RDCK FLOODPLAIN AND STEEP CREEK STUDY

Kuskonook Creek

Final
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TABLE OF REVISIONS

ISSUE	DATE	REV	REMARKS
DRAFT	March 31, 2020		Original issue
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EXECUTIVE SUMMARY

This report and its appendices provide a detailed hydrogeomorphic hazard assessment of Kuskonook Creek. It was chosen as a high priority creek amongst hundreds in the Regional District of Central Kootenay from a risk perspective because of its comparatively high hazards and estimated consequences from debris flows.

This report provides a comprehensive geomorphological and hydrological background and details the analytical techniques applied to create scenario and composite hazard rating maps for the Kuskonook Creek fan-delta. This work is the foundation for future quantitative risk assessments and/or conceptual level through to detailed design and construction of mitigation measures, if required.

Kuskonook Creek is one of ten steep creeks selected for detailed assessment, which can be grouped by hazard process as those principally dominated by floods and debris floods (Wilson, Cooper, Eagle, Kokanee, Sitkum, Harrop, Duhamel creeks); those by debris flows (Kuskonook Creek); and hybrids (Procter and Redfish creeks).

Debris flows on Kuskonook Creek are considered most likely to occur following wildfires of moderate and/or high burn severity. While such wildfires also occur on the flood and debris-flood prone creeks in the RDCK, the mainstem channels of the other creeks, with the exception of Procter Creek, are not sufficiently steep to convey debris flows downstream to or past the fan apex and thus affect the hazard on the fan-delta. The 2004 debris flows were a stark reminder as to the destructive power of post-wildfire debris flows and form the best-studied post-wildfire debris flows in the RDCK.

To assess the hazards at Kuskonook Creek, multiple hazard scenarios were developed for specific event return periods (20-, 50-, 200-, 500-year). The scenarios included bulking of flow to allow for higher organic and mineral sediment concentrations and debris flows at the 50-, 200- and 500-year return periods. Debris-flow frequency-magnitude relationships were developed through a model ensemble in which BGC compared different approaches relating to sediment recharge, a regional frequency-magnitude approach and a post-fire debris flow magnitude analysis. In the end, BGC decided on mostly rely on the post-fire analytical approach in estimating debris-flow frequencies and magnitudes up to the 500-year return period.

Two numerical hydro-dynamic models (HEC-RAS 2D and DAN 3D) were employed to simulate clear-water flood- and debris-flow hazard scenarios on the fan-delta. The reason for using multiple models was to simulate a range of results as both models have their distinct advantages and shortfalls. Bank erosion was not modeled as an existing debris basin on the fan delta is assumed to perform as designed, hence not resulting in bank erosion. Table E-1 provides key observations derived from the numerical modelling.

Table E-1. Key findings from numerical modelling of Kuskonook Creek floods and debris flows.

Process	Key Observations
Clear-water inundation (HEC-RAS model results for 20-year return period)	• Clear-water floods are believed to remain in the channel and pass through the existing and overflow culverts. • At higher return periods, debris flows dominate the fan-delta hazards
Debris flow inundation (DAN 3D model results for 50-year, 200- and 500-year return periods)	• The 50-year return period debris flow is likely to overwhelm the existing deflection berm and spill southwestwards towards the marina turn-off. • The 200-year return period debris flow will result in a substantially larger area being inundated by debris with flow spilling westward and likely covering the majority of Highway 3A on the modern fan-delta of Kuskonook Creek. A presumed avulsion channel through mid fan will likely experience high flow velocities and depths. Modelled velocities and flow depths across most of the fan upstream of Highway 3A are likely to be destructive to homes and vehicles. • The 500-year return period debris flow will likely be marginally larger in extent compared to the 200-year debris flow.
Auxiliary Hazards	• In case of a culvert blockage at the debris basin outlet, saturation of the constructed berm could potentially lead to a slope failure of the berm. However, this may have been addressed through a sufficiently high factor of safety by the berm's designers. • Long-term aggradation of the lower sections (above the fan apex of the modern fan) could potentially lead to a re-activation of the paleofan (currently considered unlikely). • Large woody debris could clog the outlet structure and lead to debris basin overtopping.

The multiple process numerical modelling ensemble approach demonstrates that the key hazards and associated risks stem from debris flows. Those could result in widespread fan inundation, particularly on the upper and central fan and affect multiple properties with possibly severe consequences similar to those witnessed on Kuskonook Creek in 2004.

Model results are cartographically expressed in two ways: The individual hazard scenarios and a composite hazard rating map. The individual hazard scenarios (defined by return period and avulsion scenarios) are captured by showing the impact force which combines flow velocity, flow depth and material density. Impact force is an index of destructiveness of an event and is suited for debris floods and debris flows alike. The individual hazard scenario maps are useful for hazard assessments of individual properties as part of the building permit process as well as to guide emergency response as they provide a high degree of detail.

The composite hazard rating map combines all hazard scenarios into one map and incorporates the respective clear-waterflood and debris flow frequencies. It provides a sense of the areas that could possibly be impacted by future events up to the highest modelled return period. The composite hazard rating map can serve to guide subdivision and other development permit approvals. It requires discussions and regulatory decisions on which of the hazard ratings is attributed to specific land use prescriptions, covenants, bylaws or other limiting clauses for both existing and proposed development. The categories range from low to very high hazard and are classified via the impact force intensity. The composite hazard rating map shows that the majority of the mid to proximal fan-delta (everything upstream of Highway 3A) is subject to high and very high hazards. The lower fan downstream of Highway 3A is subject to very high (near the outlet of Kuskonook Creek) to low (near the Marina and the northernmost fan segment) hazards.

While not comprehensive or quantitative, BGC provides several considerations for creek hazard management. These could include substantial upgrades to the existing mitigation system including raising and commensurate widening the deflection berm, installation of a new or larger culvert at the existing debris basin outlet, and erection of warning signs on Highway 3A north and south of the Kuskonook Creek fan-delta. Berm and basin upgrades are likely cost-prohibitive compared to the value of existing assets. The second option would require significant design modifications and would not prevent the existing berm from being overtopped. The last option is the most cost effective but would not prevent any property or infrastructure damage.

Some uncertainties persist in this study. As with all hazard assessments and corresponding maps, they constitute a snapshot in time. Re-assessment and/or re-modelling may be warranted due to significant alterations of the fan-delta surface topography or infrastructure, such as future fan developments, debris flows, formation of landslides in the watershed, culvert re-design or alteration to any fan infrastructure. BGC's analysis does not include breaches of the constructed deflection berm and debris basin. Furthermore, the assumptions made on changes in runoff due to climate change and sediment bulking, while systematic and well-reasoned, will likely need to be updated occasionally as scientific understanding evolves. However, since debris flows dominate the hazard at Kuskonook Creek, changes to clear-water flood behaviour will not significantly change the overall hazard on the fan-delta.

All hazards contain some component of chaotic behaviour, meaning that it is not possible to adequately model every possible scenario or outcome. For example, unforeseen log jams may alter flow directions and create avulsions into areas not specifically considered in the individual hazard scenarios. Substantial changes of Kootenay Lake levels could alter the morphodynamics of the fan-delta and the upstream channel. Similarly, sediment deposition patterns cannot be predicted exactly and are expected to be somewhat random as buildings (sheared off their foundations or remaining in place), log jams and sequential stalled debris lobes can deflect sediment in various directions. Finally, debris-flow behaviour is affected by the triggering storm intensity and duration as well as tributary landslides or debris flows in the watershed.

Despite these limitations and uncertainties, a detailed and credible hazard assessment has been achieved on which land use decisions can be based.

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1. INTRODUCTION

1.1. Summary

The Regional District of Central Kootenay (RDCK, the District) retained BGC Engineering Inc. (BGC) to complete detailed assessments and mapping of 6 floodplains and 10 steep creeks within the District (Figure 1-1, Table 1-1). The work focuses on high priority areas identified during a 2018-2019 regional study that prioritized flood and steep creek hazard areas across the District (BGC, March 31, 2019). The March 31, 2019 assessment is referred to as the "Stream 1" study, and the work described herein as the "Stream 2 study".

Table 1-1. List of study areas.

Site Classification	Geohazard Process	Hazard Code	Jurisdiction	Name
Floodplain	Clearwater Flood	340	Village of Salmo	Salmo River
		372	Village of Slocan	Slocan River
		393	Town of Creston	Goat River
		408	RDCK Electoral Area A	Crawford Creek
		375	RDCK Electoral Area K	Burton Creek
		423	Village of Kaslo	Kaslo River
Steep Creek	Debris Flood	212	RDCK Electoral Area F	Duhamel Creek
		252	RDCK Electoral Area F	Kokanee Creek
		248	RDCK Electoral Area D	Cooper Creek
		137	RDCK Electoral Area H	Wilson Creek
		242	RDCK Electoral Area E	Harrop Creek
		95	RDCK Electoral Area K	Eagle Creek
		238	RDCK Electoral Area F	Sitkum Creek
	Hybrid Debris Flood/Debris Flow	116	RDCK Electoral Area E	Procter Creek
		251	RDCK Electoral Area E	Redfish Creek
	Debris Flow	36	RDCK Electoral Area A	Kuskonook Creek

This report details the approach used by BGC to conduct a detailed steep creek geohazards assessment and mapping for Kuskonook Creek (also referred to as Kuskanook), located approximately 25 km north of Creston, BC in Electoral Area A. The site lies on the east side of Kootenay Lake near the southern end of the lake (Drawing 01).

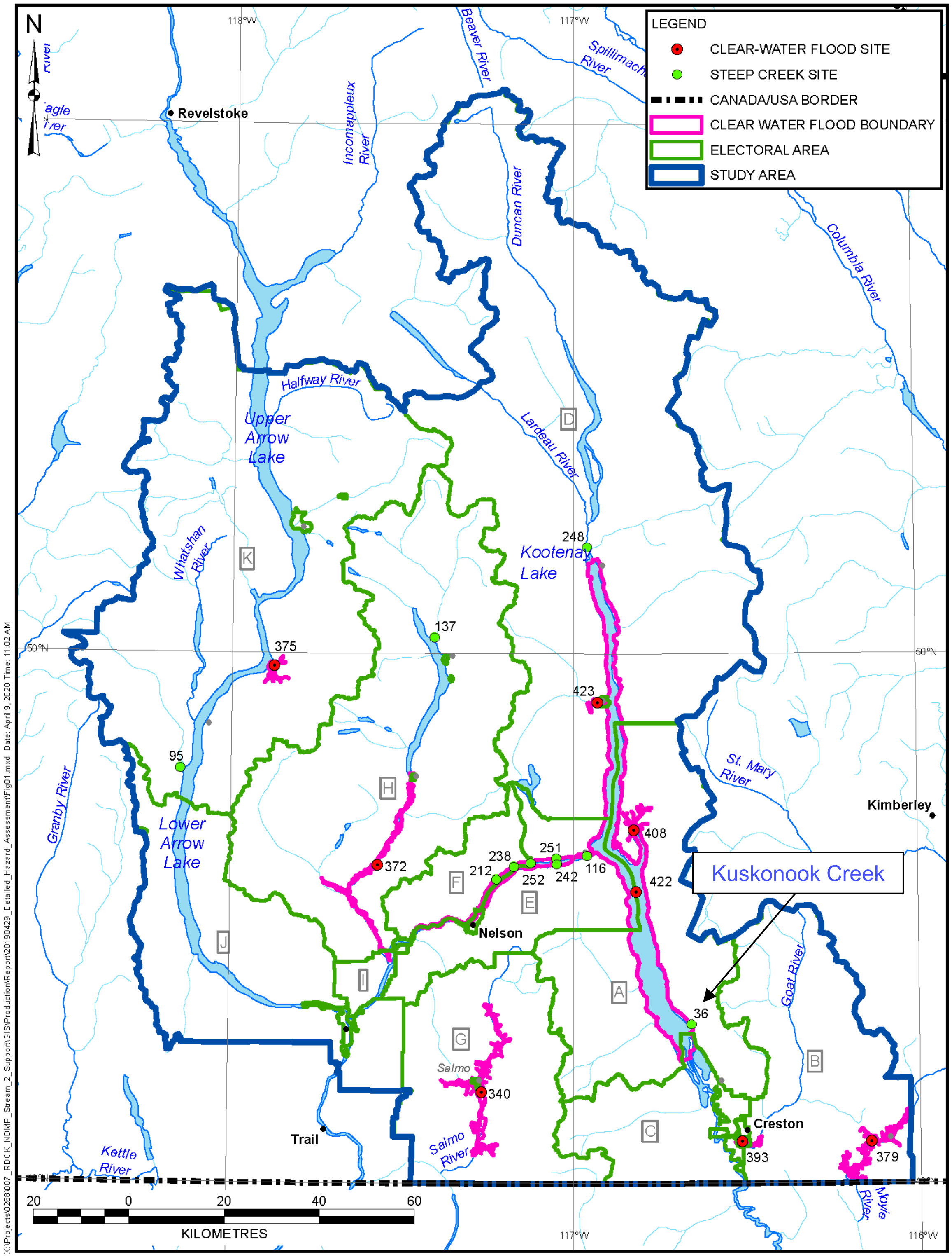

Figure 1-1. Hazard areas prioritized for detailed flood and steep creek mapping. Site labels correspond to hazard identification numbers in Cambio Communities. Kuskonook Creek (No. 36) is labelled on the figure.

The study objective is to provide detailed steep creek hazard maps and information that will support community planning, bylaw enforcement, emergency response, risk control, and asset management at Kuskonook Creek. This assessment also provides inputs to possible future work such as:

- Risk tolerance policy development (a process to evaluate situations where geohazards pose a level of risk considered intolerable by the District).
- Quantitative geohazard risk assessments as required to support the implementation of risk tolerance policy.
- Geohazards risk reduction (mitigation) plans.

In addition to this report, BGC is providing a summary report for the entire assessment across different sites, *RDCK Floodplain and Steep Creek Study Summary Report* (referred to herein as the "Summary Report"). Readers are encouraged to read the Summary Report to obtain context about the objectives, scope of work, deliverables, and recommendations of the larger study. BGC is also providing a *RDCK Floodplain and Steep Creek Study Steep Creek Assessment Methodology Report* (referred to herein as the "Methodology Report"), which describes the assessment methods applied for this study.

1.2. Scope of Work

BGC's scope of work is outlined in the proposed work plan (BGC, May 24, 2019), which was refined to best meet RDCK's needs as the project developed (BGC, November 15, 2019). It was carried out under the terms of contract between RDCK and BGC (June 20, 2019). The work scope was funded by Emergency Management BC (EMBC) and Public Safety Canada under Stream 2 of the Natural Disaster Mitigation Program (NDMP).

At Kuskonook Creek, the scope of work included:

- Characterization of the study area including regional physiography and hydroclimate, and local geology, steep creek process, and watershed, fan and creek characteristics.
- Development of a comprehensive site history of hydrogeomorphic events and mitigation activity.
- Development of frequency-magnitude (F-M) relationships (flow (discharge) and sediment volume) for steep creek flood hazard processes.
- Consideration of climate change impacts on the frequency and magnitude of steep creek flood hazard processes.
- Identification of active and inactive[1] portions of the alluvial fan and areas potentially susceptible to avulsion or bank erosion.
- Mapping of inundation areas, flow velocity, and flow depth for a spectrum of return periods.
- Recommendations for hazard management on the alluvial fan.

[1] Active alluvial fan – The portion of the fan surface which may be exposed to contemporary hydrogeomorphic or avulsion hazards. Inactive alluvial fan – Portions of the fan that are removed from active hydrogeomorphic or avulsion processes by severe fan erosion, also termed fan entrenchment.

For clarity, BGC notes that the current study is a hazard assessment. No estimation of geohazard consequences or risk were completed as part of the Stream 2 scope of work. Moreover, BGC notes that the present study does not consider ice-jam flooding hazards.

The scope of work considers the "return period ranges" and "representative return periods" outlined in Table 1-2. The representative return periods fall close to the mean of each range[2]. Given uncertainties, they generally represent the spectrum of event magnitudes within the return period ranges.

Table 1-2. Return period classes.

Return Period Range (years)	Representative Return Period (years)
10-30	20
30-100	50
100-300	200
300-1000	500

1.3. Deliverables

The deliverables of this study include this assessment report and digital deliverables (hazard maps) provided via BGC's Cambio™ web application and as geospatial data provided to RDCK.

This report is best read with access to Cambio™. Cambio displays the results of both the Stream 1 and Stream 2 studies. The application can be accessed at www.cambiocommunities.ca, using either Chrome or Firefox web browsers. A Cambio user guide is provided in the Summary Report. As outlined in Section 1.1, the report is best read with the Summary Report and Methodology Report.

1.4. Study Team

This study was multidisciplinary. Contributors are listed below, and primary authors and reviewers are listed in Table 1-3.

- Kris Holm, M.Sc., P.Geo., Principal Geoscientist
- Sarah Kimball, M.A.Sc., P.Eng., P.Geo., Senior Geological Engineer
- Matthias Jakob, Ph.D., P.Geo., Principal Geoscientist
- Hamish Weatherly, M.Sc., P.Geo., Principal Hydrologist
- Lauren Hutchinson, M.Sc., P.Eng., Intermediate Geotechnical Engineer
- Beatrice Collier-Pandya, B.A.Sc., EIT, Geological Engineer
- Matthias Busslinger, M.A.Sc., P.Eng., Senior Geotechnical Engineer
- Andrew Mitchell, M.A.Sc., P.Eng., Intermediate Geotechnical Engineer

[2] The 50- and 500-year events do not precisely fall at the mean of the return period ranges shown in Table 1-2 but were chosen as round figures due to uncertainties and because these return periods have a long tradition of use in BC.

- Joseph Gartner, Ph.D., P.E., Senior Geological Engineer
- Carie-Ann Lau, M.Sc., P.Geo., Intermediate Geoscientist
- Jack Park, B.A.Sc., EIT, GIT, Junior Geological Engineer
- Hilary Shirra, B.A.Sc., EIT, Junior Hydrotechnical Engineer
- Patrick Grover, M.A.Sc., P.Eng., Senior Hydrotechnical Engineer
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- Matthew Buchanan, B.Sc., GISP, A.D.P., GIS Analyst
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- Lucy Lee, B.A., A.D.P., GISP, GIS Analyst/Developer
- Matthew Williams, B.Sc., A.D.P., GIS Analyst.
- Alistair Beck, B.S.F., Dip CST, Database/Web Application Developer
- Michael Porter, M.Eng., P.Eng., Director, Principal Geological Engineer

Table 1-3. Study team.

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Joseph Gartner</td></tr>
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2. STEEP CREEK HAZARDS

2.1. Introduction

Steep creek or hydrogeomorphic hazards are natural hazards that involve a mixture of water ("hydro") and debris or sediment ("geo"). These hazards typically occur on creeks and steep rivers with small watersheds (usually less than 100 km^2) in mountainous terrain, usually after intense or long rainfall events, sometimes aided by snowmelt and worsened by forest fires.

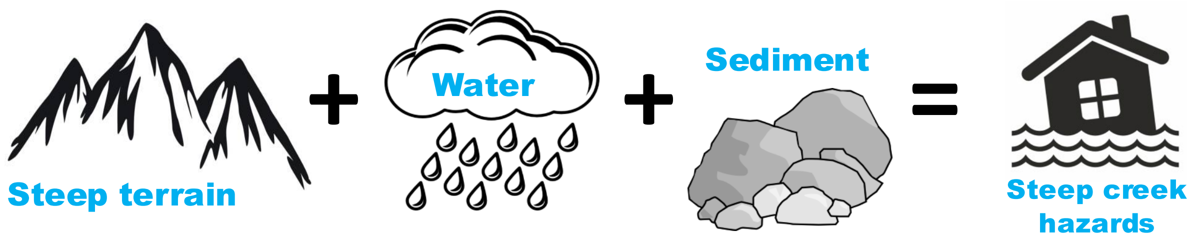

Figure 2-1. Illustration of steep creek hazards.

Steep creek hazards span a continuum of processes from clearwater floods (flood) to debris flows (Figure 2-2). Debris flow is by definition a landslide process. This section introduces these hazards; more details are provided in Section 1 of the Methodology Report. Definitions of specific hazard terminology used in this report are provided in Appendix A.

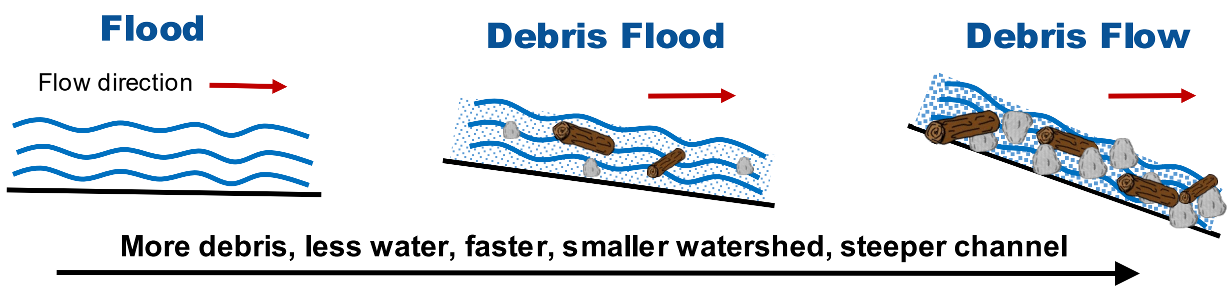

Figure 2-2. Continuum of steep creek hazards.

2.2. Floods and Debris Floods

Clearwater floods occur due to rainfall, or when snow melts. Recent major floods occurred in the RDCK on the Salmo and Slocan Rivers in May 2018.

Debris floods occur when large volumes of water in a creek or river entrain the gravel, cobbles and boulders on the channel bed; this is known as "full bed mobilization". Debris floods can occur from different mechanisms. BGC has adopted the definitions of three different sub-types of debris floods per Church and Jakob (2020):

- Type 1 – Debris floods that are generated from rainfall or snowmelt runoff resulting in sufficient water depth to result in full bed mobilization.
- Type 2 – Debris floods that are generated from diluted debris flows (e.g., a debris flow that runs into a main channel in the upper watershed).

- Type 3 – Debris floods that are generated from natural (e.g., landslide dam, glacial lake outbursts, moraine dam outbursts) or artificial dam (e.g. water retention or tailings dam) breaches.

The process of sediment and woody debris getting entrained in the water of a flood leads to an increase in the volume of organic and mineral debris flowing down a channel with a commensurate increase in peak discharge. This is referred to as flow bulking. Imagine a bucket of water filled with water. Then it is spilled down a children's slide. That's a clearwater flood. Refilling the bucket to 10 litres and taking a shovel of sand and perhaps some twigs and put it into the bucket. Now the water-sediment mixture occupies 12 litres worth of volume. It has bulked by a factor of 1.2. If one mixes it a bit and then spill it down the slide, one has a bulked debris flood with some 20% sediment concentration by volume. The experiment can be repeated with increasing volumes of sediment until it becomes a debris flow (see Section 2.3).

The effects of debris floods can range from relatively harmless to catastrophic depending on their magnitude and duration. Debris floods can be relatively harmless if of short duration and low magnitude. In contrast, they can be damaging when they cause bank erosion and channel change but do not jeopardize major infrastructure or threaten lives. A catastrophic level is reached when major infrastructure damage occurs in the form of riprap erosion, bridge foundation collapse of isolation, culverts becoming blocked or bypassed and road surfaces being eroded. Furthermore, homes are impacted beyond repair, and injuries and/or fatalities occur.

Within the RDCK, recent debris floods occurred on Fletcher Creek and Hamill Creek in June 2013 (Figure 2-3). The June 2013 events were damaging at both creeks, with multiple homes being flooded and the foundation of one home being partially eroded (Nelson Star, 2013). Another damaging debris flood occurred at Schroeder Creek on June 19, 2013 where coarse woody debris partially blocked the Highway 31 culvert, excess flow flooded the road surface, dispersed flow ran through the Schroeder Creek Resort campground, and the lower reach of Schroeder Creek (below the highway culvert) experienced significant channel scour and bank erosion (Perdue, 2015). On August 11, 2019 a damaging post-wildfire debris flood occurred on Morley Creek; where a road culvert was blocked, a water intake was destroyed, and several houses were damaged by muddy water (MFLNRORD S. Crookshanks, personal communication, August 20, 2019).

