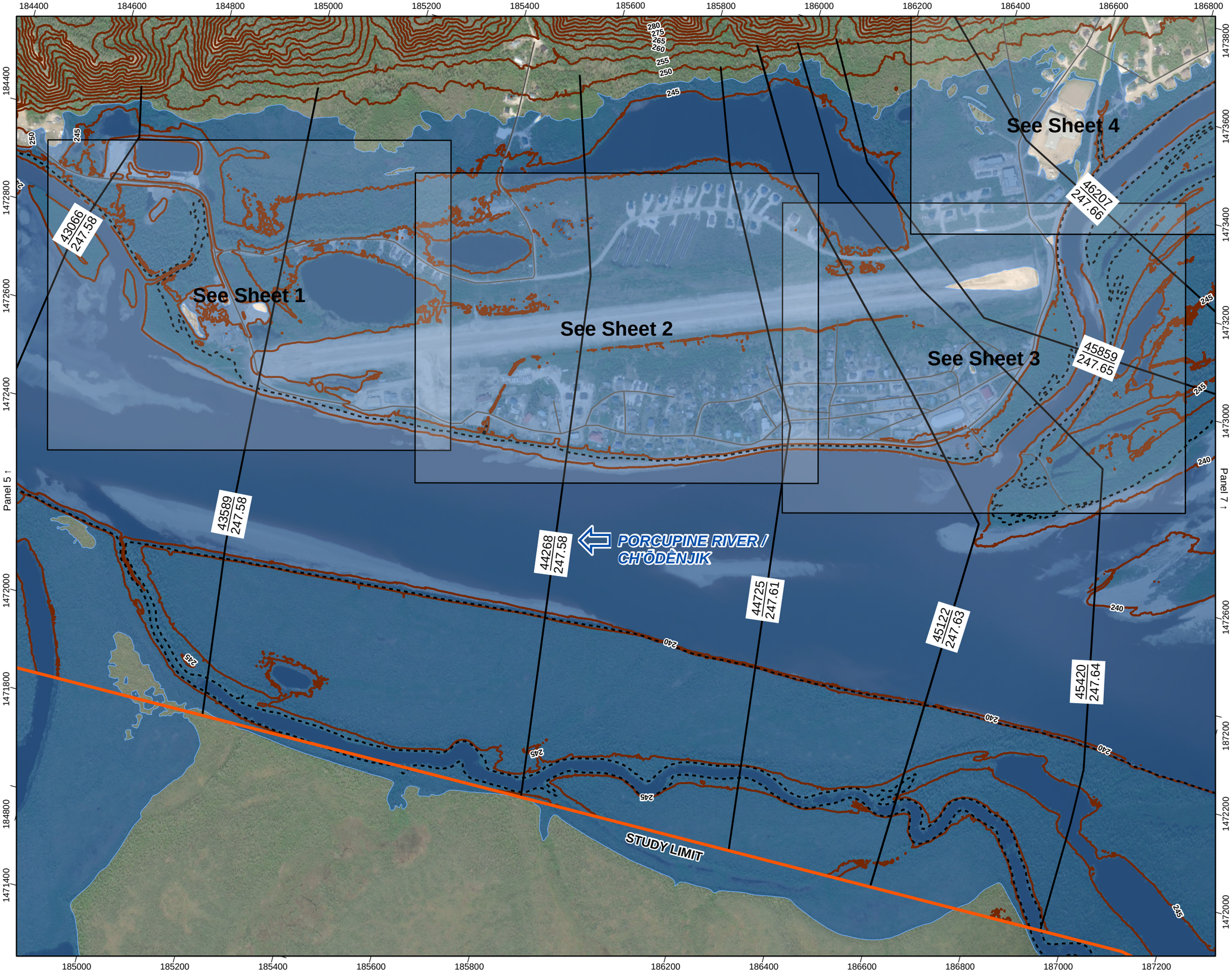
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OLD CROW FLOOD MAPPING

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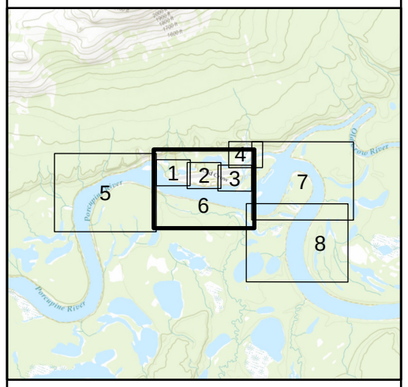
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- ROAD
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Engineer	GIS	Reviewer
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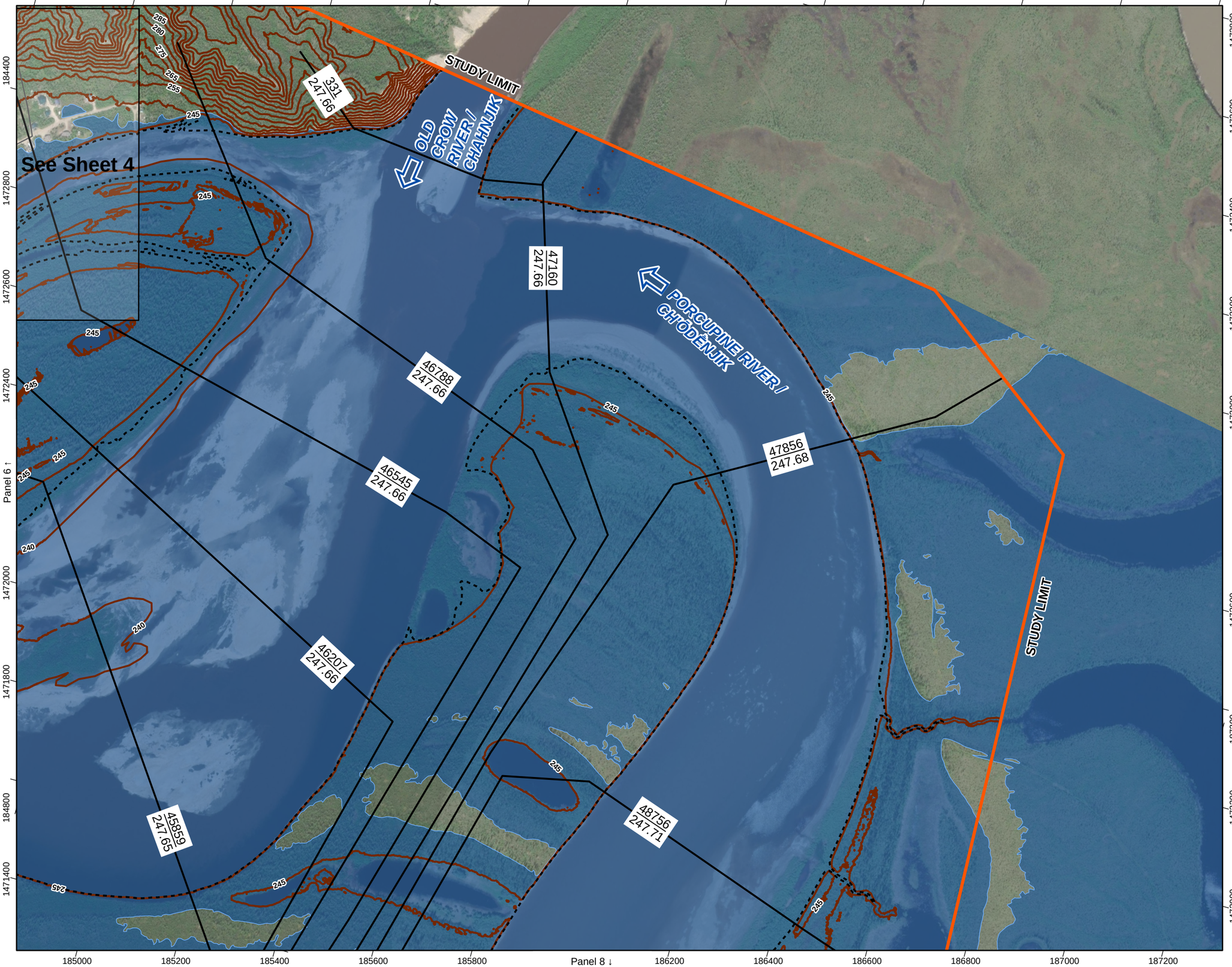
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OLD CROW FLOOD MAPPING

