Bear Brook Watershed Study – Fluvial Geomorphology Characterization Report

January 2025

Prepared for:

Ottawa

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Summary of Findings

South Nation Conservation (SNC) retained Palmer/SLR Consulting Canada Ltd. to conduct a fluvial geomorphology assessment of Bear Brook, as well as assess landslide distribution across the watershed. A detailed report written by Palmer is included in Appendix A. Below is a summary of findings from their work.

The deglacial history of the Bear Brook Watershed continues to significantly impact the area's current geomorphological processes. Natural erosion, like meander migration and cut-offs, happens at a slow rate along Bear Brook due to its gentle slope and the stable material in its bed and banks. However, human activities and landslides have notably altered these processes and contributed to the development of related hazards. Several features or mechanisms are largely responsible for geomorphological processes along Bear Brook:

- **Vars-Winchester Esker** – The sand and gravel core of the Vars-Winchester Esker acts as a prominent grade control along Bear Brook. Upstream of the esker, Bear Brook has been unable to incise into Champlain Sea sediments. The bed of the channel is only slightly below its floodplain (i.e., unconfined), resulting in a wide floodplain adjacent to the channel. Downstream of the esker, Bear Brook has incised into Champlain Sea sediments as it flows to its confluence with the South Nation River. Channel incision has created a contemporary valley, which contains flood flows and appears prone to small landslides.
- **Channel Straightening** – Prior to 1945, anthropogenic channel straightening likely resulting from agricultural activities, reduced the overall channel length and locally steepened the watercourse. The majority of straightening occurred in the upper reaches of Bear brook (i.e., upstream of the esker), where the channel is connected to its floodplain.
- **Riparian Vegetation** – The riparian vegetation along Bear Brook has been altered over the past century, especially in the upper reaches where the river is unconfined and vegetation has been extensively cleared. Along reaches flowing within a defined valley, some riparian vegetation has been removed, while vegetation on the tableland has been extensively cleared.
- **Unstable Soils** – Landslides varying in size and age are widely distributed within the Bear Brook Watershed, especially downstream of the Vars-Winchester Esker. Several large retrogressive landslides occurred millennia ago along escarpments of the Ottawa River paleochannels, well back from contemporary fluvial processes (Alysworth et al., 2000). These landslides were likely triggered by seismic activity. Numerous smaller, younger landslides punctuate the banks and valley walls of Bear Brook and its tributaries. More landslides are anticipated along this valley if system degradation continues and increases exposure of clay along the lower valley walls.

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Appendices

Appendix A: Palmer Assessment of Fluvial Geomorphology and Landslide Distribution along Bear Brook

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Fluvial Geomorphology Characterization

Fluvial geomorphology assessments are important components of Watershed Plans because they provide an in-depth understanding of the physical processes and landforms associated with river systems. These assessments examine the interactions between water flow, sediment transport, and the surrounding landscape, which contributes to the understanding of stability and safety of riverine environments.

Rivers are dynamic systems that naturally change over time. However, human activities such as urbanization, deforestation, and agriculture can accelerate these changes, leading to increased erosion, altered flow regimes, and the degradation of aquatic habitat. Capturing existing conditions and identifying key locations for ongoing monitoring efforts will help track areas that may be vulnerable to erosion and provide insight into underlying causes of erosion and instability within the Bear Brook system.

A Fluvial Geomorphology Assessment was completed by Palmer/SLR for the Bear Brook Watershed from upstream of Highway 417, downstream to the confluence with the South Nation River. Methodologies and results are presented in Appendix A.

Landslide Distribution in the Bear Brook Watershed

Palmer/SLR also conducted an exercise to screen potential landslides across watercourses in the Bear Brook Watershed. There is a need to identify these features to ensure proactive steps are taken to prevent or reduce damage to infrastructure, property, and ecosystems resulting from these hazards. Changing conditions in climate, land use, and vegetation can affect land stability over time, therefore it will be important to identify future geotechnical study or monitoring and evaluation needs. The landslide screening is detailed in Appendix A of this report.

Appendix A

Palmer Assessment of Fluvial Geomorphology and Landslide Distribution along Bear Brook

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Assessment of Fluvial Geomorphology and Landslide Distribution along Bear Brook

Palmer Project #
2302503

Prepared For
South Nation Conservation

May 30, 2024

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May 30, 2024

Katherine Watson
Coordinator, Early Warning Systems and Watershed Plans
South Nation Conservation
38 Victoria Street, Box 29
Finch, ON K0C 1K0

Dear Katherine Watson:

Re: Assessment of Fluvial Geomorphology and Landslide Distribution along Bear Brook

Palmer is pleased to provide South Nation Conservation (SNC) with our assessment of fluvial geomorphology and landslide distribution along Bear Brook. Fluvial geomorphological processes along Bear Brook are driven by a combination of local geological legacy, natural meander adjustments, anthropogenic alterations, and landsliding. Historical and ongoing land use change is altering natural geomorphological processes and may exacerbate associated hazards. A proposed geomorphology monitoring program and watershed management strategies are highlighted for SNC's consideration.

It has been a pleasure working with all parties on this interesting project. Should you have any questions, please do not hesitate to contact Dan McParland (226-979-8160, dan.mcparland@pecg.ca) or Robin McKillop (647-795-8153 ext. 106, robin.mckillop@pecg.ca). Palmer looks forward to supporting future phases on this project.

Yours truly,

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

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

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1. Introduction

Palmer was retained by South Nation Conservation (SNC) to assess the fluvial geomorphology and landslide distribution along Bear Brook (**Figure 1**). Fluvial geomorphological processes along Bear Brook reflect a combination of local geology, natural meander adjustments, anthropogenic alterations, and landsliding. SNC, in collaboration with the City of Ottawa, has commissioned this assessment recognizing that slope and erosion hazards may unknowingly pose a risk to human life, property and/or infrastructure if not properly investigated and characterized. The findings of the assessment will be incorporated into the Bear Brook Watershed Characterization Study and support planning-related decisions within the Bear Brook watershed.

Important background information, including details of the study area and key objectives (Section 1), is followed by a summary of the physical setting (Section 2). Section 3 details the methods of the assessments. Section 4 presents the results of the assessment, with reference to summary tables and figures. Section 5 discusses the implications of the results, including key drivers of geomorphological change, and provides recommendations to manage geomorphological risks along Bear Brook. A photograph log documenting field reconnaissance along each reach is presented in **Appendix A**. Comprehensive fluvial geomorphology mapping of the study area is provided in **Appendix B**. A summary of meander migration rates and trajectories is provided in **Appendix C**. A LiDAR-derived relative elevation model (REM) along Bear Brook is presented in **Appendix D**.

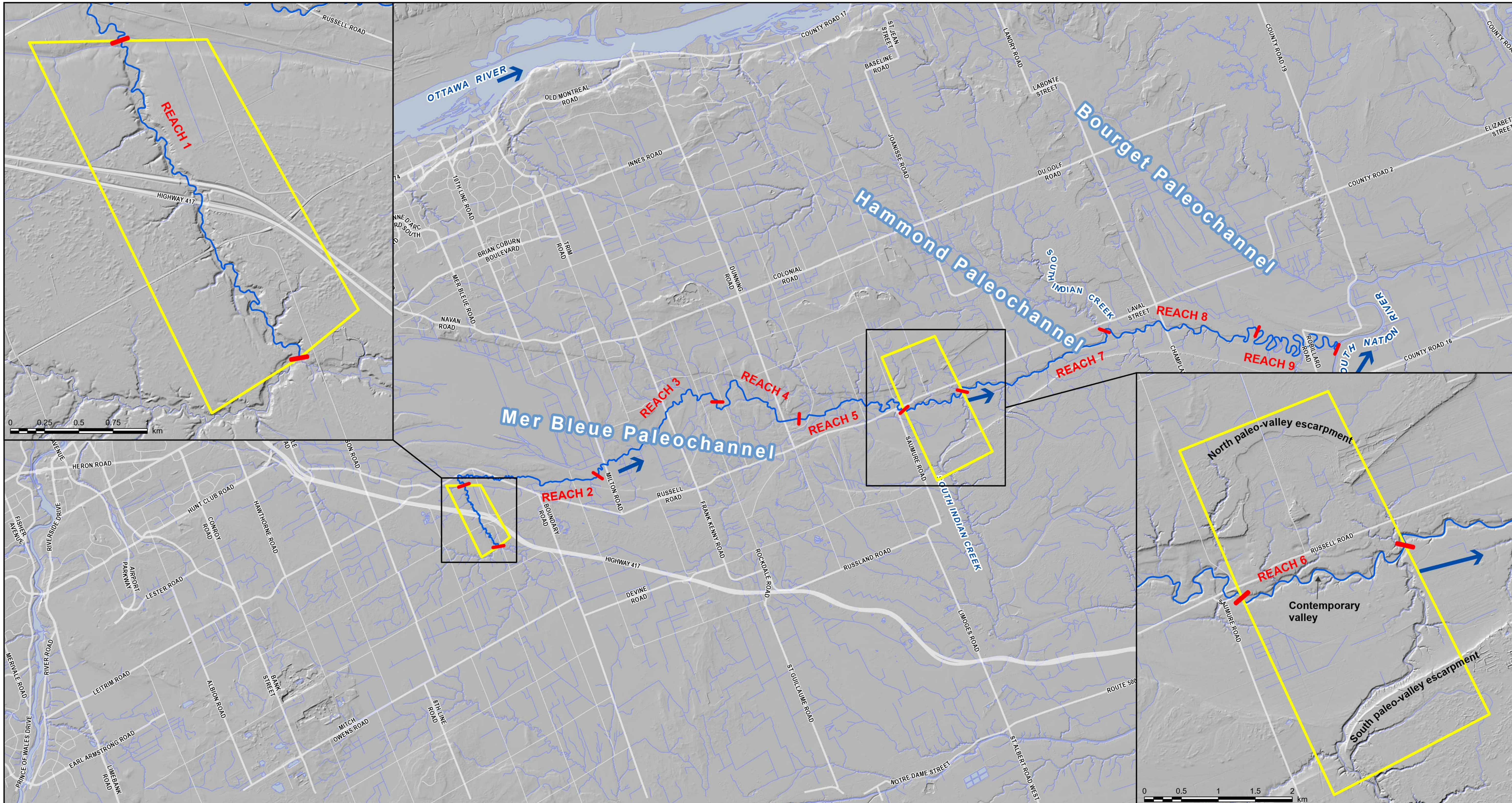
1.1 Study Area

Bear Brook is one of the largest watercourses within SNC's jurisdiction. It drains predominantly eastward through the City of Ottawa and the United Counties of Prescott and Russell (UCPR) to its confluence with South Nation River. Agricultural practices (e.g. riparian vegetation removal, straightening of tributaries, excavation of drains), urbanization, and changing climatic conditions have likely altered the timing and magnitude of channel inputs (water, sediment, wood) over the past century perturbed natural geomorphological processes. The focus of this fluvial geomorphology assessment is the main branch of Bear Brook from a tributary confluence upstream of Highway 417 downstream to the South Nation River confluence (**Figure 1**). The total channel length is approximately 59.4 km. At the confluence with South Nation River, the catchment area of Bear Brook is 488 km^2 (SNC, 2016).

1.2 Objectives

The overall objective of the fluvial geomorphology assessment is to better understand fluvial processes and associated hazards and risks along Bear Brook through the completion of several main tasks:

- Compilation and review of existing information pertinent to the assessment of fluvial processes along Bear Brook, including historical and recent aerial imagery and LiDAR-derived topographic data
- Documentation of historical changes along Bear Brook and the associated drivers of channel instability
- Identification of historical and more recent landslides throughout the Bear Brook watershed
- Recommendation of a detailed geomorphology data collection and monitoring strategy
- Discussion regarding SNC's management of erosion and, more broadly, ongoing upstream development and related SWM practices



LEGEND

- Reach Break
- Bear Brook Main Branch
- Watercourse[1]
- Flow Direction
- Study Area
- Bear Brook Watershed Boundary

1. Ontario Hydro Network (LIO, 2024)

0 1 2 3 4 5 km

North American Datum 1983
Universal Transverse Mercator Projection Zone 18

Scale: 1:140,000
Page Size: Tabloid (11 x 17 inches)

Drawn: CV/RS
Checked: RK
Date: Jun 30, 2025

NORTH

Basemap: <ita>Hillshade map of Ontario Digital Terrain Model provided by Ontario Ministry of Natural Resources and Forestry.
Notes: Contains information licensed under the Open Government Licence – Ontario and Canada.

CLIENT: South Nation Conservation (SNC)

PROJECT: Bear Brook Geomorphology

TITLE: **Bear Brook Watershed and Study Reaches**

SLR

REF. NO. 233.065303.00001-1-1

Figure 1

2. Physical Setting

2.1 Regional

The Ottawa Valley, also known as the Ottawa Valley Clay Flats, is a gently-sloping to flat-lying landscape reflecting past glaciations and post-glacial activity (Richard, 1982; Schut and Wilson, 1987). At the height of the most recent Wisconsinan Glaciation, the Ottawa Valley was occupied by the Laurentide Ice Sheet. The Laurentide Ice Sheet retreated northward during deglaciation, exposing plains of till that had been deposited beneath the ice, and forming a series of recessional moraine ridges. Meltwater channels conveyed and deposited large volumes of glaciofluvial sediment through the Ottawa Valley (Parent and Occhiett, 1999).

Champlain Sea, an inlet of the Atlantic Ocean, inundated the Ottawa Valley, including the Bear Brook watershed, between 13,900 and 11,500 years before presented (BP) (Dyke and Prest, 1987; Parent and Occhiett, 1999; Brooks et al., 2021). During this period, extensive clay-rich marine sediments were deposited throughout the inundated region. Over time, isostatic adjustment of the land surface resulted in regional uplift, causing the Champlain Sea to recede from the Ottawa Valley. Raised shorelines are still evident and extensive marine clay deposits occur along the Ottawa River valley (Gadd, 1988). The current physiography, surficial materials, and landslide activity within the Ottawa Valley still reflect the influence of Champlain Sea.

Clays deposited during the retreat of Champlain Sea, also referred to as Leda Clays or quick clays, are highly sensitive to disturbances such as earthquakes, fluvial erosion, and anthropogenic activity. During deposition, negatively charged clay particles tended to flocculate around positively charged ions in a saltwater setting. After uplift, leaching of sodium ions (Na^+) by groundwater causes these materials to become geotechnically sensitive and prone to failure in the form of earth flows, such as those throughout the Ottawa Valley (Brooks et al., 2021). The timing of many large sensitive clay earth flows in the Ottawa Valley area have been constrained by Brooks et al. (2021) using radiocarbon dates. Sensitive clay earth flows of the Ottawa Valley range in age from approximately 8,000 years BP to ‘modern’ (Aylsworth et al., 2000; Brooks et al., 2021). Earth flow deposits from approximately 5,100 years BP and younger tend to be well preserved on paleoterraces and paleochannels along the Ottawa Valley (Brooks et al., 2021).

During and following the retreat of Champlain Sea, the newly exposed Ottawa Valley was subjected to incision of tributary networks of post-glacial fluvial channels into the valley and extending well into adjacent tableland (Brooks et al., 2021). The drainage area of Ottawa River was notably larger in the early Holocene. Modern continental drainage pathways to the Mississippi River and Hudson Bay were blocked by ice and flow was diverted through the Ottawa River valley. Due to the larger drainage area and rapid glacial melt, it is estimated that flow in Ottawa River could have been as high as 200,000 to 800,000 m^3 during outburst floods (Cummings and Russell, 2007), which is two orders of magnitude higher than modern flood magnitudes. A complex channel system or large, cross-cutting channels (**Figure 1** and **Figure 2**) developed downstream of the bedrock constriction near the present-day Ottawa city centre, with channels becoming increasingly younger to the east (Aylsworth et al., 2000; Fulton and Richard, 1987). Channels are now underlain by glaciomarine clays. The interfluve areas are capped by near-shore and deltaic sands and eolian sand dunes (Aylsworth et al., 2000).

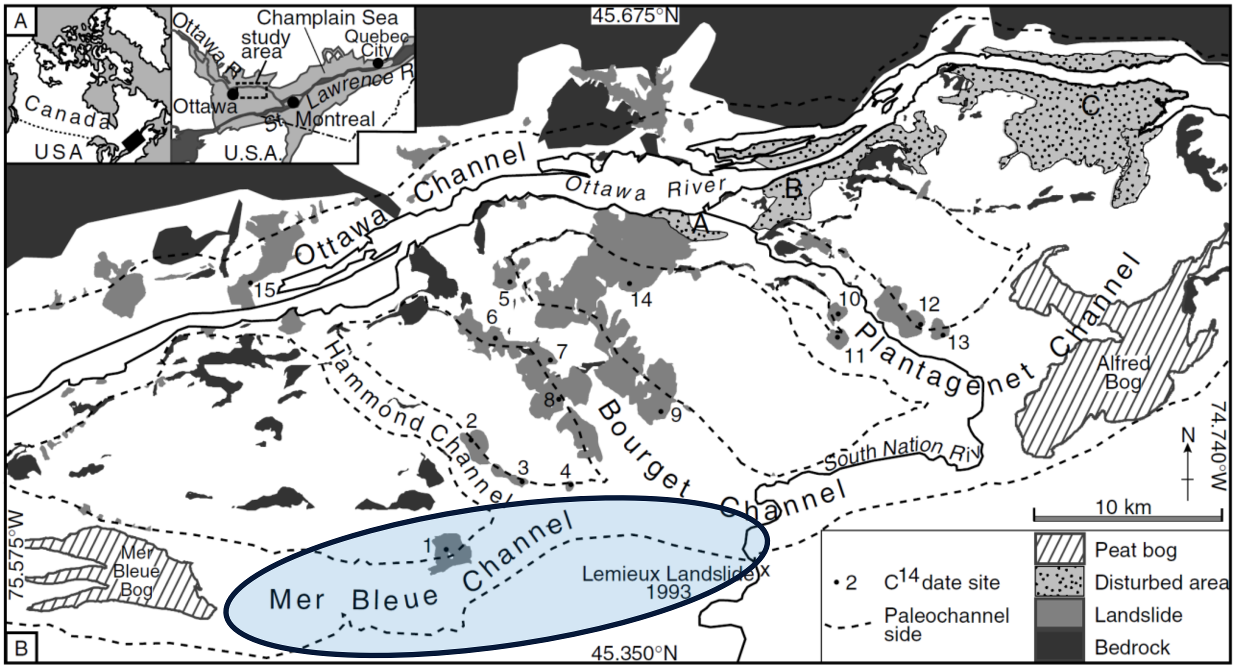


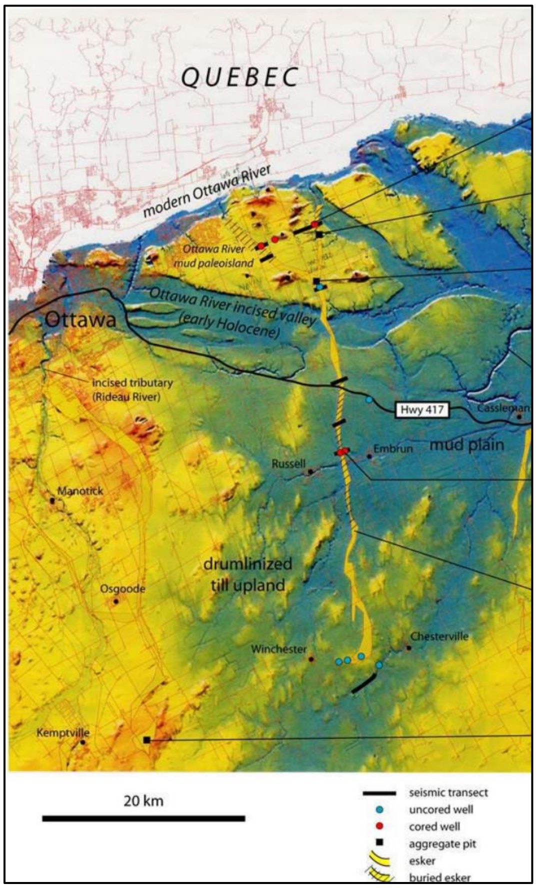
Figure 2. Locations of paleochannels of the Ottawa River (adapted from Aylsworth et al., 2000). Bear Brook flows eastward through the Mer Bleue and Bourget paleochannels to its confluence with South Nation River. The blue ellipse illustrates the approximate location of the main branch of Bear Brook. The inset figure shows the approximate extent of Champlain Sea.

The southern paleochannels (**Figure 2**) were likely abandoned by 8,000 years BP as glacial melt decreased and modern continental drainage pathways established (Aylsworth et al., 2000). Due to continued isostatic uplift, the drainage area of the modern Ottawa River did not attain its current size until about 4,700 years BP (Fulton and Richard, 1987). The paleochannels are up to 11 km wide and have steep side slopes with relief of 20 to 25 m. The scars of numerous large earth flows (i.e. landslides) punctuate the paleochannel side slopes (**Figure 2**). The probable trigger for most these large earth flows is a large earthquake event about 4,600 years BP, long after the paleochannels were abandoned (Aylsworth et al., 2000).