2.3. Debris Flows

Debris flows have higher sediment concentrations than debris floods and can approach consistencies similar to wet concrete. Using the example of a bucket again, if one adds sand to fill the bucket to the top, so that the fluid is half sand, half water, it is bulked by 100%, so a bulking factor of 2. Spilling it down the slide one now has a debris flow that behaves more like liquid concrete than a fluid.

They are typically faster than debris floods and have substantially higher peak discharges and impact forces. They are particularly threatening to life and properties due to these characteristics. Recent debris flows occurred in the RDCK on Gar Creek, impacting Johnson's Landing, in July 2012, and on Kuskonook Creek in 2004.

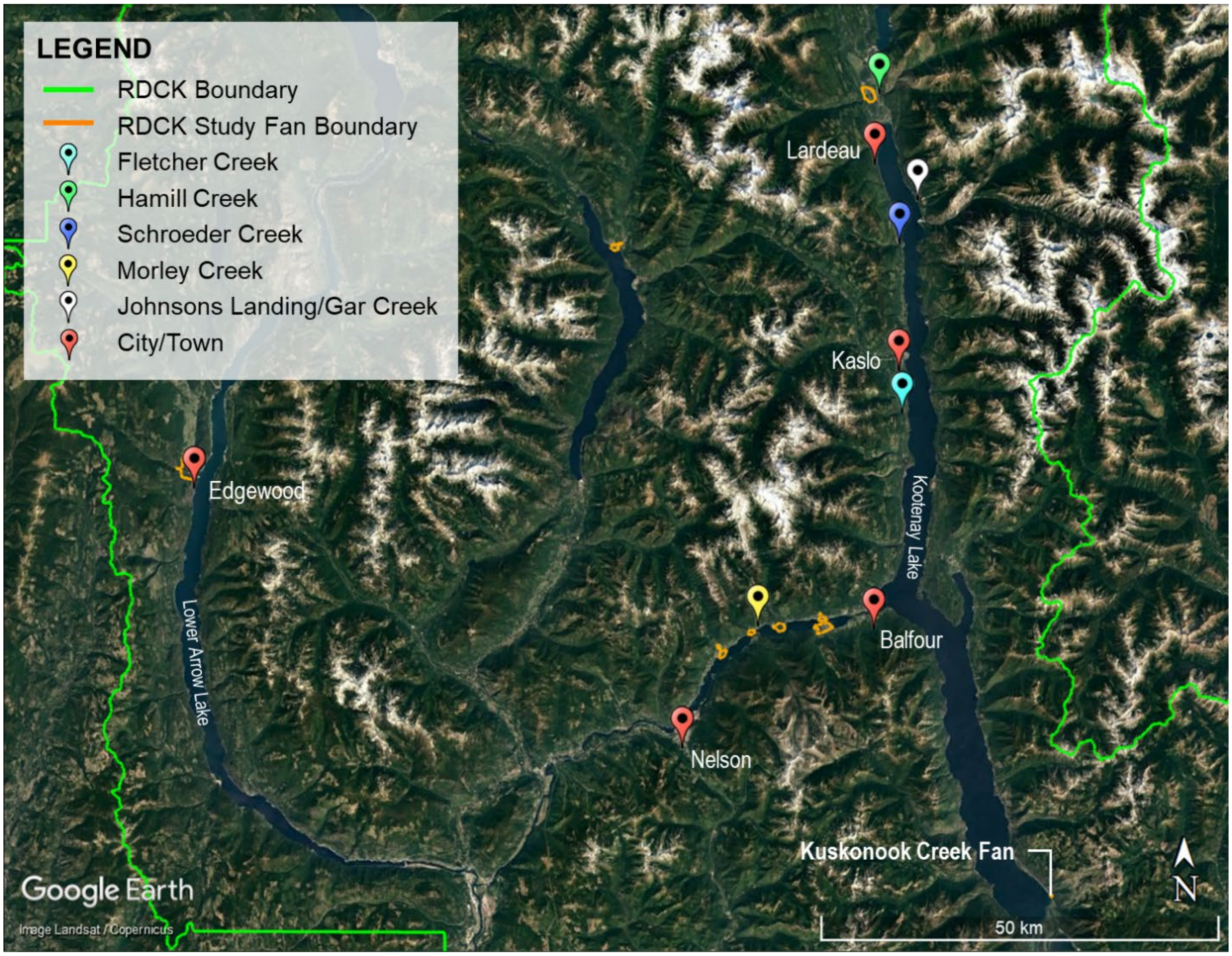

Figure 2-3. Locations of RDCK fans and recent floods, debris flows, and debris floods (Google Earth Pro, 2016).

2.4. Contextualizing Steep Creek Processes

Individual steep creeks can be subject to a range of process types and experience different peak discharges depending on the process even within the same return period class. For example, a steep creek may experience a “200-year flood” (with a return period of 200 years or a 0.5% chance of occurrence in any given year) with an observed discharge of 20 m^3/s. A 200-year flood would almost certainly be a Type 1 debris flood (after Church & Jakob, 2020) as it would result in the mobilization of the largest grains in the stream bed. In this study a Type 2 debris flood was estimated to have peak discharges 1.05 to 1.5 times higher than the clearwater flood. Type 3 debris floods were simulated on several creeks but only one (Sitkum Creek) exceeded the largest modelled Type 2 discharge at the fan apex. If the creek is subject to debris flows, the peak discharge may be 1 to 2 orders of magnitude higher than a 200-year flood (Jakob, 2005). Figure 2-4 demonstrates this concept with an example cross-section of a steep creek, including representative flood depths for the peak discharge of the following processes:

- Q_2; Clearwater flow with 2-year return period
- Q_{200}; Clearwater flow with 200-year return period (i.e., a clearwater flood)

- $Q_{max\ debris\ flood\ (full\ bed\ mobilization)}$; Type 1 debris flood generated by full bed mobilization
- $Q_{max\ debris\ flood\ (outburst\ flood)}$; Type 2 debris flood generated by an outburst flood
- $Q_{max\ debris\ flow}$; Debris flow.

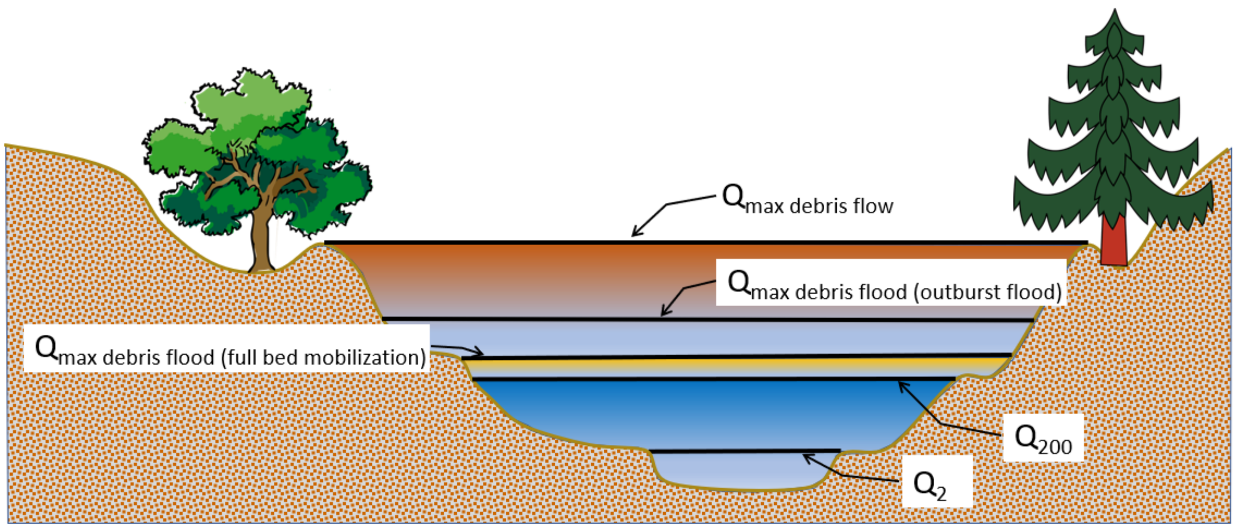

Figure 2-4. Conceptual steep creek channel cross-section showing peak discharge levels for different events. Note that for some outburst floods or debris flows the discharge may well exceed what is shown here.

This difference in peak discharge is one of the reasons that process-type identification is critical for steep creeks. For example, if a bridge is designed to accommodate a 200-year flood, but the creek experiences a debris flow with a much larger peak discharge, the bridge would likely be damaged or destroyed. For floods, a longer duration is more likely to saturate protective dikes, increasing the likelihood for piping and dike failure prior to, or instead of, the structure being overtopped. For debris floods, the duration of the event will also affect the total volume of sediment transported and the amount of bank erosion occurring.

2.5. Avulsions

An avulsion occurs when a watercourse jumps out of its main channel into a new course across its fan or floodplain (Appendix A). This can happen because the main channel cannot convey the flood discharge and simply overflows, or it occurs because the momentum of a flow allows overtopping on the outside of a channel bend. Finally, an avulsion can occur because a log jam or collapsed/blocked bridge redirects flow away from the present channel. The channel an avulsion flow travels down is referred to as an avulsion channel. An avulsion channel can be a new flow path that forms during a flooding event or a channel that was previously occupied.

In Figure 2-5, a schematic of a steep creek and fan is shown where the creek avulses on either side of the main channel. The avulsion channels are shown as dashed blue lines as avulsions only occur during severe floods (i.e., rarely). On high resolution topographic maps generated from lidar, avulsion channels are generally visible and are tell-tale signs of past and future avulsions.

Also shown on Figure 2-5 is the fan apex, which is the uppermost point of the fan, where net deposition of sediment from the creek begins. It coincides with a change in slope and confinement where the creek debouches from the mountainous upstream portion of the watershed. The hillsides flanking the fan apex are also preferential locations for remnants of paleofans, which also exists at Kuskonook Creek. These represent remaining portions of an ancient (early Holocene or some 10,000 years ago) fan that developed during a different climate, sediment transport regime or base level. Paleofan surfaces will not be inundated by contemporary debris flows, debris floods, or clearwater floods as they are well above the maximum flow depths achieved by such modern-day processes. For this reason, they are often suitable for development from a geohazard point of view.

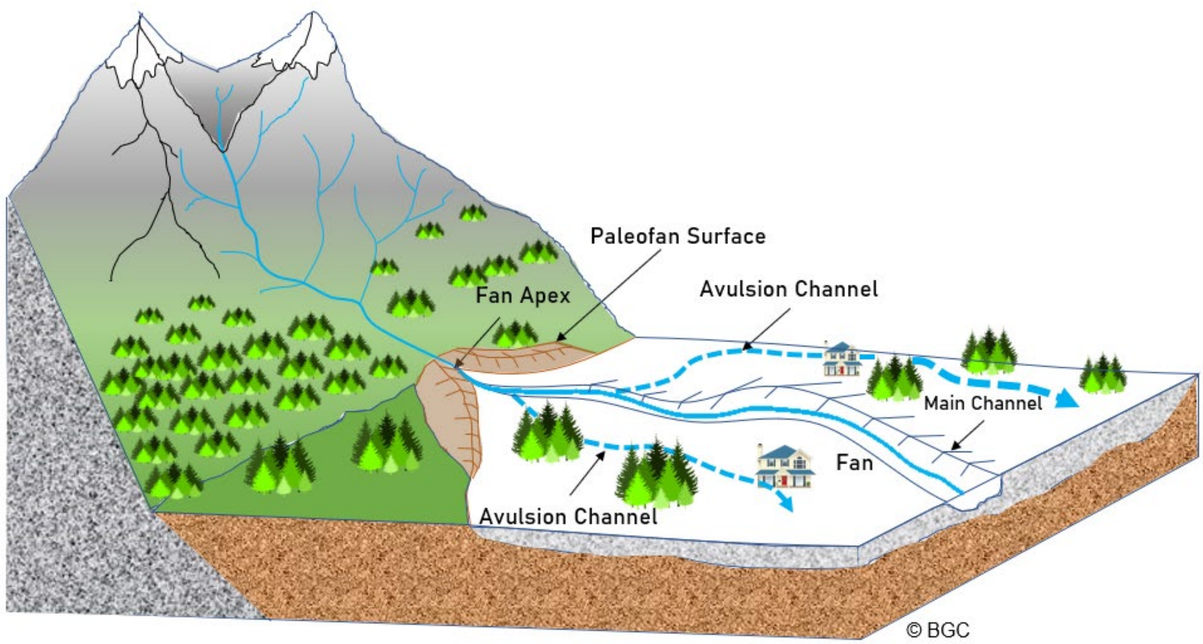

Figure 2-5. Schematic of a steep creek channel with avulsions downstream of the fan apex. Artwork by BGC.

3. STUDY AREA CHARACTERIZATION

3.1. Site Visit

Fieldwork on Kuskonook Creek was conducted on July 10, 2019 by Matthias Busslinger and Matthias Jakob of BGC. Field work included channel hikes to the fan apex, on the fan and in the vicinity of the debris basin that was constructed in 2008 after the 2004 debris flow. The upper watershed was flown by helicopter on July 6, 2019 and numerous photographs were taken for later analysis of major sediment sources to the channel (Appendix B). The channel of Kuskonook Creek was not hiked in full as regrowth of shrubby vegetation after the 2004 events had obscured much of the channel and would have made it very difficult to observe and measure channel yield rates.

3.2. Physiography

Kuskonook Creek is located approximately 25 km north of Creston, BC, on the east shore of Kootenay Lake. The site lies on the western flank of the Purcell Mountains, which are a subgroup of the Columbia Mountains in southeastern BC. The watershed falls within the Southern Purcell Mountains ecosection of the Northern Columbia Mountains ecoregion. The ecoregion is drained to the east by the Rocky Mountain Trench, to the south by the Kootenay River, and to the west by short and steep creeks that flow into Kootenay Lake (Demarchi, 2011; Holland, 1976). The ecosection is characterized by wide valleys and rounded mountains that decrease in height to the south, which are forested to their summits and decrease in height to the south. Typical vegetation includes Western Red Cedar and Western Hemlock trees at lower elevations and Engelmann Spruce and Subalpine Fir trees along the mid- and upper-mountain slopes.

3.3. Geology

3.3.1. Bedrock Geology

The Kuskonook Creek watershed is underlain by granodioritic intrusive rocks of the Mount Skelly pluton, which is part of the larger Bayonne Batholith that formed in the Mid-Cretaceous period. The rock is composed of coarse-grained biotite-hornblende granodiorite. After emplacement, the Bayonne Batholith was affected by extensional tectonics along the Purcell Trench Fault, which formed the valley within which Kootenay Lake exists today (Archibald et al., 1984). Localized fault planes and moderately steeply- to steeply-dipping (55-78°) joints have been mapped approximately 5 km north of Kuskonook Creek, though no major lineaments have been identified with the watershed (Logan & Mann, 2000).

3.3.2. Surficial Geology

Within the watershed, slopes less than 30° are overlain by veneers of sandy glacial till and colluvium with many boulders. The sandy surficial deposits have been anecdotally observed to be highly erodible (Jordan & Covert, 2009). A major forest fire in the Kuskonook Creek watershed in 2003 lead to the development of hydrophobic soils in the watershed and preceded two debris flow events the following year (VanDine et al., 2005). Because of the recent debris flow events and the lack of identifiable actively-producing sediment sources along the main channel, the watershed is characterized as supply-limited. In supply-limited watersheds, it takes time for sufficient sediment to build up within the channel and therefore be mobilized during extreme hydroclimatic events.

3.4. Geomorphology

3.4.1. Watershed

The Kuskonook Creek watershed is outlined in Drawing 01, which shows a shaded, bare earth[3] Digital Elevation Model (DEM) of the watershed, fan, and surrounding terrain created from lidar data. The DEM was used to generate the contours shown on the report drawings. Representative photographs of the watershed are provided in Appendix B.

Geomorphological analysis of Kuskonook Creek included characterization of the watershed and fan using historical air photos (Drawings 04A and 04B) and lidar supplemented by literature on the regional geology, geologic history and physiography, and a field visit. Drawing 05 shows geomorphic features of the watershed.

The headwaters of Kuskonook Creek are the slopes of an unnamed mountain with an approximate elevation of 2130 m at the eastern edge of the watershed. The main channel begins in a confined steep gully until it reaches glacial deposits that it has deeply incised into. The lower reach of Kuskonook Creek above the fan apex goes through dominantly colluvial deposits supplying sediment to the creek. The channel is steep above the fan apex (35% gradient on average, Table 3-1) with two main tributaries that join the channel from the east and west (Drawing 03).

Approximately 400 m upstream of the fan apex, the channel takes a slight bend to the south as it traces the side of a paleosurface. This paleosurface was most likely the Kuskonook Creek fan-delta, with the creek running through the paleochannels delineated in Drawing 05, when Kootenay Lake was at a higher level during glaciation and post-glaciation.

While the hillslopes are forested, there has been limited harvesting activity in the watershed (FLNRORD, n.d.). Approximately 60% of the watershed burned in the only recorded fire in the watershed in 2003 (FLNRORD, n.d.).

[3] Vegetation and buildings removed.

Table 3-1. Watershed characteristics of Kuskonook Creek.

Characteristic	Value
Watershed area (km^2)	4.0
Fan-delta area (km^2)	0.049
Active fan-delta area (km^2)[1]	0.054
Maximum watershed elevation (m)	2,135
Minimum watershed elevation (m)	566
Watershed relief (m)	1,569
Melton Ratio (km/km)[2]	0.7
Average channel gradient of mainstem above fan-delta apex (%)	35
Average channel gradient on fan-delta (%)	22
Average fan-delta gradient (%)	25

Notes:
1. Active fan-delta area includes a 10% increase to the area mapped from lidar to account for the submerged portion of the fan-delta.
2. Melton ratio is an indicator of the relative susceptibility of a watershed to debris flows, debris floods or floods.

3.4.2. Kuskonook Creek Fan-Delta

An overview of the Kuskonook Creek watershed and fan-delta is shown in Drawings 01, 02A, and 02B. Drawing 06 shows geomorphic features on the fan-delta. Locations referred to in the text below are labelled on these drawings. The fan areas delineated in the drawings have been interpreted by BGC based on lidar and field data; however, the fan extent beyond the lidar data limits at Kootenay Lake are difficult to define due to changing lake levels.

A substantial paleofan has been identified on the north side of the modern fan (Figure 3-1). Its elevation range is from 534 m to 750 m. This paleofan likely developed during the early Holocene era after deglaciation, a time with abundant unconsolidated sediment and little or no vegetation colonization. This implied a much higher sediment delivery rate to the fan than during modern times.

Figure 3-1. Paleofan and modern fan-delta of Kuskonook Creek.

Kuskonook Creek flows southerly across the fan that extends in Kootenay Lake. The creek historically flowed southwesterly down the center of the fan, but the channel has been modified to curve through a bermed basin and then flow under Highway 3A. The berm is visible in the lidar on Drawings 02A and 06 and described in the following subsections. The active channel ranges from 2 to 4 m wide on the fan. The average channel gradient decreases from approximately 27% (15°) at the fan apex to approximately 12% (7°) near the channel outlet.

The Kuskonook Creek fan has adjusted due to the raise of lake levels when Corra Linn Dam, located southwest of Nelson, was activated in 1938. The dam raised lake levels by approximately 2 m (Touchstone Nelson, 2007) and BGC understands that this level will be held. The distal portions of the fan, visible in aerial photographs (Section 6.2), were flooded by the lake level raise. Kuskonook Creek flows into Kootenay Lake in an approximately 9 m wide reach.

3.4.3. Steep Creek Process

BGC assessed the potential steep creek process types and hazards on Kuskonook Creek based on the Melton Ratio and historical and field evidence. In comparison with a large dataset of steep creeks in B.C. and Alberta, Kuskonook Creek plots in the data cluster prone to debris floods and debris flows (Figure 3-2). The points shown on the plot are subject to some error and watersheds can be subject to multiple processes at different timescales; for this reason, it is important to consider additional evidence to supplement the assessment of process type.

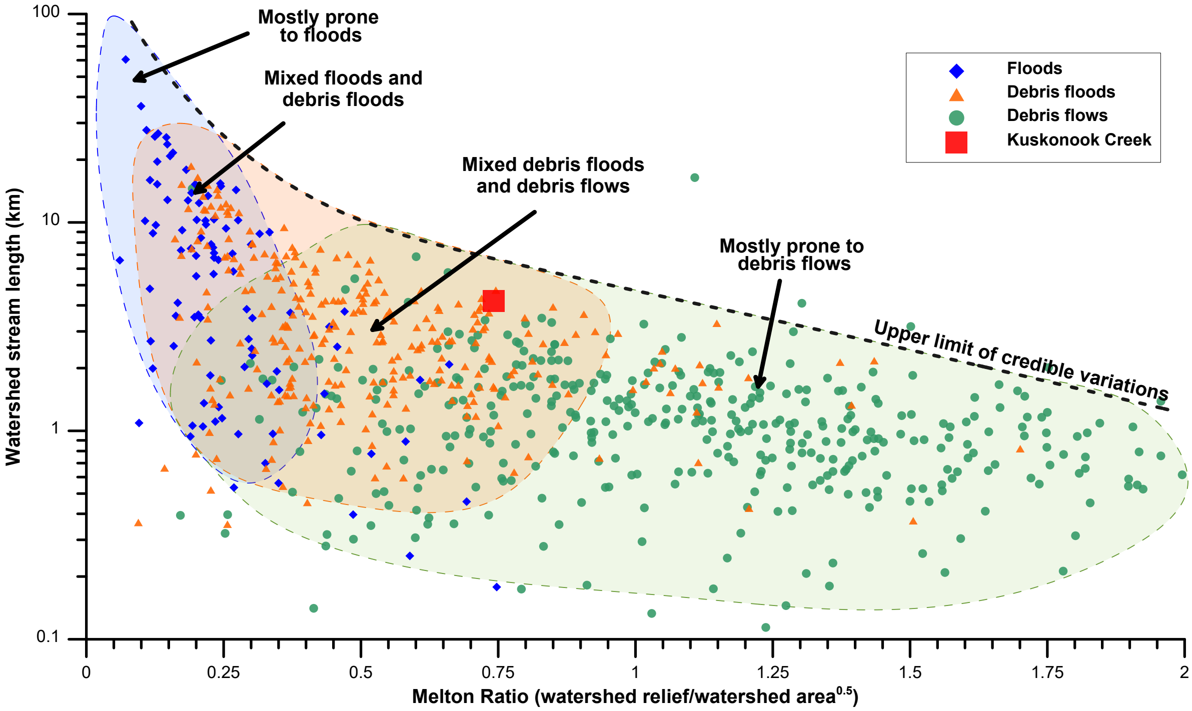

Figure 3-2. Tendency of creeks to produce floods, debris floods and debris flows, as a function of Melton Ratio and stream length (data from Holm et al., 2016 and Lau, 2017). See Section 3.4.1 for Kuskonook Creek watershed data.

Debris floods can be subdivided into three types, those triggered by the exceedance of a critical bed shear stress threshold (Type 1), those through transitions from debris flows (Type 2), and those triggered from outbreak floods (Type 3) (Section 1 of Methodology Report (BGC, March 31, 2020b)). This differentiation is not included in the above plot as such nuances are unknown for the data included above; however, it is included in this detailed assessment.

BGC interprets floods to be the dominant hydrogeomorphic process at Kuskonook Creek for the 20-year return period, while debris flows dominate at the higher return periods (50- , 200-, and 500-year) that were studied. This rationalization is discussed further in Section 6.1.

3.5. Existing Development

Development on the Kuskonook Creek fan-delta comprises the Kuskonook Harbour Boat Launch and a small number of residential buildings (Drawings 02A, 02B, 06). Highway 3A passes through the mid-to-distal fan.

The unincorporated community of Kuskonook is not listed in the 2016 census (Statistics Canada, 2016); however, given the small number of residential buildings, BGC estimates the full population to be less than 10 (BGC, March 31, 2019). The estimated total improvement value of parcels intersecting the Kuskonook Creek fan-delta based on the 2018 BC Assessment Data is $295,300 (BGC, March 31, 2019).