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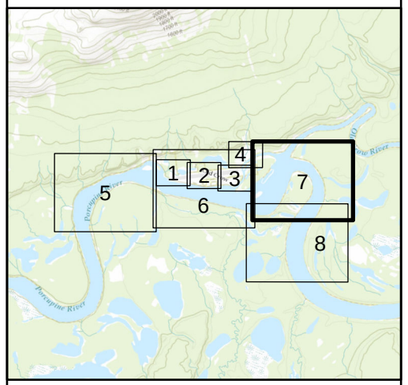
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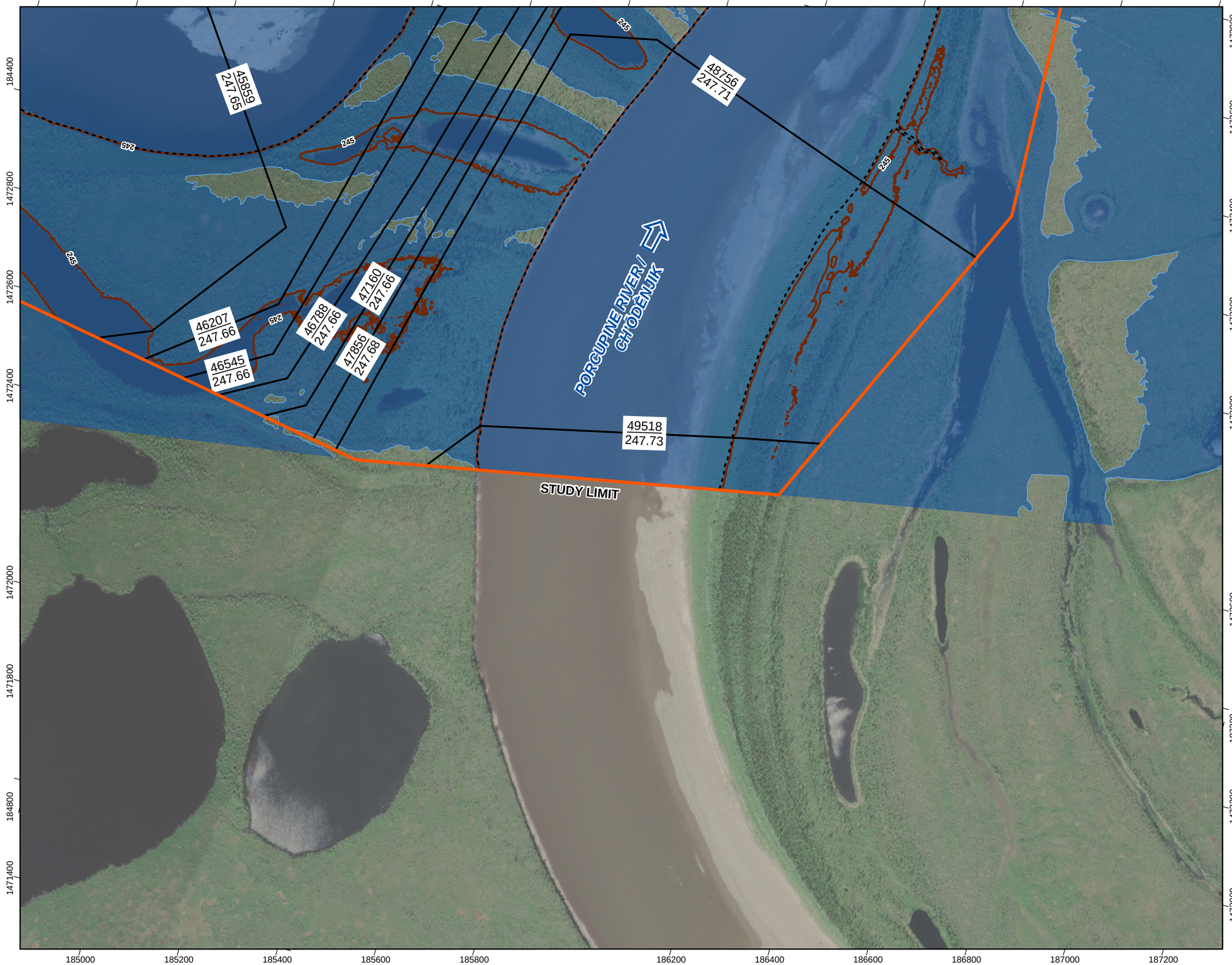
Job: 1008777 | *Date: 15-MAY-2025*