2.2 Watershed

The headwaters of Bear Brook (i.e. south of Highway 417) have incised into near-shore and deltaic sand deposits of a former Champlain Sea shoreline. This incision has created defined valleys and ravine networks. South of Highway 417, Bear Brook flows northward until it descends into the Mer Bleue paleochannel (**Figure 1**), where it abruptly flows eastward between glaciofluvial terraces and the Mer Bleue Bog following the alignment of the paleochannel. Bear Brook then flows into the Hammond paleochannel and then the Bourget paleochannel before it enters South Nation River. The bed and valley walls of the paleochannels are dominated by off-shore deposits of clay (OGS, 2007). Bear Brook is ‘misfit’ watercourse within the broader paleochannels. A large earth flow deposit immediately west of the community of Cheney (Landslide #1 on **Figure 2**) has constrained northward migration of Bear Brook.

The Vars-Winchester Esker, a glaciofluvial landform deposited during deglaciation, is oriented north-south and bisects the Mer Bleue paleochannel near Dunning Road (**Figure 3**). The esker, which is mostly buried by Champlain Sea deposits, comprises a gravelly central ridge bordered by sands and is a valuable source of aggregate and groundwater for municipalities and industry (Cummings and Russell, 2007). During deglaciation, Ottawa River had enough erosive energy to mobilize these sands and gravels, which eroded the crest of the esker (Cummings and Russell, 2007). Bear Brook has considerably less erosive energy than did Ottawa River during deglaciation and cannot readily entrain the remaining esker sediments. Bear Brook upstream of the esker is well connected to its broad floodplain. Downstream of the esker, Bear Brook has incised into the clay bed of the Mer Bleue Paleochannel to the point of entrenchment and formation of a modern valley within the broader paleochannel.



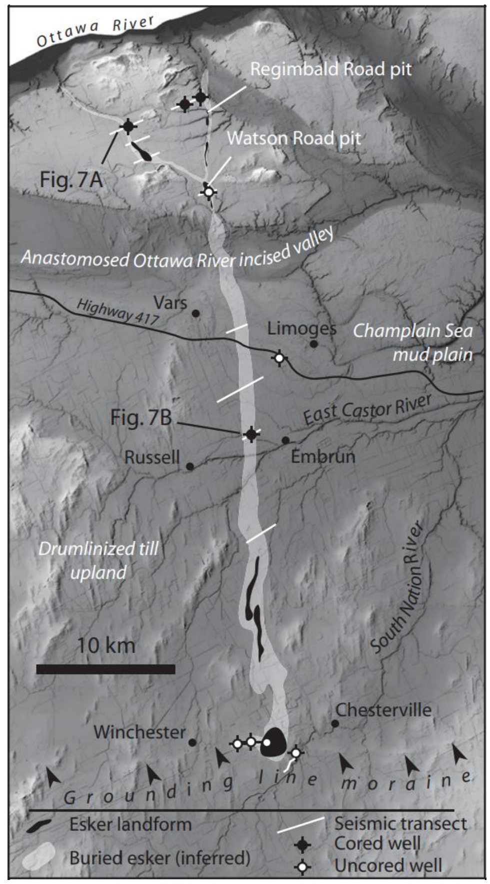


Figure 3. The Vars-Winchester Esker is oriented north-south and bisects Bear Brook near Dunning Road. Left panel figure is from Cummings and Russell (2007). Right panel figure is from Cummings et al. (2011).

Land use in the Bear Brook watershed is dominated by agriculture, especially within the paleochannels, and forests (SNC, 2016). Low topographic gradients and relatively impermeable clay soils have resulted in extensive artificial drainage networks of agricultural lands (Cummings and Russell, 2007). Urban development is increasing, especially in the upper subwatersheds within the City of Ottawa. Urbanization can alter the flow regime and sediment supply regime of the Bear Brook, which can alter channel morphology and the erosion hazard zone. Furthermore, localized channel alterations along Bear Brook are observed over the aerial photo period of record. These alterations include channel straightening, localized hardening (e.g. riprap), and vehicle crossings.

3. Methods

Palmer applied a systematic desktop- and field-based approach for documenting geomorphological conditions along Bear Brook. The methods are outlined in the following sections.

3.1 Data Compilation and Consultation

Palmer compiled and reviewed previous reports and spatial data to enhance our understanding of the geological, geomorphological, and topographic settings within the study area. Palmer reviewed pertinent reports prepared by SNC, including a watershed report card (SNC, 2016) and erosion hazard report (SNC, 2022). Particular attention was given to historical slope stability mapping along the ravine networks in eastern Ottawa (Klugman and Chung, 1976), a more recent geomorphological assessment and landslide inventory along nearby Green's Creek (Hugenholtz and Lacelle, 2004), an inventory map of large retrogressive landslides in sensitive clay within Ottawa (Brooks, 2019), and a compilation of radiocarbon dates for landslides in the Ottawa Valley (Brooks et al., 2021). Palmer staff also consulted Dr. Greg Brooks (Geological Survey of Canada) to discuss preliminary findings and associated interpretations with respect to the timing of landslide activity and valley evolution.

SNC provided Palmer with a LiDAR-derived digital terrain model (DTM) for the entire watershed (0.5 m resolution). The LiDAR data were collected in 2019 in the UCPR and in 2020 in the City of Ottawa. Ortho-rectified aerial photography within the City of Ottawa from 1965 to 2022 was accessed through the GeoOttawa webserver. Additional ortho-rectified aerial photography for the entire watershed for the years 2008, 2014, and 2019 was accessed from the Ontario Government. Historical aerial photos from 1945 and 1975 were purchased from the National Air Photo Library (NAPL). SNC shared with Palmer a fly-over video[1] showing mapped flood hazard extent draped over a LiDAR hillshade model for Bear Brook within the City of Ottawa. As well, SNC provided Palmer with watercourse, municipal drain, sub-catchment, and property parcel mapping. Long-term hydrometric data from a Water Survey of Canada (WSC) stream gauge on Bear Brook near Bourget (Station ID 02LB008) was compiled.

3.2 Data Analysis

3.2.1 Longitudinal Profiles

Longitudinal profiles of the water surface elevation were extracted from the 2019/2020 LiDAR-derived DTM along the Bear Brook centerline to better understand energy gradients, reveal important slope-breaks, and inform understanding of observed geomorphological changes through time. Hugenholtz and Lacelle (2004), in a geomorphological analysis of Green's Creek in Ottawa, demonstrated a strong association between landslides and the longitudinal profile of the creek. The point spacing interval along the channel was 1 m. Inherent vertical noise and error (up to 0.5 m) is present in the hillshade, but it did not preclude identification and interpretation of sub-reach-scale slopes and geomorphological processes. Smoothing techniques, including the use of a moving average, were utilized for interpretation and for presentation.

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[1] *https://www.youtube.com/watch?v=Ag2J7dpQsAc&ab_channel=SouthNationConservation*

3.2.2 Aerial Photo Assessment

As a basis for strengthening understanding of the locations, mechanisms and implications of greatest changes in river planform, a systematic comparative overlay analysis was completed using historical and recent aerial photos. Channel planforms, as defined by the perceived channel thalweg, were delineated for all years specified in **Table 1**. These years were selected based on the quality (resolution and georeferencing) and extent of the imagery. The 2008 and 2019 aerial imagery was previously orthorectified. The 1945 and 1975 aerial photos were georeferenced to the 2019 orthophotos using standard GIS georeferencing tools. Newer imagery is available within the City of Ottawa but for consistency the 2019 imagery was used for the analyses as it covered the whole study area. Approximately five control points were used to optimize the spatial match within the valley bottom, where relief and relative image distortion are low. Resultant errors in comparison to the orthophotos were generally ±3 m.

Table 1. **Aerial imagery used to document channel evolution along Bear Brook**

Year	Scale/Resolution	Coverage	Colour?	Source
2019	0.2 m	Entire study area	Yes	Ontario Government
2008	0.2 m	Entire	Yes	Ontario Government
1975	1:35,000	Entire	Yes	NAPL
1945	1:15,000	Entire	No	NAPL

Following channel delineation, the sinuosity (channel length divided by valley length) and number of meander cut-offs (rapid shift in channel planform) were documented to inform changes in channel planform through time. Sinuosity provides a measure of the degree of meandering along a reach, with higher values indicating a more sinuous channel and lower values indicating a straighter planform. Additionally, oxbows/meander scars and realigned channels clearly visible in the 1945 imagery were also delineated to document the historical position of the channel prior to the beginning of the photographic record.

Historical trends in channel migration offer one of the most reliable bases for forecasting future rates and trajectories of erosion, as recognized by the *Technical Guide: Erosion Hazard Limit* (Ontario Ministry of Natural Resources, 2002). For meanders exhibiting systematic (progressive) migration, time-averaged migration rates were calculated by dividing the total migration distance along a given migration trajectory by the period between 1945 and 2019 (74 years). Migration rates were not calculated for meanders that exhibited no systematic change in bank position over the period of record. Similarly, migration rates were not calculated for meanders that migrated less than 3 m over the period of record as perceived differences in bank position solely reflect georeferencing error in the 1945 and/or 1975 imagery.

3.2.3 Reach Delineation

Following the data compilation and initial desktop assessment, Bear Brook was divided into geomorphological reaches, which are defined as lengths of channel that display similar physical characteristics and have a setting that remains nearly constant along their length. Thus, along a reach, the controlling and modifying influences on the channel are similar, yielding relatively consistent geomorphological form (Hogan and Luzi, 2010). Reach delineation for Bear Brook was primarily based on the degree of channel confinement, channel gradient, history of anthropogenic modification, and landsliding activity. Delineating reaches allows for site-specific geotechnical and geomorphological findings to be extrapolated upstream and downstream.

3.2.4 Preliminary Landslide Inventory

A preliminary inventory of previous landslides was prepared for the entire Bear Brook watershed for contextual understanding of valley evolution and sediment inputs to Bear Brook. Landslides were primarily interpreted from LiDAR-derived hillshade renderings (based on only a single sun angle). Recent ortho-imagery was locally reviewed to aid interpretation, although with limited value due to tree cover and limitations associated with landslide size (many are small) and age (many are old). Palmer also thoroughly reviewed an inventory map of large retrogressive landslides in sensitive clay near Ottawa (Brooks, 2019), as well as available surficial geology (Ontario Geological Survey, 2007) and physiography mapping (Chapman and Putnam, 2007). Landslides were identified where there was morphological evidence of coherent mass failure at a scale of 1:2,500 to 1:5,000. Ravelling/sloughing slopes along the outer banks of meanders were excluded. Interpretations were complicated, and potentially locally misled, by terraced meander scars, meltwater channel fragments at the edge of tableland, gullies formed by fluvial incision or groundwater sapping, and anthropogenic disturbances.

Large (>5,000 m^2) retrogressive landslides (earth spreads and flows), most of which had been previously identified by Brooks (2019) or Ontario Geological Survey (2007), were mapped as polygons. Their boundaries were typically well-defined in headscarp areas but irregularly or poorly defined in runout areas. Smaller, commonly younger, landslides were mapped as points. The point landslides were categorized according to confidence of interpretation as Probable Landslides (i.e. higher confidence) or Possible Landslides (i.e. lower confidence). No additional attributes (e.g. trigger, activity state, dimensions) were recorded for either the landslide polygons or points.

The preliminary landslide inventory provides a useful catalogue of existing failures within the Bear Brook watershed but is subject to several important limitations. The landslide identification does not constitute a landslide hazard map, which identifies all areas susceptible to landsliding and may further characterize probabilities and potential magnitudes of landslides. Recognizing large retrogressive landslides in sensitive clay is relatively straightforward; they exhibit conspicuous morphologies and persist almost indefinitely in LiDAR-derived topographic data. They have long geomorphic "persistence time" (Guthrie and Evans, 2007). Smaller landslides that are generally restricted to valley walls, whether rotational or translational, are more challenging to recognize and have shorter geomorphic persistence time. The amphitheater-like hollows that define the headscarps and upper failure planes of rotational landslides, in particular, may be confused with meander-carved ravine walls or the heads of gullies formed by groundwater sapping. Furthermore, geomorphological records of smaller landslides, especially translational ones, are relatively quickly lost from LiDAR data through reworking and fluvial erosion of deposits. Accordingly, it should be assumed that mapped inventories of landslides may represent an under-estimate of the distribution of landsliding in the Bear Brook watershed.

3.2.5 Relative Elevation Model

To help visualize subtleties in fluvial landforms, accordancy in terraces, and local relief of valley walls, Palmer created a LiDAR-derived REM along the main branch of Bear Brook. A REM is normalized (i.e. benchmarked) to the elevation of the channel (i.e. lowest point) along a valley. Local relief is a key control of landslide potential and distribution (Hugenholtz and Lacelle, 2004). Palmer (2023) determined that the majority of landslides alongside nearby Voyageur Creek, including all earth spreads, occurred where valley wall relief is >9 m. This is consistent with literature documenting an association of retrogressive landslides in sensitive clays with a minimum relief of valley walls in Quebec (Demers et al., 2013) and Norway (Kalsnes et al., 2014). The REM does not document slope angle or slope materials, both of which are also important considerations for landsliding, or establish whether certain slope toes may be inundated during floods.

The REM was created from the 2019/2020 LiDAR-derived DTM (down-sampled to 1 m resolution) in QGIS following protocols outlined in Blazewicz et al. (2020). It was generated along a 1,000 m-wide corridor centred along the Bear Brook valley axis. The channel centreline used to establish the water surface longitudinal profile (Section 3.2.1) was defined as the lowest elevation (i.e. 0 m elevation local benchmark) along the valley. Cross-sections were generated every 1,000 m along the channel to determine the lowest elevation of the DTM along each cross-section (Min-Z). A 1,000 m spacing was sufficient given the low gradient of Bear Brook and the large study area. Some of the cross-sections were manually adjusted and additional cross-sections were added to refine the product. A triangular irregular network was created using the calculated Min-Z values, which was converted to a raster layer. The REM values were determined by subtracting the DTM absolute elevations from the Min-Z raster.

3.2.6 Hydrological Characterization

Hydrological characterization for Bear Brook was conducted using long-term continuous data from a WSC stream gauge on Bear Brook near Bourget (Station ID 02LB008). The WSC gauge has a watershed area of 448 km^2. The period of record is 1949-1953; 1955-1969; and 1976-2024. Until late 1976, discharge data were primarily collected during the months of March and April. Therefore, pre-1977 data were omitted from all hydrological analyses. Daily streamflow values were used to generate a series of hydrographs and timeseries plots to understand the long-term hydrological dynamics of Bear Brook. The following hydrological metrics were considered for this analysis:

- **Annual unit streamflow:** This metric is total annual streamflow (i.e. volume) for the calendar year (January 1 to December 31) normalized by watershed area. To account for missing observations, years for which greater than 20% of daily streamflow values were missing were excluded from the analysis. For years with less than 20% of daily streamflow values missing, missing values were replaced with the mean monthly streamflow value calculated from the 1977 to 2022 record.
- **Peak daily streamflow magnitude:** This metric is the peak daily streamflow observed each year (January 1 to December 31).
- **Timing of peak flow:** This metric is defined as the day of peak streamflow each year (January 1 to December 31).

The timeseries for each streamflow metric was analyzed using a Mann-Kendall (MK) test, which assesses if there is a monotonic upward or downward trend in the variable of interest through time. The MK test is commonly used to assess whether long-term streamflow regimes have changed through time (e.g. Zhang and Wei, 2012; Giles-Hansen et al., 2019). The MK test evaluates the null hypothesis, which is that there is no trend through time. If the null hypothesis is rejected, then a trend is considered present. The MK test is non-parametric (i.e. no underlying assumptions about distributions of values), but it does assume that individual observations are not temporally correlated. Issues with potential temporal autocorrelation were addressed by calculating streamflow metrics that are separated by a year and are therefore unlikely to be autocorrelated. Given the exploratory nature of this analysis, a p-value of 0.10 was used to test the null hypothesis and evaluate significance. The presence or absence of a statistical significance does not confirm the presence or absence of a long-term trend. Trends may exist but may not be identified by a statistical test where the period of record is short, the data are highly variable, or the magnitude of a trend is small.

The magnitude of change was calculated separately using the Sen slope estimation technique, which is also commonly used to characterize changes in hydrometeorological metrics through time (e.g. Atker et al., 2019; Masingi et al., 2021). This approach calculates the median slope of all lines through all pairs of points and is generally considered to be insensitive to outliers and more robust than calculating slope using least squares regression techniques. This approach is useful for identifying long-term trends in the streamflow regime; however, it does not identify the causation of any noted change in hydrology.

3.3 Field Reconnaissance and Rapid Assessments

Palmer's Principal Fluvial Geomorphologist completed initial field reconnaissance along Bear Brook on November 15, 2023. Discharge of Bear Brook was 2.2 m^3/s as measured at the WSC gauge near Bourget (ID 02LB008), which is less than the long-term average discharge for November (5.4 m^3/s) and the mean annual discharge (6.2 m^3/s). Most of Bear Brook flows through private (mostly agricultural) property. Reconnaissance was limited to public watercourse crossings or where Bear Brook flowed near a public property. All delineated reaches were at least partly investigated in the field.

The purpose of this reconnaissance was to observe channel conditions, examine patterns and processes of local erosion, and ground truth aerial photograph-based interpretations. As part of this, a Rapid Geomorphic Assessment (RGA; Ontario Ministry of the Environment, 2003) was completed along each delimited reach to document evidence of channel aggradation, degradation, widening and/or planimetric form adjustment. The RGA tool provides a useful checklist of evidence to consider, but its results are dependent on the presence or absence of a set number of specific features within a reach and thus must be interpreted carefully to ensure accuracy (McKillop, 2016). The RGA is also one of many rapid assessment techniques that fails to meaningfully represent the sediment transport considerations fundamental to fluvial geomorphology (Papangelakis et al., 2023ab). The Rapid Stream Assessment Technique (RSAT) field method was also applied along the study corridor to gain a general understanding of stream characteristics and overall health (Galli, 1996).

4. Results

The results of the geomorphological assessment are provided in the following subsections. Representative field photographs of each reach are presented in **Appendix A**. Mapping depicting historical overlay analyses, channel cut-offs, and landslide distribution are presented in **Appendix B**. Migration rates and trajectories of individual meanders are presented in **Appendix C**. The REM of Bear Brook, including the distribution of landslides for comparison with local relief of valley walls, is displayed in **Appendix D**.

4.1 Channel Morphology and Fluvial Processes

Bear Brook was divided into nine geomorphic reaches (**Figure 1**), basic characteristics of which are summarized in **Table 2**. Reach length ranges from 3.2 to 10.3 km. Reach 1 has a natural, irregular meandering planform and flows within a defined valley formed though channel incision into near-shore and deltaic sand deposits (**Photo 1**). Reaches 2 though 4 flow within the Mer Bleue paleochannel (**Figure 2**). These reaches have been locally straightened and have good access to the floodplain (i.e. not entrenched) (**Photo 2**). Reaches 5 though 9 have incised into the former paleochannel and Champlain Sea deposits, creating a contemporary valley (**Photo 3**). The contemporary valley contains all flood flows as observed in in SNC's flood mapping[2].

Photo 1. Representative photograph (looking upstream) of Reach 1 flowing within a defined, forested valley formed through channel incision of near-shore sands and deltaic sands.

[2] *https://www.youtube.com/watch?v=Ag2J7dpQsAc&ab_channel=SouthNationConservation*

Table 2. Geomorphic summary of delineated reaches along Bear Brook.

Reach	Upstream Chainage[1] (km)	Downstream Chainage[1] (km)	Upstream Reach Break Rationale	Reach Length[2] (KM)	Slope[3] (%)	Bankfull Width[4] (m)	Sinuosity[5]
1	0.0	3.7	Confluence with major tributary	3.7	0.06	11	1.28
2	3.7	11.2	Channel becomes less confined, notable anthropogenic straightening	7.5	0.04	13	1.29
3	11.2	19.0	Channel unconfined, drastic increase in flood hazard extent, lack of riparian buffer	7.8	0.02	17	1.29
4	19.0	24.5	Reduction in flood hazard extent, increase in meander radii and amplitudes	5.5	0.02	17	1.14
5	24.5	30.5	Increase in slope downstream of Vars-Winchester Esker, onset of channel incision, onset of more widespread landsliding	6.0	0.16	19	1.41
6	30.5	33.7	Upstream extent of large retrogressive landslide, increase in contemporary valley relief	3.2	0.03	20	1.32
7	33.7	40.7	Downstream extent of large retrogressive landslide, South Indian Creek confluence	7.0	0.03	22	1.17
8	40.7	49.1	North Indian Creek confluence	8.4	0.03	23	1.42
9	49.1	59.4	Channel descends into a Bourget paleochannel, onset of tortuously meandering planform	10.3	0.04	24	3.08

Notes:

1. Length along 2019 centreline starting from upstream limit of study area
2. Reach length (m) = downstream chainage (m) – upstream chainage (m)
3. Reach-averaged slope determined from 2019/2020 LiDAR-derived longitudinal profile
4. Bankfull width was averaged by reach measurements every 1,000 m using 2019 orthophotographs and LiDAR data
5. Sinuosity (m/m) = 2019 channel length (m) ÷ valley length (m)

Photo 2. ***Representative photograph (looking upstream) of Bear Brook within the Mer Bleue paleochannel upstream of the Vars-Winchester Esker (i.e. Reach 2 through Reach 4). The channel is unconfined, with good access to its floodplain, and the riparian vegetation has been largely cleared.***

Photo 3. ***Representative photograph (looking downstream) of Bear Brook downstream of the Vars-Winchester Esker (i.e. Reach 5 through Reach 9). The channel has incised through the paleochannel deposits leading to channel confinement, lack of floodplain access, and localized landsliding.***

The sinuosity of all reaches of Bear Brook, except Reach 9, is less than 1.5. Upon entering the Bourget paleochannel (i.e. Reach 9), Bear Brook exhibits a tortuously meandering planform. The planform of the upstream reaches is mostly irregular meandering. Localized channel straightening has reduced sinuosity and increased channel slope. The reach-averaged slope of Bear Brook is currently 0.04% (**Figure 4**). The Vars-Winchester Esker is a prominent grade control. Bear Brook does not have sufficient energy to mobilize the gravelly esker deposits, so upstream reaches 2 through 4 remain gentle and are unable to incise into the clay substrates. These reaches are unconfined and floods readily spill onto their floodplains. Downstream of the esker, Bear Brook has been able to incise into the bed of the paleochannel to form a contemporary valley. Reaches 5 through 9 are confined within the contemporary valley, which contains flood flows. Landsliding (discussed in further detail in Section 4.3) is most prominent along these downstream reaches.