3.5.1. Debris Flow Protection Structure

Kuskonook and Kuskonook Harbour are protected by a large flood protection structure approximately 170 m in length and 4 m high that was built in 2008, following the 2004 debris flows, on the right bank just upstream of Highway 3A (Figure 3-3). This structure is not identified on the iMapBC Flood Protection Structural Works layer and while BGC has access to the design drawings, BGC has not been able to obtain the design report or as-built drawings and therefore the estimates of height and length were made using a combination of lidar and BGC's field notes (Klohn Crippen Berger Ltd. (KCB), 2007). A layer of larger angular rip rap lines the channel at the base of the berm. The banks are well vegetated with grasses and shrubs as shown in photos in Figure 3-3.

An original mitigation design was to have a capacity of 30,000 m^3, but the requirements by MoTI appear to have been reduced as a smaller structure was built (Klohn Crippen Consultants (Klohn), 2005). Debris deposition angles are typically reported as ranging between one half to two thirds of the original channel slope. The channel slope within the basin is approximately 20%. Using this range, BGC estimated the debris basin capacity to range between 6,700 to 7,500 m^3. Exact numbers are not available as the deposition angle depends, for example, on the amount of hyperconcentrated afterflow. Furthermore, the deposition slope is not a single line, but a concave line, but cannot modeled with any degree of certainty. Even at the high estimate (7,500 m^3), this would contain only about half of the 50-year return period debris flow (see Section 6.3).

As this structure was built for MoTI, its primary function is likely to reduce impact to the highway, rather than protect development on the fan-delta in general.

A) Standing on berm looking downstream (south) showing rip rap at the base of the berm.

B) Standing on berm looking upstream(north) showing rip rap at the base of the berm.

C) Standing on berm looking west at Kuskonook Rd (gravel road) and Highway 3A.

D) Standing on berm looking downstream (south) towards the end of the berm.

E) Standing on shoulder of Highway 3A looking at Kuskonook Rd (gravel road) and the end of the berm.

Figure 3-3. Kuskonook berm on right bank of Kuskonook Creek. BGC photos taken July 10, 2019.

3.5.2. Culverts

There are two culverts that convey flow underneath Highway 3A from the debris flow protection structure. The first culvert (debris basin culvert) directs the main flow of Kuskonook Creek under Highway 3A from the downstream end of the debris basin (Figure 3-4). The culvert has concrete wingwalls on either side and a trash rack. The culvert dimensions were not measured in the field but according to the iMap Culverts- MoTI Layer, the galvanized culvert has a 500 mm diameter which agrees with the KCB construction drawing specifications (2007).

The second culvert (spillway culvert) allows flow that overflows the debris basin at the downstream end to also be diverted under Highway 3A to Kootenay Lake. This culvert also has concrete wingwalls on either side and a trash rack. The culvert dimensions were not measured in the field but according to the iMap Culverts – MoTI Layer, the galvanized culvert has a 200 mm diameter while the construction drawing specifications (KCB, 2007) refer to a 500 mm dimeter culvert (Figure 3-5). Based on site photographs, BGC has assumed the culvert has a 500 mm diameter and that the iMap measurement is most likely out of date.

Figure 3-4. Location of debris basin culvert at downstream end of debris basin indicated by red arrow. Culvert inlet is constructed similarly to the spillway culvert shown in Figure 3-5 below. BGC photo taken July 10, 2019.

Figure 3-5. Spillway culvert crossing Highway 3A at Kuskonook. BGC photo taken July 10, 2019.

3.6. Hydroclimate

3.6.1. Historical Conditions

Climate normal data were obtained from Environment and Climate Change Canada's (ECCC's) Creston station (538 m), located approximately 25 km south of the Kuskonook Creek outlet (Environment and Climate Change Canada, n.d.). Daily precipitation and temperature data are available from 1912 to 2015. Figure 3-6 shows the average temperature and precipitation for this station from the 1981 to 2010 climate normals. Average annual precipitation is 662 mm, as summarized in Table 3-2.

The measured historical precipitation (1981 to 2010) at the Creston weather station is lower than the historical (1961 to 1990) precipitation in the Kuskonook Creek watershed, where the mountaintops extend approximately 1500 m above Kootenay Lake. This difference in precipitation is due to orographic effects, which occur when an air mass is forced up over rising terrain from lower elevations. As it gains altitude it quickly cools down, the water vapour condenses (forming clouds), ultimately resulting in precipitation.

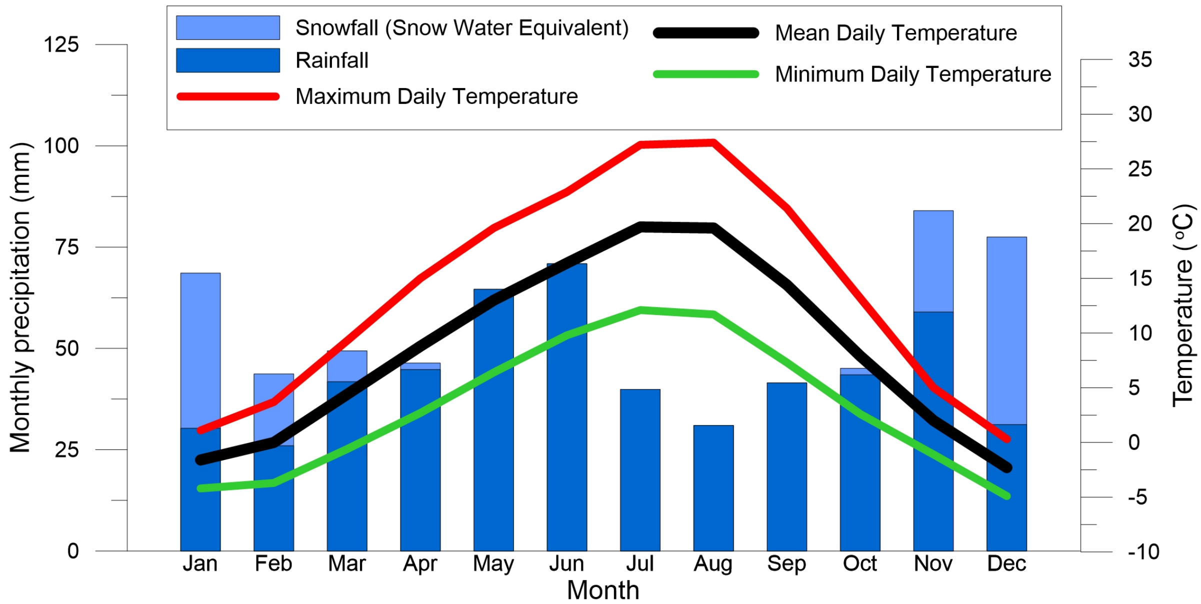

Figure 3-6. Climate normal data for Creston station from 1981 to 2010.

Table 3-2. Annual total of climate normal data for Creston station from 1981 to 2010.

	Annual Total	Percent of total annual precipitation (%)
Rainfall (mm)	525	79
Snowfall (cm)	138	21
Precipitation (mm)	662	100

To understand the regional distribution of precipitation and snowfall patterns and supplement the data from the Creston station, BGC obtained climate data based on the CRU-TS 3.22 dataset (Mitchell & Jones, 2005) for the period 1961 to1990. This dataset was generated with the ClimateNA v5.10 software package, available at *http://tinyurl.com/ClimateNA*, based on methodologies described by Wang et al. (2016). The historical Mean Annual Precipitation (MAP) over the watershed is 1176 mm, varying as a function of elevation. The same trend is evident in the Precipitation as Snow (PAS) over the watershed where the historical average PAS is 612 mm. PAS increases with elevation; therefore, Kuskonook Creek watershed accumulates greater precipitation falling as snow compared to the Creston weather station.

3.6.2. Climate Change Impacts

The watershed falls within the Southern Purcell Mountains ecosection of the Northern Columbia Mountains ecoregion. Extreme flood events in this region are often associated with rain-on-snow events in the spring (Harder et al., 2015). Although the effects of climate change on precipitation are not clear, projected increases in temperature are expected to have the largest impact on annual minimum temperatures occurring in the winter months (Harder et al., 2015).

The effects of temperature change differ throughout the region. High elevation regions throughout parts of the Montane Cordillera (e.g., Upper Columbia watershed) are projected to experience increases in snowpack, limiting the response in high elevation watersheds while lower elevations are projected to experience a decrease in snow water equivalent (Loukas & Quick., 1999; Schnorbus et al., 2014).

The Climate NA model provides downscaled climate projections for future conditions (Wang et al., 2016). The projections based on the Representative Carbon Pathway (RCP) 8.5 indicate that the mean annual temperature (MAT) in the Kuskonook Creek watershed is projected to increase from 3.1ºC (historical period 1961 to 1990) to 6.6 ºC by 2050 (average for projected period 2041 to 2070). The MAP is projected to increase from 1176 mm to 1237 mm while PAS is projected to decrease from 612 mm to 375 mm by 2050 (Table 3-3).

Table 3-3. Projected change (RCP 8.5, 2050) from historical (1961 to 1990) conditions for the Kuskonook Creek watershed (Wang et. al, 2016).

Climate Variable	Projected Change
Mean Annual Temperature (MAT)	+3.5 ºC
Mean Annual Precipitation (MAP)	+62 mm
Precipitation as Snow (PAS)	-237 mm

Changes in streamflow vary spatially and seasonally based on snow and precipitation changes and topography-based temperature gradients. Researchers anticipate that streamflow will increase in the winter and spring in this region due to earlier snowmelt and more frequent rain-on-snow events, while earlier peak discharge timing is expected in many rivers (Schnorbus et al., 2014; Farjad et al., 2016). Peak flows may increase or decrease depending on the watershed characteristics and the balance of temperature and precipitation changes in the future.

4. SITE HISTORY

4.1. Introduction

Kuskonook Creek flows through an unincorporated community of Kuskonook and into Kootenay Lake near the southern end of the Lake. Residents have lived on the alluvial fan since the late 1800s.

The First Nations name Kuskonook signifies 'End of the lake'. The name was established on January 26, 1898 when Kaslo and Slocan Railway president Daniel J. Munn and chief engineer John Hamilton Gray arrived to survey the townsite. According to an article by Nesteroff in the newspaper Nelson Star (August 16, 2015, see also article from August 9, 2015), there is the ongoing debate about the proper name spelling – Kuskonook vs. Kuskanook – of the community and its creek.

4.2. Document Review

In developing a flood, mitigation, and development history for Kuskonook Creek, BGC reviewed several documents, including:

- Archival records from the BC Archives and Nelson Touchstone Museum.
- Reports provided to BGC by RDCK (Table 4-1), including:
  - Precondition applications (building permit, subdivision, and site-specific exemptions, etc.).
  - Hazard assessments (flooding, post-wildfire, etc.).
- Reports provided to BGC by Ministry of Forests, Lands, Natural Resource Operations and Rural Development (MFLNRORD) (Table 4-1).
- Historical flood and landslide events from the following sources:
  - Social media and online media reports.
  - Septer (2007).
  - DriveBC historical events (2009 to 2017).
  - Canadian Disaster Database (Public Safety Canada, n.d.).
  - MFLNRORD.
- Historical wildfire perimeters (MFLNRORD, n.d.).
- Cutblock perimeters (MFLNRORD, n.d.)

Table 4-1. Previous reports and documents on Kuskonook Creek.

Year	Month/Day	Assessment Author	Purpose
1998	February 23	Klohn Crippen Consultants Ltd.	Alluvial and Debris Torrent Fan Inventory
2004	March – October	RDCK	Post-wildfire Hazard Assessment
2004	August 13	Kootenay Lake Forest District	Debris Flow Assessment
2005	January 21	Klohn Crippen Consultants Ltd.	Debris Event Analysis and Mitigation
2005		VanDine, Rodman, Jordan, and Dupas	Research Article
2006	December 15	O. Hungr Geotechnical Research Inc.	Debris Basin Review
2007	January 31	O. Hungr Geotechnical Research Inc.	Debris Basin Review
2007	August 31	Klohn Crippen Berger Ltd.	Debris Basin Construction Guidelines, Drawings and Quantities
2013	August 25-31	Jordan	Post Wildfire-Debris Flow Conference Presentation

4.2.1. Klohn Crippen Consultants (1998)

As part of a terrain stability inventory for alluvial and debris torrent fans in the Kootenay Region, Klohn Crippen Consultants (Klohn) reviewed Kuskonook Creek watershed and fan. The fan was described as being steep and round with a 'typical convex surface'. The channel was described as deeply incised near the apex with very low activity. Klohn noted that there was a water intake approximately 70 m upstream of the fan apex and the access road to the intake was a potential avulsion point. Klohn acknowledged that based on the steep gradient of the stream and fan that Kuskonook Creek could have a history of debris flows but that no contemporary evidence of events in the form of scoured channel, lobes or levees were observed and interpreted that, due to the deep incision of the channel near the apex and lack of debris accumulation upstream of the water intake weir, the fan experiences only fluvial activity (Klohn, 1998).

4.2.2. Jordan (2004)

Following the August 7, 2004 debris flow on Kuskonook, Peter Jordan, Research Geomorphologist provided a brief summary of the causes of the event to the Kootenay Lake Forest District (Jordan, 2004). The debris flow destroyed two houses and Highway 3A was closed for several days as described below and shown in Figure 4-1C. Jordan indicated that the most intense part of the 2003 wildfire occurred in the upper part of the Kuskonook Creek watershed. Based on the post-debris flow site visit, Jordan provided a series of observations and conclusions:

- Heavy rainfall on the night of August 6-7, 2004 was apparent by local anecdotal evidence although the high intensities do not show up in regional weather stations (Creston or Akokli Creek). Since this report, Jordan has estimated the rainfall to be a 5- to 10-year event (pers. comm. April 3, 2020).

- The areas that experienced the intense burn were hydrophobic (water-repellant due to organic compounds produced by the fire). The composition of soils in the Kuskonook watershed, reported to be coarse sandy soil were noted to be particularly prone to developing a hydrophobic layer in response to burns.
- Evidence of abundant overland flow was greatest in the areas that were most intensely burned, with a lesser amount observed where burn intensities were lower, and no evidence of overland flow was observed in areas of unburned forest.
- The debris flow initiated in the western most headwater channel (Kuskonook Creek Trib B, Drawing 03). The other two channels were not interpreted to have contributed significant sediment.
- The debris flow stripped the channel to bare bedrock by entrainment of sediment, soil, and woody debris.

Jordan (2004) estimated the volume of debris on the fan to be 10,000 m^3 (covering an area measuring approximately 150 m by 60 m to a depth of 1 m). Based on the deposition composition, Jordan described the event as a coarse, sandy, debris flow and noted that the observed deposition angle (15%) was consistent with this type of debris flow. Given that the debris flow stripped the channel and reduced the overall material availability, Jordan expected that future debris flows would be of smaller volume.

4.2.3. Klohn Crippen Consultants (2005)

In 2005, Klohn completed a Kuskonook Creek Debris Event Analysis and Mitigation report. The report indicates that Jordan revised the 2004 volume estimate of 10,000 m^3 (Jordan, 2004) to 28,000 m^3 (Klohn, 2005). Klohn outlined that damages from the 2004 debris flow included destruction of two houses, a Heritage Building, and a water supply system, along with damage to other buildings, unoccupied parked vehicles and a power pole. There were no deaths of injuries.

A second event occurred on September 11-12, 2004, with an estimated volume less than 1,000 m^3 comprised of finer material than the August 2004 debris flow. Klohn described this latter event as a debris flood. It also resulted in closure of Kuskonook Rd and Highway 3A and damage to Highway 3A culverts.

Klohn referred to dendrochronological analyses of the oldest trees on the fan growing on top of debris from a previous debris flow event that pointed to the last debris flow event being approximately a century prior to the 2004 event.

Klohn estimated an upper bound for future debris flow events in the Kuskonook Creek watershed as 40,000 m^3 using an empirical design debris volume relationship from coastal BC (VanDine, 1996); however, they indicated that this volume would require significant time for sediment and debris accumulation in the channel and in the short term, debris flows or debris floods could be anticipated to mobilize volumes up to approximately 12,000 m^3 (Klohn, 2005). Klohn developed an F-M relationship for Kuskonook Creek with associated estimated costs for mitigation structures (Table 4-2).

Table 4-2. Proposed debris event magnitude/frequency/cost relationship for Kuskonook Creek from Klohn (2005).

Frequency (Annual Probability)	Debris Volume (m^3)	Mitigation Structure Costs[1]	Most Probable Event Type
<1/10-year return period	<1,500	<$260,000	Small debris flood
1/10 – 1/50-year return period	1,500 – 15,000	<$260,000	Large debris floods, small debris flows
1/50 – 1/100-year return period	15,000 – 30,000	$260,000 to $550,000	Moderate debris flows
>1/100-year return period	>30,000	>$550,000	Large debris flow

Based on estimated probable costs provided in the Klohn (2005) report.

4.2.4. VanDine et al. (2005)

VanDine, Rodman, Jordan & Dupas (2005) completed an analysis of the Kuskonook Creek debris flows. The analysis included the development of a frequency-magnitude (F-M) relationship for future debris events on Kuskonook and a partial risk assessment was completed. Post-event photographs of the watershed, debris flow deposit and burned areas are included in Figure 4-1.

Based on stream morphometrics, VanDine et al, concluded that Kuskonook Creek is susceptible to debris flows, even in absence of wildfires. The proposed an F-M relationship as summarized in Table 4-3. They further propose, based on the partial risk assessment, that a 50-year return period event with an event volume of 50,000 m^3 be used for design of mitigation measures to protect users of Highway 3A.

Table 4-3. Debris event F-M relationship for Kuskonook Creek proposed by VanDine et al. (2005)

Frequency (Annual Probability)	Debris Volume (m^3)	Most probable event type
<1/10-year return period	<1,500	Debris flood or small debris flow
1/10 – 1/50-year return period	1,500 – 15,000	Moderate debris flow
1/50 – 1/100-year return period	15,000 – 30,000	Large debris flow
>1/100-year return period	>30,000	Very large debris flow

A) Overview photograph of the Kuskonook Creek watershed and fan-delta (VanDine et al, 2005).

B) Upper part of Kuskonook Creek watershed affected by the 2003 forest fire.

C) August 2004 debris flow deposit on Kuskonook Creek fan-delta. P. Jordan photo.

D) Debris on Kuskonook fan-delta. Maximum boulder size reported to be 1 m. D. VanDine photo.

E) Overland flow and erosion. M. Curren photo.

Figure 4-1. Post-2004 debris flow photographs of Kuskonook Creek watershed (A), burned area (B), debris flow deposits on the fan-delta (C, D), and overland flow and erosion (E) (VanDine, 2005).

4.2.5. O. Hungr Geotechnical Research Inc. (2006, 2007)

O. Hungr Geotechnical Research Inc. (OHGR) reviewed the Klohn (2005) report and estimated annual risk of loss of life on Kuskonook as: 1:1,700 (pre-fire conditions), 1:200 (post fire, pre-2004 debris flow), and 1:400 (conditions at time of writing allowing for 'relatively rapid recharged of debris in the main channels'). Estimates were also provided for conditions with the mitigation options presented by Klohn (2005) in place. OHGR acknowledged that these estimates are higher than existing standards of risk to residential developments but were not unusual compared to the risks on other highways in BC (OHGR, 2006; 2007). The event volume estimates from UHGR are summarized in Table 4-4.

Table 4-4. Debris-flow event volumes and return periods from OHGR (2007).

Return Period (years)	Event Volume (m^3)
10	1500
50	15,000
100	30,000

4.3. Historic Timeline

Figure 4-2 provides a timeline summary of geohazard events and mitigation history for Kuskonook Creek. For location references, refer to Drawings 01, 02A, and 02B. The historical event inventory is assumed to be incomplete, but the information contained within it can be used to identify the location of past geohazards events and associated consequences of these events. From this information, the following can be concluded:

- A forest fire burned a large portion of the Kuskonook Creek watershed in 2003.
- A post-wildfire debris flow and debris flood occurred in the year after the forest fire.
- A debris flow mitigation structure was constructed on the fan in approximately 2008.
- Water levels at the toe of the fan are influenced by the reservoir levels on Kootenay Lake.

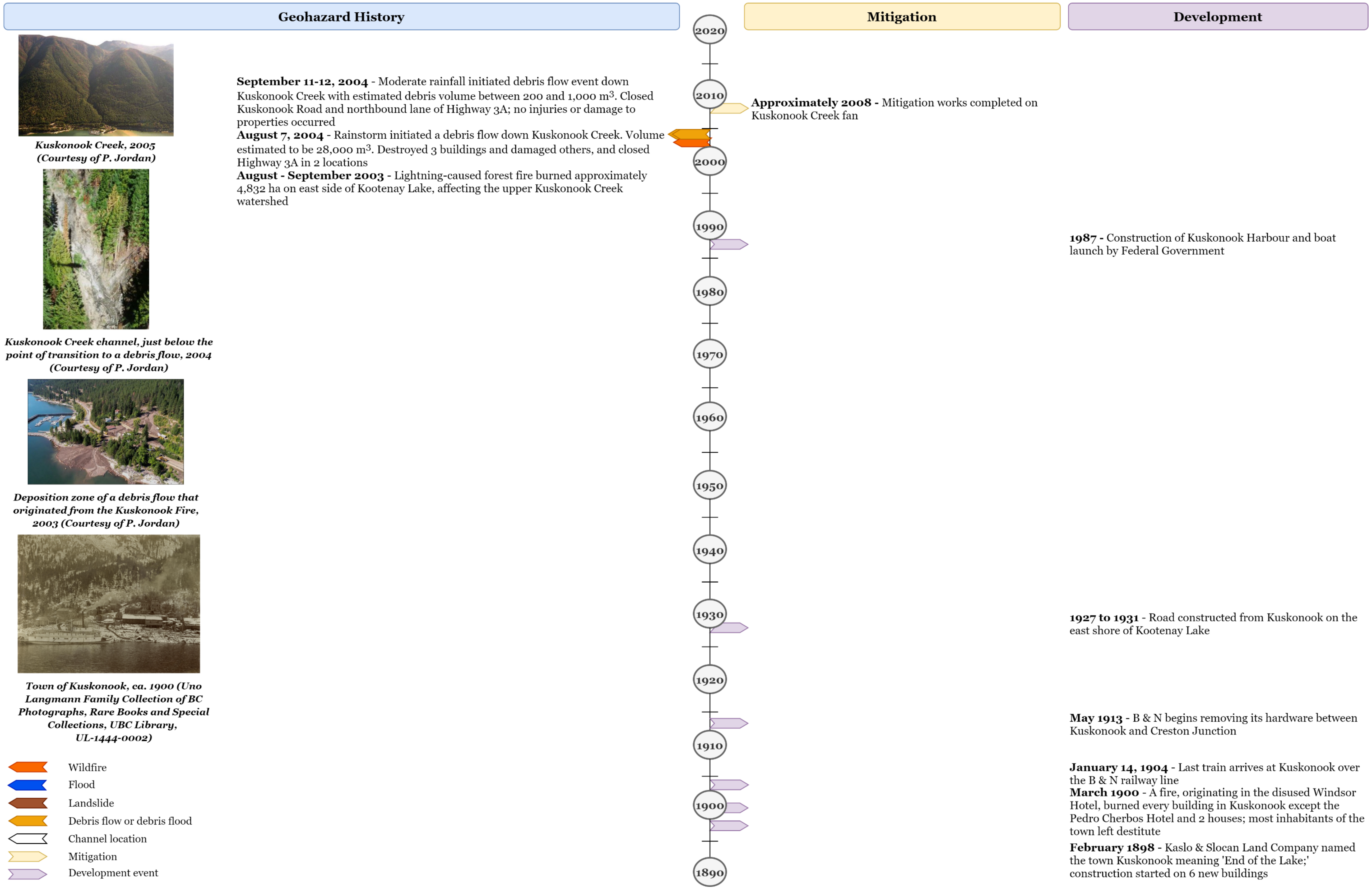

Figure 4-2. Summary of recorded geohazard, mitigation, and development history at Kuskonook Creek.