OLD CROW FLOOD MAPPING

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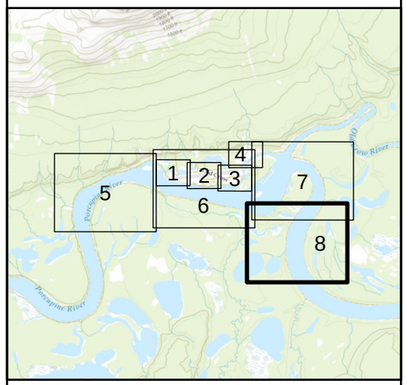
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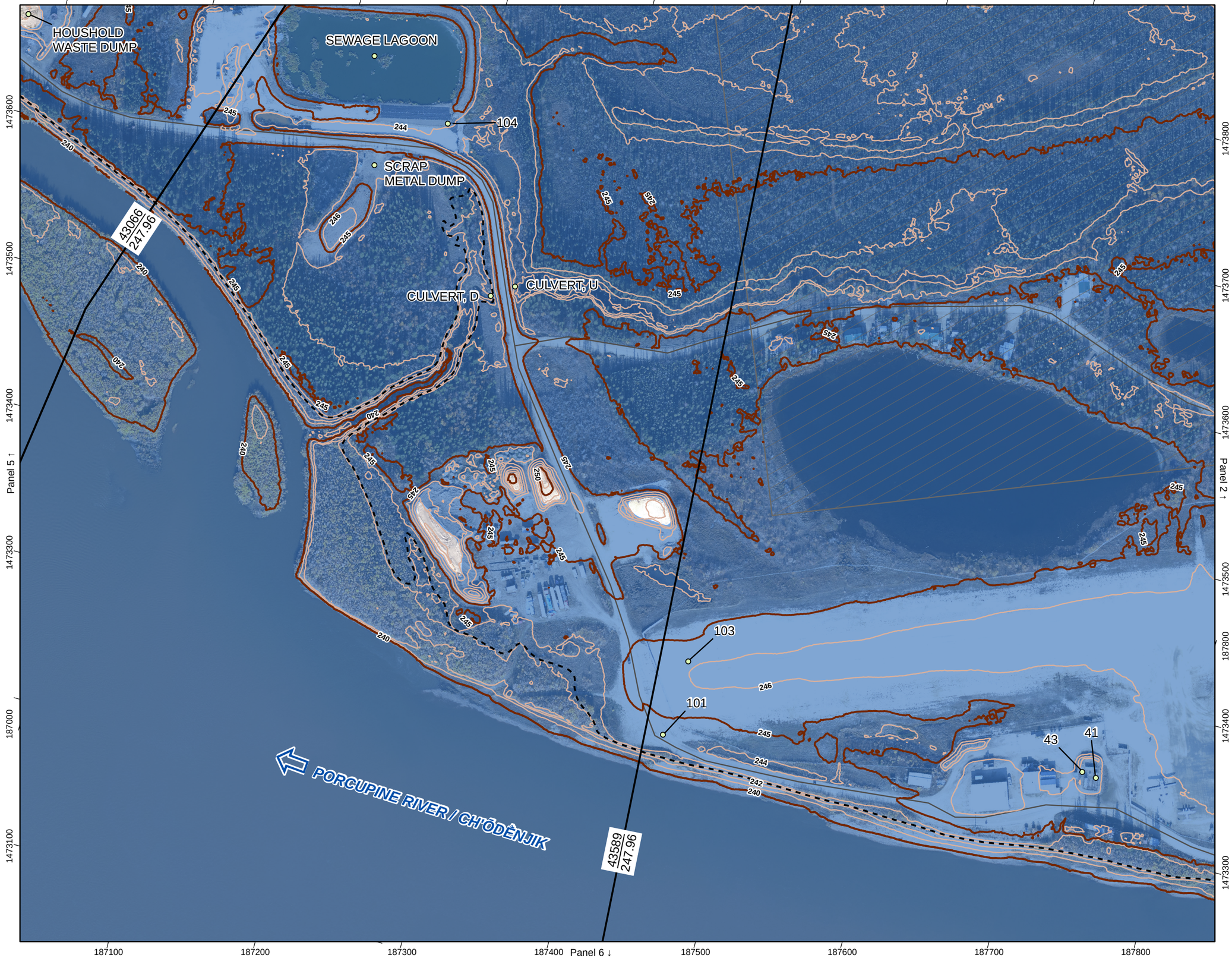
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OLD CROW FLOOD MAPPING

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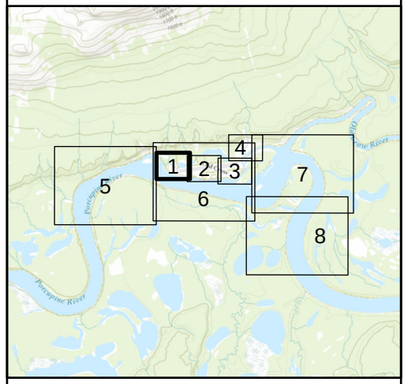
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- POINT OF INTEREST
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DATA SOURCES: REFER TO NOTES ON INDEX MAP

Engineer	GIS	Reviewer
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SCALE - 1:2,500

0 25 50 75 100 M

N

Coordinate System: NAD 1983 CSRS YUKON ALBERS
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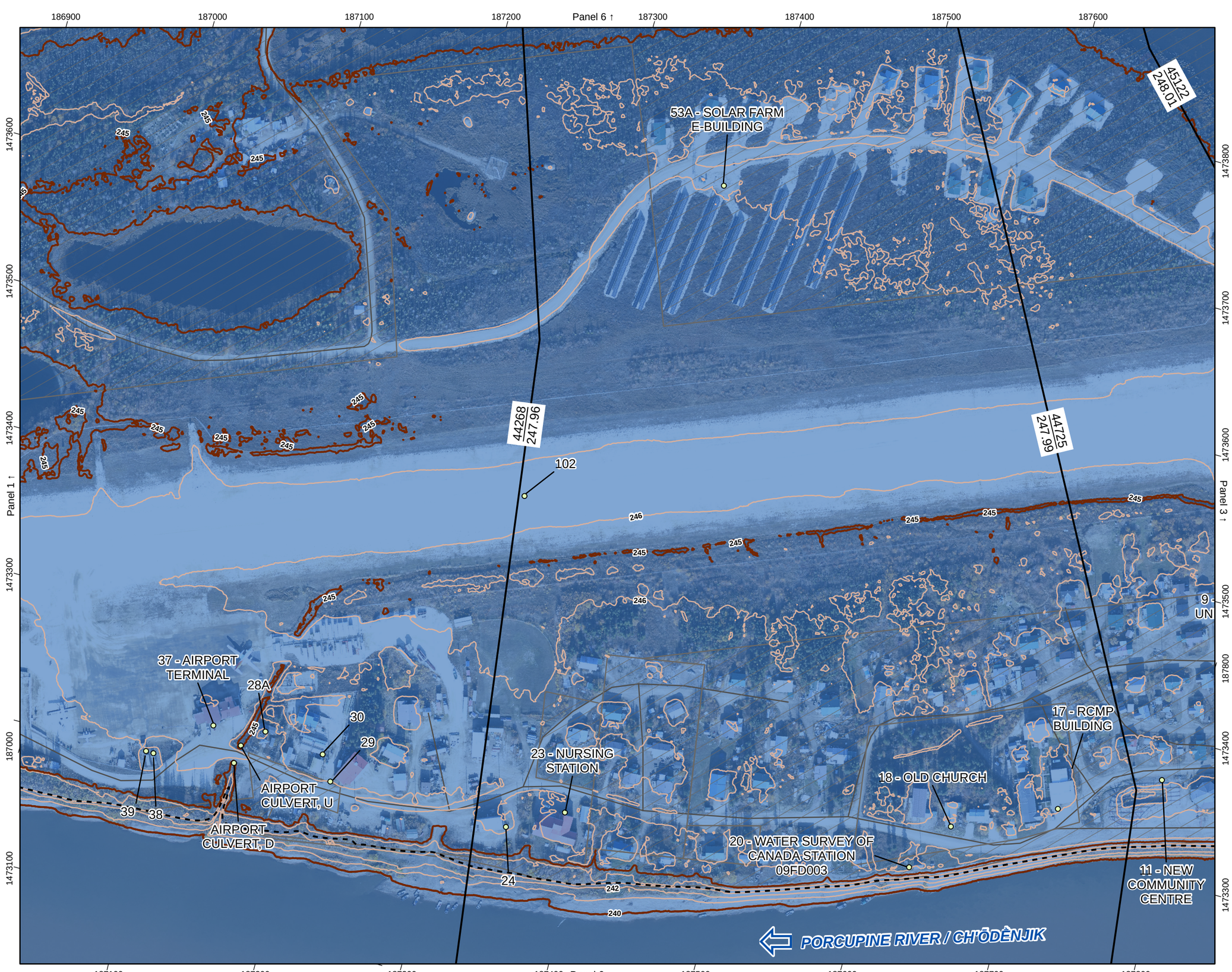
Job: 1008777	Date: 15-MAY-2025