Riparian vegetation along Reaches 2, 3, and 4 has been extensively cleared, mostly for agricultural purposes. A riparian vegetation buffer is present along the contemporary valleys of Reach 1 and Reaches 5 though 9. Occasionally debris jams were observed along these reaches. he tablelands above the contemporary valleys are dominated by agricultural activities. Gravels and lag cobble and boulder deposits were locally observed in Reach 1 and Reach 5. The remaining reaches have silt and fine-sand bed material. Bank materials are dominated by clay, silts, and fine sands. Anthropogenic rock weirs were observed beneath numerous vehicle crossings.

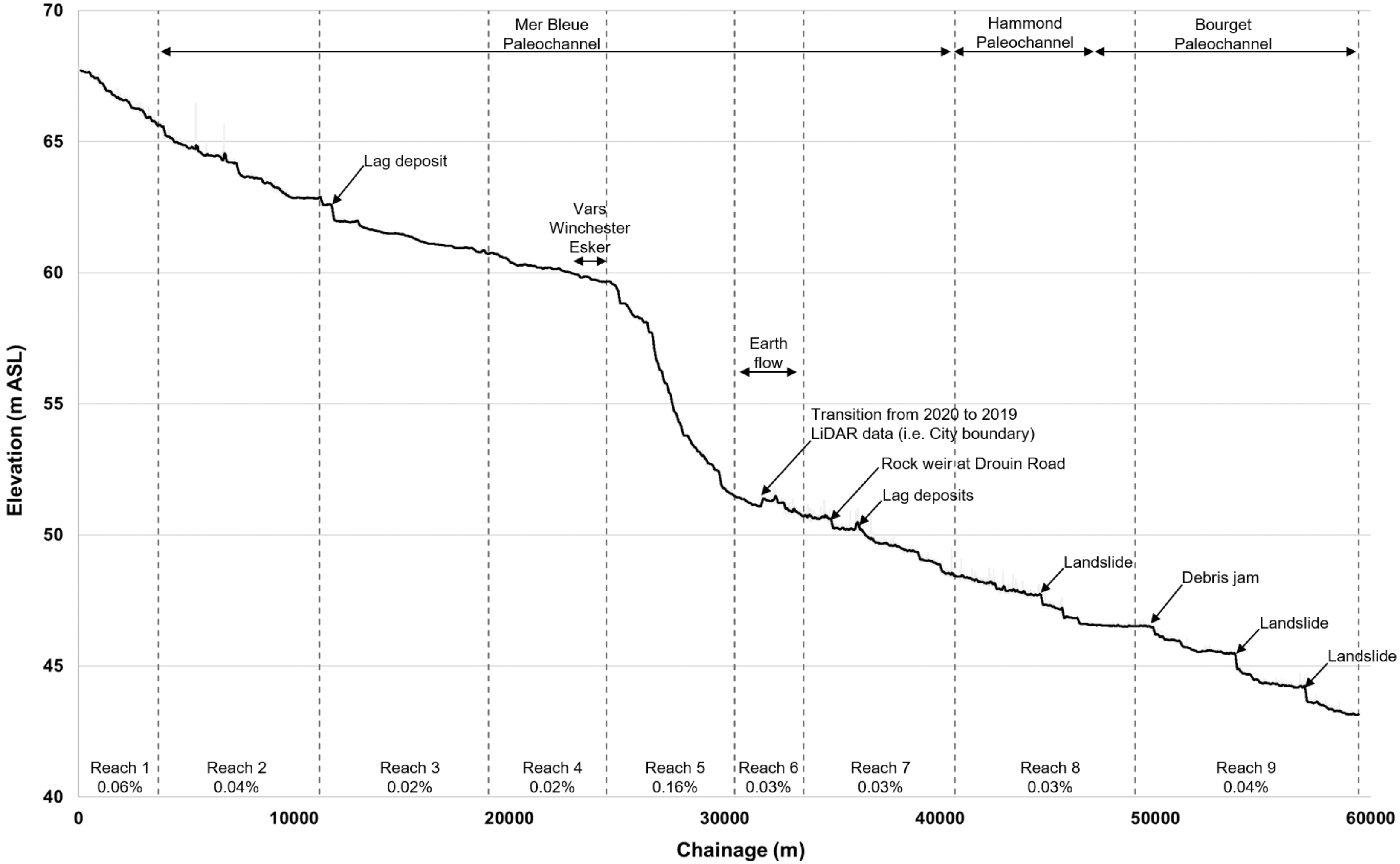


Figure 4. Longitudinal profile of Bear Brook. The faint grey line represents elevations extracted every 1 m along the 2017 water surface centreline. The dark black line represents a 100 m moving average that helps smooth inherent noise in LiDAR data (e.g. apparent downstream rise in water surface). The vertical dashed lines divide reaches, also shown on Figure 1, with their average gradients shown as percentages. The extents of the paleochannels are shown on Figure 1 and Figure 2. The Vars-Winchester Esker is a prominent vertical (grade) control that impacts profile development both upstream and downstream. The profile is locally controlled by debris jams, landsliding, and anthropogenic rock weirs.

4.2 Historical Assessments

Mapping depicting the results of historical overlay analyses is presented in **Appendix B**. The overall channel length of Bear Brook remained relatively consistent over the period of record (**Table 3**). The loss of channel length from localized channel straightening was generally offset by meander migration between 1945 and 2019. However, numerous meander cut-offs, mostly anthropogenic, were observed in the 1945 imagery (**Table 4**). The exact timing of these pre-1945 cut-offs is challenging to constrain but likely occurred as the Bear Brook valley was being developed for agriculture in the 19th and early 20th century. Mapping of the pre-1945 channel features (**Appendix B**) suggests the channel length was reduced by a maximum of 5.7 km before 1945 as a result of the cut-offs. The majority of the pre-1945 channel shortening occurred along Reaches 2, 3 and 4 (**Table 5**), where the channel is unconfined and anthropogenic realignment is more feasible. Since 1945, only four cut-offs were observed. However, some natural meander cut-offs were also observed, including a prominent meander cut-off in Reach 9.

Table 3. Total channel length (all reaches) of Bear Brook through time

Year	Channel Length (km)
2019	59.3
2008	59.5
1975	59.2
1945	59.9

Table 4. Channel cut-offs along Bear Brook by time period

Time Period	Number of Cut-offs
2008 to 2019	1
1975 to 2008	0
1945 to 1975	3
Pre-1945	22
Total	**26**

Table 5. Number of cut-offs by reach along Bear Brook

Reach	Number of Cut-offs
1	3
2	6
3	9
4	4
5	3
6	0
7	0
8	0
9	1
Total	**26**

A total of 48 meanders have exhibited largely systematic migration since 1945 (**Appendix B**). Meander migration rates are summarized by reach in **Table 6**. Migration rates and trajectories for each of the 48 meanders are presented in **Appendix C**. Overall, meander migration has occurred relatively slowly, presumably due to low channel gradient, cohesive (clay) bank materials, and localized confinement. Reach 5 had the most meanders with systematic migration and the highest average migration rate, which is likely the result of its higher channel gradient (**Figure 4**).

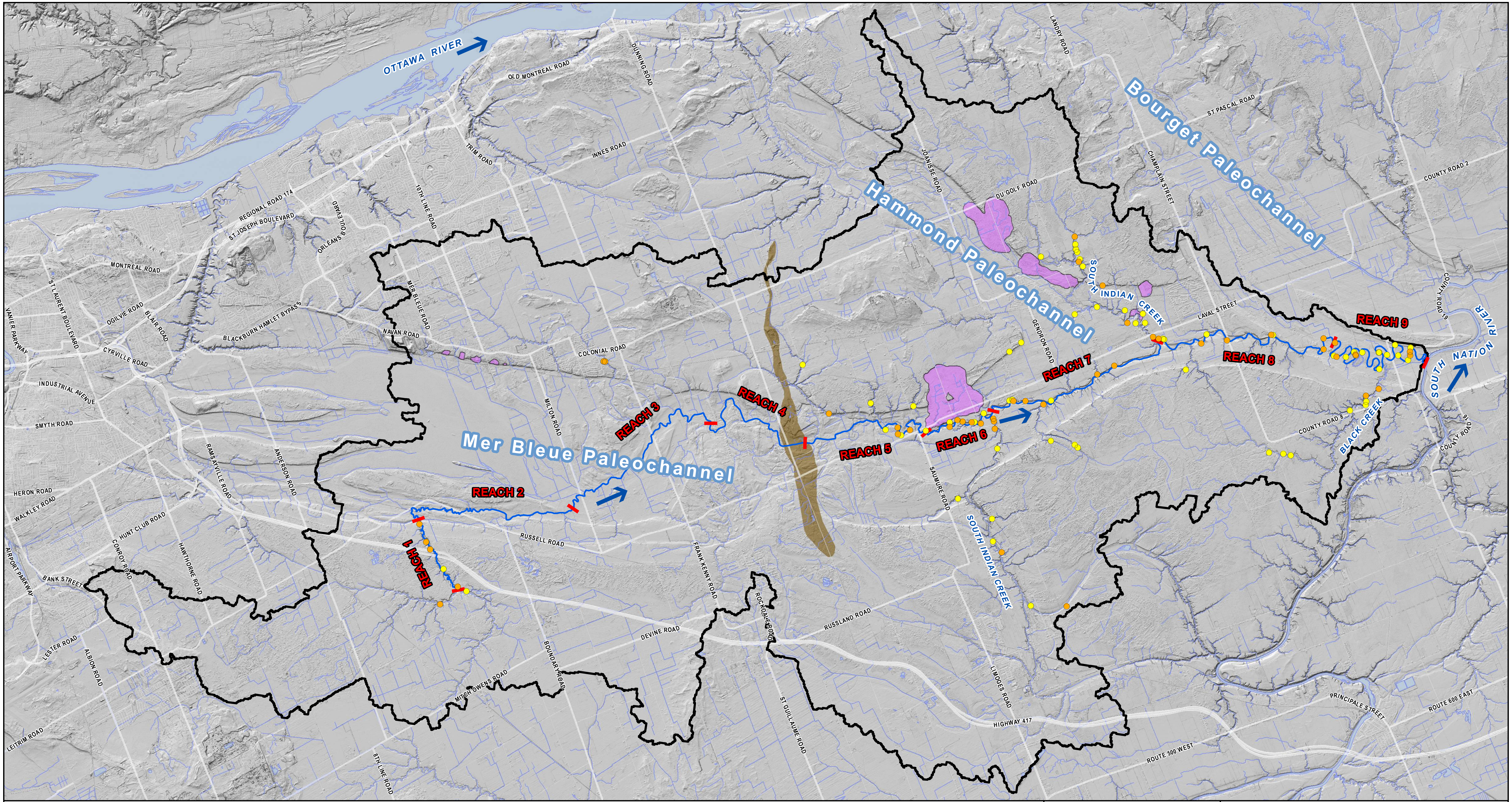
Table 6. Average migration rates, by reach, for meanders exhibiting systematic migration from 1945 to 2019. Migration rates for individual meanders are presented in Appendix B.

Reach	Number of Meanders with Systematic Migration	Migration Rate from 1945 to 2019 (m/yr)
1	7	0.1
2	1	0.1
3	10	0.1
4	3	0.1
5	14	0.2
6	4	0.2
7	1	0.1
8	3	0.1
9	5	0.1

4.3 Preliminary Landslide Inventory

The preliminary landslide inventory for the Bear Brook watershed is presented on **Figure 5**. Ten large retrogressive landslides were identified, eight of which were previously identified by Brooks (2019) and/or OGS (2007). These large failures are generally located along escarpments at the edges of the paleochannels. Five large retrogressive landslides were identified on the north escarpment of the Mer Bleue paleochannel immediately west of Navan. These landslides are not dated. The landslide deposits appear to be truncated, which suggests the deposits were eroded when there was flow within the paleochannel or they have been reworked over time. The five others large retrogressive landslides were identified east of the Vars-Winchester Esker. Four of these have been dated between 4,590 BP and 2,760 BP and were likely triggered by seismic activity (Aylsworth et al., 2000). The deposits from each of these landslides are well preserved, indicating they occurred after the paleochannels were abandoned.

In addition to the large retrogressive landslides, 104 smaller landslides (59 Possible, 45 Probable) were identified in the watershed (**Figure 5**). Most of these landslides occur east (i.e. downstream) of the Vars-Winchester Esker, where the channels have been able to incise into the clayey substrates to create sufficient relief for landsliding. Additionally, landslides were also noted along the escarpments at the edges of the paleochannels and along Reach 1 where the main branch of Bear Brook has incised through sandy near-shore deposits and created a defined valley. Along Bear Brook and its tributaries, relief of valley walls varies locally and not consistently in a downstream direction. The majority of inventoried landslides occurred where slopes were higher than 8 m. However, landslides were observed on slopes with relief between 4 and 8 m (e.g. most small landslides along Reach 9).



LEGEND

- Large retrogressive landslide (approximate)
- Possible Landslide
- Probable Landslide
- Reach Break
- Bear Brook Main Branch
- Watercourse[1]
- Flow Direction
- Esker (partly buried; approximate)[2]
- Bear Brook Watershed Boundary

Note: The absence of mapped landslides is not an indication of past, present, or future slope stability; it merely reflects a lack of geomorphological indicators of coherent mass failure at the time of LiDAR acquisition

1. Ontario Hydro Network (LIO, 2024)
2. The approximate extent of the Vars-Winshester Esker in the vicinity of Bear Brook is shown on the map. The eskter extends further north and south than shown

0 1 2 3 4 5
km

North American Datum 1983
Universal Transverse Mercator Projection Zone 18

Scale: 1:120,000
Page Size: Tabloid (11 x 17 inches)

Drawn: CV
Checked: DM
Date: May 10, 2024

NORTH

Basemap: *Hillshade map of Digital Terrain Model* (2019-20), Government of Canada; Natural Resources Canada; Strategic Policy and Innovation Sector
Notes: Contains information licensed under the Open Government Licence – Ontario and Canada.

CLIENT	South Nation Conservation (SNC)
PROJECT	Bear Brook Geomorphology
TITLE	**Bear Brook Watershed - Preliminary Landslide Inventory**
REF. NO.	2302503-5-2

Palmer. PART OF SLR

Figure 5

4.4 Hydrology

The hydrology of Bear Brook is characterized by peak flows during late winter or early spring caused by melting snowpack in the watershed (**Figure 6**). Throughout the summer and fall, secondary peaks are relatively common in response to localized rainstorms. In general, low flows occur during the fall and winter months. The annual yield of Bear Brook has varied between 845 mm in 2017 and 217 mm in 2011, with a mean value of 434 mm. Statistical analysis indicates that annual yield appears to have increased by a rate of 0.87 mm/year from 1977 to 2022 (**Figure 7, Table 9**); however, this trend is not statistically significant.

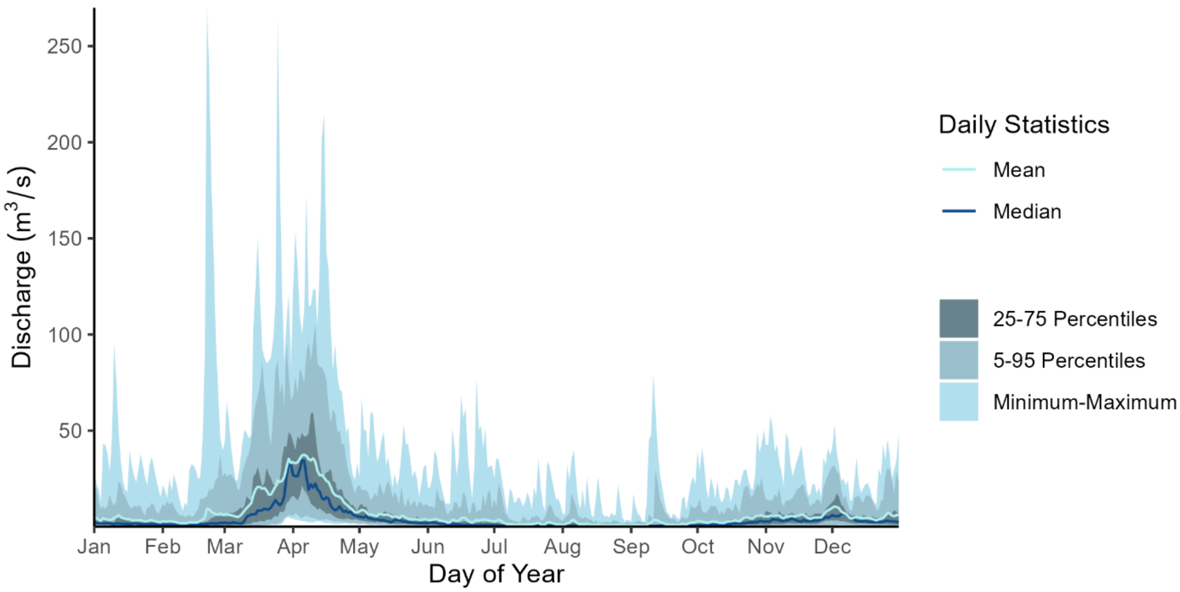


Figure 6. Hydrograph of daily streamflow variability of Bear Brook from 1977 to 2022 [02LB008]

Table 7. Summary of Mann-Kendall statistical tests for hydrological metrics

Metric	p-value	Trend
Annual Yield	0.448	0.87 mm / year
Peak Flow Magnitude	**0.009***	**-1.30 m^3/s / year**
Peak Flow Timing	**0.084**	**0.3 days / year**

*statistically significant results (p<0.10) are bolded

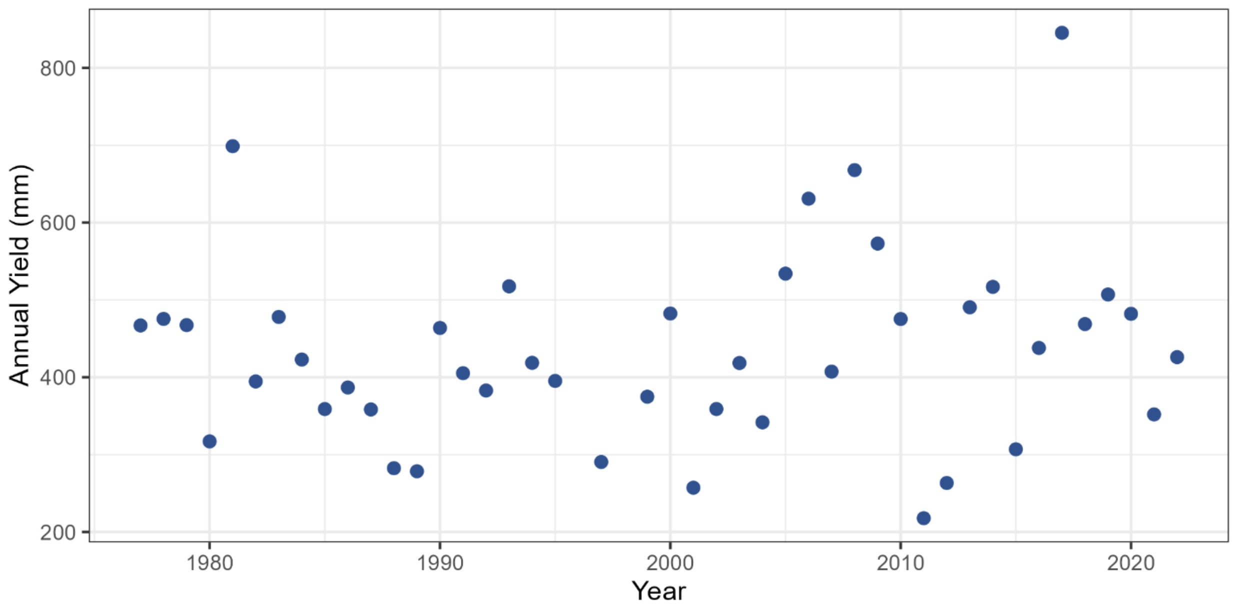


Figure 7. Time-series of annual yield (total streamflow divided by watershed area) of Bear Brook [02LB008]

The timeseries of annual daily peak flow for Bear Brook indicates that peak flow magnitude is decreasing over time at a statistically significant rate (**Figure 8, Table 9**). Visual interpretation of Figure 1.3 suggest that this change was most prevalent in the first decade of record and has stabilized from the 1990s to present day. The cause of this reduction is unknown, but it may be due to a reduction in snowpack accumulation during winter months, long-term weather patterns (e.g. atmospheric teleconnections), land-use change within the watershed, and/or other environmental factors. Decreasing flood magnitudes may contribute to the relatively modest migration rates. Annual peak flow timing has historically occurred in March and April. In some more recent years, annual peak flows occurred during the summer months. This trend is statistically significant (**Figure 8, Table 9**). The later peak flows further implies they are driven less by decreasing winter snowpacks and, instead, are increasingly affected by summer precipitation events. High flows occurring later in the year allows vegetation to increase bank strength (i.e. reduce erosion potential) and may reduce the likelihood of ice jamming.