5. METHODS

The overall assessment methodology applied to the nine flood and debris flood prone steep creeks in the RDCK is summarized in the Methodology Report (BGC, March 31, 2020b). This section summarizes the overall workflow as well as any specific deviations from the steep creek methodology applied at Kuskonook Creek. Figure 5-1 shows the workflow to develop frequency-magnitude (F-M) relationships for Kuskonook Creek and other flood and debris flow prone creeks in the RDCK.

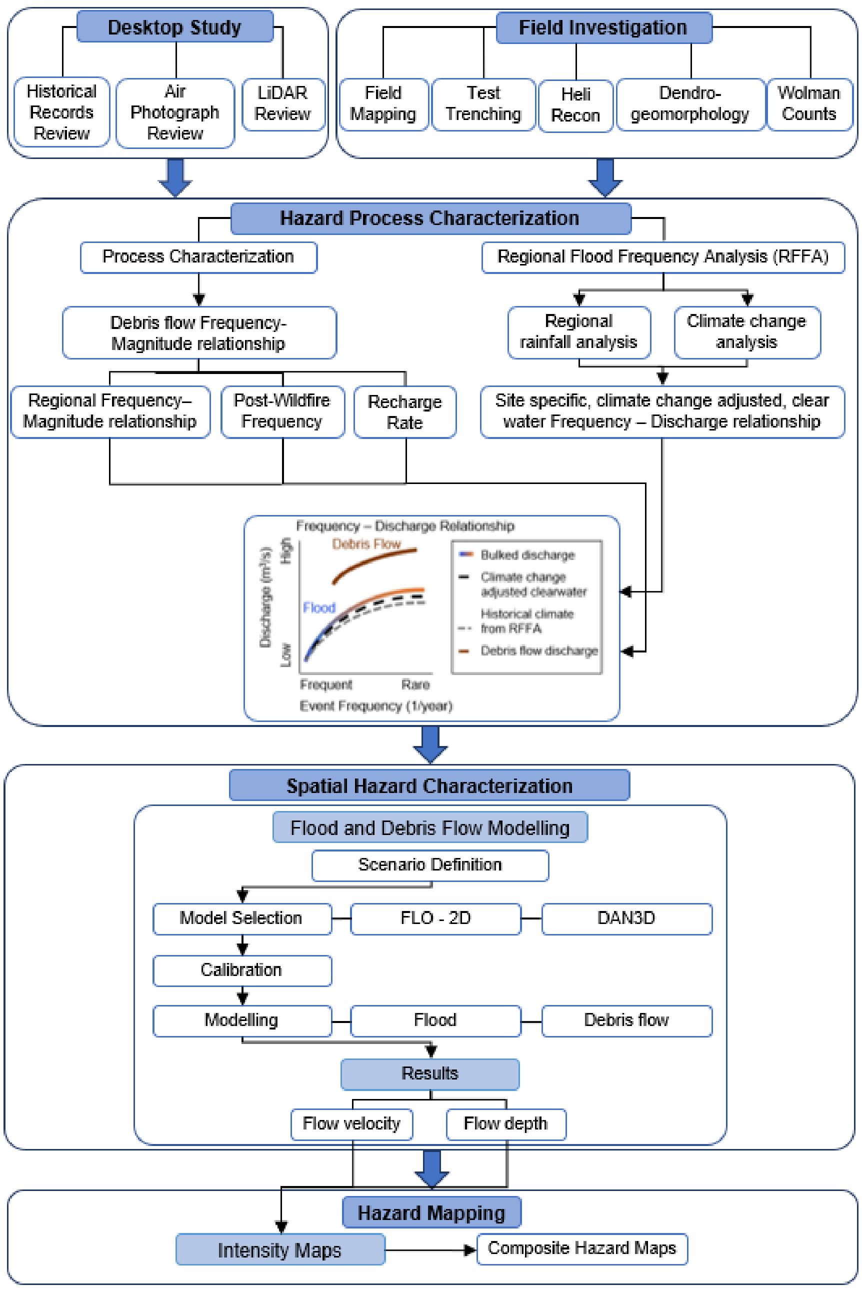

Figure 5-1. Flood and debris flow prone steep creeks workflow used for developing frequency-magnitude relationships, modelling, and preparing hazard maps.

5.1. Frequency-Magnitude Relationships

An F-M relationship answers the question “how often (frequency) and how big (magnitude) can steep creek hazards events become?”. The ultimate objective of an F-M analysis is to develop a graph that relates the frequency of the hazard to its magnitude. For this assessment frequency is expressed using return periods[4], and both peak discharge (for clearwater flows and debris flows) and volume (only for debris flows) are used as measures of magnitude. For more background on F-M the reader is referred to the Methodology Report (BGC, March 31, 2020b).

BGC assessed Kuskonook Creek for the 20-, 50-, 200-, and 500-year return periods. At these return periods, the hydrogeomorphic process was identified as clearwater flood at the 20-year return period and debris flow for the higher (50-, 200- and 500-year) return periods based on previous event observations and stream morphometrics.

A detailed discussion of the methodology is provided in Section 2 of the Methodology Report (BGC, March 31, 2020b).

5.2. Debris Flow Frequency Assessment

This section combines the methods employed to estimate debris flow frequencies from remote sensing and empiricism paired with air photo interpretation.

5.2.1. Air Photo Interpretation

Air photos dated between 1945 and 2017 were examined for evidence of past sediment transport events on Kuskonook Creek. A complete list of the air photos reviewed is included in Appendix C. Events were identified from the appearance of bright areas and disturbed vegetation relative to previous air photos that is indicative of debris flow deposits. Smaller events that did not deposit sediment outside the channel or significantly change the course of the channel are not captured in this analysis. Similarly, events that occurred during large gaps between air photos or successive events that overlap may also not be identified by this approach. Air photo interpretation was supplemented by historical records of past events (Section 4).

5.2.2. Post-Wildfire Debris-Flow Frequency

There have been two recorded post-wildfire debris flows in the Kuskonook Creek watershed (Jordan, 2004) which highlights that post-wildfire debris flows are a possible hazard in Kuskonook Creek. Evidence of post-wildfire erosion and sediment transport was identified during BGC excavations on the distal reaches of Harrop Creek fan, located approximately 50 km northwest of Kuskonook Creek, that identified abundant charcoal overlying sandy or gravelly flood units. Post-wildfire debris flows are a common occurrence in the dry areas of southern and south-western BC (Jordan & Covert, 2009; Jordan, 2013).

Post-wildfire debris flow frequencies can be estimated by combining the probability of a wildfire occurring with that of a potential debris flow triggering storm occurring in the critical post-wildfire period, which is about 2 years (Cannon & Gartner, 2005). For example, in a region with a 100-year

[4] Except for periods of T<1, the return period (T) is the inverse number of frequency F (i.e., T=1/F).

fire frequency, the post-wildfire debris flow probability of a watershed impacted by a storm with a 10-year return period within the first two years after the fire would be 0.002 (which is equivalent to a 500-year return period).

Regional analysis for southeastern BC indicates that the historic frequency of a stand-replacing wildfire in the vicinity of Kuskonook Creek ranges between 35 years (at lower elevation) and 100 years (higher elevation) (Blackwell, Grey, & Compass, 2003, see Figure 5-2).

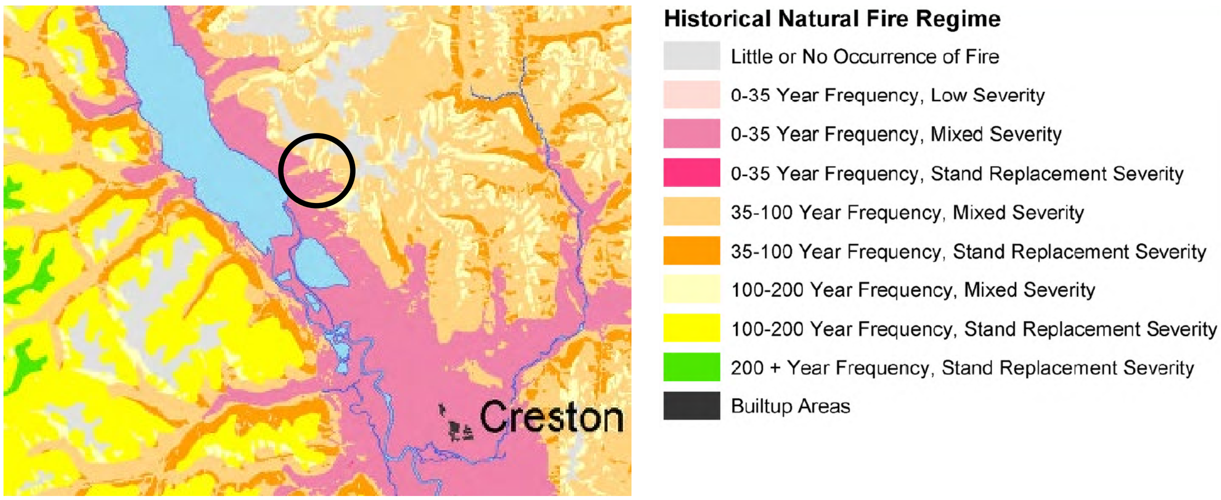

Figure 5-2. Cut-out image of historic natural fire regime (Blackwell, Grey, & Compass, 2003). The Kuskonook watershed is circled in black.

One wildfire has occurred in the Kuskonook watershed in the air photo record. Jordan (2004) reported that a wildfire also ravaged the community of Kuskonook at the turn of the 19th century destroying buildings on the fan. These observations may suggest a 1:50-year fire frequency. However, the frequency of wildfire will likely increase at Kuskonook Creek in the future due to progressive warming and loss of winter snowpack (Kirchmeier-Young et al., 2019; Westerling et al., 2006).

Previous research in California and Colorado has demonstrated that even a 2-year return period storm, which has a 50% chance of occurring in any given year, can trigger a debris flow (Cannon et al., 2008; Staley et al., 2020). It is not clear if this is the case in southeastern BC (Jordan, pers. comm. 2020) as there is a pronounced general decrease in rainfall intensity from California to BC for all durations. This said, the 2-year return period, 15-minute rainfall from Creston (a nearby ECCC station with rainfall intensity-duration-frequency data [IDF]) exceeds the rainfall thresholds for debris-flow initiation defined for Colorado and California within the first year after a fire (Cannon et al., 2008; Cannon et al., 2011). This suggests that even relatively frequent (2-year) storm events could be sufficient to trigger post-wildfire debris flows in the RDCK if all other factors (soil composition and fire alteration, burn severity, and geomorphology) were similar.

5.3. Debris Flow Sediment Volume Estimates

5.3.1. Yield Rate Approach

One can estimate the volume of potential debris recruited by a debris flow by estimating the volume of debris stored in a channel. This is done by choosing reaches with relatively homogenous channel geometry and debris fill characteristics and noting their segmental debris volumes expressed as cubic meters per metre channel length (m^3/m). By summing all channel reaches one can arrive at the total potential debris volume (Hungr et al. 1984; Jakob, 2005). This method is strongly dependent on the time since the last debris flow or major flood capable of transporting sediment out of a given reach. Given that the time since the last debris flow is known (15 years), it should be possible to estimate the recharge that has occurred since and compare it with numerical estimates of recharge based on studies elsewhere. BGC did not hike the channel as the underbrush was so dense in various stream sections that a reasonable estimate of colluvium would be hampered. Moreover, several waterfalls would not have allowed a safe full ascent. BGC did, however, conduct numerous helicopter overflights and obtained a reasonable estimate of channel yield rates.

5.3.2. Recharge Rate Approach

Of interest in this analysis is the time required for sediment to accumulate along the channel substrate, which is a pre-requisite for debris-flow initiation. For relatively small watersheds in coastal areas of BC, channel recharge typically occurs over a long period (decadal to century scale) through raveling and sloughing from side slopes and minor landsliding from adjacent valley slopes (Jakob, Bovis & Oden, 2005). When debris flows occur, a majority of this in-channel sediment is transported onto the fan.

Channel recharge rates can be estimated by the research of Jakob et al. (2005). In that work, the authors provided predictive equations for time-normalized channel recharge rates from southwestern BC and Haida Gwaii (formerly the Queen Charlotte Islands). The southwestern BC dataset is heavily biased by creeks in volcanic rocks that recharge very quickly. However, the Haida Gwaii non-logged dataset may be a suitable analog for Kuskonook Creek should the watershed be allowed to recover from the wildfire and not be subject to timber harvesting:

$$R_t = 0.2t_e^{-0.49} \qquad \text{[Eq. 5-1]}$$

where R_t is the normalized recharge rate and t_e is the time since the last debris flow.

Assuming timber harvesting to occur, then the following equation may be more applicable:

$$R_t = 0.3t_e^{-0.77} \qquad \text{[Eq. 5-2]}$$

The results from both equations are discussed in Section 6.3.

5.3.3. Empirical Estimates for Post-Wildfire Debris-Flow Volumes

Empirical models for predicting post-wildfire debris-flow volumes (e.g., Cannon et al., 2010; Gartner et al., 2014) can be used to assess hazards posed by debris flows following wildfires. These models predict volumes of material that may flow past a given point along a debris flow channel. The Gartner et al. (2014) model is currently used by the U.S. Geological Survey (USGS) for emergency assessments of post-wildfire debris-flow hazards (available online at https://landslides.usgs.gov/hazards/postfire_debrisflow/). The inputs for the model include the contributing watershed area burned at moderate and high severity[5], the relief of the contributing watershed area, and the storm rainfall intensity measured over a 15-minute duration. The model is applicable for up to two years following the wildfire, after which plant re-growth and/or source area sediment depletion render it less reliable.

The Gartner et al. (2014) model was developed using data from southern California and has not been tested in southeastern BC. To affirm that the general methodology of the model is valid in southern BC, a comparative analysis was conducted in which the predicted and observed debris-flow volumes were compared. This comparative analysis involved the following steps:

1. A database on post-wildfire debris flows in southeastern BC compiled by Jordan (2015) was accessed and relevant data for estimating debris flow volumes using the Gartner et al. (2014) model were extracted.
2. The Jordan (2015) dataset did not contain reliable short-duration rainfall data from nearby rain gauges that are needed to implement the Gartner et al. (2014) model. Therefore, BGC used IDF data from the Creston climate station to approximate the rainfall conditions. The rainfall data used included the 15-minute rainfall intensity for the 2-, 5-, 10- and 25-year return periods, with this range capturing the parameter uncertainty.
3. The observed debris flow volumes reported in Jordan (2015) were compared to volumes predicted by the Gartner et al. (2014) model using watershed data from Jordan (2015) and rainfall IDF data from the Creston climate station. The comparison is shown in Figure 5-3. The ratios between the observed and predicted volumes were also calculated.

[5] Burn severity describes the degree of vegetative loss in a burned area and is considered a proxy for the hydrologic changes to the soil due to the wildfire.

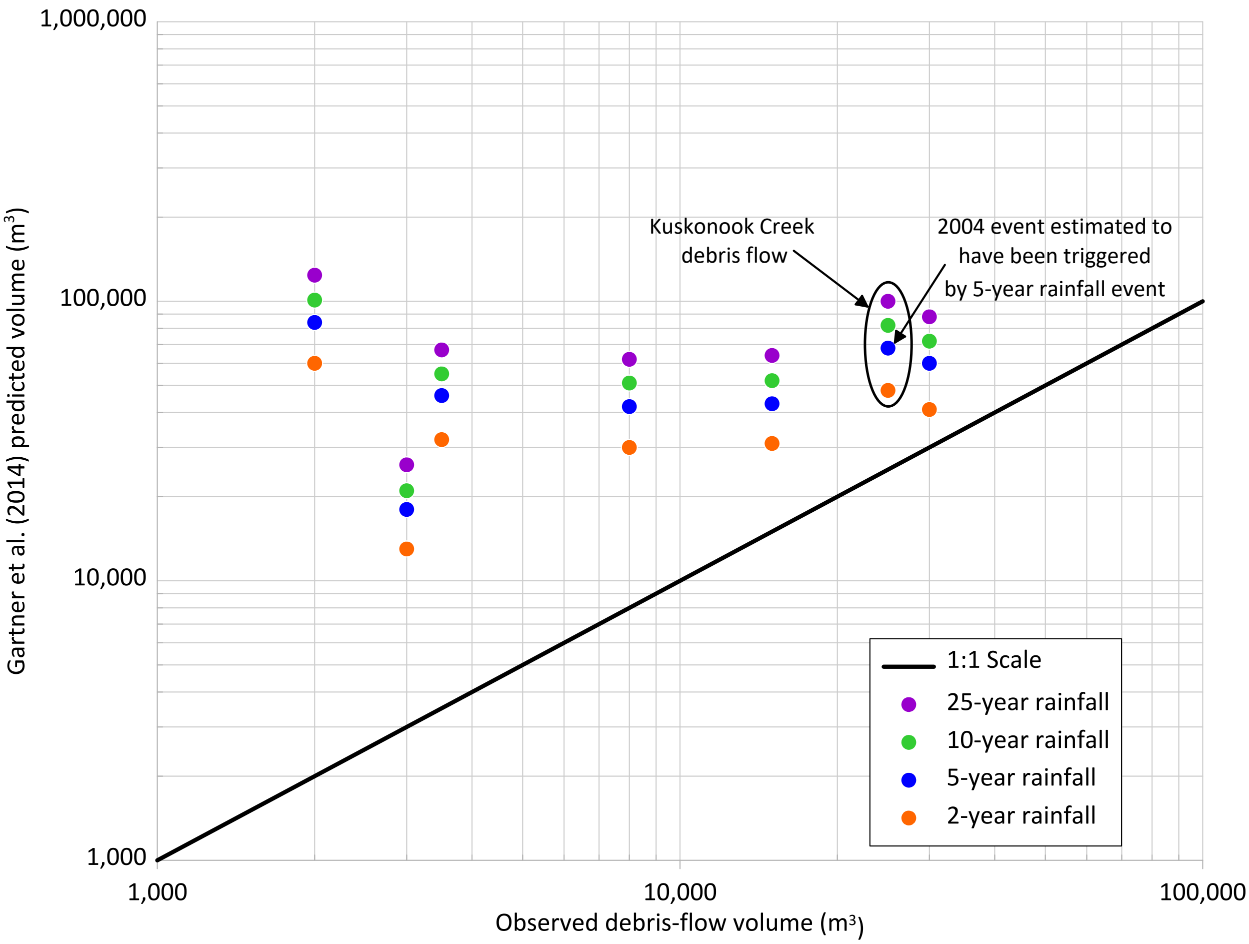

Figure 5-3. Correlation between observed (Jordan, 2015) and Gartner et al.'s (2014) model debris flow volume predictions. Note the outlying Ingersoll 10 data (far left dataset). The black line is a 1:1 line and values above this line are overpredicted. The ratio between the measured volume of the 2004 Kuskonook debris flow and the volume predicted by the Gartner et al., (2014) model using the 5-year rainfall is 0.37.

The comparisons shown in Figure 5-3 demonstrate that the Gartner et al. (2014) model overpredicts the available debris-flow dataset in southeastern BC by at least a factor of 2. Because the occurrence of post-wildfire debris flows is much less frequent in southeastern BC than southern California, it is not surprising that the Gartner et al. (2014) model, which is based on data from southern California, would overpredict debris-flow magnitudes in southeastern BC. At Kuskonook Creek, a measured volume can be used to directly compare Gartner et al., (2014) model estimates to post-wildfire debris flow volumes at Kuskonook Creek. A rainfall event with a 5-year return period was assumed to have triggered the 2004 debris flow. The ratio of the measured volume of the 2004 Kuskonook debris flow (25,000 m^3) and the volume predicted by the Gartner et al. (2014) model (68,000 m^3) is 0.37. Therefore, BGC considers it reasonable to apply a multiplier of 0.37 to the Gartner et al. (2014) model results when applying this model to Kuskonook Creek.

For this assessment, the "emergency assessment model" in Gartner et al. (2014) was used to estimate post-wildfire debris flow volumes at the fan apex of Kuskonook Creek. BGC estimated the debris-flow volume for Kuskonook Creek assuming that a wildfire affects two-thirds of the watershed at a moderate to high burn severity, which appears to be a reasonable value according to the Jordan (2015) dataset.

The ”emergency assessment model” from Gartner et al. (2014) is applicable for two years after a wildfire, after which time vegetation regeneration leads to progressive watershed recovery from the effects of wildfire and debris flows become quickly less likely. In that two-year period, BGC investigated what debris-flow volumes would be generated from rainfall events with intensities corresponding to 5-year and 10-year return periods (annual probabilities ranging from 0.2 to 0.1). Rainfall intensities were obtained from the IDF curves for Creston, located approximately 30 km south of Kuskonook Creek.

Section 6.3.7summarizes the results from this analysis.

5.4. Peak Discharge Estimates

5.4.1. Clearwater Peak Discharge Estimation

There are no hydrometric stations on Kuskonook Creek, therefore peak discharges (flood quantiles) were estimated using a regional flood frequency analysis (Regional FFA) and compared with the results from previous studies. The regionalization of floods procedure was completed using the index-flood method. For this project, the mean annual flood was selected as the index-flood and dimensionless regional growth curves were developed from Water Survey of Canada (WSC) data to scale the mean annual flood to other return periods. The index-flood for Kuskonook Creek was determined from watershed characteristics. The index-flood was estimated using a regional and provincially based ensemble of multiple regression models. Based on its watershed characteristics, the Kuskonook Creek watershed was assigned to the ‘4 East hydrologic region for watersheds less than 500 km^2’. Details of the Regional FFA are presented in Section 3 of the Methodology Report (BGC, March 31, 2020b).

5.4.2. Climate-Change Adjusted Peak Discharges

The Engineers and Geoscientists British Columbia (EGBC) offer guidelines that include procedures to account for climate change when flood magnitudes for protective works or mitigation procedures are required (EGBC, 2018). The impacts of climate change on peak discharge estimates in Kuskonook Creek were assessed using statistical and processed-based methods as per Section 4 of the Methodology Report (BGC, March 31, 2020b). The statistical methods included a trend assessment on historical flood events using the Mann-Kendall test as well as the application of climate-adjusted variables (mean annual precipitation, mean annual temperature, and precipitation as snow) to the Regional FFA model. The process-based methods included the trend analysis for climate-adjusted flood and precipitation data offered by the Pacific Climate Impacts Consortium (PCIC).

The results of the statistical and process-based methods were found to be inconsistent across the RDCK by 2050 (2041 to 2070). The climate change impact assessment results were difficult to synthesise in order to select climate-adjusted peak discharges on a site-specific basis. The assessment of the trends in the discharge records was inconclusive. The results of the statistical flood frequency modelling generally show a small decrease in the flood magnitude, while the results of the process-based discharge modelling generally show an increase with a wide range in magnitude. As a result, peak discharge estimates were adjusted upwards by 20% to account for the uncertainty in the impacts of climate change in the RDCK as per Section 4 of the Methodology Report (BGC, March 31, 2020b).

5.4.3. Sediment Concentration Adjusted Peak Discharges

For debris-flood prone creeks, BGC accounted for expected flow bulking from organic and mineral sediment by multiplying the climate adjusted clearwater discharge with a bulking factor specific to each return period as outlined in Section 2 of the Methodology Report. For Kuskonook Creek, this method is not appropriate as debris floods are not considered a credible hazard. Kuskonook Creek is thought to produce either high streamflow (i.e., a clearwater flood) or a debris flow, if associated with an upper watershed landslide or a post-wildfire runoff concentration.

5.4.4. Debris Flow Peak Discharge

Debris-flow peak discharge was estimated using a method developed by Bovis and Jakob (1999), who provide empirical correlations between peak discharge and debris-flow volume based on observations of 33 debris flow basins in southwestern British Columbia (Figure 5-4). This relationship was constructed for "muddy" debris flows and "granular" debris flows. Muddy debris flows are those with a relatively fine-grained matrix as found from volcanic source areas or fine-grained sedimentary rocks, while granular debris flows are those typical for granitic source areas with large clasts embedded in the flow which slow the flow through friction thus creating large surge fronts. For many (not all) post-wildfire debris flows, the initiation occurs via progressive bulking of flows (Cannon & Gartner (2005) quote some 75% bulked by runoff-dominated erosion). This occurs via rilling and gullying in recently burned terrain and sometimes hydrophobic (water repellent) soils have developed. The peak discharge of debris flows initiated by runoff-dominated erosion contrasts debris flows initiated by infiltration-triggered landslide mobilization. The latter results in comparatively higher peak flows.