OLD CROW FLOOD MAPPING

0.5% ICE INDUCED ANNUAL EXCEEDANCE PROBABILITY

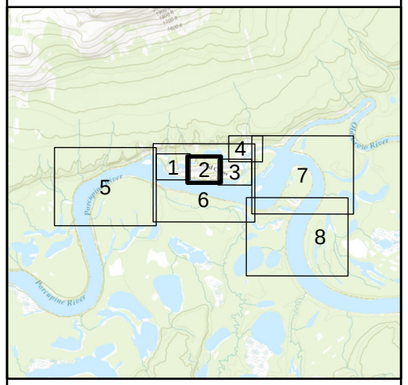
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JXD, \\mainfile-van\Projects\Active\1008777 Old Crow\95 GIS\1008777_JXD_FLoodMapping_2p5k_2.aprx



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SGZ	JXD	FMH/PKK

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0 25 50 75 100 M

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Coordinate System: NAD 1983 CSRS YUKON ALBERS
Units: METRES; Vertical Datum: CGVD2013 (CGG2013a)

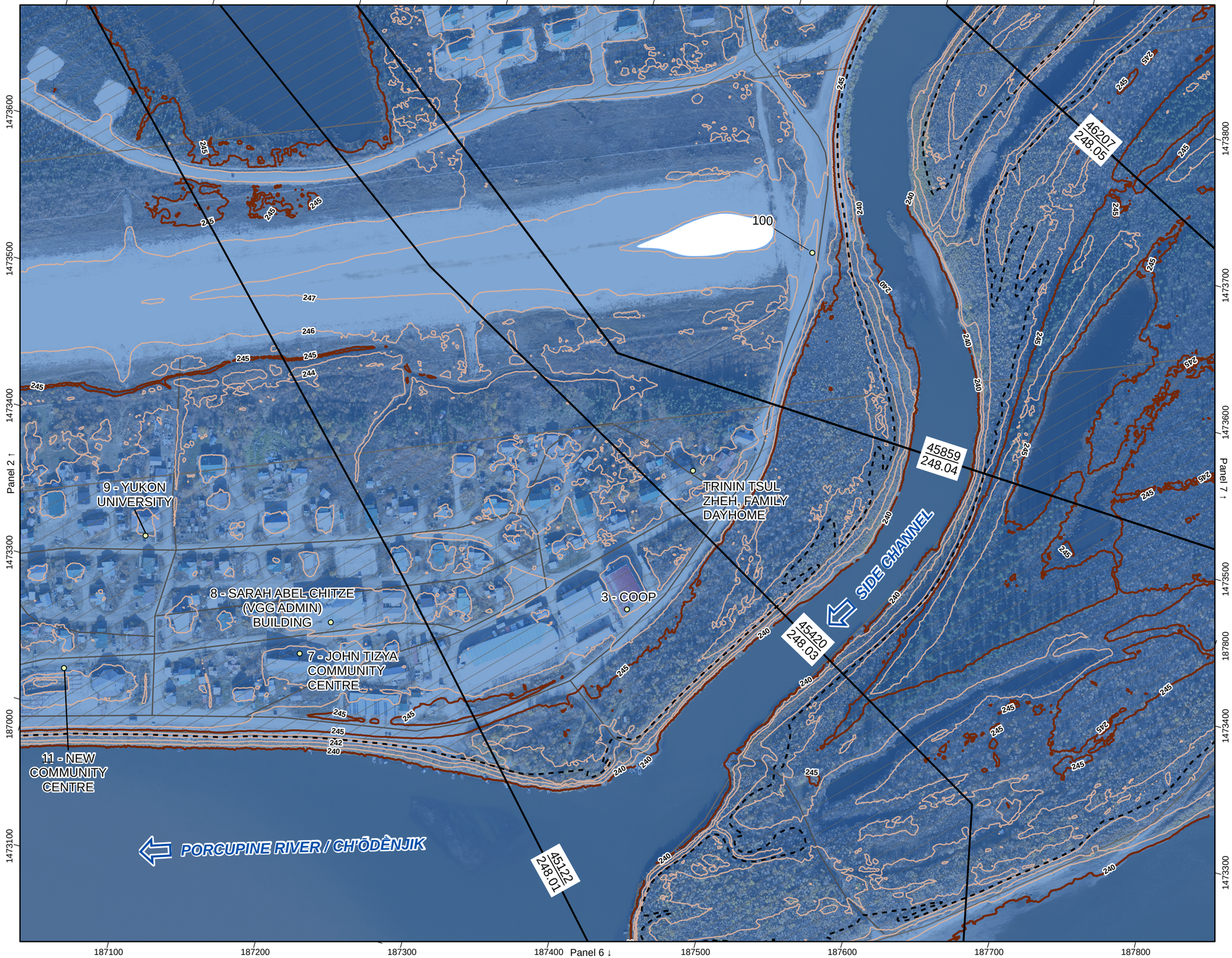
Job: 1008777	Date: 15-MAY-2025

OLD CROW FLOOD MAPPING

0.5% ICE INDUCED ANNUAL EXCEEDANCE PROBABILITY

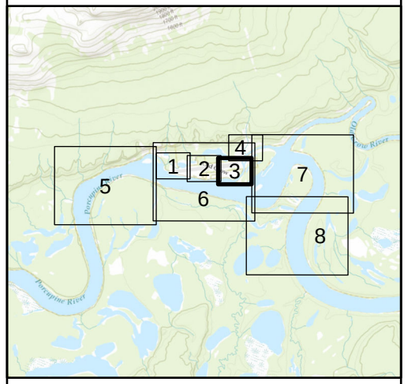
SHEET 2 of 8

JXD, \\mainfile-van\Projects\Active\1008777 Old Crow\95 GIS\1008777_JXD_FLoodMapping_295k_2.aprx



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- POINT OF INTEREST
  Asset ID number (see General Notes)
- ROAD
- MAJOR CONTOUR AT 5M INTERVAL
  Labelled with elevation in metres
- MINOR CONTOUR AT 1M INTERVAL
  Labelled with elevation in metres
- MODELLED CROSS-SECTION
- 40757 / 246.43 STATIONING *(Labelled in metres)* WATER SURFACE ELEVATION *(Labelled in metres)*
- 50% AEP OPEN WATER EXTENT
- INUNDATION EXTENT
- VUNTUT GWITCHIN FIRST NATION SETTLEMENT LAND
- FLOW DIRECTION