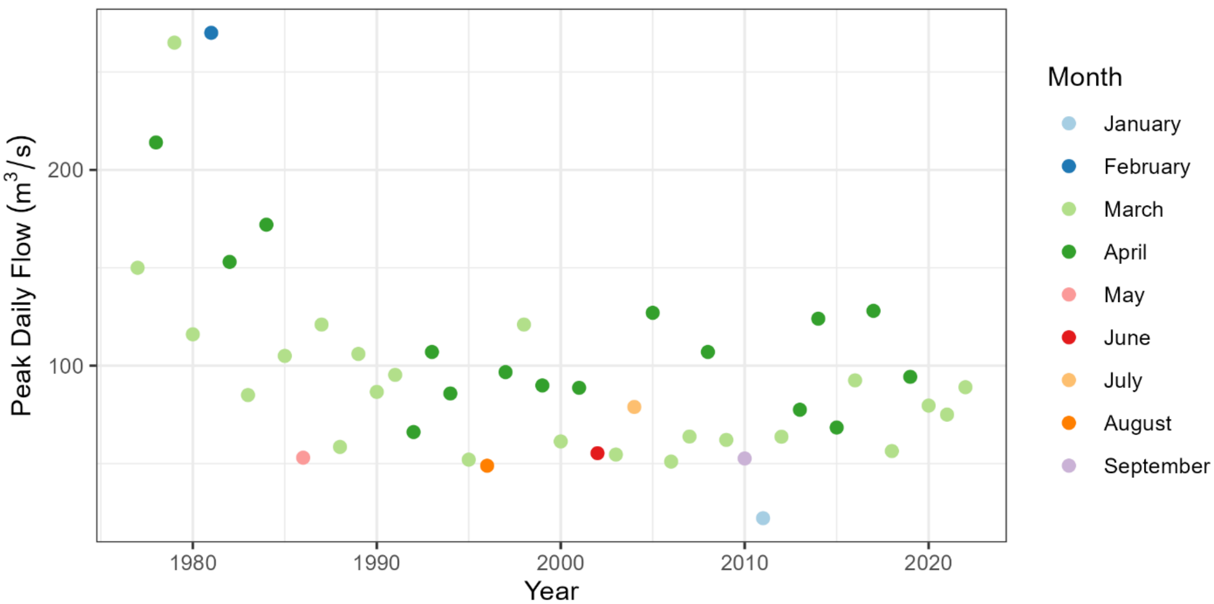


Figure 8. Long-term timeseries of peak streamflow magnitude and timing for Bear Brook [02LB008]

4.5 Rapid Assessments

All reaches have overall stabilities described as “transitional” or “in adjustment,” according to scoring in the RGA, except Reach 1, which concurs with field observations (**Table 8**). Reach 1 is the least anthropogenically disturbed reach and is classified as “in regime”. Widening is the dominant mode of adjustment in eight of the nine reaches. The extensive removal of riparian vegetation and reduction of upstream sediment supply likely contributes to widening. Degradation is the dominant mode of adjustment in Reach 5, as the channel has incised into the bed of the paleochannel downstream of the Vars-Winchester Esker. The results of the RSAT indicate that Reach 1 has “good” quality, as it scored well in the indices of channel scouring/sediment deposition and physical in-stream habitat (**Table 8**). The remaining reaches have “fair” or “poor” quality, namely due to low scores in the indices of physical in-stream habitat, riparian habitat conditions, and channel stability.

Table 8. Summary results of the RGA for Bear Brook

Form/Process	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5	Reach 6	Reach 7	Reach 8	Reach 9
Aggradation	0.14	0.14	0.29	0.14	0.00	0.00	0.00	0.00	0.00
Degradation	0.00	0.00	0.17	0.50	0.67	0.43	0.57	0.57	0.50
Widening	0.43	0.71	0.57	0.57	0.57	0.71	0.71	0.71	0.71
Planimetric Form Adjustment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average (Stability Index)	**0.14**	**0.21**	**0.26**	**0.30**	**0.31**	**0.29**	**0.32**	**0.32**	**0.30**
Classification[1]	In Regime	Transitional	Transitional	Transitional	Transitional	Transitional	Transitional	Transitional	Transitional
Dominant Mode of Adjustment	Widening	Widening	Widening	Widening	Degradation	Widening	Widening	Widening	Widening

1 – Stability Index Interpretation: 0.00 to 0.20 = In Regime, 0.21 to 0.40 = Transitional or Stressed, >0.40 = In Adjustment

Table 9. Summary results of the RSAT for Bear Brook

Evaluation Category	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5	Reach 6	Reach 7	Reach 8	Reach 9
Channel Stability	8	4	4	4	4	4	3	3	3
Channel Scouring/Sediment Deposition	6	1	3	3	5	3	3	3	3
Physical In-stream Habitat	5	1	1	1	3	1	1	1	1
Water Quality[1]	3	3	3	3	3	3	3	3	3
Riparian Habitat Conditions	5	2	0	2	2	4	3	3	2
Biological Indicators[1]	3	3	3	3	3	3	3	3	3
Total	**30**	**14**	**14**	**16**	**20**	**18**	**16**	**16**	**15**
Verbal Ranking[2]	Good	Poor	Poor	Fair	Fair	Fair	Fair	Fair	Poor

1 – Based on information provided in the Bear Brook Subwatershed Report Card (2016)

2 – Verbal Rankings: < 16 = Poor, 16-29 = Fair, 30-41 = Good, 42-50 = Excellent

5. Discussion and Recommendations

The unique deglacial history of the Bear Brook watershed (**Section 2**) strongly influences modern geomorphological processes. Rates of natural erosional processes (meander migration, natural cut-offs) are relatively modest along Bear Brook due to its low channel gradient and cohesive bed and bank materials. Anthropogenic modifications and landsliding have notably affected fluvial geomorphological processes and the evolution of associated hazards. The following subsections discuss key drivers and processes of geomorphological change, recommend a geomorphological monitoring program tailored to the dynamics of Bear Brook, and highlight potential watershed management strategies.

5.1 Key Drivers of Geomorphological Processes

This assessment has demonstrated the mechanisms primarily and secondarily responsible for geomorphological processes along Bear Brook. A brief synopsis of each mechanism, many of which are interrelated, is provided below.

- **Vars-Winchester Esker** – The sand and gravel core of the Vars-Winchester Esker acts as a prominent grade control along Bear Brook. During the early Holocene, the paleo Ottawa River was able to entrain some of the sand and gravel deposits of the Vars-Winchester Esker (Cummings and Russell, 2007). Bear Brook, which has notably less flow than the Ottawa River, does not have sufficient energy to mobilize the sands and gravel core of the Vars-Winchester Esker (**Figure 9**). Accordingly, upstream of the esker, Bear Brook has been unable to incise into the Champlain Sea sediments and the bed of the channel is only slightly below its floodplain (i.e. the channel is unconfined). As per recent flood modelling, the lateral extent of the flood hazard can extend over 1 km into the adjacent floodplain upstream of the esker[3]. Downstream of the esker, Bear Brook has incised into the Champlain Sea sediments as it flows to its confluence with South Nation River (**Figure 4**). The channel incision has created a contemporary valley, which contains flood flows and appears prone to small landslides (**Figure 5**).

- **Channel Straightening –** Prior to 1945, anthropogenic channel straightening, presumably for agricultural purposes, notably reduced the overall channel length and locally steepened the watercourse (Section 4.2). The majority of straightening occurred along Reaches 2 through 4 (i.e. upstream of the esker), where the channel is well connected to its floodplain. Downstream of the esker, the channel flows within a contemporary valley, which contains less productive agricultural lands. The historical straightening has reduced floodplain storage, contributed to local bed erosion and downstream bank erosion, and reduced in-stream habitat complexity.

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[3] *https://www.youtube.com/watch?v=Ag2J7dpQsAc&ab_channel=SouthNationConservation*

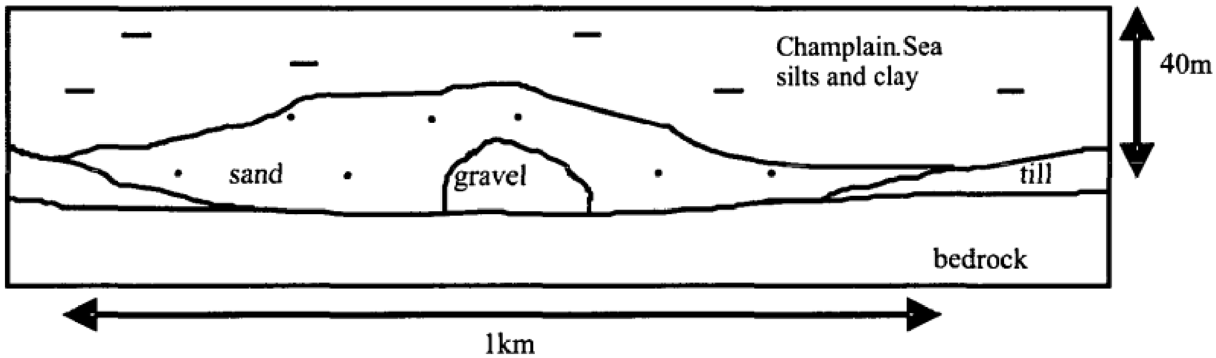

Figure 9. Cross-sectional view of Vars-Winchester Esker (Charland, 2009). Flow is from left to right. Bear Brook has incised through the Champlain Sea sediments to intercept the buried esker, but it does not have sufficient energy to readily entrain the sand and gravel core.

- **Landsliding** – Landslides varying in size and age are widely distributed within the Bear Brook watershed, especially east (downstream) of the Vars-Winchester Esker (**Figure 5**). The large retrogressive landslides generally occurred millennia ago along escarpments of the Ottawa River paleochannels, well back from any contemporary fluvial processes (Aylsworth et al., 2000). These landslides were likely triggered by seismic activity and have locally altered valley morphology and contributed to reach-scale rerouting of watercourses.

  Numerous smaller, younger landslides punctuate the banks and valley walls of Bear Brook and its tributaries. Along the main branch of Bear Brook, landslides have entered and at least temporarily altered the channel along Reach 1 and along Reaches 5 through 9. In Reach 1, the channel has incised through near-shore and deltaic deposits, potentially into underlying clay, to form a valley with relief locally greater than 10 m (OGS, 2007). More landslides are anticipated along this valley in the future if degradation continues and increases exposure of clay along the lower valley walls. Channel incision downstream of the esker (i.e. Reaches 5 though 9) has produced contemporary valley walls susceptible to landsliding, commonly at current or former contacts of migrating meanders. The channel is sufficiently narrow that even small landslides are capable of altering channel morphology. Flow deflection around landslide deposits commonly forces flows into the opposite bank, which in turn erodes and forms conspicuous hollows.

  Landslide deposits can also at least temporarily backwater sections of channel immediately upstream, due to localized narrowing and/or raising of the bed, such that deposition is promoted upstream and degradation may accelerate downstream. South Nation River was temporarily impounded by the Lemieux Landslide before its clay-rich landslide dam was gradually incised (Evans and Brooks, 1994). In some instances, the formation and sudden breach of a landslide dam can generate an outburst flood that travels downstream at rates that far exceed those estimated based on local hydrology (Jakob and Jordan, 2001; Jakob et al., 2016). Landsliding was also noted along tributaries where local relief approached or exceeded 8 m. The lack of channel incision in Reach 2 through 4 (i.e. insufficient relief upstream of the esker) has inhibited landsliding along those reaches.

The relatively small landslides that are so common along many reaches of Bear Brook were likely caused by one or more drivers of instability: 1) fluvial undercutting of banks and/or valley walls, which can increase shear stress to a point that it exceeds shear strength, a process that may be accelerated by upstream urbanization and climate change; 2) increases in pore water pressure due to intense or prolonged rainfall/snowmelt, anthropogenic alteration to drainage patterns, or crop irrigation; and/or 3) riparian vegetation clearing, which affects slope stability by exposing soils to erosion from surface runoff, reducing rates of evapotranspiration, and eliminating rooting strength contributions. Earthquakes may also be triggers of small landslides. Landsliding along Bear Brook and its major tributaries is likely to continue for millennia, until slopes reach a stable morphology.

- **Riparian Vegetation** – The natural riparian vegetation along Bear Brook has been altered over the past century. Along reaches flowing within a defined valley, riparian vegetation has been locally removed and vegetation on the tableland has been extensively cleared. Along Reaches 2 through 4, riparian vegetation has been extensively cleared. A lack of riparian vegetation and its associated root structures significantly reduce bank strength (Eaton, 2006) and contribute to bank slumping, which was observed throughout Reaches 2 though 4. Riparian vegetation also helps reduce soil moisture, which can contribute to bank failure, by increasing local rates of evapotranspiration. The lack of riparian vegetation also negatively impacts water quality, water temperature, and in-stream and riparian habitat.

- **Hydrology and Drainage** – The preliminary hydrology assessment suggests that peak flow magnitudes are decreasing along Bear Brook (Section 4.4), which may be contributing to the modest rates of meander migration. However, the natural drainage patterns and timing have been distributed by agricultural (e.g. tile drains) and urban development (e.g. stormwater management ponds). The perturbations to drainage patterns are locally increasing erosion and may be contributing to landsliding.

5.2 Geomorphology Monitoring Program

Establishing a geomorphology monitoring program along Bear Brook will further strengthen understanding of fluvial geomorphology processes now and in the future. It will also enable documentation of changes over time. Through previous discussions, SNC and Palmer agreed to establish four monitoring sites along Bear Brook. The sites should be distributed along the channel to provide the appropriate representation of conditions to support erosion risk assessment and evaluation of different stormwater management scenarios. Other considerations for choosing monitoring sites include reach or sub-reach sensitivity, site access/land ownership, proximity to existing hydrometeorology gauges, proximity to ongoing or future development, and distribution amongst different physiographic units. Four potential sites for geomorphology monitoring are highlighted and rationalized in **Table 10**. Other good candidate monitoring sites are available if any of the highlighted sites in **Table 10** are not feasible.

Table 10. Proposed geomorphology monitoring sites along Bear Brook

Reach	Approximate Chainage	Nearest Road	Rationale
1	1,100 m	Upstream of Piperville Road	• Having a monitoring site within a relatively stable reach will help discern future geomorphology changes and overall watershed health • The site will contribute to the understanding of impacts of development in the headwaters (e.g. Tewin Lands) on hydrogeomorphic processes • The proposed site is located on public lands • The site is located downstream of an existing SNC water quantity gauging site
3	15,800 m	Downstream of Frank Kenny Road	• The site is within the Ottawa River paleochannel upstream of Vars-Winchester Esker • The site will contribute to the understanding of impacts of development in the headwaters (e.g. McKinnons Creek) on hydrogeomorphic processes • The site is immediately downstream of numerous anthropogenic cut-offs, which are likely still impacting natural fluvial processes
6	32,800 m	Downstream of Indian Creek Road	• The site is within the Ottawa River paleochannel downstream of Vars-Winchester Esker • The site is located immediately downstream of an existing SNC water quantity gauging site • The impacts of nearby landsliding may be observed at this site
9	56,300 m	Downstream of Robillard Road	• The site may help capture perturbations throughout the watershed • The site is located downstream of the WSC gauge

At each of the monitoring sites, Palmer will help establish the monitoring program, which will include:

- Surveying representative cross-sections (five cross-sections minimum) as well as the longitudinal profile (both bed and bankfull). Each surveyed cross-section will be 'monumented' to allow for repeat measurements in the future.
- Characterizing bed and bank materials using acceptable methods (e.g. Wolman (1954) pebble counts) or laboratory grain size analyses. Each surveyed cross-section will be 'monumented' to allow for repeat measurements in the future.
- Establishing monumented photo locations and erosion pins for future monitoring. A newly available alternative to traditional erosion pins that SNC may want to consider for prioritized sites is Erosion*Alert* sensors that continuously track and alert managers to erosion in real-time via satellite uplink.
- Estimating erosion thresholds for each site using collected field data and appropriate empirical methods (e.g. Shields, 1936; Chow, 1959). The modelled erosion thresholds will be compared to observed field conditions, bankfull flow conditions, and available hydrologic data (WSC).

5.3 Watershed Management and Mitigative Strategies

Fluvial geomorphological processes along Bear Brook are driven by a combination of natural adjustments along meandering watercourses, anthropogenic realignments, and landsliding. A number of considerations or recommendations are provided below to help manage erosion-related risks, improve riparian and aquatic habitat, and increase resiliency of the Bear Brook watershed to future changes in flow and sediment regimes:

- **Avoidance or Minimization of New Channel Realignments** – Due to the extent of channel realignments that have already occurred along Bear Brook, especially along Reaches 2 though 4, any proposed future channel realignments that would result in loss of channel length should be highly scrutinized. If a channel realignment is unavoidable, total channel length should ideally be maintained and the principles of 'natural channel design' should be adopted. SNC could additionally seek opportunities to restore channel length and conditions along previously straightened sections of channel, where land use and property ownership allow, principally as a means of moderating erosion and improving riparian and aquatic ecology.
- **Re-establishment of Riparian Vegetation Buffers** – A lack of riparian vegetation along Bear Brook is contributing to erosion and negatively impacting water quality and ecological conditions. SNC should consider working in collaboration with municipalities and other agencies to establish minimum riparian buffers along both sides of Bear Brook. Such buffers would help restore natural stability of the watercourse and significantly improve local aquatic and terrestrial habitat. The buffers can be generic (e.g. 10 m from top of bank) or can be scaled based on channel size, drainage area, or local land use constraints. Uptake by landowners for re-establishment of riparian buffers may be challenging, but there have been successes through education and funding support in other jurisdictions in Canada.
- **Drainage and Stormwater Management** – Agricultural activity and urban development continue to alter the natural drainage patterns of tributaries of Bear Brook. Any proposed drainage changes should be carefully considered to ensure fluvial and/or slope hazards are not exacerbated. As well, the risk of landsliding, flooding, and erosion near any new infrastructure should be investigated. Based on review of aerial photographs and LiDAR-derived topographic data, historical changes to drainage patterns have exacerbated slope erosion, destabilized ravines and gullies, and contributed to landsliding (**Figure 10**). Furthermore, some recently constructed infrastructure, including stormwater management ponds, is positioned at the edge of tableland, near slopes that may be susceptible to landsliding.
- **Erosion Mitigation Approach** – Generic responses or actions should be avoided when managing natural or urban channel systems because of how readily one alteration can lead to unexpected consequences. Consideration should be given to the reach-scale context of the contemplated change, and the potential for unfavourable site-specific impacts downstream (or upstream), especially along valley systems where a channel interacts with its valley walls. Channel bed and/or bank stabilization measures should generally be as 'soft' as site-specific conditions and risks will allow. At least some degree of 'bioengineering' can usually be incorporated, such as strategic live stakes or plantings within stone, or in-stream habitat features constructed with stone. Approaches that rely entirely on log structures or live vegetation typically have shorter effective lifespans and are appropriate for protection of undeveloped portions of private property but are unlikely to satisfactorily mitigate long-term risks to infrastructure.