VanDine et al. (2005) estimated the volume of the 2004 debris flow on Kuskonook Creek at 20,000 m^3 to 30,000 m^3 (VanDine et al., 2005). Solving the muddy and granular equations in Figure 5-4 for Q, one obtains:

$$Q_{muddy} = 0.03 \cdot V^{1.01} \qquad \text{[Eq. 5-3]}$$

$$Q_{granular} = 0.04 \cdot V^{0.9} \qquad \text{[Eq. 5-4]}$$

Equation 5-3 yields a peak flow estimate on Kuskonook Creek for the 20,000 and 30,000 m^3 range quoted by VanDine et al. (2005) of 70 to 100 m^3/s, while Equation 5-4 yields a peak discharge of (rounded) 300 and 430 m^3/s. VanDine et al. (2005) reported a back-calculated discharge range of 200 to 480 m^3/s for the 2004 Kuskonook Creek debris flow which would indicate that this debris flow had more granular than muddy characteristics. However, the debris-flow initiation was described to be a channel bed and bank failure at a point where the channel slope increased (VanDine et al., 2005; Hope et al., 2015). This initiation by bed and bank failure and the resultant peak discharge may be more similar to a debris flow initiated by infiltration triggered landslide mobilization than a debris flow initiated by runoff dominated erosion following a wildfire. Given the precedent of an event that had more granular than muddy characteristics, BGC estimated peak discharges on Kuskonook Creek using Equation 5-4.

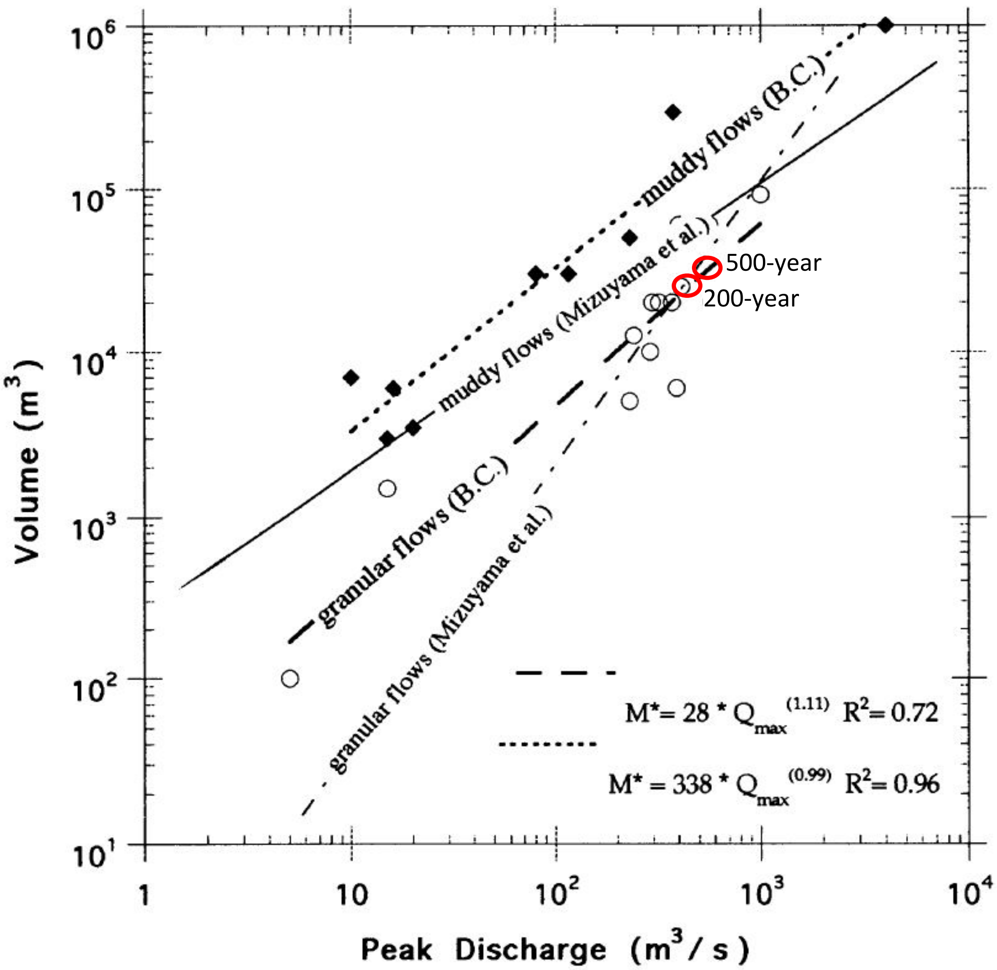

Figure 5-4. Bovis and Jakob (1999) relationship between peak discharge and volume for British Columbia, with comparison regressions computed by Mizuyama et al. (1992).

Using debris flow volumes from the F-M curve (Section 5.3.3), the expected peak discharge is used as a model input.

5.5. Numerical Flood and Debris Flow Modelling

Kuskonook Creek floods were modelled for the 20-year return period flood and debris flows were modeled for 50-, 200- and 500-year return periods. Details of the numerical modelling techniques are summarized in Section 2 of the Methodology Report (BGC, March 31, 2020b) and Section 5.5.1 below. The 20-year return period event was modeled with FLO-2D (Version 19.07.21), a Federal Emergency Management Agency (FEMA) approved model.

DAN3D (McDougall & Hungr, 2004; 2005) was used to model debris flows on Kuskonook as the modelling software can simulate the physics of superelevation in a channel bend, a functionality that FLO-2D does not possess. DAN3D was developed specifically for the analysis of rapid landslide motion across complex 3D terrain and is well-suited to the simulation of coarse debris flows that deposit on relatively steep slopes, like the Kuskonook Creek fan-delta. BGC has used DAN3D for the same purposes on other projects. As the infrastructure on this creek directs the flow through a steep, sharp bend, being able to best represent the super elevation was considered essential in the modelling to best capture what would happen during a debris flow event.

Topography for both software packages was developed with lidar flown in 2017 using a 5 m grid. Manning's *n* values were input in FLO-2D as detailed in Table 5-1, while DAN3D does not require a Manning's n input since resistance is included in the rheological parameters in DAN3D. Modelling a downstream lake level for Kuskonook Creek was not considered necessary as the lake level would have negligible effects on modelling results due to the configuration of the culverts that outlet the creek into Kootenay Lake as well as due to the magnitude of the debris flows modelled. Further details on modelling methods are presented in Section 2 of the Methodology Report (BGC, March 31, 2020b) for FLO-2D and in Section 5.5.1 below for DAN3D.

Table 5-1. Summary of Manning's n values used in FLO-2D.

Location	Value
Channel	0.06
Main roads	0.02
Fan	0.10

A series of modelling scenarios were developed for Kuskonook Creek as presented in Appendix D. Modelling scenarios include different return periods and culvert capacities.

BGC did not attempt to assign conditional probabilities to each hazard scenario or sub-scenario. Those would need to be estimated for a quantitative risk assessment which would support the choice and scale of mitigation measures.

5.5.1. DAN3D Basic Setup and Input Parameters

The debris flow models were run on a grid created from a DEM constructed from lidar dated 2017. Grid spacing was set at 5 m as this is a typical grid size used in the simulation of flows of this magnitude. The grid was subsequently smoothed to reduce sharp features in the model that can lead to numerical instabilities or unrealistic model behaviours.

The models were run with the source volume initiating just upstream of the paleofan (shown on Drawing 05) within the active channel (900 m upstream of the Kuskonook fan-delta apex). The source was placed at the apex of the paleofan to provide enough time for the model flow depths and velocities to stabilize before they reached the apex of the modern fan-delta. The modelled volume was determined based on the frequency magnitude curve as discussed in Section 6.3.8. Material entrainment was not considered in this model. The modelled discharge was compared to the estimated peak discharge at each return period to confirm they had an acceptable match.

Debris-flow modelling also requires the definition of rheological parameters, which inform the flow behaviour of the water and debris slurry. There are several rheological models available in

DAN3D, with the Voellmy rheology being commonly used for debris flows. The Voellmy model is governed by two parameters: 1) a friction coefficient (f), which determines the slope angle on which material begins to deposit (i.e., if the friction coefficient is higher than the local slope gradient, material will decelerate and begin to deposit); and 2) a turbulence parameter (ξ), which produces a velocity-dependent resistance that tends to limit flow velocities (similar to air drag acting on a falling object). These parameters can be modified during model calibration in order to achieve the best possible match with the behaviour of known events. Neither variable is directly measured from observed events.

For Kuskonook Creek, although there has been a known event, the fan topography has been significantly altered since the event and no pre-event topography is available. Therefore, the rheological parameters have been checked against the flow characteristics from the 2004 event and against a calibration case of a similar fan in BC (Bear Creek). The rheological parameters are presented in Table 5-2.

Table 5-2. Rheological parameters used in DAN3D modelling.

Friction Coefficient	Turbulence Coefficient
0.011	530

These parameters are generally consistent with other calibrations of highly mobile debris flows in BC using DAN3D.

5.6. Hazard Mapping

BGC prepared hazard maps based on the results from the numerical flood and debris flow modelling. Bank erosion on the fan was not considered for two reasons: First, banks are not believed to be susceptible to erosion during unconfined flow over the fan should debris flows avulse. Second, the banks in the basin are armoured and will be protected by erosion once the basin fills and creates a depositional slope.

BGC prepared two types of steep creek hazard maps for Kuskonook Creek: flood and debris flow model result maps and a composite hazard rating map. The model result maps support emergency planning and risk analyses, and the composite hazard rating map supports communication and policy implementation, as described further below.

5.6.1. Flood and Debris Flow Model Result Maps

Model result maps display the following, for each scenario considered:

1. The hazard intensity and extent of inundated areas from FLO-2D and DAN3D modelling.
2. Areas of sediment deposition extracted from DAN3D modelling.

FLO-2D and DAN3D model outputs include grid cells showing the velocity, depth, and extent of flood and debris flow inundation. These variables describe the intensity of an event. Hazard quantification needs to combine the intensity of potential events and their respective frequency. Sites with a low probability of being impacted and low intensities (for example, slow flowing ankledeep muddy water) need to be differentiated from sites that are impacted frequently and at high intensities (such as water and rocks flowing at running speed). For the latter, the resulting geohazard risk is substantially higher and development must be more restrictive than the former.

5.6.2. Composite Hazard Rating Map

BGC prepared a “composite” hazard rating map that displays all modelled scenarios together on a single map. The composite hazard rating map is intended for hazard communication and decision making, where different zones on the map may be subject to specific land use prescriptions, covenants, bylaws or other limiting clauses for both existing and proposed development.

Given their application in policy, the composite map provided with this assessment is subject to further review and discussion with RDCK. Even where the underlying hazard scenarios do not change, cartographic choices (i.e., map colours and categories) can influence interpretation of the maps. BGC anticipates that discussions about hazard map application in policy will extend beyond final report delivery, and that these discussions may lead to further modifications of the composite hazard rating maps.

The composite hazard rating map is based on an impact intensity frequency (IIF) geohazard mapping procedure that consists of two principal components: the intensity expressed by an impact force and the frequency of the respective events. The underlying equation is:

$$IIF = v^2 \times \rho_f \times d_f \times P(H) \qquad \text{[Eq. 5-5]}$$

where v is flow velocity (m/s), d_f is the fluid’s flow depth (m), ρ_f is the fluid density (kg/m^3) to obtain a unit of force per metre flow width for the three left terms in Equation 5-5 and $P(H)$ is the annual probability of the geohazard. The unit of IIF is then Newton or kilo Newton per metre per year (kN/m per yr).

Equation 5-5 can be translated into a matrix in which the impact force (*IF*) is on one axis and the return period (annual probability or *P(H)*) on the other. The matrix is then colour-coded to indicate the total hazard from yellow (low hazard) to dark red (extreme hazard) (Figure 5-5).

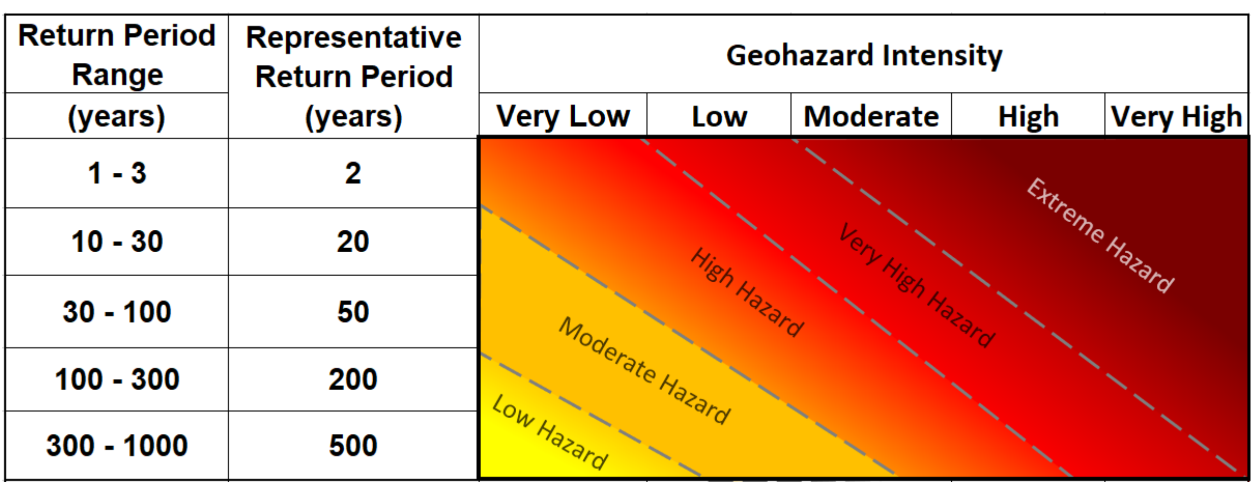

Figure 5-5. Simplified geohazard impact intensity frequency matrix.

The advantage of this mapping type is that a single map immediately codifies which areas are exposed to what hazard. Given that impact force is a surrogate for the destructiveness of a geohazard, *IIF* maps are relative proxies for risk assuming elements at risk are present in the specific hazard zones and the loss(es) associated with an event scale with impact force. For clarity, the values do not represent an absolute level of risk, which also depends on their vulnerability and their being present in the hazard area at the time of impact.

Interpreted hazard maps showing *IIF* values were developed for each return period class at all locations within the study area. For the individual hazard scenario maps that are added to the Cambio web application, the raw (no interpretation nor zone homogenization) impact force modelling results are presented. For the composite hazard rating map, the different intensities were interpreted by BGC to homogenize zones into easily identifiable polygons that are likely to fall into the range of intensity bins reported above. In some cases, individual properties may have been artificially raised and are thus less prone to debris flow impact. Such properties would need to be identified at a site-specific level of detail, for example, if the owner wishes to subdivide or renovate and ask for an exemption to existing bylaws.

6. RESULTS

6.1. Hydrogeomorphic Process Characterization

Figure 3-2 indicates that Kuskonook Creek is prone to debris flows. This result is consistent with the following evidence:

- The creek produced a debris flow in 2004.
- The average channel gradient above the fan apex is greater than 35% (Drawing 03), which allows sustained debris flow transport.
- The average fan gradient of 25% is typical of creeks prone to debris flows.
- A cut into the fan deposits on the northern fan portion shows sediments typical for debris flows (i.e., matrix supported, poorly sorted angular clasts).

Together, this evidence indicates that Kuskonook Creek is subject to channel supply-limited debris flows for return periods greater than 20 years. Two types of triggers are conceivable. Given the paucity of previous debris flows observed on air photos or historic accounts, rainstorm-triggered debris flows in absence of wildfires likely need to exceed a 100-year return period to initiate a debris flow. For post-wildfire conditions the trigger rainstorm is conditioned on the location and severity of the wildfire.

6.2. Frequency Assessment – Air Photo and Historical Record Interpretation

Results of the debris flow frequency assessment are presented in this section. As noted above, Kuskonook Creek is believed to be subject to clearwater floods for the 20-year return period and debris flows for higher return periods (50-, 200- and 500-year).

At least two notable hydrogeomorphic events have occurred since 1945 as identified from the air photo interpretation and historical records. Drawings 04A and 04B show air photos with events delineated. The August 2004 debris flow event is delineated on the 2006 air photo. As the 2004 event caused significant damage, it was a well-studied event that did not require further interpretation from BGC. VanDine et al. (2005) interprets the volume to be between 20,000 and 30,000 m^3. As outlined in Klohn (2005), Jordan estimated a volume of 28,000 m^3. Average deposit depths on the fan were reported by Jordan (2004) of just over 1 m.

The other event noted in the historical record, a debris flow in September of 2004, was not visible in the air photos as it is difficult to discern between the larger debris flow event earlier in the same year. BGC classifies this event as a debris flow due to the steep gradient of Kuskonook Creek and the deposition morphology. A volume of 1000 m^3 was deposited across the highway during this event according to Klohn (2005) records.

Both events are considered post-wildfire events as they happened within a year of a significant portion (60%) of the watershed burning severely in 2003 (VanDine et al., 2005).

6.3. Frequency-Magnitude Relationships

6.3.1. Introduction

This section provides the reasoning for the compilation of various F-M approaches and F-M ensemble curves from which a best estimate is extracted. Several techniques were combined to obtain the most reasonable F-M curve available.

6.3.2. Flood Frequency Assessment

The dominant hydrogeomorphic hazard at Kuskonook Creek is debris flow. However, for completeness, the flood frequency analysis is included. This is also useful to design specific outlet structures for floods should the present design be altered or amended.

6.3.3. O. Hungr Geotechnical Research Inc. (2007) Frequency-Magnitude Approach

In 2007, O. Hungr Geotechnical Research Inc. (OHGR) provided a debris basin review report to the BC Ministry of Transportation. In it, OHGR generally agreed with the technical aspects of Klohn who had produced a report in 2005. OHGR expressed concern of the Klohn report use of the 1:475 hazard probability limit. OHGR questioned the use of the 1:475 hazard probability which was meant for subdivision approvals rather than for highways, arguing that society could not afford mitigation for all landslide hazards at this probability affecting the provincial highway network. Other key observations as they pertain to this report are:

1. Between the fan apex and 1200 m elevation, the 2004 debris flow had eroded to bedrock setting the yield rate “clock” back to zero except for a 300 m long reach downstream of elevation 750 m where OHGR estimated a yield rate of 3 m^3/m. He also estimated that over time the recharge will increase to 8 m^3/m as it was estimated prior to the 2004 debris flow. OHGR estimated 20 to 50 years of recharge to reach pre-2004 conditions, however no evidence is provided to ascertain this estimate.
2. Upstream of elevation 1200 m, photos by Mr. G.D. Bysouth showed deep colluvial deposits with unstable banks with a potential yield rate (in 2007) of approximately 5 m^3/m with local deviations up to 20 m^3/m.
3. The upper gullies had scoured to bedrock, but two creek branches were considered to be able to trigger debris flows up to 5000 m^3 which would be included in a future debris flow in the long term.
4. Given the above estimates, OHGR estimated debris-flow volumes of 14,000 m^3 in the short term (20 years from 2007, so by approximately the year 2027), and up to 30,000 m^3 by approximately 2057. This implies that there are no small, intermediate debris flows which would set back the “recharge clock”.
5. OHGR estimated the peak discharge of the 2004 event at 370 m^3/s.
6. In terms of remedial measures, OHGR estimated that retention basins constructed at the bottom to safeguard the public could have a design capacity of 15,000 m^3 or 30,000 m^3.

Note that OHGR’s work pertained to risk to highway users, not existing or proposed future homes or users of the marina at Kootenay Lake. The F-M relationship as estimated by OHGR (2007) is included in Table 4-4.

OHGR's (2007) F-M curve was extrapolated with a linear and logarithmic fit. The linear fit produces a volume of 157,000 m^3 which, given sediment supply limitations is practically impossible. A logarithmic fit yields a 500-year return period debris flow of 46,000 m^3.

6.3.4. Regional Frequency-Magnitude Approach

The regional approach for debris floods is summarized in the Methodology Report (BGC, March 31, 2020b). For debris flows, a different equation (Equation 6-1) is being used which has been calibrated by several debris-flow F-M relationships in southwestern British Columbia (Jakob et al., 2020 in print). The fan area used in Equation 6-1 is 0.054 km^2. This fan area is based on the measured fan area plus a 10% allowance for the submerged portion of the fan.

The predictive equation for debris flows for southwestern BC is:

$$V = A_f[97{,}393\ln(T) - 353{,}596] \quad \text{[Eq. 6-1]}$$

where A_f is the fan area in square kilometers and T is the return period in years.

The same analysis was repeated with an independent dataset of debris flows in the Bow Valley near Canmore, AB. In this case, the predictive equation is:

$$V = A_f[13{,}910\ln(T) - 33{,}236] \quad \text{[Eq. 6-2]}$$

The regional F-M approach results for southwestern BC are summarized in Figure 6-2. When compared for the same return periods, the volumes of debris flows in the Bow Valley are substantially smaller than for southwestern BC. This may be attributable to the fact that the hydroclimate and engineering geology of debris-flow basins in southwestern Alberta are distinctly different from that in southwestern BC. Convective storms, which are the dominant debris-flow trigger in southwestern AB, are more frequent and heavier than in southwestern BC which may explain more frequent but smaller debris flows. Rock types in the Canmore area are sedimentary which tend to fragment into smaller clasts compared to many igneous intrusive rocks found in southwestern BC and that underlay the Kuskonook Creek watershed (Section 3.3.1). While these assertions are somewhat speculative, they indicate that use of the Canmore debris flow dataset to reconstruct debris-flow F-M curves is likely inappropriate. This is supported by the fact that if the 2004 debris flow on Kuskonook Creek was plotted on the Canmore dataset, it would appear as a multi-million year return period event, which is not credible. The southwestern BC-calibrated relationship suggests an approximately 500-year return period volume of 14,000 m^3. The estimated 25,000 m^3 volume of the 2004 debris flow would correspond to a 4000-year return period event, which is highly unlikely. Therefore, BGC considers the regional approach not to be conservative enough. The reason for the discrepancy may be an underestimation of the submerged delta volume, or that the regional F-M relationship developed for southwestern BC is not applicable to southeastern BC for reasons of different climate and geomorphology.

6.3.5. Yield Rate Approach

As shown in Figure 6-1, the existing yield of debris appeared highly variable with an average yield rate estimate between 1 and 3 m^3/m. Given a stream length of 3,400 m, this would imply a total yield of 3,400 to 10,200 m^3, corresponding to an annual recharge of approximately 230 m^3 to

680 m^3, or 0.07 m^3/m to 0.2 m^3/m per year. To achieve the same volume as the 2004 debris flow, and assuming linear recharge rate, it would take approximately 50 to 140 years ignoring point source failures (i.e., gully sidewall debris avalanches). It is very difficult to estimate the volume of point source failures as those depend strongly on the intensity of future storms and soil thickness which is largely unknown. BGC did not attempt to estimate locations of point source failures because none of those could be identified on air photographs. The estimated 50 to 140 years of recharge roughly corresponds to the presumed return period of wildfires at higher elevations upon whose occurrence post-wildfire debris flows become likely (Blackwell, Grey, & Compass, 2003). It is also in general agreement with previous estimates of debris-flow frequency at Kuskonook Creek (Table 4-3, VanDine et al., 2005).

Figure 6-1. Channel of Kuskonook Creek in mid reaches (elevation ~ 1300 m) with bedrock sections alternating with coarse angular debris. Photo: BGC, July 7, 2019.

6.3.6. Recharge Rate Approach

Assuming Equation 5-1 is applicable to Kuskonook Creek, one can calculate how long it would take to accumulate the estimated average debris-flow volume. Using Equation 5-1 and again ignoring point source failures, the approximate time to recharge Kuskonook Creek for the respective frequency-magnitude pairs suggested by OHGR (2007) are summarized in Figure 6-1.

Table 6-1. Debris-flow recharge time for assumed event volumes and return periods from OHGR (2007). Recharge times are calculated via Equation 5-1.