DATA SOURCES: REFER TO NOTES ON INDEX MAP

Engineer	GIS	Reviewer
SGZ	JXD	FMH/PKK

SCALE - 1:2,500

0 25 50 75 100 M

N

Coordinate System: NAD 1983 CSRS YUKON ALBERS
Units: METRES; Vertical Datum: CGVD2013 (CGG2013a)

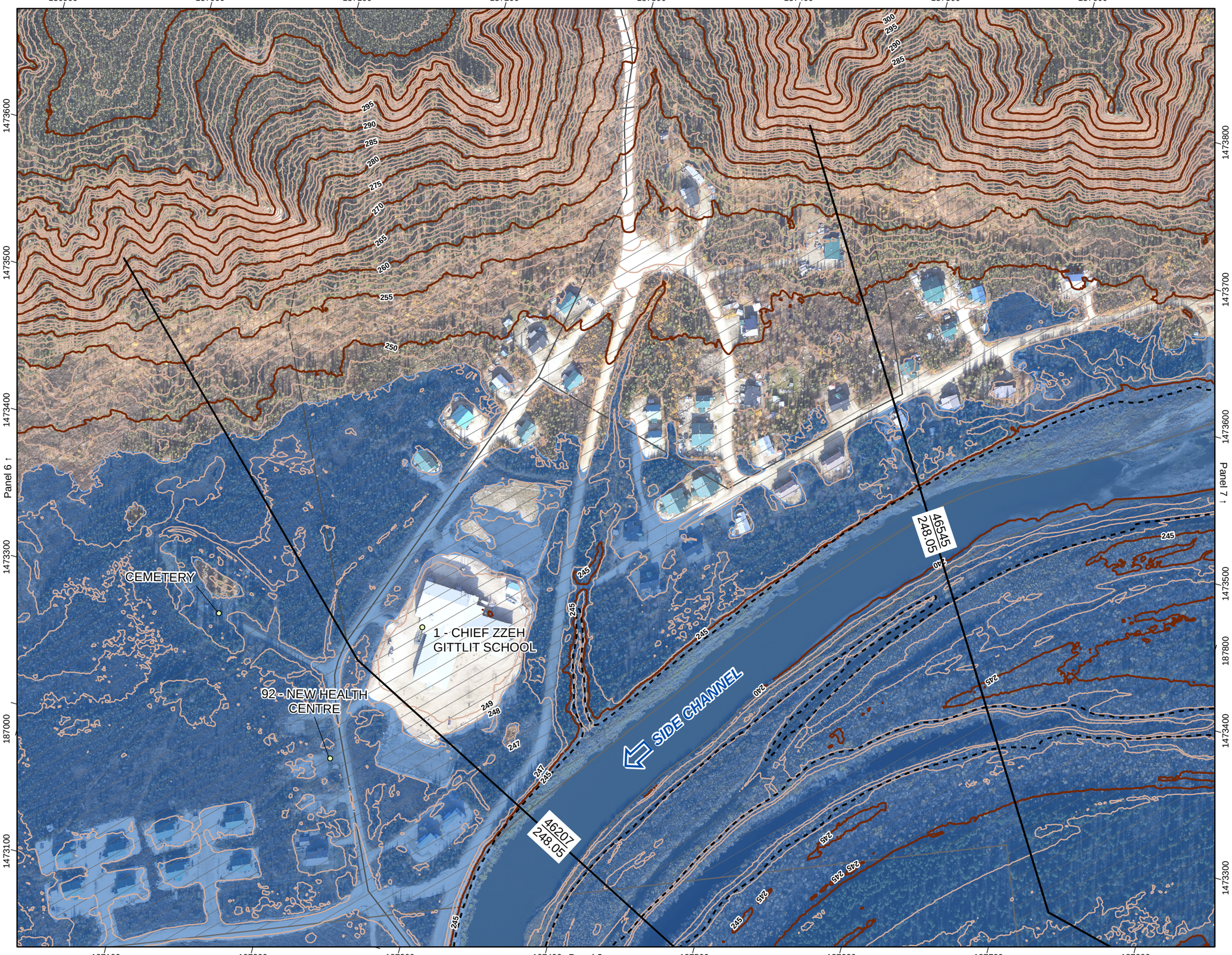
Job: 1008777	Date: 15-MAY-2025

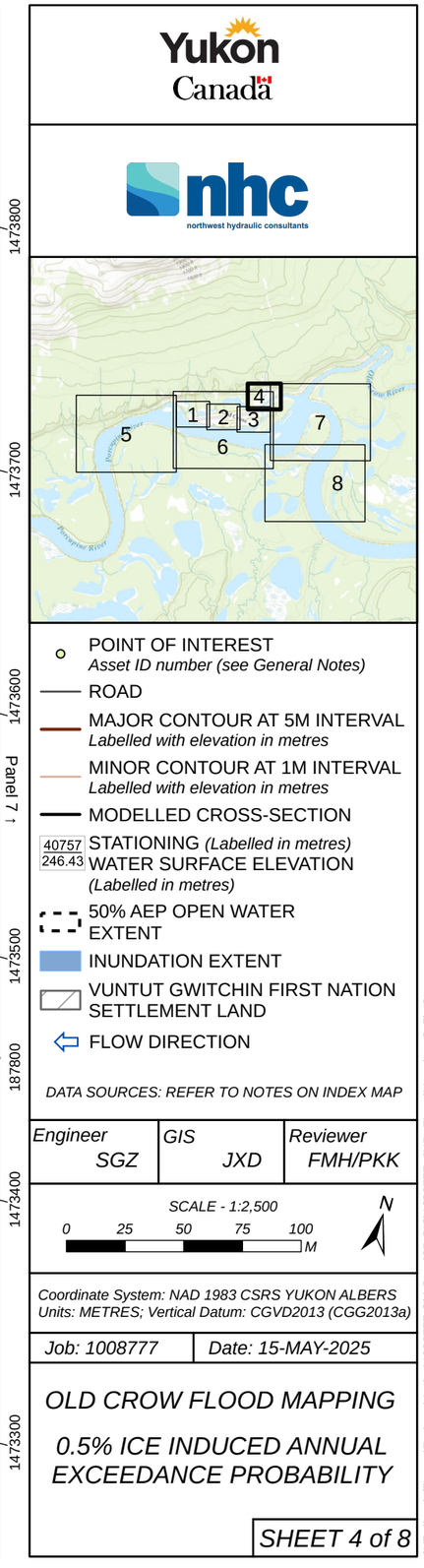
OLD CROW FLOOD MAPPING

0.5% ICE INDUCED ANNUAL EXCEEDANCE PROBABILITY

SHEET 3 of 8

JXD, \\mainfile-van\Projects\Active\1008777 Old Crow\95 GIS\1008777_JXD_FLoodMapping_2p5k_2.aprx





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- POINT OF INTEREST
  Asset ID number (see General Notes)
- ROAD
- MAJOR CONTOUR AT 5M INTERVAL
  Labelled with elevation in metres
- MINOR CONTOUR AT 1M INTERVAL
  Labelled with elevation in metres
- MODELLED CROSS-SECTION
- 40757 / 246.43 STATIONING *(Labelled in metres)* / WATER SURFACE ELEVATION *(Labelled in metres)*
- 50% AEP OPEN WATER EXTENT
- INUNDATION EXTENT
- VUNTUT GWITCHIN FIRST NATION SETTLEMENT LAND
- FLOW DIRECTION