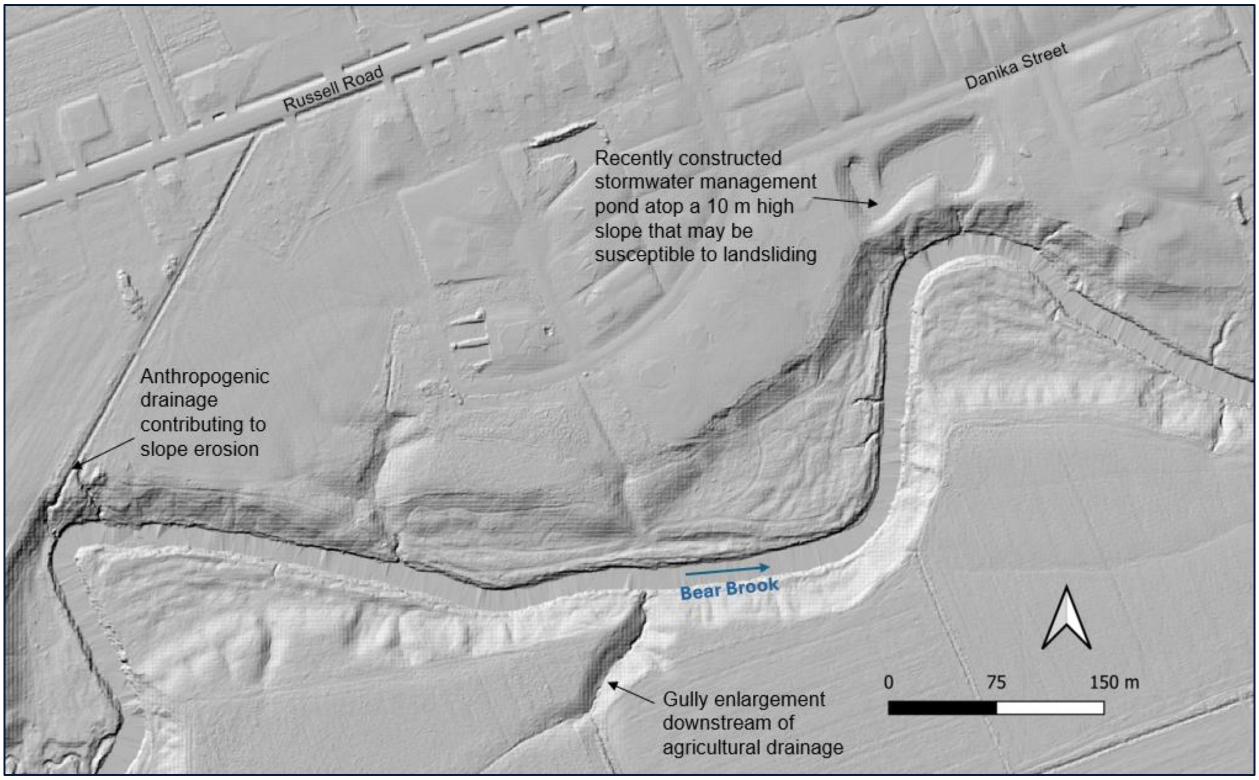

Figure 10. Anthropogenic drainage and a recently constructed stormwater management pond near Cheney

- **Detailed Landslide Hazard Assessment** – The preliminary inventory of landslides completed as part of this geomorphological assessment (**Figure 5**) draws attention to a variety of infrastructure and property that may be at risk from slope failures alongside Bear Brook and its tributaries. Additional assessment is required to better understand the triggers and extent of landslide hazards and associated risks along Bear Brook through the completion of more detailed mapping, investigation and evaluation of landslide boundaries and characteristics. The additional assessments should include documentation of the size, probable trigger and movement mechanisms, and potential impacts using recently collected LiDAR data and orthophotographs. Field-based confirmation of ground conditions should also be undertaken to provide certainty in assessment of activity states and triggers, and to examine surficial materials and indicators of displacement that cannot be reliably interpreted remotely. A landslide hazard assessment would help refine hazard delineation along prioritized sections of valley, support funding applications(e.g. Disaster Mitigation and Adaption Fund), and inform risk mitigation options.

6. Certification

This report was prepared and reviewed by the undersigned:

Prepared By:

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

Prepared, Reviewed, and Approved By:

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

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Appendix A

Photograph Log

Photograph Log

Client Name:	Project No.	Site Location:
South Nation Conservation	2302503	Bear Brook

Photo #:	Date.
1	11/15/2023
Direction Photo Taken	S

Description

Reach 1 – Looking upstream near Piperville Road. The channel has an irregular meandering planform and flows within a defined valley.

Photo #:	Date.
2	11/15/2023
Direction Photo Taken	S

Description

Reach 1 – Looking upstream at a debris jam near Piperville Road.

Client Name:	Project No.	Site Location:
South Nation Conservation	2302503	Bear Brook

Photo #:	Date.
3	11/15/2023
Direction Photo Taken	E

Description

Reach 2 – Looking downstream from Hall Road. The channel was anthropogenically straightened between 1945 and 1975.

Photo #:	Date.
4	11/15/2023
Direction Photo Taken	W

Description

Reach 2 – Looking upstream from Carlsbad Lane. Shrub and tree riparian vegetation has been removed.

Photo #:	Date.
5	11/15/2023
Direction Photo Taken	W

Description

Reach 3 – Looking upstream from Milton Road. The banks are locally slumping.

Photo #:	Date.
6	11/15/2023
Direction Photo Taken	S

Description

Reach 3 – Looking upstream from Frank Kenny Road. The channel is locally overwidened at the crossing (bottom-left corner).

Photograph Log

Client Name:	Project No.	Site Location:
South Nation Conservation	2302503	Bear Brook

Photo #:	Date.
7	11/15/2023
Direction Photo Taken	W

Description

Reach 4 – Looking upstream from McNeely Road. Trees are leaning inward and banks are slumping.

Photo #:	Date.
8	11/15/2023
Direction Photo Taken	E

Description

Reach 4 – Looking downstream from Dunning Road. The channel is flowing across the buried Vars-Winchester Esker.

Photograph Log

Client Name:	Project No.	Site Location:
South Nation Conservation	2302503	Bear Brook

Photo #:	Date.
9	11/15/2023
Direction Photo Taken	W

Description

Reach 5 – Looking upstream from Ruissellet Road. Relatively coarse lag deposits (gravel, cobble, boulders) likely sourced from the Vars-Winchester Esker, are present.

Photo #:	Date.
10	11/15/2023
Direction Photo Taken	S

Description

Reach 5 – Looking downstream from Russell Road. The channel has become partially confined downstream of the Vars-Winchester Esker.

Photograph Log

Client Name:	Project No.	Site Location:
South Nation Conservation	2302503	Bear Brook

Photo #: 11	Date. 11/15/2023
Direction Photo Taken	W

Description

Reach 6 – Looking upstream from Indian Creek Road. Anthropogenic rock has been placed on the banks.

Photo #: 12	Date. 11/15/2023
Direction Photo Taken	E

Description

Reach 6 – Looking downstream from Indian Creek Road. Leaning and fallen trees are present.

Client Name:	*Project No.*	*Site Location:*
South Nation Conservation	2302503	Bear Brook

Photo #:	*Date.*
13	11/15/2023
Direction Photo Taken	N

Description

Reach 7 – Rock weir beneath Drouin Road. Several similar rock weirs were observed at road crossings along Bear Brook.

Photo #:	*Date.*
14	11/15/2023
Direction Photo Taken	E

Description

Reach 7 – Looking downstream from Drouin Road. The channel is locally overwidened downstream of the undersized crossing and rock weir.

Client Name:	Project No.	Site Location:
South Nation Conservation	2302503	Bear Brook

Photo #:	Date.
15	11/15/2023
Direction Photo Taken	N

Description

Reach 8 – Looking upstream at Champlain Road. This is the location of the Water Survey of Canada Gauge (02LB008) for Bear Brook (not shown).

Photo #:	Date.
16	11/15/2023
Direction Photo Taken	E

Description

Reach 8 – Looking downstream from Ettyville Road. Bear Brook is entrenched such that it cannot readily access its floodplain during flood events.

Client Name:	Project No.	Site Location:
South Nation Conservation	2302503	Bear Brook

Photo #:	Date.
17	11/15/2023
Direction Photo Taken	E

Description

Reach 9 – Looking downstream from Ettyville Road. Both banks are relatively steep due to ongoing channel incision.

Photo #:	Date.
18	11/15/2023
Direction Photo Taken	W

Description

Reach 9 – Looking upstream from Robilliard Road. Bank slumping and leaning trees are observed.

Appendix B

Fluvial Geomorphology Map Book

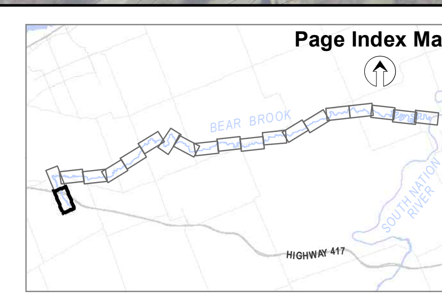
LEGEND

- Possible Landslide
- Probable Landslide
- River Chainage (m)[1]
- Channel Cutoffs
- Watercourse[2]
- Surface Elevation Contour (1m)
- Systematic Meander Migration ID[3]
- Reach Break
- Flow Direction

Channel Planform Year

- 2019
- 2008
- 1975
- 1945
- Pre-1945

1. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.
2. Ontario Hydro Network (LIO, 2024).
3. Migration rates and trajectories are provided in the main report and Appendix C.



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CLIENT
South Nation Conservation (SNC)

PROJECT
Bear Brook Geomorphology

TITLE
Bear Brook
Fluvial Geomorphology Mapping

Palmer PART OF SLR

REF. NO. 2302503-5-1

Appendix B-1

LEGEND

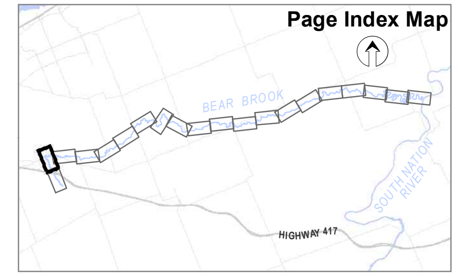
- Possible Landslide
- Probable Landslide
- River Chainage (m)[1]
- Channel Cutoffs
- Watercourse[2]
- Surface Elevation Contour (1m)
- Xx Systematic Meander Migration ID[3]
- Reach Break
- Flow Direction

Channel Planform Year

- 2019
- 2008
- 1975
- 1945
- Pre-1945

1. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.
2. Ontario Hydro Network (LIO, 2024).
3. Migration rates and trajectories are provided in the main report and Appendix C.

Page Index Map



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PROJECT
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TITLE
Bear Brook Fluvial Geomorphology Mapping

Palmer PART OF SLR

REF. NO. 2302503-5-1

Appendix B-2

LEGEND

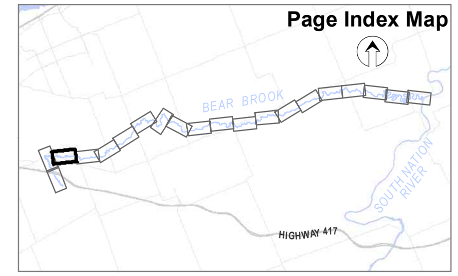
- Possible Landslide
- Probable Landslide
- River Chainage (m)[1]
- Channel Cutoffs
- Watercourse[2]
- Surface Elevation Contour (1m)
- Xx Systematic Meander Migration ID[3]
- Reach Break
- Flow Direction

1. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.
2. Ontario Hydro Network (LIO, 2024).
3. Migration rates and trajectories are provided in the main report and Appendix C.

Channel Planform Year

- 2019
- 2008
- 1975
- 1945
- Pre-1945

Page Index Map



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Fluvial Geomorphology Mapping

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REF. NO. 2302503-5-1

Appendix B-3

LEGEND

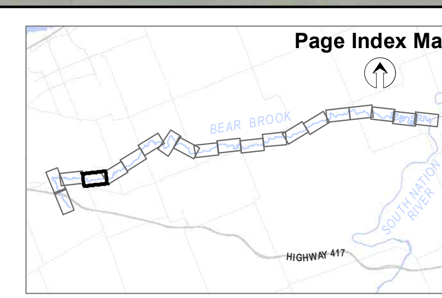
- Possible Landslide
- Probable Landslide
- River Chainage (m)[1]
- Channel Cutoffs
- Watercourse[2]
- Surface Elevation Contour (1m)
- Systematic Meander Migration ID[3]
- Reach Break
- Flow Direction

1. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.
2. Ontario Hydro Network (LIO, 2024).
3. Migration rates and trajectories are provided in the main report and Appendix C.

Channel Planform Year

- 2019
- 2008
- 1975
- 1945
- Pre-1945

Page Index Map



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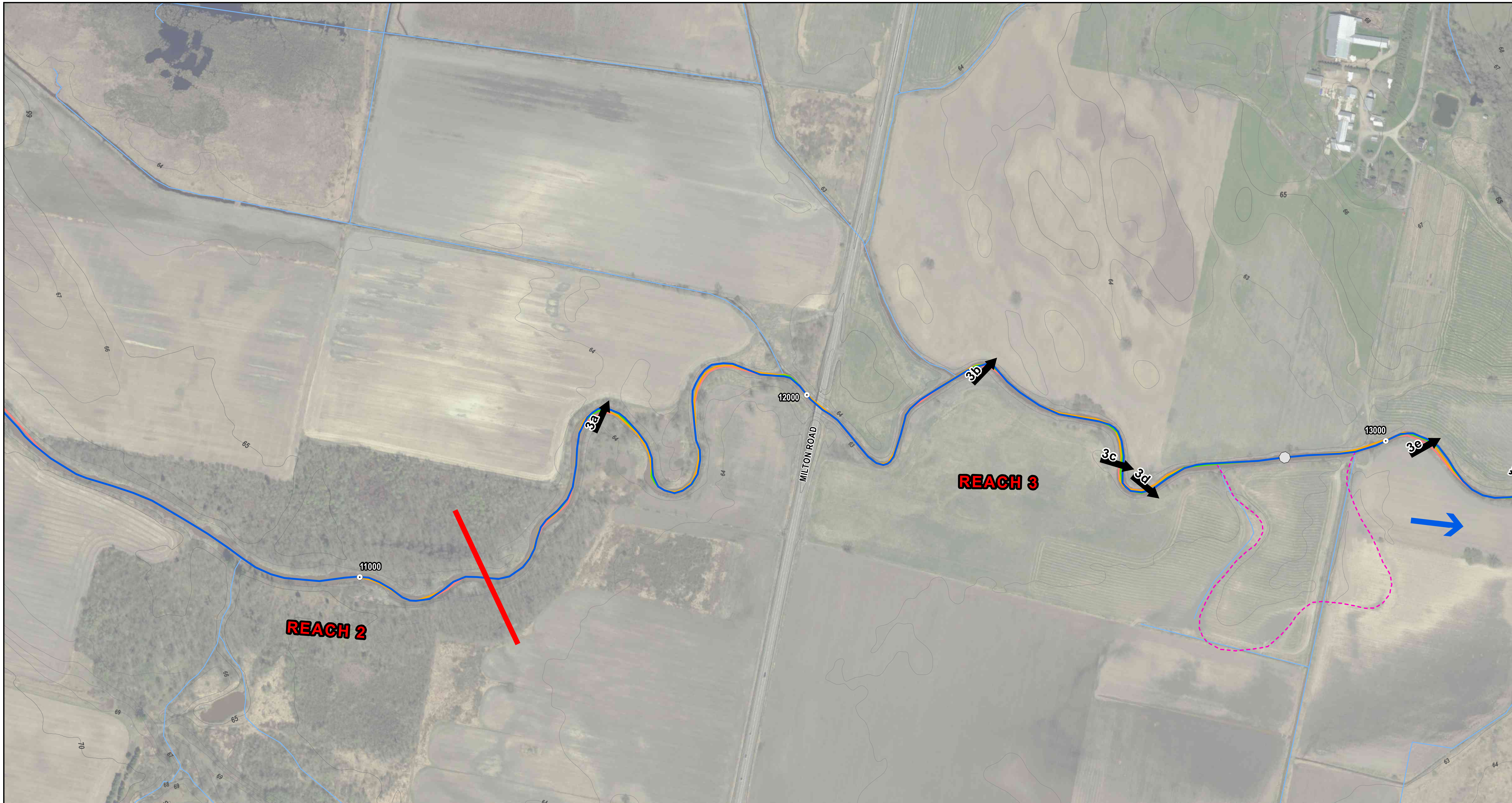
Appendix B-4



LEGEND

- Possible Landslide
- Probable Landslide
- River Chainage (m)[1]
- Channel Cutoffs
- Watercourse[2]
- Surface Elevation Contour (1m)
- Systematic Meander Migration ID[3]
- Reach Break
- Flow Direction

Channel Planform Year

- 2019
- 2008
- 1975
- 1945
- Pre-1945

1. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.
2. Ontario Hydro Network (LIO, 2024).
3. Migration rates and trajectories are provided in the main report and Appendix C.

Page Index Map

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Fluvial Geomorphology Mapping

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REF. NO. 2302503-5-1

Appendix B-5

LEGEND

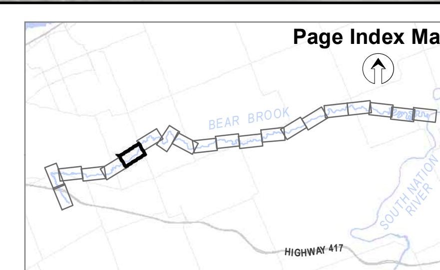
- Possible Landslide
- Probable Landslide
- River Chainage (m)[1]
- Channel Cutoffs
- Watercourse[2]
- Surface Elevation Contour (1m)
- Systematic Meander Migration ID[3]
- Reach Break
- Flow Direction

Channel Planform Year

- 2019
- 2008
- 1975
- 1945
- Pre-1945

1. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.
2. Ontario Hydro Network (LIO, 2024).
3. Migration rates and trajectories are provided in the main report and Appendix C.

Page Index Map



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Fluvial Geomorphology Mapping

Palmer. PART OF SLR

REF. NO. 2302503-5-1

Appendix B-6

LEGEND

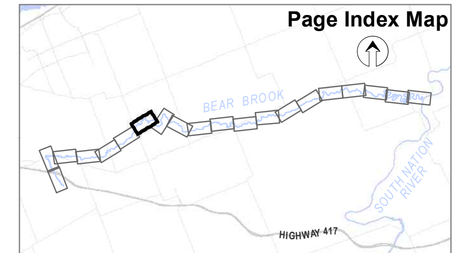
- Possible Landslide
- Probable Landslide
- River Chainage (m)[1]
- Channel Cutoffs
- Watercourse[2]
- Surface Elevation Contour (1m)
- Systematic Meander Migration ID[3]
- Reach Break
- Flow Direction

Channel Planform Year

- 2019
- 2008
- 1975
- 1945
- Pre-1945

1. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.
2. Ontario Hydro Network (LIO, 2024).
3. Migration rates and trajectories are provided in the main report and Appendix C.

Page Index Map



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Universal Transverse Mercator Projection Zone 18

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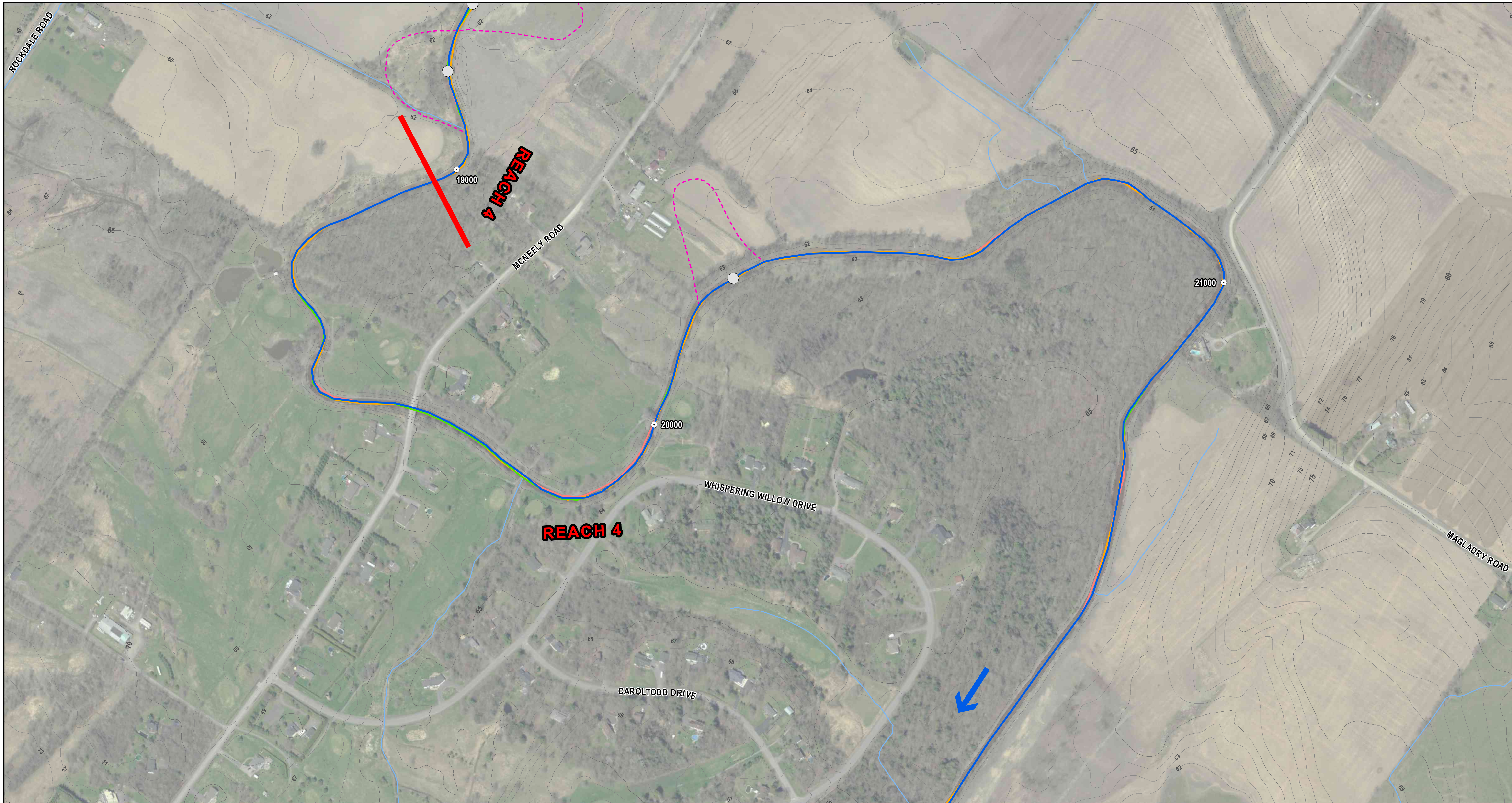
REF. NO. 2302503-5-1

Appendix B-7



LEGEND

- Possible Landslide
- Probable Landslide
- River Chainage (m)[1]
- Channel Cutoffs
- Watercourse[2]
- Surface Elevation Contour (1m)
- Xx Systematic Meander Migration ID[3]
- Reach Break
- Flow Direction

Channel Planform Year

- 2019
- 2008
- 1975
- 1945
- Pre-1945

1. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.
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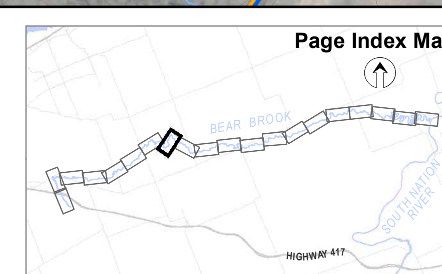
3. Migration rates and trajectories are provided in the main report and Appendix C.