Return Period (years)	Event Volume (m^3)	Recharge Time (years)
10	1500	2 to 3
50	15,000	130 to 540
100	30,000	500 to 7000

The recharge time estimates suggest at least some 500 years for debris flows to recharge to volumes witnessed during the 2004 debris flow assuming another post-wildfire storm. However, time to recharge and return periods are not interchangeable, they are instead linked. The former indicates that a sufficient volume of sediment needs to accumulate in a channel prior to a debris flow of a given volume to occur. The latter describes the average period between events. Also, some sediment is likely eroded and transported in the steep (on average >35% channel gradient) Kuskonook Creek channel during floods. This means that the true recharge time may be longer than suggested by the Jakob et al. (2005) method.

Further, it needs to be recognized that the cumulative debris volume estimates as per Equation 5-1 are highly sensitive to the exponent of Equation 5-1 which may not apply to recharge rates of Kuskonook Creek. They should therefore be interpreted as rough approximations. In summary, the recharge approach likely underestimates debris flow volumes, especially for return periods less than 500 years.

6.3.7. Post-wildfire Debris Flows

The magnitude of the 50-year return period event was estimated by assuming a 2-year return period rainstorm (15-minute rainfall intensity = 7 mm/hr) in combination with a 50-year return period wildfire. The 200-year return period debris flow was estimated by assuming a 10-year return period rainstorm (15-minute rainfall intensity = 15 mm/hr) in combination with a 50-year return period wildfire. This frequency was multiplied by 2 to account for post-wildfire susceptibility that is most likely for the first two years following the fire. The result is an approximate return period of 250 years for this scenario, which was considered a proxy for the 200-year return period event. The post-wildfire debris-flow volume associated with this return period was estimated to be 30,000 m^3. This volume is the result of the Gartner et al. (2014) model estimate for Kuskonook Creek (83,000 m^3) multiplied by the 0.37 calibration factor to apply the southern California based model in Gartner et al. (2014) to southern BC watersheds.

A similar approach was used to estimate the magnitude of the 500-year return period event. A 25-year return period rainstorm (15-minute rainfall intensity = 20 mm) was used to calculate a post-wildfire debris-flow volume using the Gartner et al. (2014) model. This storm rainfall return period, in combination with a 50-year return period wildfire and multiplied by 2 for the period of heightened post-wildfire debris-flow susceptibility following wildfire, resulted in a 625-year return period. The 625-year return period was considered a proxy for the 500-year event and the associated post-wildfire debris-flow volume was estimated to be 37,000 m^3. This volume is the result of the Gartner et al. (2014) model estimate for Kuskonook Creek (100,000 m^3) multiplied by the 0.37 calibration factor.

Given the post-wildfire debris-flow precedent at Kuskonook Creek, and the absence of any other debris flows not associated with debris flows, the analysis presented herein appears to provide a reasonable approximation of F-M relationships for Kuskonook Creek. A key question is that of climate change which will very likely increase the frequency of wildfires, increase the frequency of extreme hourly rainfall and increase the magnitude of extreme precipitation (Prein et al., 2017). In combination, those factors imply a shift of the F-M curve to the left towards a higher return period of debris flows but possibly lower magnitudes. This is because the increased frequency of debris flows allows for less recharge time between consecutive events, however, this assumption is still speculative, and science has not advanced to a point where this effect can be realistically quantified. In this analysis, BGC assumes some climate change effect by stipulating a 50-year debris flow return period (compared to a 100-year return period assumed by VanDine, 2005). However, no adjustments to magnitude have been made as those would be less conservative and, due to their speculative nature, not warranted.

6.3.8. Frequency-Magnitude Model Ensemble and Best Fit Estimate

Three distinct methods were used to create an F-M model ensemble for Kuskonook Creek. One was based on a regional fan area – F-M relationship, one on channel recharge and one on empirical model estimates for post-wildfire debris-flow volumes. These were compared to OHGR (2007) F-M estimates. None of the three methods applied by BGC can produce precise results, however, BGC concludes that the post-wildfire analysis is most credible and also results in the highest relative hazard. The results of the three methods are shown in Figure 6-2. Selecting the conservative estimates provided by the post-wildfire analysis is warranted due to the potential for life loss and major infrastructure damage at Kuskonook Creek.

The yield rate recharge method is a first approximation but ignores the post-fire debris-flow processes as it was developed to estimate debris-flow volumes in Haida Gwaii where post-fire debris flows are absent. Hence, this method likely yields F-M estimates that are too low for return periods less than about 500-years. Since the yield rate recharge method is not specific to the RDCK, BGC has low confidence in the results produced by this method. It is notable, however, that the recharge curve for undisturbed terrain converges with BGC’s best estimate for a return period of approximately 630 years.

The regional fan-area method developed for southwestern BC yields the lowest F-M curve, which may be attributable to slower recharge rates in that area, and where post-wildfire debris flows are extremely rare and channel roughness is high. This approach may also suffer from underestimated fan areas that are submerged as well as from climate and geomorphology differences between the calibration dataset in southwestern BC and the study area at Kuskonook Creek. Such differences can be pertinent as outlined by Jakob et al. (in print). BGC’s confidence in this method is therefore low.

The post-wildfire debris flow analysis appears useful as long as it is locally calibrated, as has been done in this study. BGC considers that post-wildfire debris flows dominate the hazard at

Kuskonook Creek as well as for other small (< ~ 8 km^2) watersheds in southeastern BC where few active unvegetated debris source areas available. BGC's confidence in this method is moderate to high.

The estimates provided by OHGR (2007) converge with BGC's estimate for the 100-year return period event. However, BGC believes that a 50-year return period post-wildfire debris flow could be substantially larger than estimated by OHGR (2007). Furthermore, extrapolation of the OHGR estimate would yield very high volumes and assume channel and watershed supply-unlimited conditions. OHGR (2007) was likely aware of this and thus did not attempt to extrapolate the F-M relationship beyond the 100-year return period.

Informed by the above methods, BGC has the highest confidence in the post-wildfire method to provide realistic results. The volume and peak discharge estimates from this analysis was used as an input for the numerical modeling.

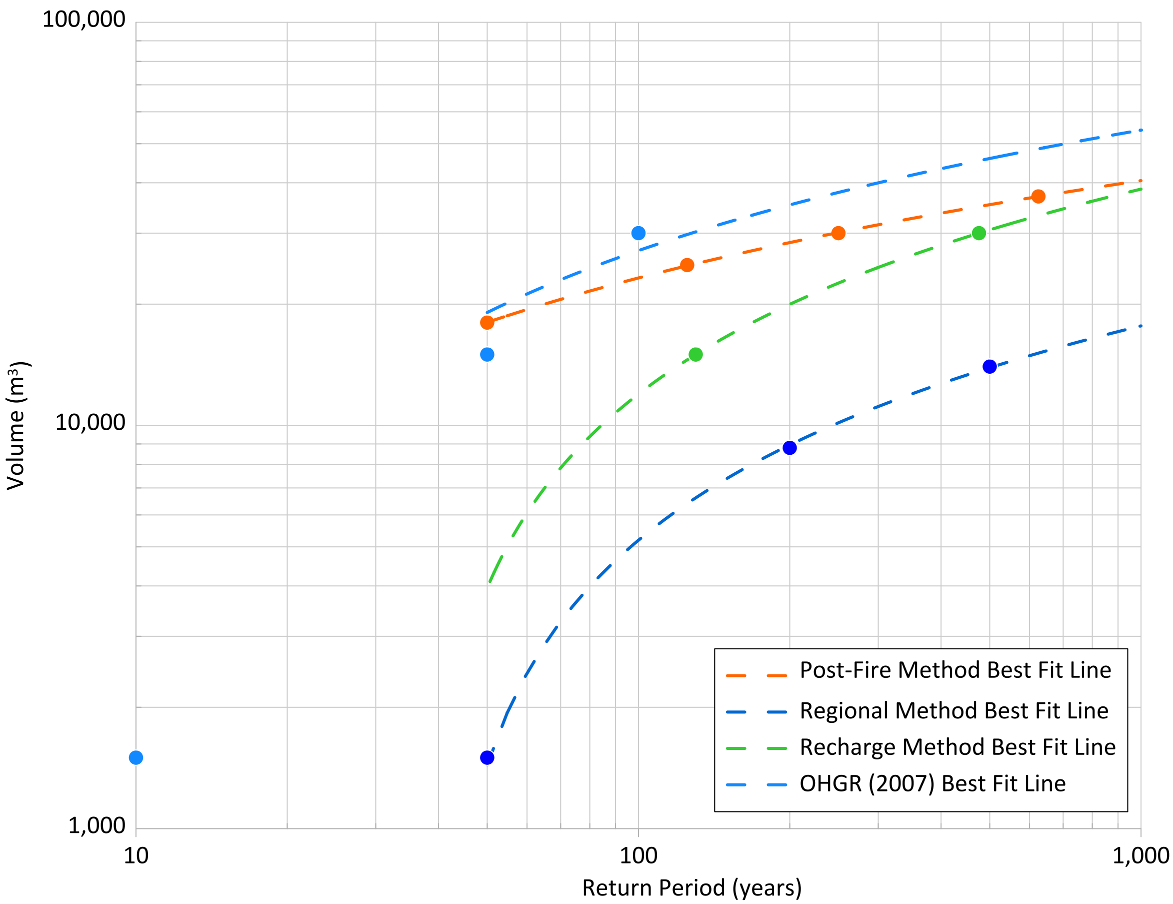

Figure 6-2. The frequency-magnitude methods considered reasonable for Kuskonook Creek. Best fit lines are trimmed at the 50-year return period as BGC believes that debris flows below that return period are not likely. The OHGR method is extrapolated beyond what was reported by OHGR (2007) using an exponential fit.

BGC's best estimates for a post-wildfire climate-change adjusted F-M curve are summarized in Table 6-2.

Table 6-2. Frequency-magnitude pairs of debris-flow volumes for Kuskonook Creek as estimated by BGC using the post-wildfire, climate change method.

Return Period (years)	Debris Flow Volume (m^3)
20	n/a
50	18,000
200	30,000
500	37,000

Note: The debris-flow sediment volumes should not be interpreted as precise and are associated with some unquantified error.

6.4. Peak Discharge Estimates

Peak discharges for different return periods were estimated to serve as input to the numerical modelling. For clearwater floods (20-year return period), the workflow entailed an estimate of clearwater peak discharges, followed by a climate-change adjustment. For the 50-, 200- and 500-year return period debris flows, the workflow entailed estimating the volume of the debris flow based on the F-M relationship and then calculating the associated peak discharge using the Bovis and Jakob (1999) equation that relates peak discharge to total volume for coarse-granular debris flows. Results of the analysis are presented in Figure 6-3 and Table 6-3. With respect to these results, the reader should note the following:

- Because there are no hydrometric stations on Kuskonook Creek, historical peak discharges (flood quantiles) were estimated using a Regional FFA. The regional index-flood model was selected because it produced slightly higher peak discharges than the provincial model.
- The climate change impact assessment results were difficult to synthesise in order to select climate-adjusted peak discharges on a site-specific basis. Consequently, a 20% increase in peak discharge was adopted as per Section 4 of the Methodology Report (BGC, March 31, 2020b).
- The climate-adjusted discharge was used in the numerical modelling of floods.
- The debris-flow discharges were used in the debris flow modelling. Debris flow peak discharges are two orders of magnitude higher than those of clearwater floods and thus dictate hazards and risks (Jakob & Jordan, 2001).

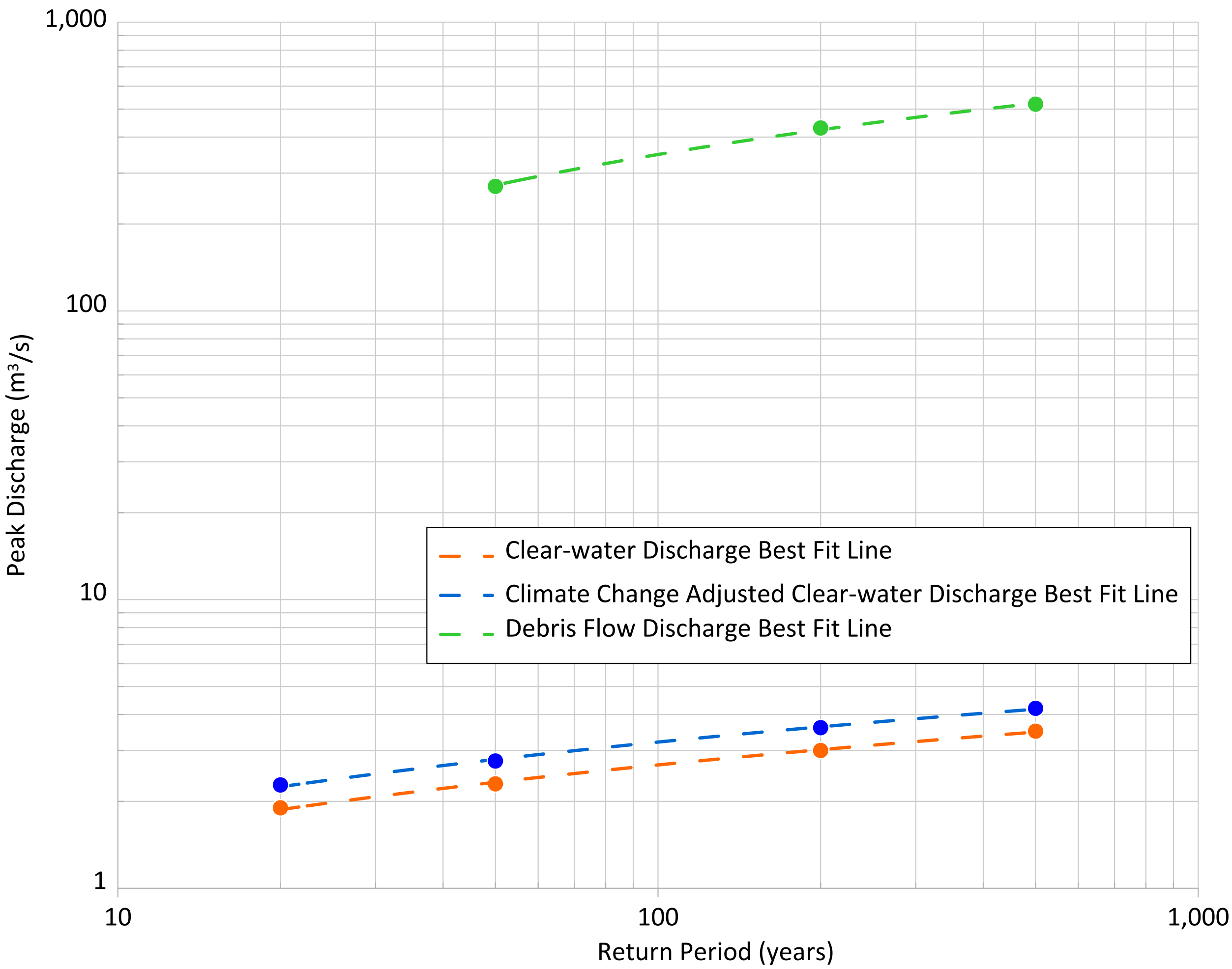

Figure 6-3. Frequency-discharge relationship for Kuskonook Creek. The best fit debris flow discharge line is based on the post-fire analysis which is considered to strike a reasonable balance between conservativism and analytical rigor.

Table 6-3. Peak discharges for selected return period events. Note that non-wildfire debris flows are theoretically possible on Kuskonook Creek but have not been observed to date.

Return Period (years)	Non-adjusted Peak Discharge (RFFA) (m^3/s)	Climate-adjusted Peak Discharge (m^3/s)	Peak Discharge (m^3/s)	Comments
20	1.9	2.3	n/a	Clearwater Flood
50	2.3	n/a	270	Post-Wildfire Debris Flow
200	3.0	n/a	430	Post-Wildfire Debris Flow
500	3.5	n/a	520	Post-Wildfire Debris Flow

6.5. Numerical Flood and Debris-Flow Modelling and Hazard Mapping

6.5.1. Results

A summary of the key observations from the flood and debris flow modelling is included in Table 6-4. The 200-year return period model result is shown on Drawing 07 and all return period model results are presented in Cambio Communities. A Cambio user guide is included in the Summary Report (BGC, March 31, 2020a).

Table 6-4. Summary of modelling results.

Process	Key Observations
Clear-water inundation (HEC-RAS model results for 20-year return period)	• Clear-water floods are believed to remain in the channel and pass through the existing and overflow culverts. • At higher return periods, debris flows dominate the fan-delta hazards
Debris flow inundation (DAN 3D model results for 50-year, 200- and 500-year return periods)	• The 50-year return period debris flow is likely to overwhelm the existing deflection berm and spill southwestwards towards the marina turn-off. • The 200-year return period debris flow will result in a substantially larger area being inundated by debris with flow spilling westward and likely covering the majority of Highway 3A on the modern fan-delta of Kuskonook Creek. A presumed avulsion channel through mid fan will likely experience high flow velocities and depths. Modelled velocities and flow depths across most of the fan upstream of Highway 3A are likely to be destructive to homes and vehicles. • The 500-year return period debris flow will likely be marginally larger in extent compared to the 200-year debris flow.
Auxiliary Hazards	• In case of a culvert blockage at the debris basin outlet, saturation of the constructed berm could potentially lead to a slope failure of the berm. However, this may have been addressed through a sufficiently high factor of safety by the berm's designers. • Long-term aggradation of the lower sections (above the fan apex of the modern fan) could potentially lead to a re-activation of the paleofan (currently considered unlikely). • Large woody debris could clog the outlet structure and lead to debris basin overtopping.

6.5.2. Model Check

Griswold and Iverson (2008) developed an empirical correlation between the planimetric area inundated by non-volcanic debris flows and the associated deposited volume. The chosen volumes for each return period (red triangles in Figure 6-4) plot somewhat above the expected range of typical non-volcanic debris flows based on the modelled surface inundation area. In other words, for the given debris-flow volume, the planimetric area is somewhat lower than expected. This could be attributed to the fact that the debris discharging into Kootenay Lake is not accounted for or the fan alteration following berm construction. If there were no lake, one would expect significant sediment spreading, especially on the distal fan portions where flows become thin and tend to spread out.

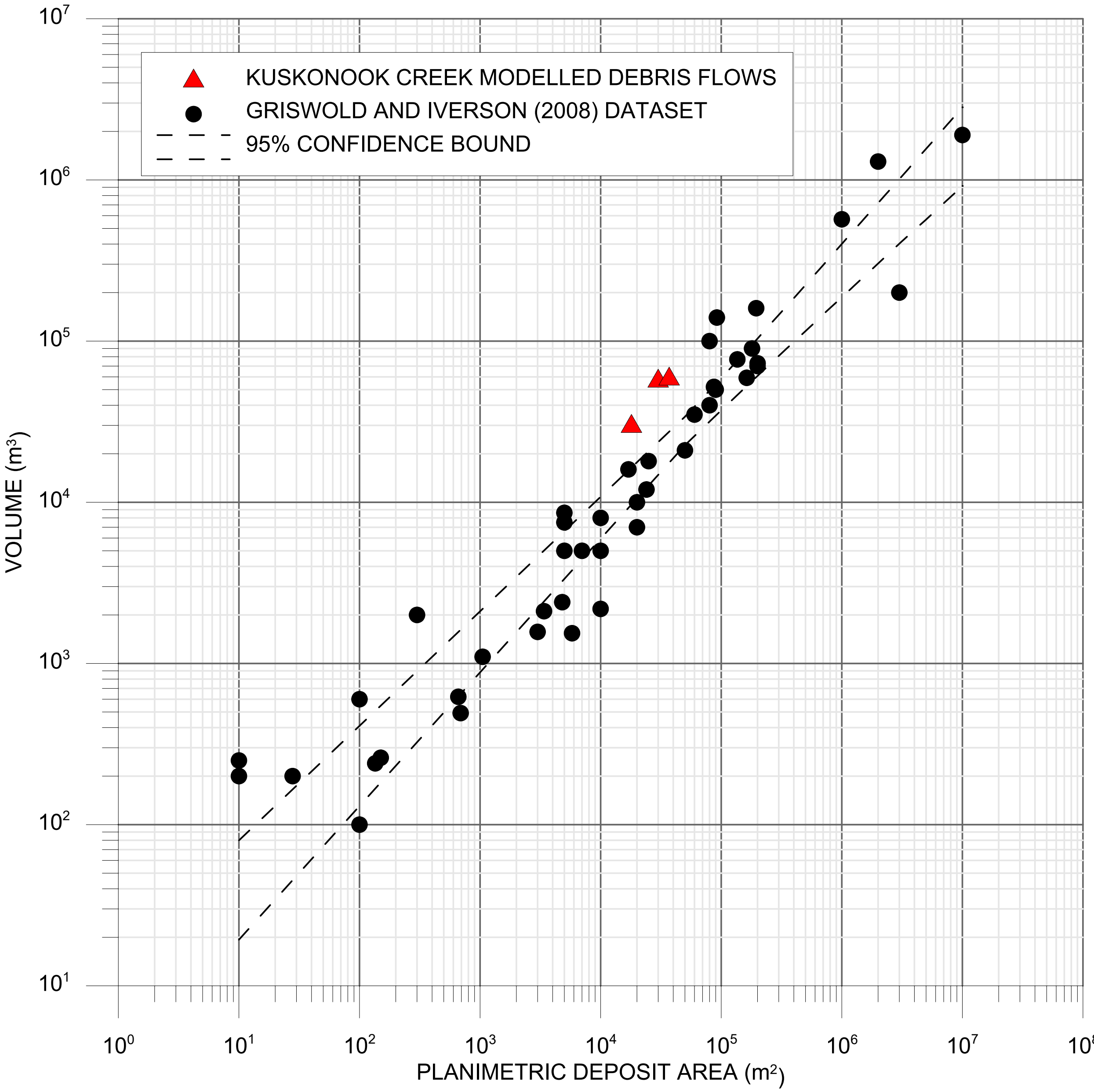

Figure 6-4. Modelled event volumes for Kuskonook Creek (red) in comparison to typical non-volcanic debris flow dataset (black) developed by Griswold and Iverson (2008).

In summary, while the debris flow volume and peak discharge estimates are derived rather indirectly, this independent check verifies that the debris-flow inundated area for the input volumes appears reasonable.

6.6. Hazard Mapping

Drawing 07 provides the 200-year debris flow model result map. Drawing 08 provides a composite hazard rating map showing the maximum extent of all hazard scenarios.

As noted in Section 5.6.2, hazard rating zones shown on the composite hazard rating map reflect categorization applicable to a wide range of hazard types, from clearwater floods to large landslides. The choice of categorization may affect interpretation by the map user and is subject to review and discussion with RDCK.

The composite hazard rating map demonstrates that the hazards of hydrogeomorphic events are dominated by the 50-, 200- and 500-year debris flows as those results in much higher peak flows and thus higher intensities expressed in impact force than the clearwater floods. The main channel of Kuskonook Creek is colour-coded in brown implying an extreme hazard with dark red (very high) areas extending over the berm and beginning to encroach on the developed area. The developed area is mid-fan is entirely encompassed by the red (high) hazard area. This implies that for those areas debris flows will likely result in substantial building damage or destruction. Much of Highway 3A is in the red to orange (high to moderate) hazard area with development downstream of the highway in the orange to yellow (moderate to low) areas.

7. SUMMARY AND RECOMMENDATIONS

7.1. Introduction

This report provides a detailed hazard assessment of the Kuskonook Creek fan-delta. Kuskonook Creek was chosen as a high priority creek amongst hundreds in the RDCK due to its comparatively high risk. This report has resulted in digital hazard maps that provide the backbone of any eventual quantitative risk assessment. It also provides the basis to inform the conceptualization and eventual design and construction of any additional mitigation measures should those be found to be required for Kuskonook Creek.

Kuskonook Creek is an exception with respect to the 10 chosen high priority creeks for three reasons: First, it is the only one in which debris flow hazards dominate 3 out of 4 considered return periods. Unlike Procter Creek on the West Arm of Kootenay Lake, Kuskonook Creek is not considered subject to debris floods due to its steepness. Second, it has recently (2004) experienced a debris flow which allows for some calibration of the runout model. Third, debris-flow hazards to the highway have been mitigated by installation of a deflection berm/debris basin. A key aspect of the work on Kuskonook Creek is therefore to check if the existing mitigation works are sufficient to reduce the projected hazard and commensurate risk to a value deemed tolerable by the RDCK.