DATA SOURCES: REFER TO NOTES ON INDEX MAP

Engineer	GIS	Reviewer
SGZ	JXD	FMH/PKK

SCALE - 1:2,500

0 25 50 75 100 M

N

Coordinate System: NAD 1983 CSRS YUKON ALBERS
Units: METRES; Vertical Datum: CGVD2013 (CGG2013a)

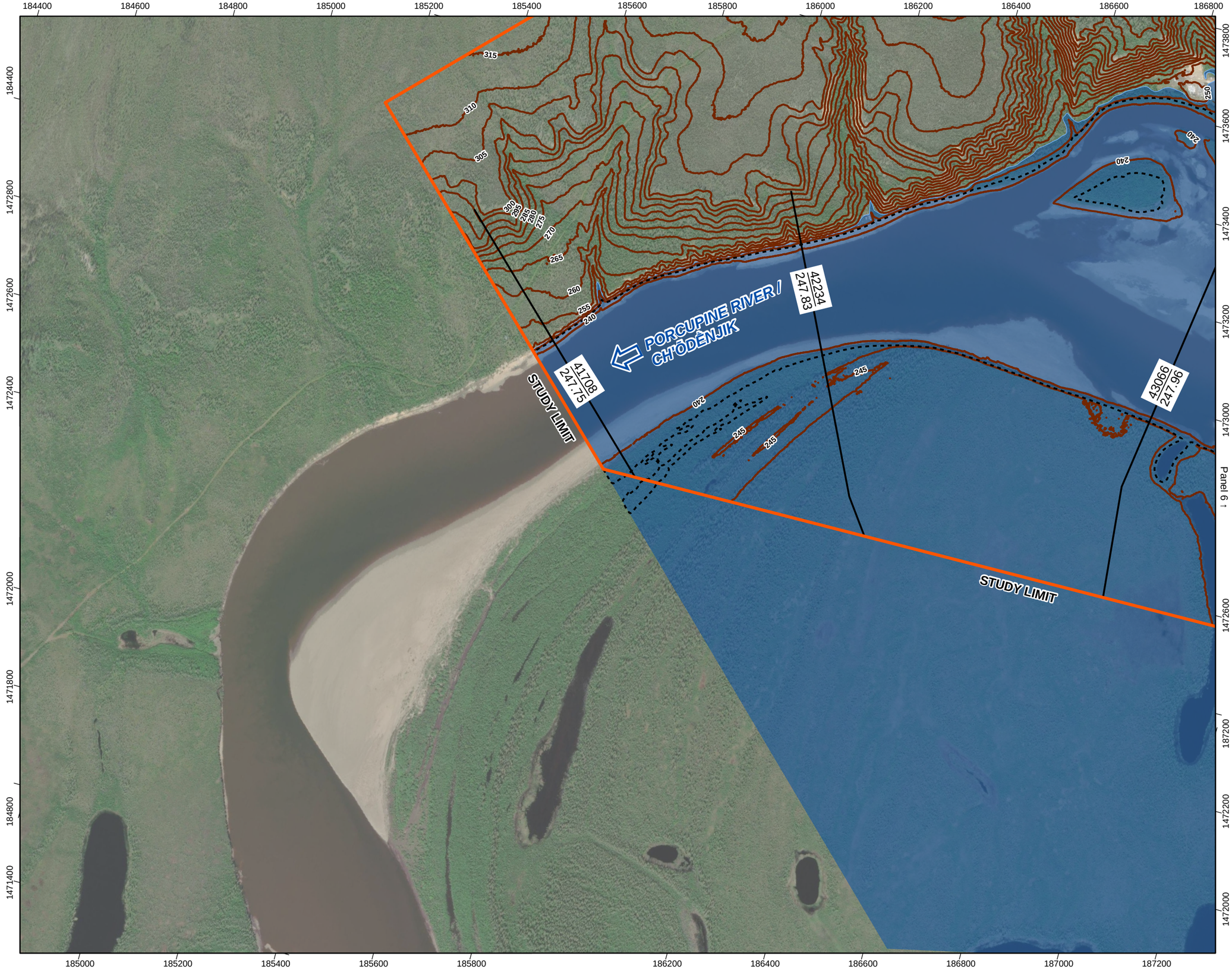
Job: 1008777	Date: 15-MAY-2025

OLD CROW FLOOD MAPPING

0.5% ICE INDUCED ANNUAL EXCEEDANCE PROBABILITY

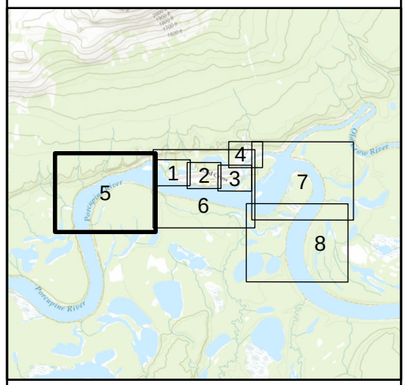
SHEET 4 of 8

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- ROAD
- STUDY LIMIT
- MAJOR CONTOUR AT 5M INTERVAL
  Labelled with elevation in metres
- MODELLED CROSS-SECTION
- 40757 / 246.43 STATIONING *(Labelled in metres)* / WATER SURFACE ELEVATION *(Labelled in metres)*
- 50% AEP OPEN WATER EXTENT
- INUNDATION EXTENT
- FLOW DIRECTION

DATA SOURCES: REFER TO NOTES ON INDEX MAP

Engineer	GIS	Reviewer
SGZ	JXD	FMH/PKK

SCALE - 1:7,500

0 50 100 150 200 250 300 M

N

Coordinate System: NAD 1983 CSRS YUKON ALBERS
Units: METRES; Vertical Datum: CGVD2013 (CGG2013a)