Page Index Map



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North American Datum 1983
Universal Transverse Mercator Projection Zone 18

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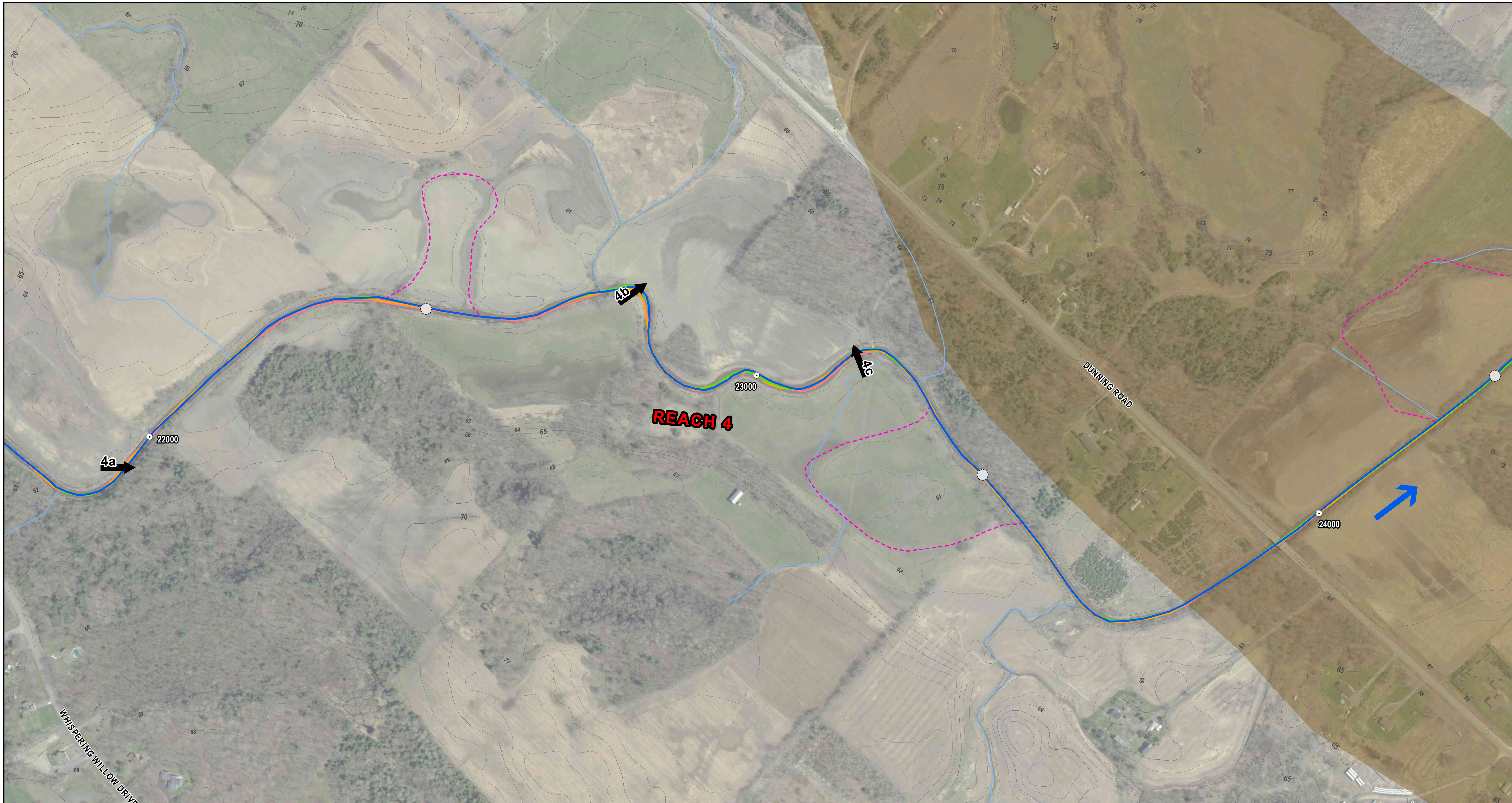
PROJECT
Bear Brook Geomorphology

TITLE
Bear Brook
Fluvial Geomorphology Mapping

Palmer. PART OF SLR

REF. NO. 2302503-5-1

Appendix B-8



LEGEND

- Possible Landslide
- Probable Landslide
- River Chainage (m)[1]
- Channel Cutoffs
- Watercourse[2]
- Surface Elevation Contour (1m)
- Systematic Meander Migration ID[3]
- Reach Break
- Flow Direction

Channel Planform Year

- 2019
- 2008
- 1975
- 1945
- Pre-1945

- Esker (approximate)[4]

1. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.
2. Ontario Hydro Network (LIO, 2024).
3. Migration rates and trajectories are provided in the main report and Appendix C.
4. The approximate extent of the Vars-Winshester Esker in the vicinity of Bear Brook is shown on the map. The eskter extends further north and south than shown.

Page Index Map

0 40 80 120 160 200 m

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TITLE: **Bear Brook Fluvial Geomorphology Mapping**

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Appendix B-9

LEGEND

- Possible Landslide
- Probable Landslide
- River Chainage (m)[1]
- Channel Cutoffs
- Watercourse[2]
- Surface Elevation Contour (1m)
- Systematic Meander Migration ID[3]
- Reach Break
- Flow Direction

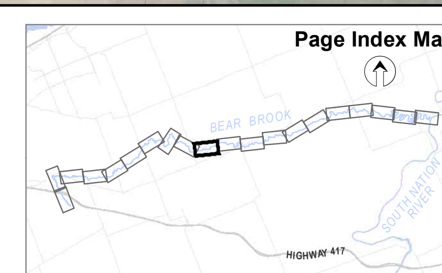
Channel Planform Year

- 2019
- 2008
- 1975
- 1945
- Pre-1945

Esker (approximate)[4]

1. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.
2. Ontario Hydro Network (LIO, 2024).
3. Migration rates and trajectories are provided in the main report and Appendix C.
4. The approximate extent of the Vars-Winshester Esker in the vicinity of Bear Brook is shown on the map. The eskter extends further north and south than shown.

Page Index Map



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North American Datum 1983
Universal Transverse Mercator Projection Zone 18

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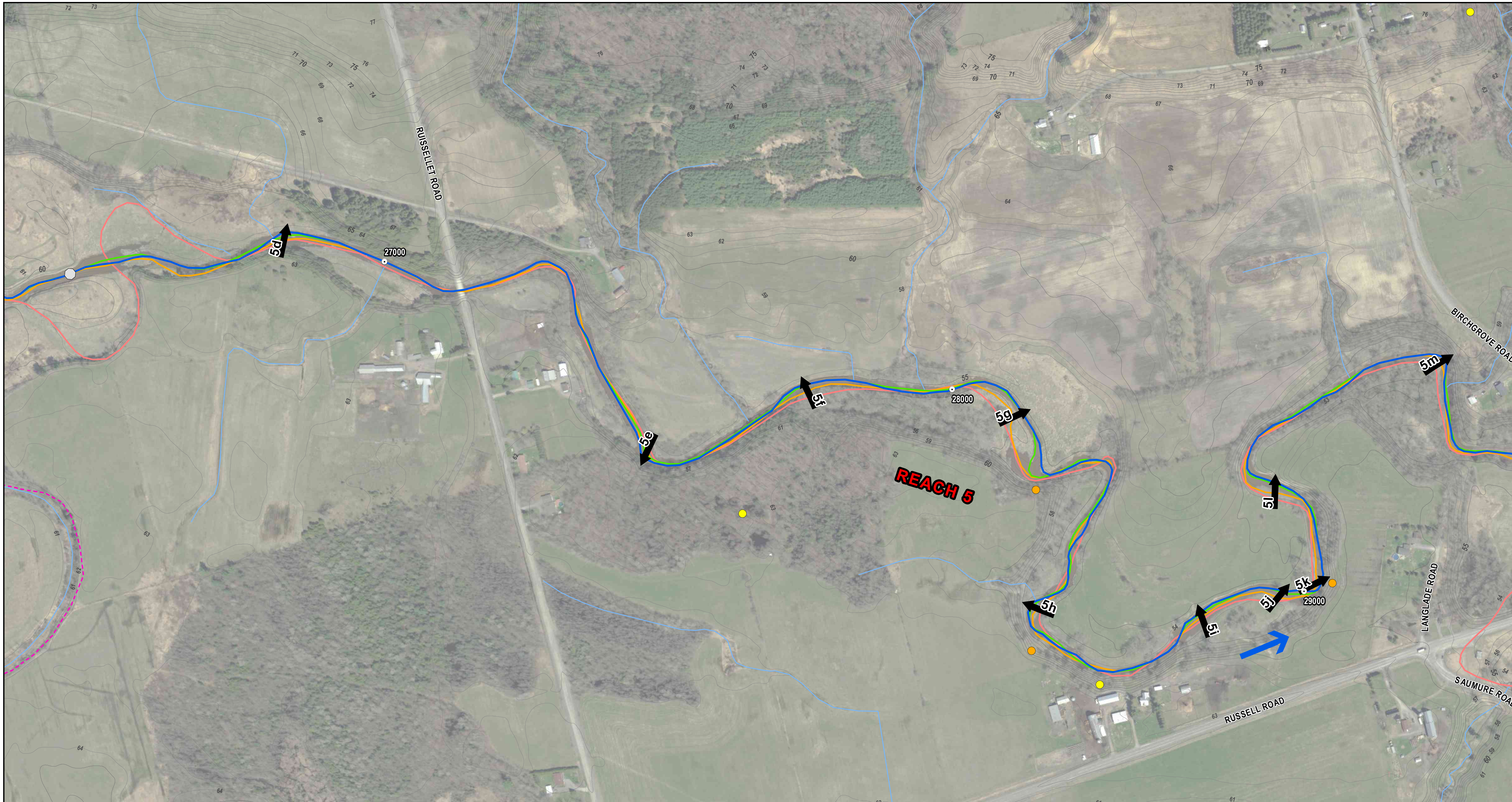
Appendix B-10



LEGEND

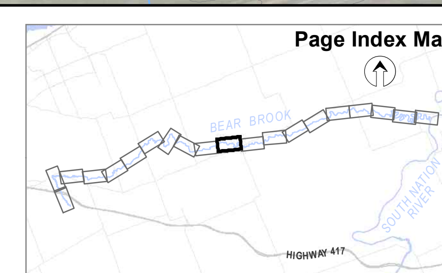
- Possible Landslide
- Probable Landslide
- River Chainage (m)[1]
- Channel Cutoffs
- Watercourse[2]
- Surface Elevation Contour (1m)
- Systematic Meander Migration ID[3]
- Reach Break
- Flow Direction

Channel Planform Year

- 2019
- 2008
- 1975
- 1945
- Pre-1945

1. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.
2. Ontario Hydro Network (LIO, 2024).
3. Migration rates and trajectories are provided in the main report and Appendix C.

Page Index Map



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Appendix B-11

LEGEND

- Possible Landslide
- Probable Landslide
- River Chainage (m)[1]
- Channel Cutoffs
- Watercourse[2]
- Surface Elevation Contour (1m)
- Systematic Meander Migration ID[3]
- Reach Break
- Flow Direction

Channel Planform Year
- 2019
- 2008
- 1975
- 1945
- Pre-1945

- Large retrogressive landslide (approximate)

1. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.
2. Ontario Hydro Network (LIO, 2024).
3. Migration rates and trajectories are provided in the main report and Appendix C.

Page Index Map

0 40 80 120 160 200 m

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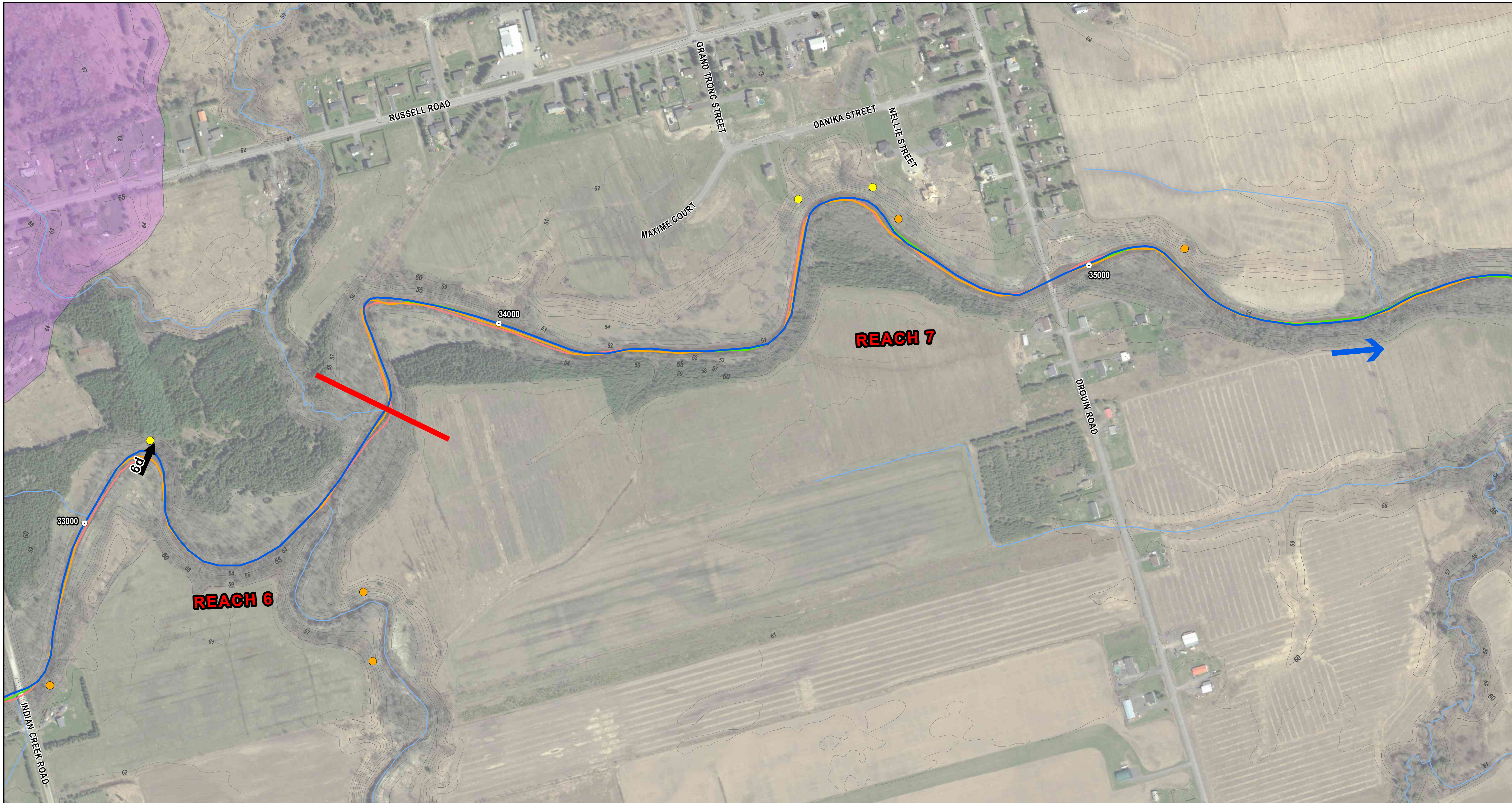
Appendix B-12



LEGEND

- Possible Landslide
- Probable Landslide
- River Chainage (m)[1]
- Channel Cutoffs
- Watercourse[2]
- Surface Elevation Contour (1m)
- Systematic Meander Migration ID[3]
- Reach Break
- Flow Direction

Channel Planform Year
- 2019
- 2008
- 1975
- 1945
- Pre-1945

Large retrogressive landslide (approximate)

1. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.
2. Ontario Hydro Network (LIO, 2024).
3. Migration rates and trajectories are provided in the main report and Appendix C.

Page Index Map

North American Datum 1983
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Appendix B-13

LEGEND

- Possible Landslide
- Probable Landslide
- River Chainage (m)[1]
- Channel Cutoffs
- Watercourse[2]
- Surface Elevation Contour (1m)
- Systematic Meander Migration ID[3]
- Reach Break
- Flow Direction

Channel Planform Year

- 2019
- 2008
- 1975
- 1945
- Pre-1945

1. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.
2. Ontario Hydro Network (LIO, 2024).
3. Migration rates and trajectories are provided in the main report and Appendix C.

Page Index Map

0 40 80 120 160 200
m

North American Datum 1983
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Appendix B-14

LEGEND

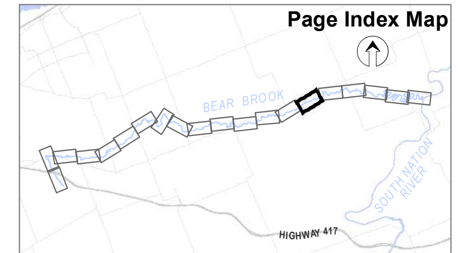
- Possible Landslide
- Probable Landslide
- River Chainage (m)[1]
- Channel Cutoffs
- Watercourse[2]
- Surface Elevation Contour (1m)
- Systematic Meander Migration ID[3]
- Reach Break
- Flow Direction

Channel Planform Year

- 2019
- 2008
- 1975
- 1945
- Pre-1945

1. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.
2. Ontario Hydro Network (LIO, 2024).
3. Migration rates and trajectories are provided in the main report and Appendix C.

Page Index Map



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Appendix B-15

LEGEND

- Possible Landslide
- Probable Landslide
- River Chainage (m)[1]
- Channel Cutoffs
- Watercourse[2]
- Surface Elevation Contour (1m)
- Systematic Meander Migration ID[3]
- Reach Break
- Flow Direction

Channel Planform Year

- 2019
- 2008
- 1975
- 1945
- Pre-1945

1. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.
2. Ontario Hydro Network (LIO, 2024).
3. Migration rates and trajectories are provided in the main report and Appendix C.

Page Index Map

0 40 80 120 160 200 m

North American Datum 1983
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TITLE	**Bear Brook Fluvial Geomorphology Mapping**
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LEGEND

- Possible Landslide
- Probable Landslide
- River Chainage (m)[1]
- Channel Cutoffs
- Watercourse[2]
- Surface Elevation Contour (1m)
- Systematic Meander Migration ID[3]
- Reach Break
- Flow Direction

Channel Planform Year

- 2019
- 2008
- 1975
- 1945
- Pre-1945

1. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.
2. Ontario Hydro Network (LIO, 2024).
3. Migration rates and trajectories are provided in the main report and Appendix C.

Page Index Map

0 40 80 120 160 200
m

North American Datum 1983
Universal Transverse Mercator Projection Zone 18

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Appendix B-17

LEGEND

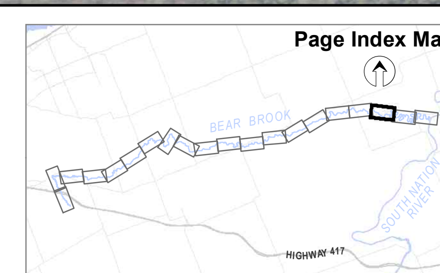
- Possible Landslide
- Probable Landslide
- River Chainage (m)[1]
- Channel Cutoffs
- Watercourse[2]
- Surface Elevation Contour (1m)
- Xx Systematic Meander Migration ID[3]
- Reach Break
- Flow Direction

Channel Planform Year

- 2019
- 2008
- 1975
- 1945
- Pre-1945

1. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.
2. Ontario Hydro Network (LIO, 2024).
3. Migration rates and trajectories are provided in the main report and Appendix C.

Page Index Map



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Appendix B-18

LEGEND

- Possible Landslide
- Probable Landslide
- River Chainage (m)[1]
- Channel Cutoffs
- Watercourse[2]
- Surface Elevation Contour (1m)
- Systematic Meander Migration ID[3]
- Reach Break
- Flow Direction

Channel Planform Year

- 2019
- 2008
- 1975
- 1945
- Pre-1945

1. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.
2. Ontario Hydro Network (LIO, 2024).
3. Migration rates and trajectories are provided in the main report and Appendix C.