A variety of analytical desktop and field-based tools and techniques were combined to decipher Kuskonook Creek's geomorphological and hazard history, its hydrology and hydraulics.

7.2. Summary

7.2.1. Hydrogeomorphic Process

Based on field observations and remote sensing data, Kuskonook Creek is subject to debris flows for return periods in excess of the 20-year return period and assuming the frequency of wildfires and high intensity rainfall will increase in the future.

7.2.2. Air Photo Interpretation

These techniques were completed to gain an understanding of watershed and channel changes on the fan-delta and help with the construction of an F-M relationship. Only the August 2004 event is visible in the air photo record as well as the construction of debris flow mitigation post-event. This event is considered a post-wildfire debris flow.

7.2.3. Frequency-Magnitude Relationship

Frequency-volume relationships were constructed from a post-wildfire, climate change analysis as summarized in 6.3.8. Peak discharges used for modelling the various return period events are also reported in Table 7-1.

Key findings from estimating peak discharges suitable for modelling are:

- The climate change impact assessment results were difficult to synthesise in order to select climate-adjusted peak discharges on a site-specific basis. Consequently, a 20% increase in peak discharge was adopted as per Section 4 of the Methodology Report (BGC, March 31, 2020b).

- The climate-change adjusted peak discharges for Kuskonook Creek were used for the 20-year return period.
- For the 50-, 200- and 500-year return periods, BGC assumed post-wildfire debris flows with peak discharges estimated using the empirical equations of Bovis and Jakob (1999). These debris flows dominate the hazard on Kuskonook Creek.

Table 7-1. Kuskonook Creek flood and debris flow frequency-volume relationship. Note that the 20-year return period peak discharge assume the effects of climate change.

Return Period (years)	Peak Discharge (m^3/s)	Event Volume (m^3)
20	2	N/A
50	270	18,000
200	430	30,000
500	520	37,000

7.2.4. Numerical Modelling

Clearwater floods of the 20-year return period were modelled using FLO-2D software, while debris flows were modeled with DAN3D to simulate the chosen hazard scenarios on the Kuskonook Creek fan-delta. Table 6-4 provides key observations derived from the numerical modelling.

The multiple process numerical modelling ensemble approach demonstrates that the key hazards and associated risks at Kuskonook Creek stem from debris flows of the 50-, 200- and 500-year return periods which are believed to be possible after stand-replacing fires and cause debris flow lobes to avulse just downstream of the fan apex as well as overtop the bottom of the debris flow basin.

7.2.5. Bank Erosion Assessment

A bank erosion assessment was not completed because the berm constructed in 2008 is designed for debris flow impact and the deposition of debris in the basin will backwater very quickly (within minutes of the debris flow) thereby protecting the banks from erosion.

7.2.6. Hazard Mapping

Model results are cartographically expressed in two ways:

- The individual hazard scenarios are captured through an index of impact force that combines flow velocity, bulk density and flow depth. These maps are useful for assessments of development proposals and emergency planning. These hazard scenarios are presented in Cambio Communities and a representative example from the 200-year return period is shown on Drawing 07.
- A composite hazard rating map (impact intensity frequency map) that combines the clearwater flood and debris flow intensity (impact force) and frequency up to the 500-year

return period event. This map is useful to designate hazard zones. It is included as Drawing 08.

Both the individual scenario maps and the composite hazard rating map serve as decision-making tools to guide subdivision and other development permit approvals. Details on how to translate the hazard map into tangible land use decisions will be developed collaboratively between the RDCK and BGC.

7.3. Limitations and Uncertainties

While systematic scientific methods were applied in this study, some uncertainties prevail. As with all hazard assessment and concordant maps, the hazard maps prepared at Kuskonook Creek represent a snapshot in time. Future changes to the Kuskonook Creek watershed or fan including the following may warrant re-assessment and/or re-modelling:

- Future fan development and debris flow events
- Significant wildfires (defined as those affecting > 20% of the watershed at moderate or higher burn intensity)
- Berm and basin re-design.

The assumptions made on changes in runoff due to climate change, while not unreasonable, are not infallible and will likely need to be updated occasionally as scientific understanding of such processes evolves.

BGC recognizes that all hazard processes display some chaotic behaviour and therefore not all hazards or hazard scenarios can be adequately modelled. For example, unforeseen log jams may alter flow directions and create avulsions into areas not specifically considered in the individual hazard scenarios. Despite these limitations and uncertainties, BGC believes that a credible hazard assessment has been achieved on which land use decisions can be made.

7.4. Considerations for Hazard Management

Recommendations are provided in the Summary Report (BGC, March 31, 2020a) as they pertain to all studied RDCK creeks. This section notes Kuskonook Creek-specific issues that could be considered in the short term given the findings of this report. They are purposely not named “recommendations” as those would come out of a more in-depth discussion on what potential losses due to debris flows would be considered intolerable by the RDCK. It would also require discussions with other stakeholders with assets on the Kuskonook Creek fan-delta.

Mitigation considerations as discussed below are summarized in Figure 7-1.

- The current debris-flow deflection berm and basin was likely designed in terms of its volume and peak flows with the principal of reasonableness (i.e., what can be achieved with the space and money available). The mitigation works will likely not fully contain debris flows at the 50-year return period and higher (see Section 3.5.1).
- Properties on the north side of the fan could be impacted if the existing berm is overtopped and/or incised. Protection of these properties by engineered structures may exceed the

value of those properties and thus result in disproportionate costs compared to property acquisition.

Table 7-2 summarizes the possible mitigation considerations for Kuskonook Creek.

Table 7-2. Mitigation considerations for Kuskonook Creek fan-delta

Option	Description	Effect on Flood Hazard Reduction
(a)	To protect Highway 3A from the modelled debris flows, the current mitigation system would have to be substantially upgraded with the deflection berm raised and widened.	Reduction in avulsion potential that could impact existing properties, Highway 3A and the marina.
(b)	Installation of new culvert and/or spillway at the basin outlet. Alternatively, a ford could be constructed in addition to the culvert which would entail a low point in the road and abrasion-resistant (concrete) lining and toe protection.	Will reduce the chance of debris covering Highway 3A (increased basin outlet culvert) or eroding (ford) Highway 3A.
(c)	Erection of warning signs on the N-side (C_N) and S-side (C_S). Warning signs could be as simple as warning motorists that there could be debris on the road during heavy storms and that they should not attempt to cross the debris and to turn around and not leave their vehicles.	Will reduce the risk to impact of motorists

Option (a) will be difficult to justify given that Kuskonook Creek has already been partially mitigated and there are many unmitigated yet developed steep debris-flow prone fans elsewhere along Kootenay Lake and within the RDCK. Option (b) would also require significant design modifications but would not avoid berm overtopping for the modeled debris flows. Option (c) is the most cost effective but would not prevent any property or infrastructure damage.

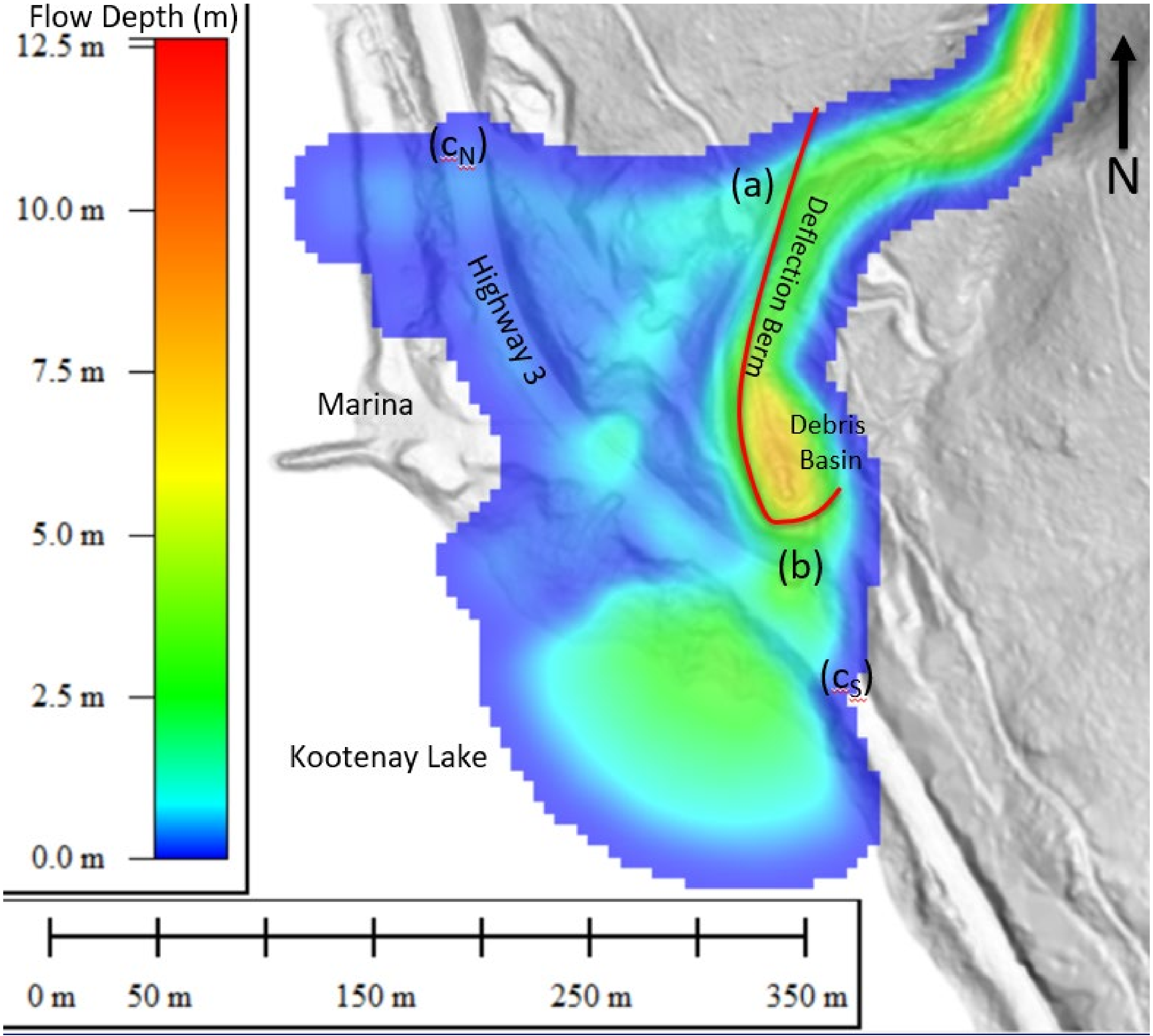

Figure 7-1. Debris-flow inundation map showing flow depths for a 500-year return period debris flow (Q_{MAX} = 520 m^3/s) on Kuskonook Creek from DAN3D modelling with conceptual-level mitigation options. Note that these mitigation options have not been tested by numerical modelling and only serve as an impetus for further discussion. Other options will likely be developed at the conceptual design level.

8. CLOSURE

We trust the above satisfies your requirements at this time. Should you have any questions or comments, please do not hesitate to contact us.

Yours sincerely,

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KH/HW/mp/mm

Final stamp and signature version to follow once COVID-19 restrictions are lifted

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APPENDIX A
TERMINOLOGY

Table A-1 provides defines terms that are commonly used in geohazard assessments. BGC notes that the definitions provided are commonly used, but international consensus on geohazard terminology does not fully exist. **Bolded terms** within a definition are defined in other rows of Table A-1.

Table A-1. Geohazard terminology.

Term	Definition	Source
Active Alluvial Fan	The portion of the fan surface which may be exposed to contemporary hydrogeomorphic or avulsion hazards.	BGC
Aggradation	Deposition of sediment by a (river or stream).	BGC
Alluvial fan	A low, outspread, relatively flat to gently sloping mass of loose rock material, shaped like an open fan or a segment of a cone, deposited by a stream at the place where it issues from a narrow mountain valley upon a plain or broad valley, or where a tributary stream is near or at its junction with the main stream, or wherever a constriction in a valley abruptly ceases or the gradient of stream suddenly decreases	Bates and Jackson (1995)
Annual Exceedance Probability (P_H) (AEP)	The Annual Exceedance Probability (AEP) is the estimated **probability** that an event will occur exceeding a specified magnitude in any year. For example, a flood with a 0.5% AEP has a one in two hundred chance of being reached or exceeded in any year. AEP is increasingly replacing the use of the term **'return period'** to describe flood recurrence intervals.	Fell et al. (2005)
Avulsion	Lateral displacement of a stream from its main channel into a new course across its fan or floodplain. An "avulsion channel" is a channel that is being activated during channel avulsions. An avulsion channel is not the same as a paleochannel.	Oxford University Press (2008)
Bank Erosion	Erosion and removal of material along the banks of a river resulting in either a shift in the river position, or an increase in the river width.	BGC
Clear–water flood	Riverine and lake flooding resulting from inundation due to an excess of clear-water discharge in a watercourse or body of water such that land outside the natural or artificial banks which is not normally under water is submerged.	BGC
Climate normal	Long term (typically 30 years) averages used to summarize average climate conditions at a particular location.	BGC
Consequence (C)	In relation to risk analysis, the outcome or result of a **geohazard** being realised. Consequence is a product of **vulnerability** (V) and a measure of the **elements at risk** (E)	Fell et al. (2005); Fell et al. (2007), BGC

Term	Definition	Source
Consultation Zone	The Consultation Zone (CZ) includes all proposed and existing development in a geographic zone defined by the approving authority that contains the largest credible area affected by specified **geohazards**, and where damage or loss arising from one or more simultaneously occurring specific **geohazards** would be viewed as a single catastrophic loss.	Adapted from Porter et al. (2009)
Debris Flow	Very rapid to extremely rapid surging flow of saturated, non-plastic debris in a steep channel (Hungr, Leroueil & Picarelli, 2014). Debris generally consists of a mixture of poorly sorted sediments, organic material and water (see Appendix B of this report for detailed definition).	BGC
Debris Flood	A very rapid flow of water with a sediment concentration of 3-10% in a steep channel. It can be pictured as a flood that also transports a large volume of sediment that rapidly fills in the channel during an event (see Appendix B of this report for detailed definition).	BGC
Elements at Risk (E)	This term is used in two ways: a) To describe things of value (e.g., people, infrastructure, environment) that could potentially suffer damage or loss due to a **geohazard**. b) For risk analysis, as a measure of the value of the elements that could potentially suffer damage or loss (e.g., number of persons, value of infrastructure, value of loss of function, or level of environmental loss).	BGC
Encounter Probability	This term is used in two ways: a) **Probability** that an event will occur and impact an element at risk when the element at risk is present in the **geohazard** zone. It is sometimes termed **"partial risk"** b) For quantitative analyses, the **probability** of facilities or vehicles being hit at least once when exposed for a finite time period L, with events having a **return period** T at a location. In this usage, it is assumed that the events are rare, independent, and discrete, with arrival according to a statistical distribution (e.g., binomial or Bernoulli distribution or a Poisson process).	BGC
Erosion	The part of the overall process of denudation that includes the physical breaking down, chemical solution and transportation of material.	Oxford University Press (2008)

Term	Definition	Source
Flood	A rising body of water that overtops its confines and covers land not normally under water.	American Geosciences Institute (2011)
Flood Construction Level (FCL)	A designated flood level plus freeboard, or where a designated flood level cannot be determined, a specified height above a natural boundary, natural ground elevation, or any obstruction that could cause flooding.	BGC
Flood mapping	Delineation of flood lines and elevations on a base map, typically taking the form of flood lines on a map that show the area that will be covered by water, or the elevation that water would reach during a flood event. The data shown on the maps, for more complex scenarios, may also include flow velocities, depth, or other hazard parameters.	BGC
Floodplain	The part of the river valley that is made of unconsolidated river-borne sediment, and periodically flooded.	Oxford University Press (2008)
Flood setback	The required minimum distance from the natural boundary of a watercourse or waterbody to maintain a floodway and allow for potential bank erosion.	BGC
Freeboard	Freeboard is a depth allowance that is commonly applied on top of modelled flood depths. There is no consistent definition, either within Canada or around the world, for freeboard. Overall, freeboard is used to account for uncertainties in the calculation of a base flood elevation, and to compensate for quantifiable physical effects (e.g., local wave conditions or dike settlement). Freeboard in BC is commonly applied as defined in the BC Dike Design and Construction manual (BC Ministry of Water, Land and Air Protection [BC MWLAP], 2004): a fixed amount of 0.6 m (2 feet) where mean daily flow records are used to develop the design discharge or 0.3 m (1 foot) for instantaneous flow records.	BC Ministry of Water, Land and Air Protection [BC MWLAP] (2004)

Term	Definition	Source
Frequency (f)	Estimate of the number of events per time interval (e.g., a year) or in a given number of trials. Inverse of the **recurrence interval** (**return period**) of the **geohazard** per unit time. Recurring **geohazards** typically follow a **frequency**-magnitude (F-M) relationship, which describes a spectrum of possible **geohazard magnitudes** where larger (more severe) events are less likely. For example, annual **frequency** is an estimate of the number of events per year, for a given **geohazard event magnitude**. In contrast, annual **probability** of exceedance is an estimate of the **likelihood** of one or more events in a specified time interval (e.g., a year). When the expected **frequency** of an event is much lower than the interval used to measure **probability** (e.g., **frequency** much less than annual), **frequency** and **probability** take on similar numerical values and can be used interchangeably. When **frequency** approaches or exceeds 1, defining a relationship between **probability** and **frequency** is needed to convert between the two. The main document provides a longer discussion on **frequency** versus **probability**.	Adapted from Fell et al. (2005)
Hazard	Process with the potential to result in some type of undesirable outcome. Hazards are described in terms of scenarios, which are specific events of a particular frequency and magnitude.	BGC
Hazardous flood	A flood that is a source of potential harm.	BGC
Geohazard	Geophysical process that is the source of potential harm, or that represents a situation with a potential for causing harm. Note that this definition is equivalent to Fell et al. (2005)'s definition of Danger (threat), defined as an existing or potential natural phenomenon that could lead to damage, described in terms of its geometry, mechanical and other characteristics. Fell et al. (2005)'s definition of danger or threat does not include forecasting, and they differentiate Danger from Hazard. The latter is defined as the **probability** that a particular danger (threat) occurs within a given period of time.	Adapted from CSA (1997), Fell et al. (2005).

Term	Definition	Source
Geohazard Assessment	Combination of **geohazard analysis** and evaluation of results against a **hazard tolerance standard** (if existing). Geohazard assessment includes the following steps: a. **Geohazard analysis**: identify the **geohazard** process, characterize the geohazard in terms of factors such as mechanism, causal factors, and trigger factors; estimate **frequency** and magnitude; develop **geohazard scenarios**; and estimate extent and intensity of **geohazard scenarios**. b. Comparison of estimated hazards with a hazard tolerance standard (if existing)	Adapted from Fell et al. (2007)
Geohazard Event	Occurrence of a **geohazard**. May also be defined in reverse as a non- occurrence of a **geohazard** (when something doesn't happen that could have happened).	Adapted from ISO (2018)
Geohazard Intensity	A set of parameters related to the destructive power of a **geohazard** (e.g. depth, velocity, discharge, impact pressure, etc.)	BGC
Geohazard Inventory	Recognition of existing **geohazards.** These may be identified in geospatial (GIS) format, in a list or table of attributes, and/or listed in a **risk register**.	Adapted from CSA (1997)
Geohazard Magnitude	Size-related characteristics of a **geohazard**. May be described quantitatively or qualitatively. Parameters may include volume, discharge, distance (e.g., displacement, encroachment, scour depth), or acceleration. In general, it is recommended to use specific terms describing various size-related characteristics rather than the general term magnitude. Snow avalanche magnitude is defined differently, in classes that define destructive potential.	Adapted from CAA (2016)
Geohazard Risk	Measure of the **probability** and severity of an adverse effect to health, property the environment, or other things of value, resulting from a geophysical process. Estimated by the product of **geohazard probability** and **consequence**.	Adapted from CSA (1997)
Geohazard Scenario	Defined sequences of events describing a **geohazard** occurrence. Geohazard scenarios characterize parameters required to estimate risk such **geohazard extent** or **runout exceedance probability,** and **intensity.** Geohazard scenarios (as opposed to **geohazard risk scenarios**) typically consider the chain of events up to the point of impact with an element at risk, but do not include the chain of events following impact (the **consequences**).	Adapted from Fell et al. (2005)

Term	Definition	Source
Hazard	Process with the potential to result in some type of undesirable outcome. Hazards are described in terms of scenarios, which are specific events of a particular frequency and magnitude.	BGC
Inactive Alluvial Fan	Portions of the fan that are removed from active hydrogeomorphic or avulsion processes by severe fan erosion, also termed fan entrenchment.	BGC
LiDAR	Stands for Light Detection and Ranging, is a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth. These light pulses - combined with other data recorded by the airborne system - generate precise, three-dimensional information about the shape of the Earth and its surface characteristics.	National Oceanic and Atmospheric Administration, (n.d.).
Likelihood	Conditional **probability** of an outcome given a set of data, assumptions and information. Also used as a qualitative description of **probability** and **frequency**.	Fell et al. (2005)
Melton Ratio	Watershed relief divided by square root of watershed area. A parameter to assist in the determination of whether a creek is susceptible to flood, debris flood, or debris flow processes.	BGC
Nival	Hydrologic regime driven by melting snow.	Whitfield, Cannon and Reynolds (2002)
Orphaned	Without a party that is legally responsible for the maintenance and integrity of the structure.	BGC
Paleofan	Portion of a fan that developed during a different climate, base level or sediment transport regime and which will not be affected by contemporary geomorphic processes (debris flows, debris floods, floods) affecting the active fan surface	BGC
Paleochannel	An inactive channel that has partially been infilled with sediment. It was presumably formed at a time with different climate, base level or sediment transport regime.	BGC
Pluvial – hybrid	Hydrologic regime driven by rain in combination with something else.	BGC

Term	Definition	Source
Probability	A measure of the degree of certainty. This measure has a value between zero (impossibility) and 1.0 (certainty) and must refer to a set like occurrence of an event in a certain period of time, or the outcome of a specific event. It is an estimate of the **likelihood** of the magnitude of the uncertain quantity, or the **likelihood** of the occurrence of the uncertain future event. There are two main interpretations: i) Statistical – **frequency** or fraction – The outcome of a repetitive experiment of some kind like flipping coins. It includes also the idea of population variability. Such a number is called an "objective" or relative frequentist probability because it exists in the real world and is in principle measurable by doing the experiment. ii) Subjective (or Bayesian) probability (degree of belief) – Quantified measure of belief, judgement, or confidence in the **likelihood** of an outcome, obtained by considering all available information honestly, fairly, and with a minimum of bias. Subjective probability is affected by the state of understanding of a process, judgement regarding an evaluation, or the quality and quantity of information. It may change over time as the state of knowledge changes.	Fell et al. (2005)
Return Period (Recurrence Interval)	Estimated time interval between events of a similar size or **intensity**. Return period and **recurrence interval** are equivalent terms. Inverse of **frequency**.	BGC
Risk	Likelihood of a geohazard scenario occurring and resulting in a particular severity of consequence. In this report, risk is defined in terms of safety or damage level.	BGC
Rock (and debris) Slides	Sliding of a mass of rock (and debris).	BGC
Rock Fall	Detachment, fall, rolling, and bouncing of rock fragments.	BGC
Scour	The powerful and concentrated clearing and digging action of flowing air or water, especially the downward erosion by stream water in sweeping away mud and silt on the outside curve of a bend, or during a time of flood.	American Geological Institute (1972)
Steep-creek flood	Rapid flow of water and debris in a steep channel, often associated with avulsions and bank erosion and referred to as debris floods and debris flows.	BGC

Term	Definition	Source
Steep Creek Hazard	Earth-surface process involving water and varying concentrations of sediment or large woody debris. (see Appendix B of this report for detailed definition).	BGC
Uncertainty	Indeterminacy of possible outcomes. Two types of uncertainty are commonly defined: a) Aleatory uncertainty includes natural variability and is the result of the variability observed in known populations. It can be measured by statistical methods, and reflects uncertainties in the data resulting from factors such as random nature in space and time, small sample size, inconsistency, low representativeness (in samples), or poor data management. b) Epistemic uncertainty is model or parameter uncertainty reflecting a lack of knowledge or a subjective or internal uncertainty. It includes uncertainty regarding the veracity of a used scientific theory, or a belief about the occurrence of an event. It is subjective and may vary from one person to another.	BGC
Waterbody	Ponds, lakes and reservoirs	BGC
Watercourse	Creeks, streams and rivers	BGC

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APPENDIX B
SITE PHOTOGRAPHS

Photo 1.