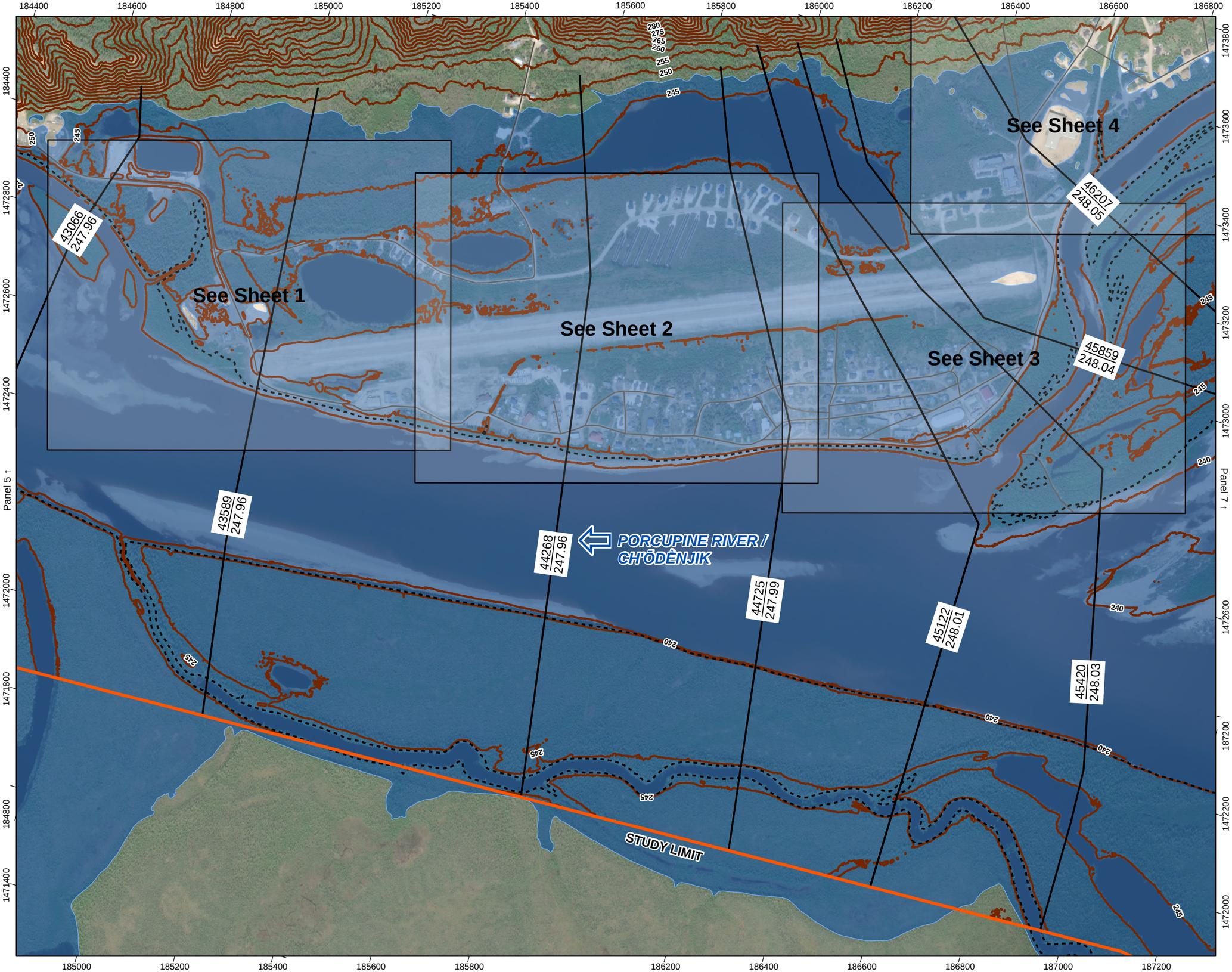
Job: 1008777	Date: 15-MAY-2025

OLD CROW FLOOD MAPPING

0.5% ICE INDUCED ANNUAL EXCEEDANCE PROBABILITY

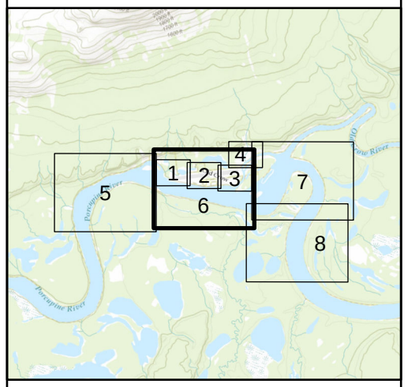
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- ROAD
- STUDY LIMIT
- MAJOR CONTOUR AT 5M INTERVAL *Labelled with elevation in metres*
- MODELLED CROSS-SECTION
- 40757 STATIONING *(Labelled in metres)*
- 246.43 WATER SURFACE ELEVATION *(Labelled in metres)*
- 50% AEP OPEN WATER EXTENT
- INUNDATION EXTENT
- FLOW DIRECTION

DATA SOURCES: REFER TO NOTES ON INDEX MAP

Engineer	GIS	Reviewer
SGZ	JXD	FMH/PKK

SCALE - 1:7,500

0 50 100 150 200 250 300 M

N

Coordinate System: NAD 1983 CSRS YUKON ALBERS
Units: METRES; Vertical Datum: CGVD2013 (CGG2013a)