Page Index Map

BEAR BROOK
SOUTH NATION RIVER
HIGHWAY 417

0 40 80 120 160 200 m

North American Datum 1983
Universal Transverse Mercator Projection Zone 18

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Appendix B-19

LEGEND

- Possible Landslide
- Probable Landslide
- River Chainage (m)[1]
- Channel Cutoffs
- Watercourse[2]
- Surface Elevation Contour (1m)
- Systematic Meander Migration ID[3]
- Reach Break
- Flow Direction

Channel Planform Year

- 2019
- 2008
- 1975
- 1945
- Pre-1945

1. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.
2. Ontario Hydro Network (LIO, 2024).
3. Migration rates and trajectories are provided in the main report and Appendix C.

Page Index Map

0 40 80 120 160 200
m

North American Datum 1983
Universal Transverse Mercator Projection Zone 18

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Appendix B-20

Appendix C

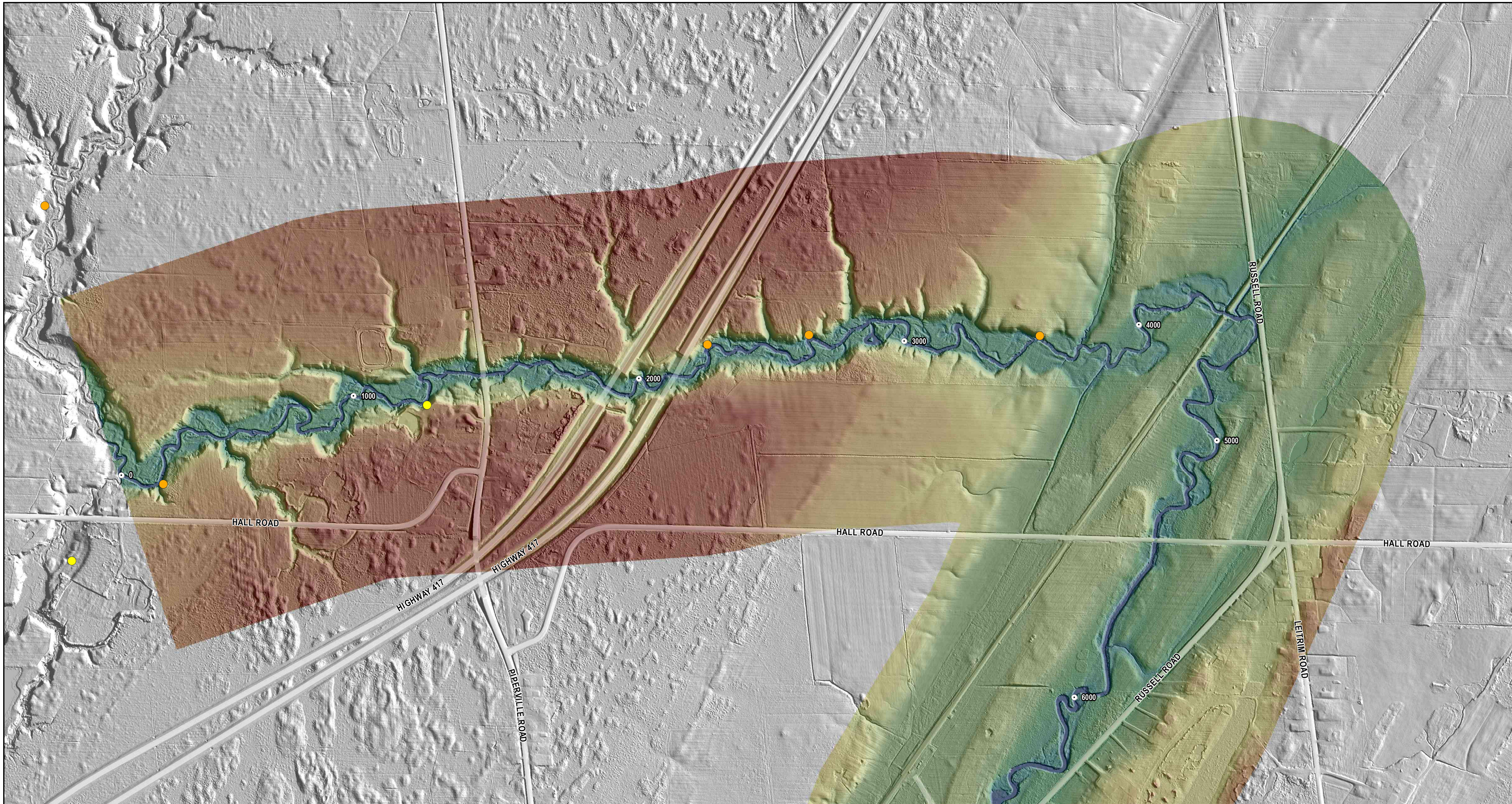
Migration Rates and Trajectories

Table 1. Migration rates for individual meanders of Bear Brook exhibiting systematic migration between 1945 and 2019. The location of each meander is identified in Appendix B.

Meander ID	Migration Rate (m/yr)	Trajectory
1a	0.2	N
1b	0.1	N
1c	0.1	N
1d	0.1	N
1e	0.1	N
1f	0.1	N
1g	0.1	N
2a	0.1	E
3a	0.1	N
3b	0.1	N
3c	0.1	E
3d	0.1	E
3e	0.1	NE
3f	0.1	E
3g	0.1	E
3h	0.1	N
3i	0.1	NE
3j	0.1	N
4a	0.1	SE
4b	0.1	E
4c	0.1	N
5a	0.1	N
5b	0.1	NW
5c	0.1	N
5d	0.2	N
5e	0.2	S
5f	0.3	NW
5g	0.4	NE
5h	0.2	W
5i	0.1	N
5j	0.3	NE
5k	0.2	NE
5l	0.3	N
5m	0.3	NE
5n	0.3	E
6a	0.1	N
6b	0.1	N
6c	0.2	N
6d	0.1	N
7a	0.1	NE
8a	0.1	SE
8b	0.1	E
8c	0.1	S
9a	0.1	S
9b	0.1	E
9c	0.2	NE
9d	0.2	E
9e	0.1	E

Appendix D

Relative Elevation Model



LEGEND

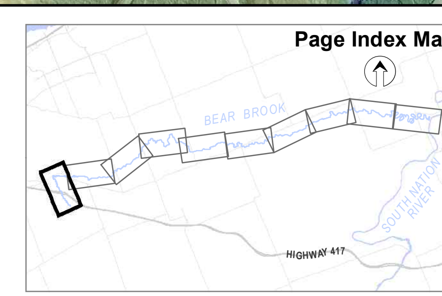
Relative Elevation[1,2] Above Bear Brook

12+ m
8 m
4 m
0 m

Possible Landslide
Probable Landslide
River Chainage (m)[3]

1. Relative Elevation Model (REM) created using 1 m resolution 2019-20 Lidar-derived Digital Terrain Model.
2. Bear Brook is 0 m relative elevation.
3. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model platform.

Page Index Map



0 50 100 150 200 250
m

North American Datum 1983
Universal Transverse Mercator Projection Zone 18

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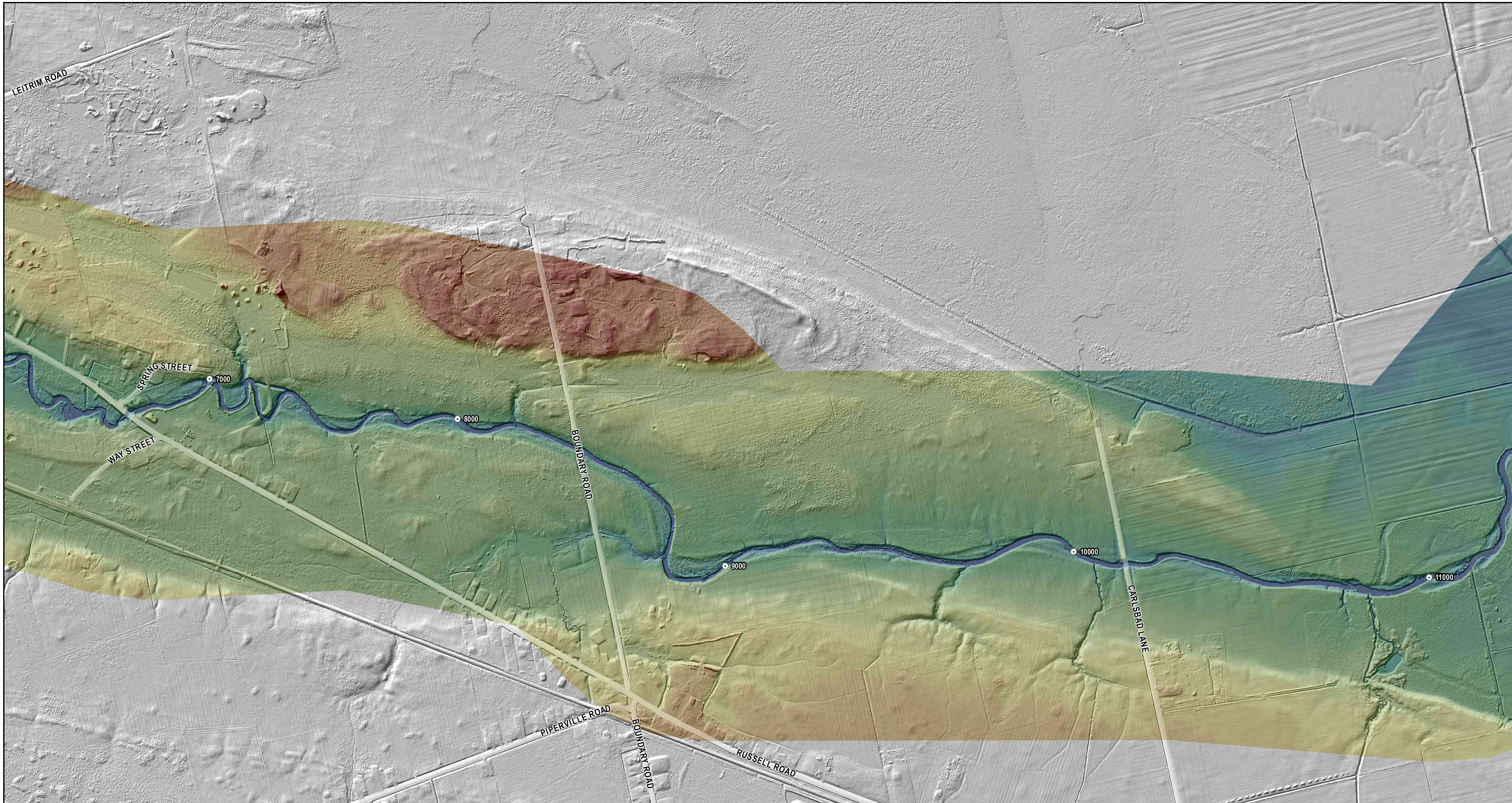
Bear Brook Geomorphology

TITLE
Bear Brook Relative Elevation Model

Palmer PART OF SLR

REF. NO. 2302503-D-1

Appendix D-1



LEGEND

Relative Elevation[1,2] Above Bear Brook

12+ m
8 m
4 m
0 m

Possible Landslide

Probable Landslide

River Chainage (m)[3]

1. Relative Elevation Model (REM) created using 1 m resolution 2019-20 Lidar-derived Digital Terrain Model.
2. Bear Brook is 0 m relative elevation.
3. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.

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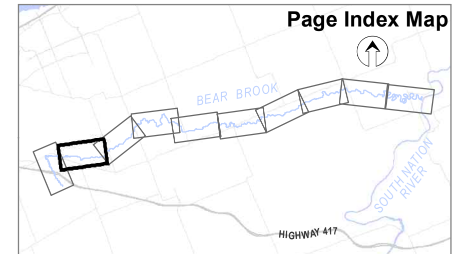

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m

North American Datum 1983
Universal Transverse Mercator Projection Zone 18

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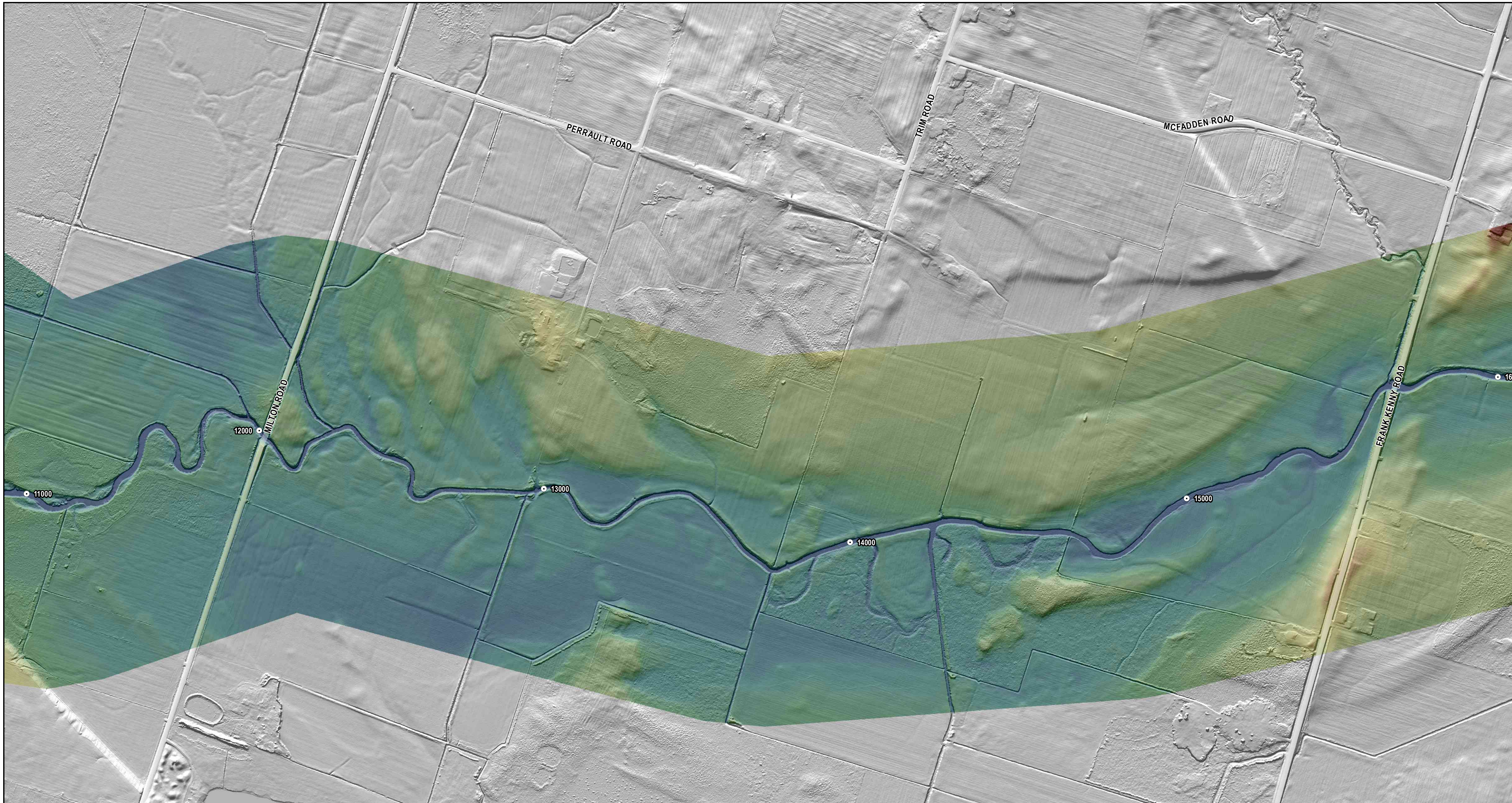
Appendix D-2



LEGEND

Relative Elevation[1,2] Above Bear Brook

12+ m
8 m
4 m
0 m

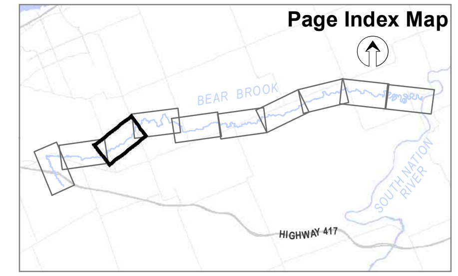
Possible Landslide

Probable Landslide

River Chainage (m)[3]

1. Relative Elevation Model (REM) created using 1 m resolution 2019-20 Lidar-derived Digital Terrain Model.
2. Bear Brook is 0 m relative elevation.
3. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.

Page Index Map



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m

North American Datum 1983
Universal Transverse Mercator Projection Zone 18

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REF. NO. 2302503-D-1

Appendix D-3

LEGEND

Relative Elevation[1,2] Above Bear Brook

12+ m
8 m
4 m
0 m

Possible Landslide

Probable Landslide

River Chainage (m)[3]

1. Relative Elevation Model (REM) created using 1 m resolution 2019-20 Lidar-derived Digital Terrain Model.
2. Bear Brook is 0 m relative elevation.
3. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.

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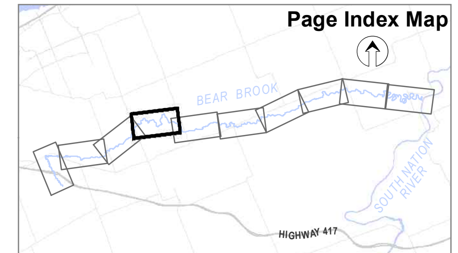

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m

North American Datum 1983
Universal Transverse Mercator Projection Zone 18

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Bear Brook Relative Elevation Model

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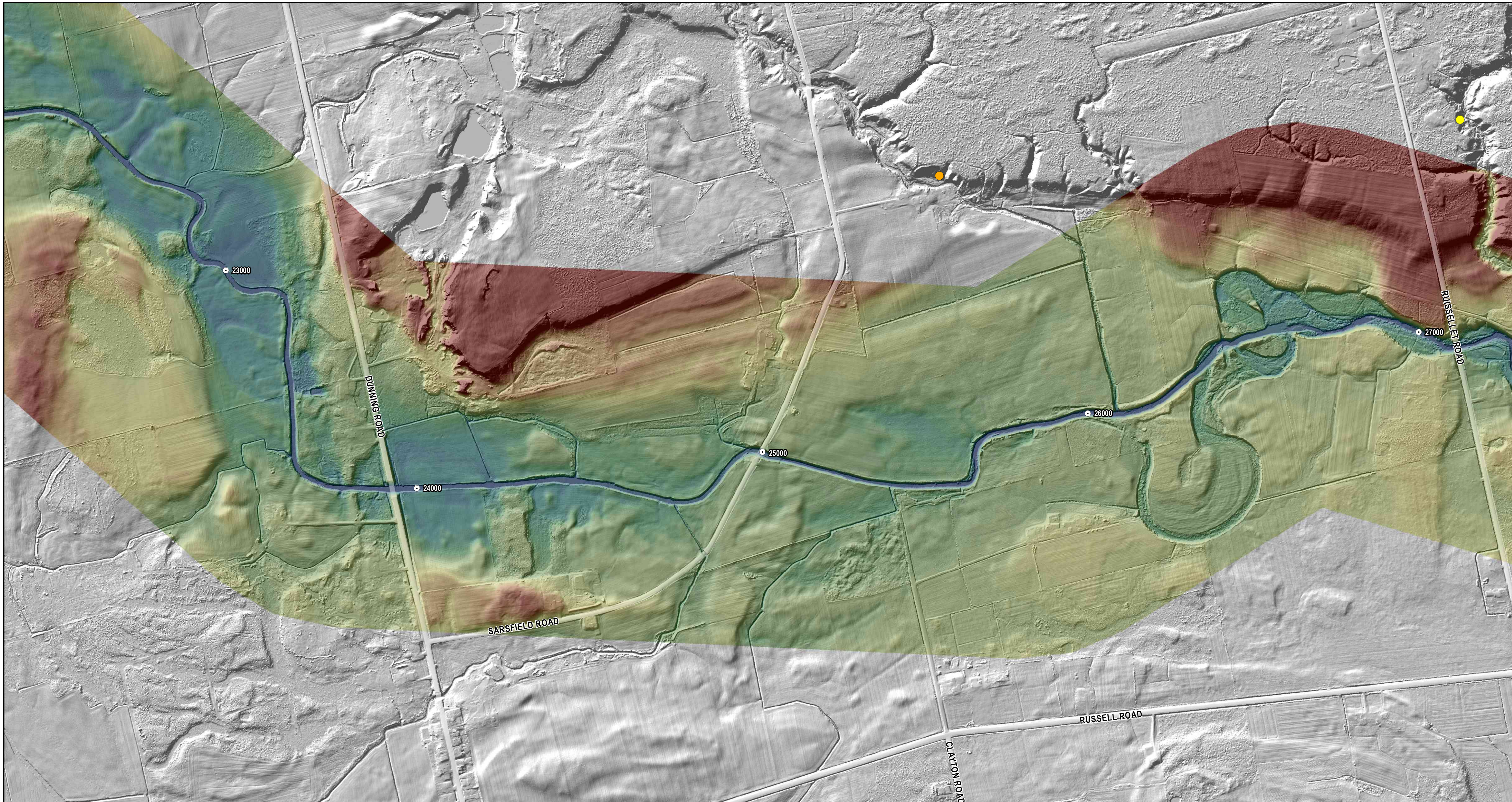
REF. NO. 2302503-D-1

Appendix D-4



LEGEND

Relative Elevation[1,2] Above Bear Brook

12+ m
8 m
4 m
0 m

- Possible Landslide
- Probable Landslide
- River Chainage (m)[3]

1. Relative Elevation Model (REM) created using 1 m resolution 2019-20 Lidar-derived Digital Terrain Model.
2. Bear Brook is 0 m relative elevation.
3. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.