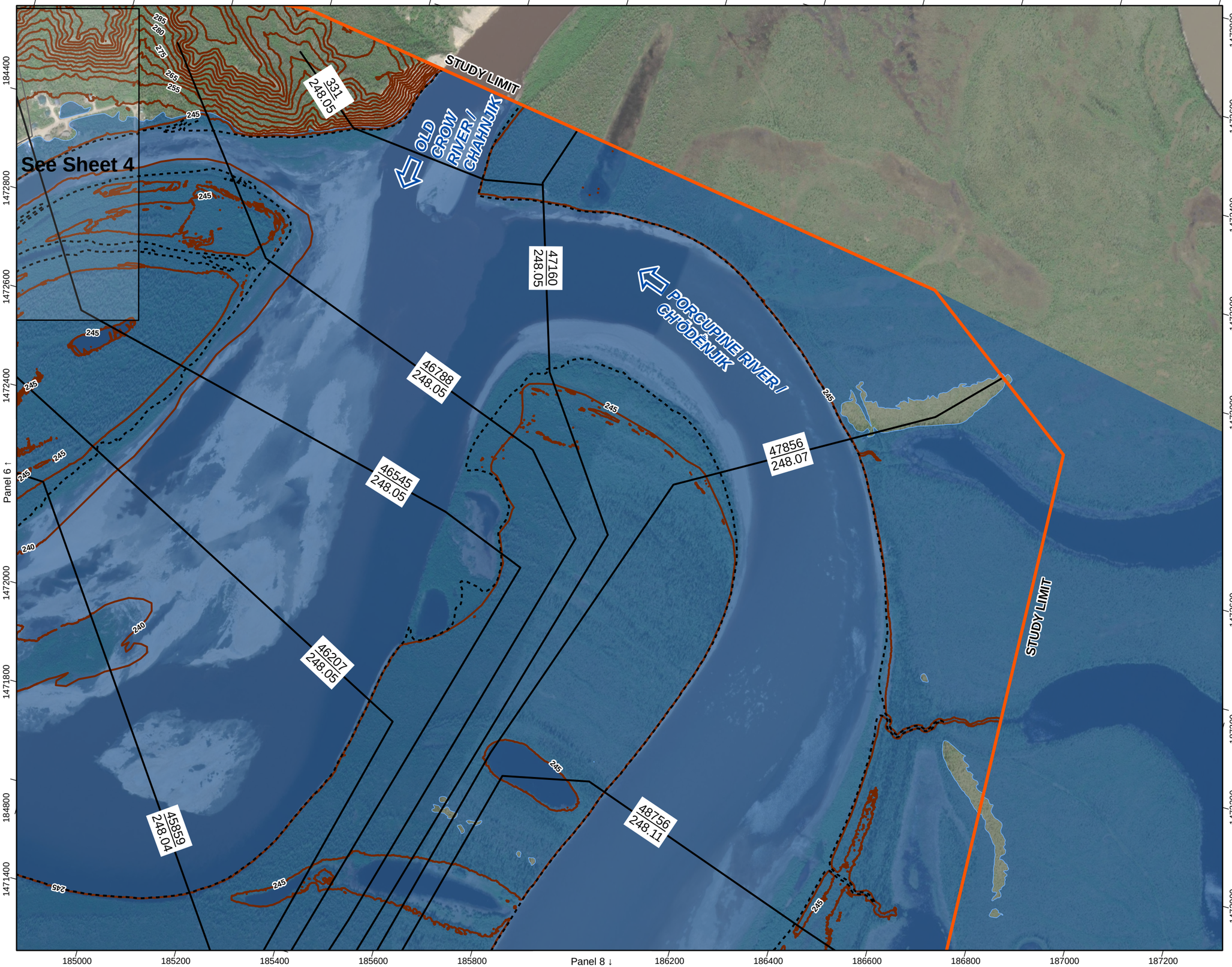
Job: 1008777	Date: 15-MAY-2025

OLD CROW FLOOD MAPPING

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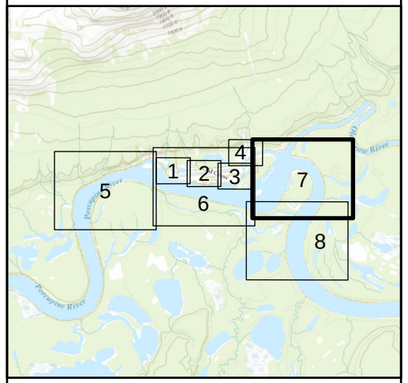
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JXD, \\mainfile-van\Projects\Active\1008777 Old Crow\95 GIS\1008777_JXD_FLoodMapping_7p5k_2.aprx



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- ROAD
- STUDY LIMIT
- MAJOR CONTOUR AT 5M INTERVAL *Labelled with elevation in metres*
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DATA SOURCES: REFER TO NOTES ON INDEX MAP

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SGZ	JXD	FMH/PKK

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0 50 100 150 200 250 300 M

N

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Units: METRES; Vertical Datum: CGVD2013 (CGG2013a)

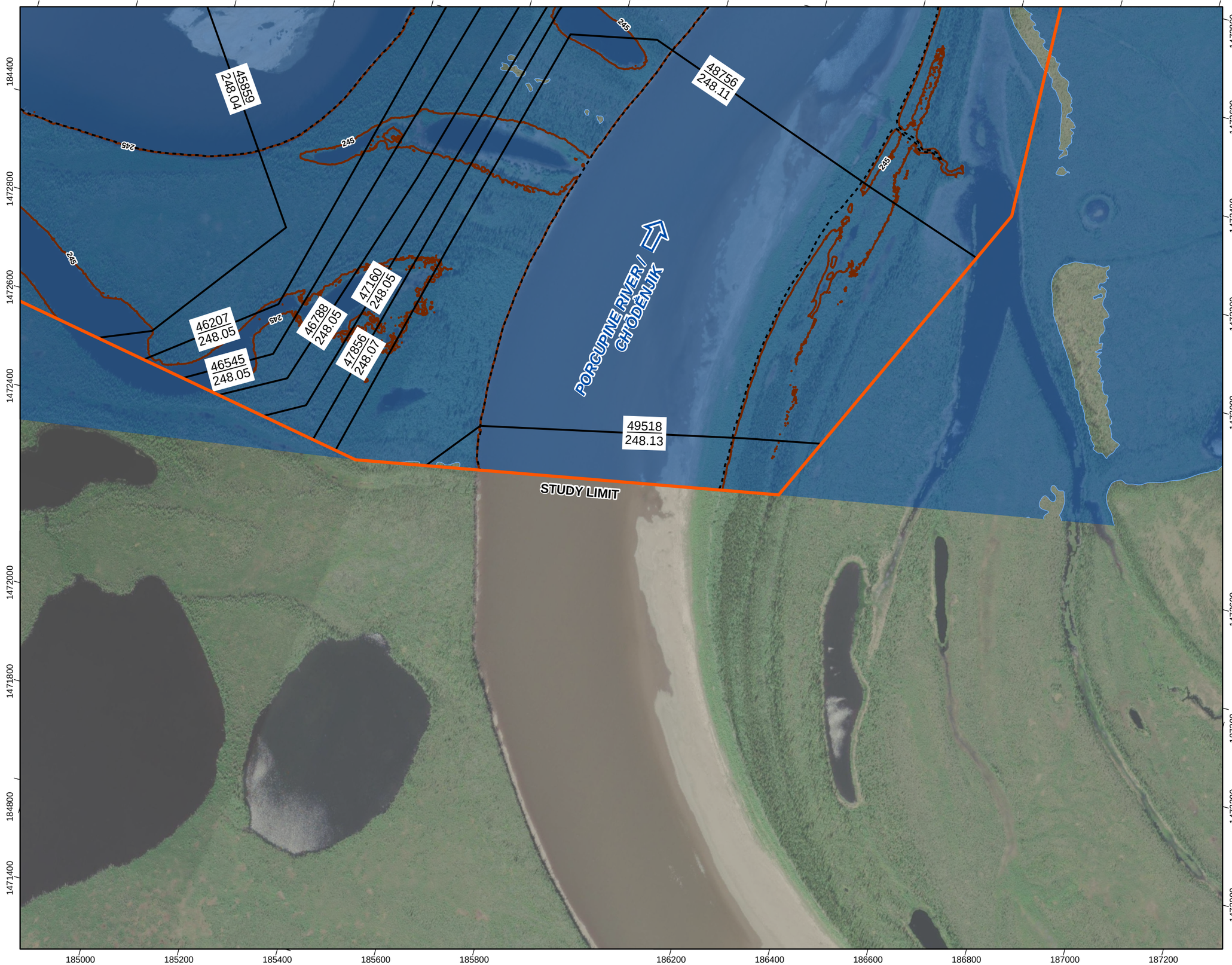
Job: 1008777 | *Date: 15-MAY-2025*

OLD CROW FLOOD MAPPING

0.5% ICE INDUCED ANNUAL EXCEEDANCE PROBABILITY

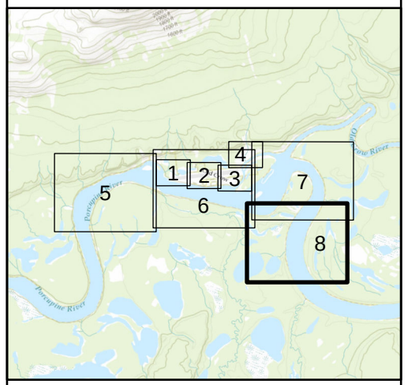
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JXD, \\mainfile-van\Projects\Active\1008777 Old Crow\95 GIS\1008777_JXD_FLoodMapping_7p5k_2.aprx



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Engineer	GIS	Reviewer
SGZ	JXD	FMH/PKK

SCALE - 1:7,500

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Job: 1008777	Date: 15-MAY-2025

OLD CROW FLOOD MAPPING

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