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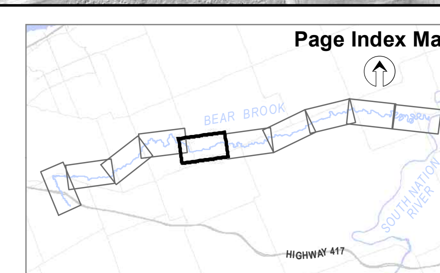

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m

North American Datum 1983
Universal Transverse Mercator Projection Zone 18

Scale: 1:10,000
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CLIENT
South Nation Conservation (SNC)

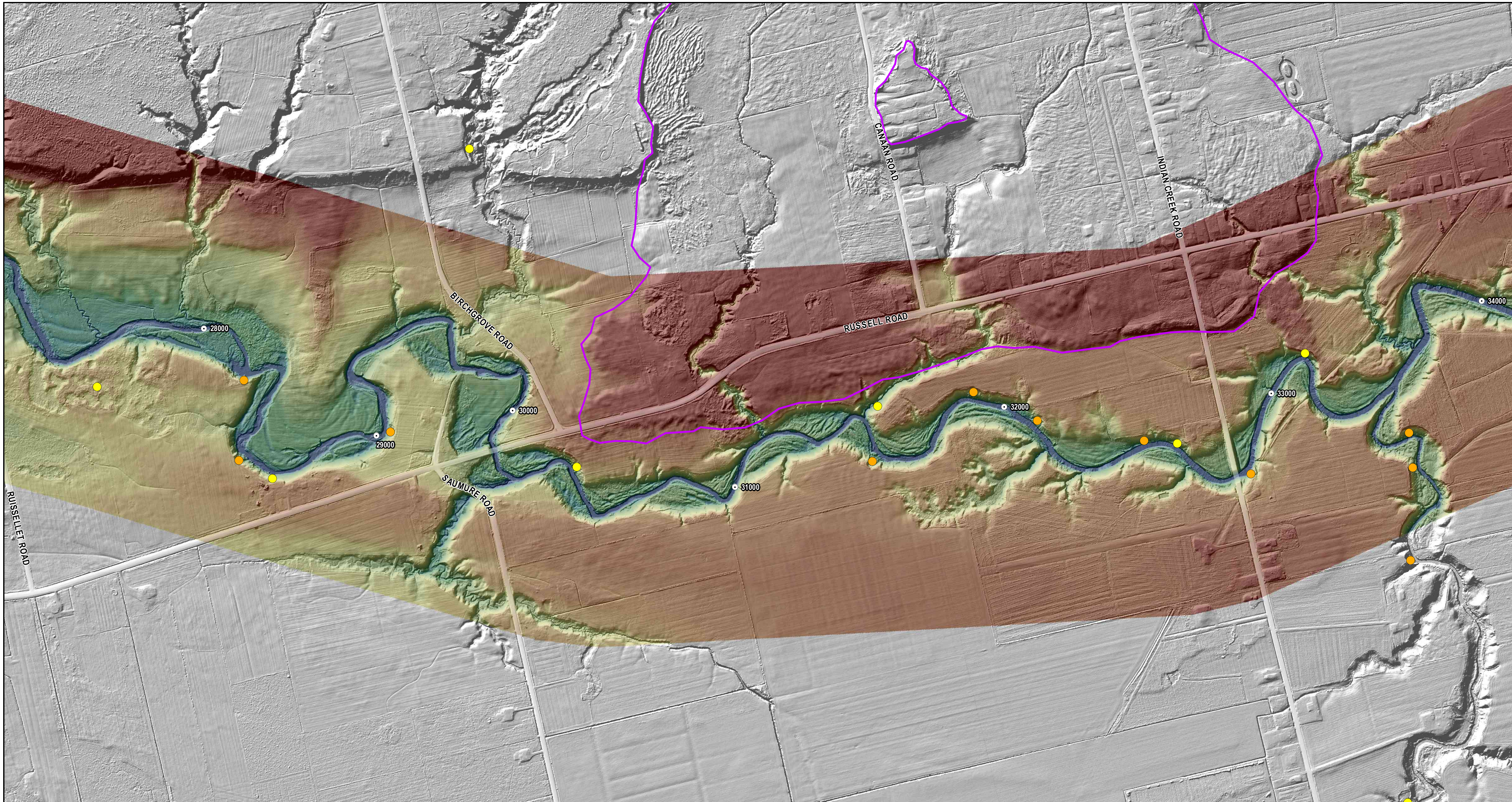
PROJECT
Bear Brook Geomorphology

TITLE
Bear Brook Relative Elevation Model

Palmer | PART OF SLR

REF. NO. 2302503-D-1

Appendix D-5



LEGEND

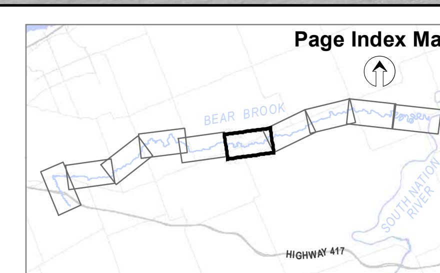
Relative Elevation[1,2] Above Bear Brook

12+ m
8 m
4 m
0 m

Large retrogressive landslide (approximate)
Possible Landslide
Probable Landslide
River Chainage (m)[3]

1. Relative Elevation Model (REM) created using 1 m resolution 2019-20 Lidar-derived Digital Terrain Model.
2. Bear Brook is 0 m relative elevation.
3. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.

Page Index Map



0 50 100 150 200 250
m

North American Datum 1983
Universal Transverse Mercator Projection Zone 18

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South Nation Conservation (SNC)

PROJECT
Bear Brook Geomorphology

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Bear Brook Relative Elevation Model

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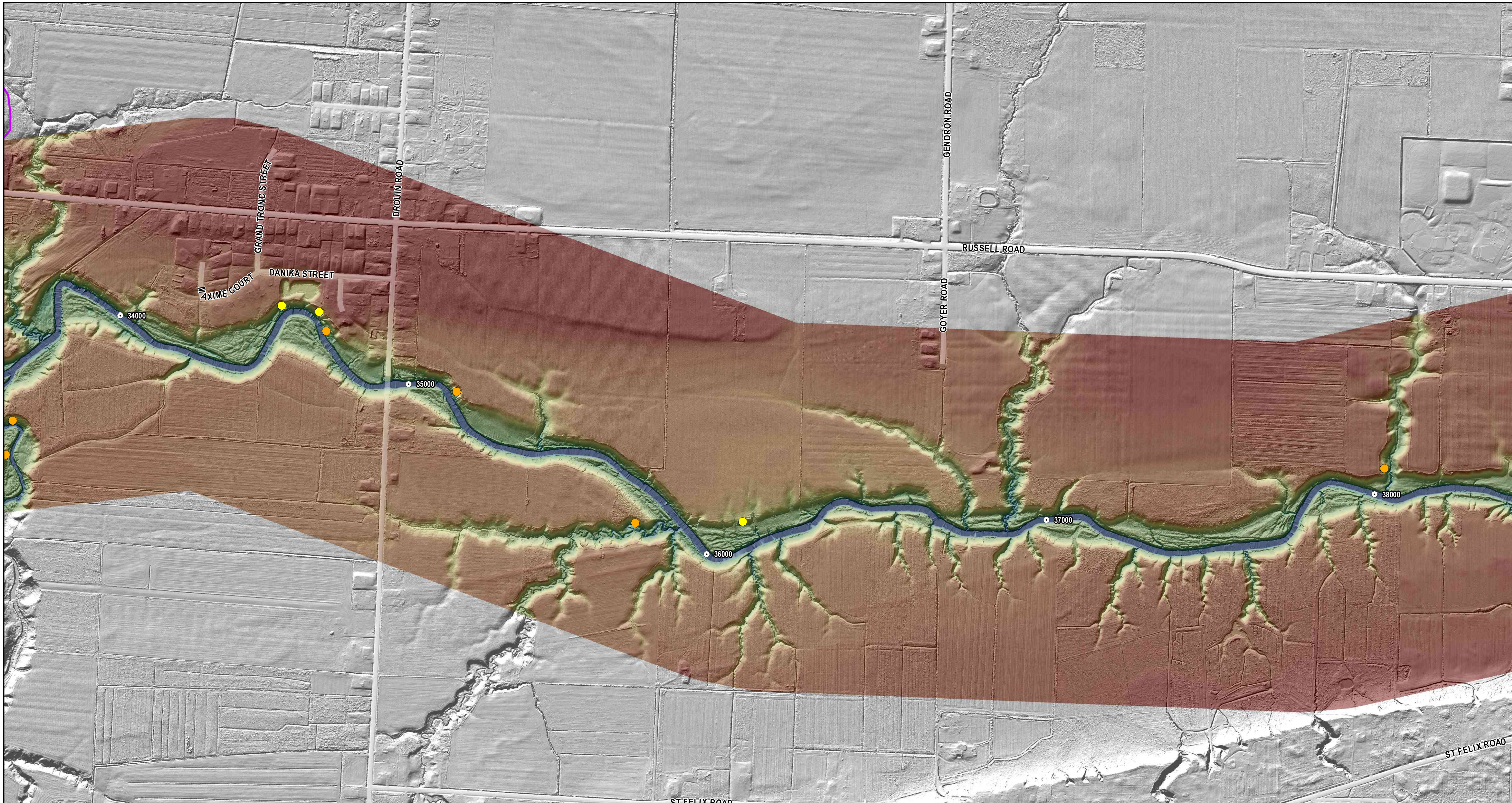
REF. NO. 2302503-D-1

Appendix D-6



LEGEND

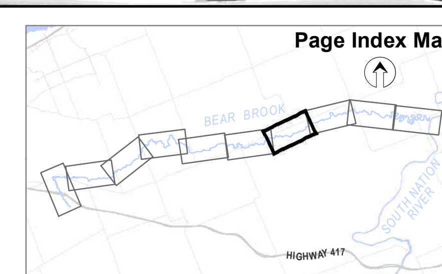
Relative Elevation[1,2] Above Bear Brook

12+ m
8 m
4 m
0 m

Large retrogressive landslide (approximate)
Possible Landslide
Probable Landslide
River Chainage (m)[3]

1. Relative Elevation Model (REM) created using 1 m resolution 2019-20 Lidar-derived Digital Terrain Model.
2. Bear Brook is 0 m relative elevation.
3. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.

Page Index Map



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m

North American Datum 1983
Universal Transverse Mercator Projection Zone 18

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South Nation Conservation (SNC)

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Bear Brook Geomorphology

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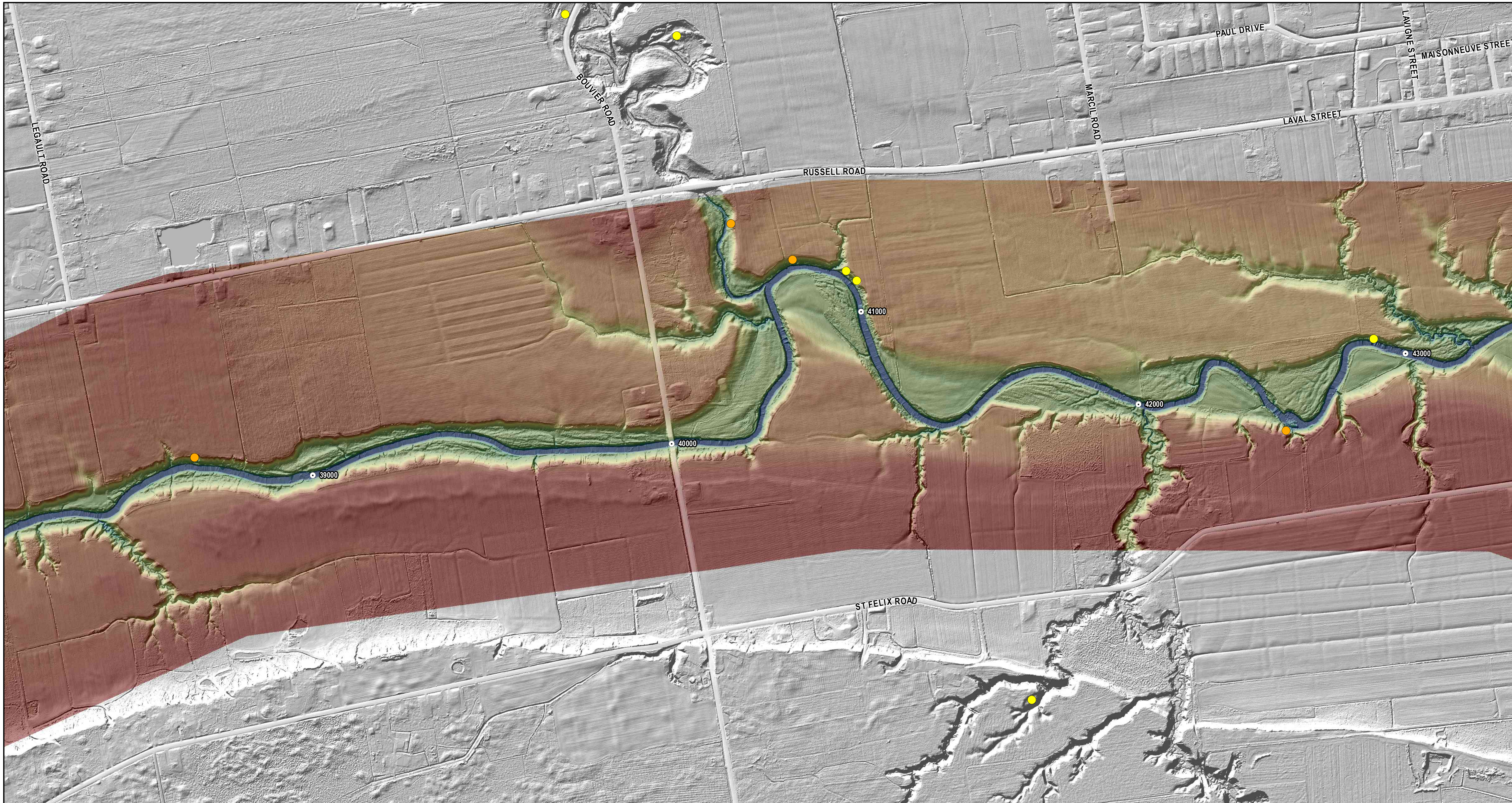
Appendix D-7



LEGEND

Relative Elevation[1,2] Above Bear Brook

12+ m
8 m
4 m
0 m

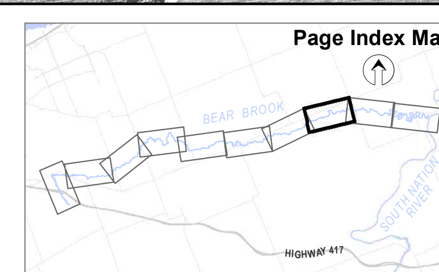
Possible Landslide

Probable Landslide

River Chainage (m)[3]

1. Relative Elevation Model (REM) created using 1 m resolution 2019-20 Lidar-derived Digital Terrain Model.
2. Bear Brook is 0 m relative elevation.
3. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.

Page Index Map



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m

North American Datum 1983
Universal Transverse Mercator Projection Zone 18

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Appendix D-8

LEGEND

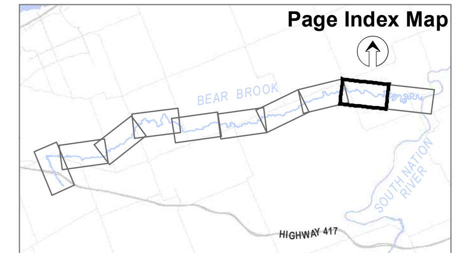
Relative Elevation[1,2] Above Bear Brook

12+ m
8 m
4 m
0 m

Possible Landslide
Probable Landslide
River Chainage (m)[3]

1. Relative Elevation Model (REM) created using 1 m resolution 2019-20 Lidar-derived Digital Terrain Model.
2. Bear Brook is 0 m relative elevation.
3. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.

Page Index Map



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m

North American Datum 1983
Universal Transverse Mercator Projection Zone 18

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Bear Brook Geomorphology

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Bear Brook Relative Elevation Model

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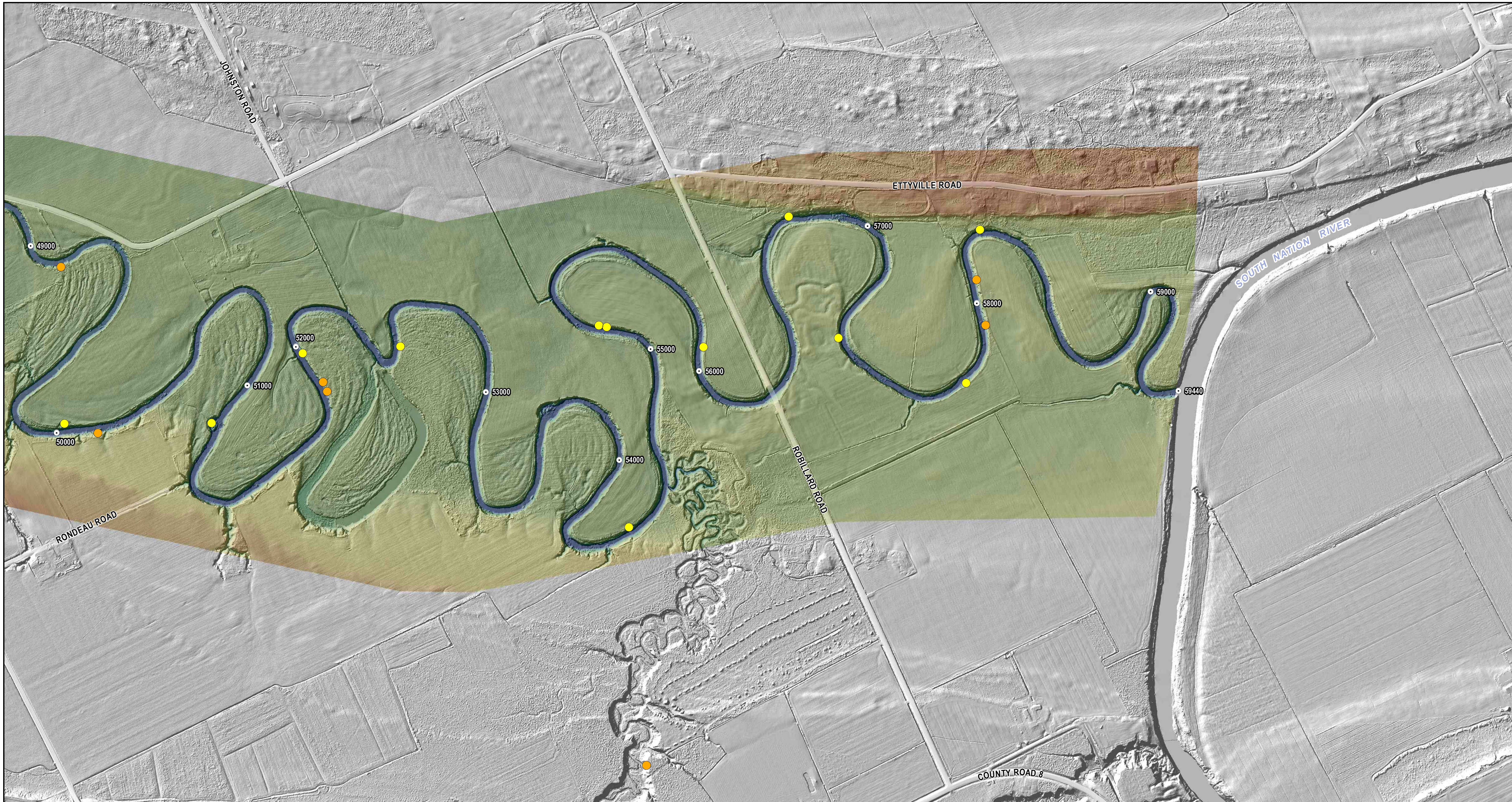
Appendix D-9



LEGEND

Relative Elevation[1,2]
Above Bear Brook

12+ m
8 m
4 m
0 m

Possible Landslide
Probable Landslide
River Chainage (m)[3]

1. Relative Elevation Model (REM) created using 1 m resolution 2019-20 Lidar-derived Digital Terrain Model.
2. Bear Brook is 0 m relative elevation.
3. River Chainage is based on 2019-20 Lidar-derived Digital Terrain Model planform.

Page Index Map

0 50 100 150 200 250
m

North American Datum 1983
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Bear Brook Geomorphology

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REF. NO. 2302503-D-1

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