Overview photo taken during helicopter overflight looking east at the Kuskonook Creek watershed. Photo: BGC, July 6, 2019.

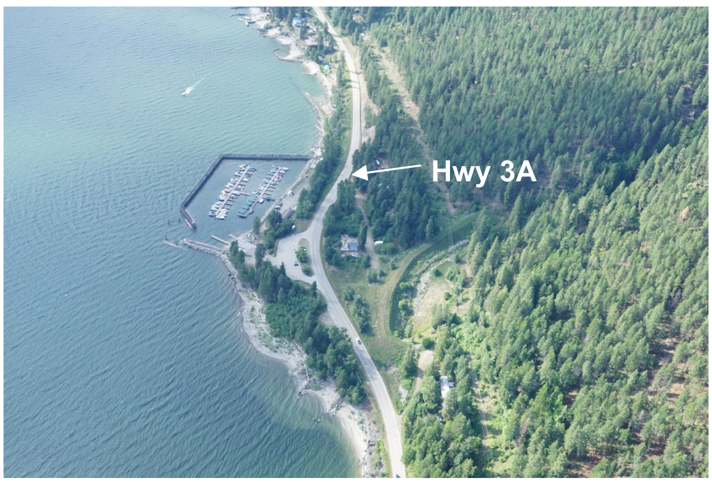


Photo 2.

Overview photo taken during helicopter overflight looking north at the Kuskonook Creek fan-delta with Hwy 3A (top to bottom) running across Kuskonook Creek. Photo: BGC, July 6, 2019.

Photo 3.

Overview photo taken July 6, 2019 during helicopter overflight looking northeast at the Kuskonook Creek fan-delta with Hwy 3A (left to right) running across Kuskonook Creek. Part of the Kuskonook Creek watershed is visible. Photo: BGC, July 6, 2019.

Photo 4.

Overview photo taken during helicopter overflight looking southwest at the Kuskonook Creek watershed, approximately 3 km upstream of the fan apex. Photo: BGC, July 6, 2019.

Photo 5.

Overview photo taken during helicopter overflight looking down (west) Kuskonook Creek, approximately 2.5 km upstream of the fan apex. Photo: BGC, July 6, 2019.

Photo 6.

Photo taken during helicopter overflight looking upstream (east) at Kuskonook Creek, approximately 500 m upstream of the fan apex. Photo: BGC, July 6, 2019.

Photo 7.

At the Kuskonook Harbour boat launch looking upstream (northeast) at the fan. Photo: BGC, July 10, 2019.

Photo 8.

On a debris flow berm looking upstream (northeast) at Kuskonook Creek, approximately 200 m upstream of the outlet to Kootenay Lake. Photo: BGC July 10, 2019.

Photo 9.

Standing at a Gazebo by the Kuskonook Creek outlet to Kootenay Lake looking east at Hwy 3A. Photo: BGC, July 10, 2019.

Photo 10.

Standing just upstream of the Hwy 3A culvert conveying Kuskonook Creek. Photo: BGC, July 10, 2019.

Photo 11.

On Hwy 3A looking northwest towards Kuskonook Creek from approximately 200 m southeast. Photo: BGC, July 10, 2019.

APPENDIX C
AIR PHOTO RECORDS

Table C-1 presents air photo records from the Kuskonook Creek analysis. In addition to the air photos listed, RDCK provided BGC with an air photo from 2017. The original source of the 2017 image is unknown.

Table C-1. Kuskonook Creek air photo records.

Year	Date	Roll Number	Photo Number	Scale
2006	7/15/2006	BCC06058	176-177	20,000
2000	7/30/2000	BCB00021	51-52, 98-99	15,000
1993	9/5/1993	BCB93019	142, 143, 201, 203	15,000
1988	7/22/1988	BC88031	276-277	15,000
1981	7/2/1981	BC81037	46-48	15,000
1978	8/5/1978	BC78142	128-129	40,000
1972	8/7/1972	BC7429	76-78	15,840
1967	7/18/1967	BC7007	202-204	15,840
1958	7/19/1958	BC2450	20-21	15,840
1952	7/1/1952	BC1487	75-76	31,680
1945	5/2/1945	A7728	125, 128	15,000

APPENDIX D
MODELLING SCENARIOS

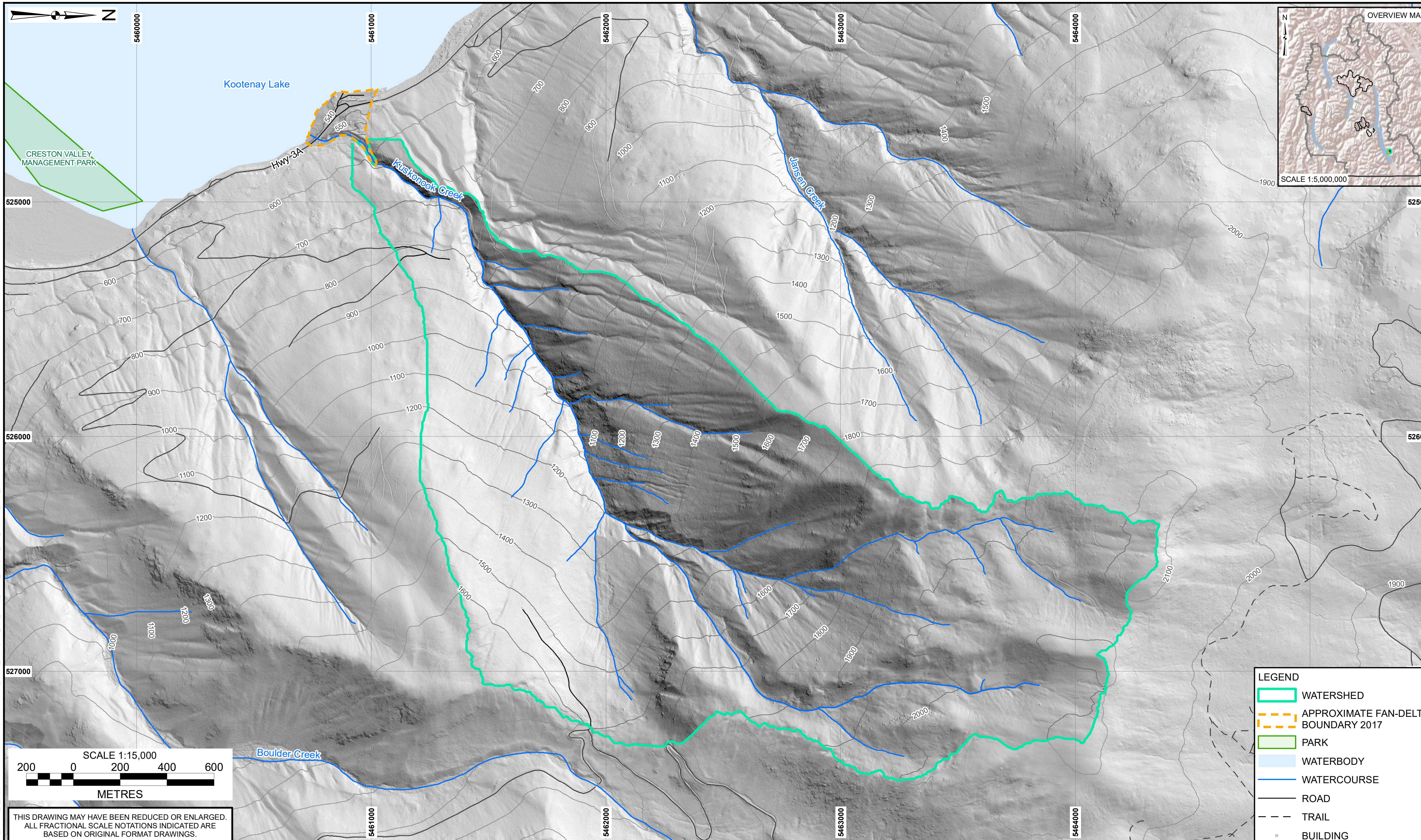
D.1. MODELLING SCENARIOS

The scenarios analyzed for Kuskonook Creek are presented in Table D-1, along with the information on the bulking factor. Sediment concentration total discharge and the type of modelling executed are also described.

Table D-1. Modeling scenario summary for Kuskonook Creek.

Scenario Name	Return Period (years)	Process Type	Peak Discharge (m^3/s)	Conveyance Structures			Flood Protection Structures				
				Name	Estimated Capacity (m^3/s)	Assumption	Name	Type	Bank Erosion Encroaching	$\tau/\tau c \geq 2$	Assumption
KSK-1	20	Flood	2	Debris Basin Culvert	N/A	Functioning as intended	Debris Flow Protection Structure	Berm	N	N	Functioning as intended
				Spillway Culvert	N/A	Functioning as intended					
KSK-2	50	Debris Flow	500	Debris Basin Culvert	N/A	Blocked by debris	Debris Flow Protection Structure	Berm	N	N	Functioning as intended
				Spillway Culvert	N/A	Blocked by debris					
KSK-3	200	Debris Flow	630	Debris Basin Culvert	N/A	Blocked by debris	Debris Flow Protection Structure	Berm	N	N	Functioning as intended
				Spillway Culvert	N/A	Blocked by debris					
KSK-4	500	Debris Flow	680	Debris Basin Culvert	N/A	Blocked by debris	Debris Flow Protection Structure	Berm	N	N	Functioning as intended
				Spillway Culvert	N/A	Blocked by debris					

DRAWINGS



NOTES:
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2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "RDCK FLOODPLAIN AND STEEP CREEK STUDY - KUSKONOOK CREEK", AND DATED MARCH 2020.
3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY RDCK DATED 2017. CONTOUR INTERVAL IS 100 m AND 10 m ON FAN.
4. THE FAN BOUNDARY AS DRAWN IS APPROXIMATE AND DELINEATES THE LANDFORM BASED ON LIDAR DATED 2017. THE BOUNDARY SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DOES IT SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
5. BUILDING FOOTPRINTS DIGITIZED BY BGC BASED ON LIDAR AND REPRESENT ONLY A SUBSET OF TOTAL BUILDINGS ON THE FAN-DELTA. PARKS DATA FROM GOVERNMENT OF BC. ROADS DATA FROM BC DIGITAL ROAD ATLAS.
6. PROJECTION IS NAD 1983 UTM ZONE 11N.
7. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED OR USED FOR ANY PURPOSE OTHER THAN THE PURPOSE FOR WHICH BGC GENERATED IT. BGC SHALL HAVE NO LIABILITY FOR ANY DAMAGES OR LOSS ARISING IN ANY WAY FROM ANY USE OR MODIFICATION OF THIS DOCUMENT NOT AUTHORIZED BY BGC. ANY USE OF OR RELIANCE UPON THIS DOCUMENT OR ITS CONTENT BY THIRD PARTIES SHALL BE AT SUCH THIRD PARTIES' SOLE RISK.

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APPROVED:	MJ

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CLIENT:

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: KUSKONOOK SITE LOCATION MAP

PROJECT No.: 0268007

DWG No: 01

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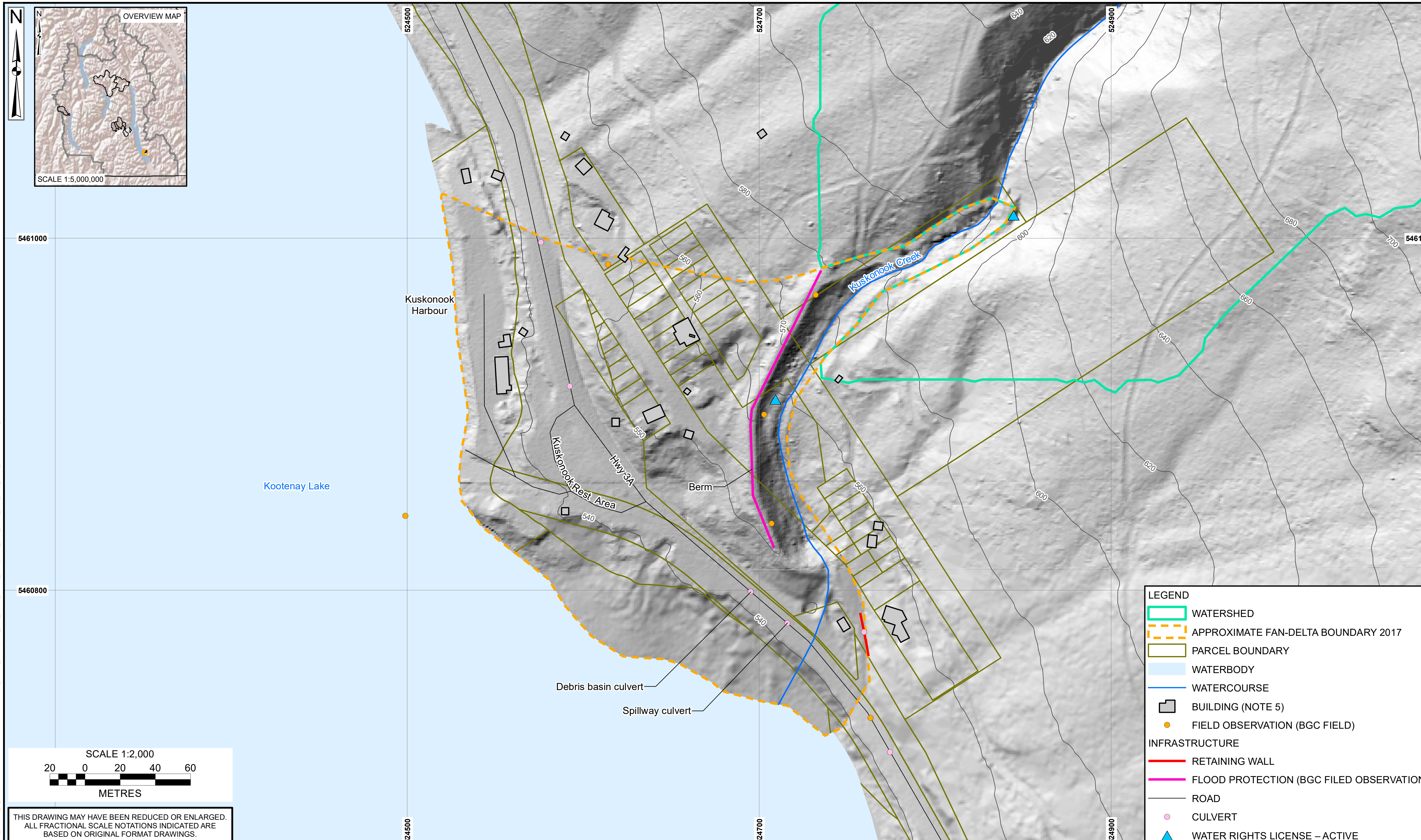

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3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY RDCK, DATED 2017. CONTOUR INTERVAL IS 20 m AND 10 m ON FAN.
4. THE FAN BOUNDARY AS DRAWN IS APPROXIMATE AND DELINEATES THE LANDFORM BASED ON LIDAR DATED 2017. THE BOUNDARY SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DOES IT SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
5. WATER DATA FROM CANVEC, UPDATED BASED ON BGC FIELD OBSERVATIONS, WHERE APPLICABLE. BUILDING FOOTPRINTS DIGITIZED BY BGC BASED ON LIDAR AND REPRESENT ONLY A SUBSET OF TOTAL BUILDINGS ON THE FAN-DELTA. CULVERT LOCATIONS FROM BC MINISTRY OF TRANSPORTATION AND BGC FIELD OBSERVATIONS. ROADS DATA FROM BC DIGITAL ROAD ATLAS. WATER RIGHTS LICENSE DATA FROM GEOBC. PARCELS FROM PARCELMAP BC. FLOOD PROTECTION DATA FROM BGC FIELD OBSERVATIONS (APPROXIMATE).
6. PROJECTION IS NAD 1983 UTM ZONE 11N.
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TITLE: KUSKONOOK CREEK FAN-DELTA SITE MAP

PROJECT No.:	DWG No:
0268007	02A

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2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "RDCK FLOODPLAIN AND STEEP CREEK STUDY - KUSKONOOK CREEK", AND DATED MARCH 2020.
3. BASE TOPOGRAPHIC DATA AND ORTHOPHOTO BASED ON LIDAR PROVIDED BY RDCK, DATED 2017. CONTOUR INTERVAL IS 20 m AND 10 m ON FAN.
4. THE FAN BOUNDARY AS DRAWN IS APPROXIMATE AND DELINEATES THE LANDFORM BASED ON LIDAR DATED 2017. THE BOUNDARY SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DOES IT SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
5. WATER DATA FROM CANVEC, UPDATED BASED ON BGC FIELD OBSERVATIONS, WHERE APPLICABLE. BUILDING FOOTPRINTS DIGITIZED BY BGC BASED ON LIDAR AND REPRESENT ONLY A SUBSET OF TOTAL BUILDINGS ON THE FAN-DELTA. CULVERT LOCATIONS FROM BC MINISTRY OF TRANSPORTATION AND BGC FIELD OBSERVATIONS. ROADS DATA FROM BC DIGITAL ROAD ATLAS. WATER RIGHTS LICENSE DATA FROM GEOBC. PARCELS FROM PARCELMAP BC. FLOOD PROTECTION DATA FROM BGC FIELD OBSERVATIONS (APPROXIMATE).
6. PROJECTION IS NAD 1983 UTM ZONE 11N.
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PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: KUSKONOOK CREEK FAN-DELTA SITE MAP

PROJECT No.: 0268007

DWG No: 02B

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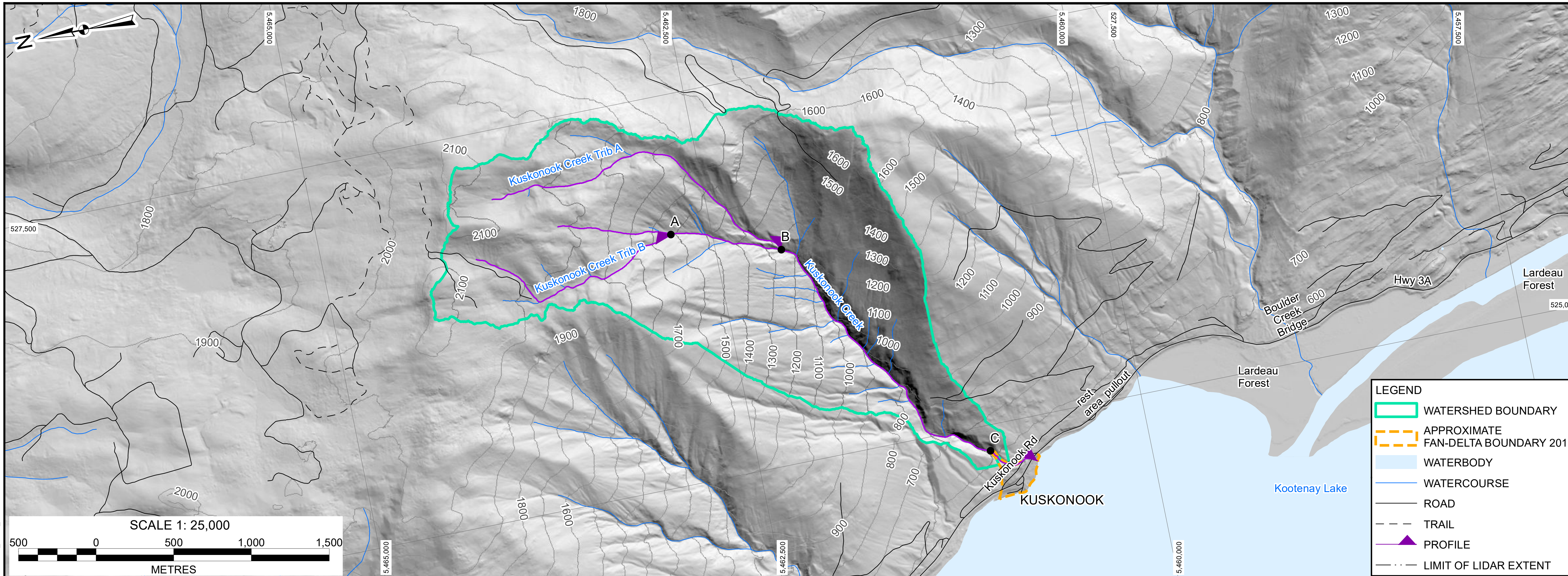

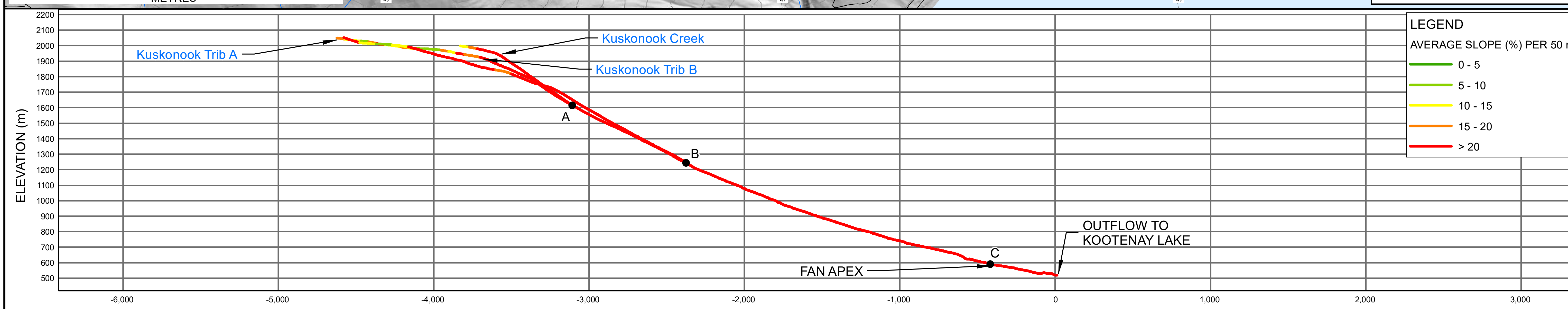

NO VERTICAL EXAGGERATION

NOTES:
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3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY RDCK, DATED 2017.
4. THE WATERSHED AND FAN BOUNDARES AS DRAWN ARE APPROXIMATE AND DELINEATE THE LANDFORMS. THE BOUNDARIES SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DO THEY SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
5. WATERSHED BOUNDARIES DELINEATED FROM BGC'S RIVER NETWORK TOOLS, WATERBODIES SOURCED FROM CANVEC, WATERCOURSES SOURCED FROM BGC'S RIVER NETWORK TOOLS AND CANVEC, ROADS AND TRAILS SOURCED FROM GEOBC DIGITAL ROAD ATLAS.
6. ELEVATION PROFILE SHOWS DISTANCE RELATIVE TO THE CREEK OUTLET ON X-AXIS AND ELEVATION DERIVED FROM THE BASE TOPOGRAPHIC DATA ON Y-AXIS
7. PROJECTION IS NAD 1983 UTM ZONE 11N.
8. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED OR USED FOR ANY PURPOSE OTHER THAN THE PURPOSE FOR WHICH BGC GENERATED IT. BGC SHALL HAVE NO LIABILITY FOR ANY DAMAGES OR LOSS ARISING IN ANY WAY FROM ANY USE OF OR MODIFICATION OF THIS DOCUMENT NOT AUTHORIZED BY BGC. ANY USE OF OR RELIANCE UPON THIS DOCUMENT OR ITS CONTENT BY THIRD PARTIES SHALL BE AT SUCH THIRD PARTIES' SOLE RISK.

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CLIENT:

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: KUSKONOOK CREEK PROFILE

PROJECT No.: 0268007

DWG No: 03

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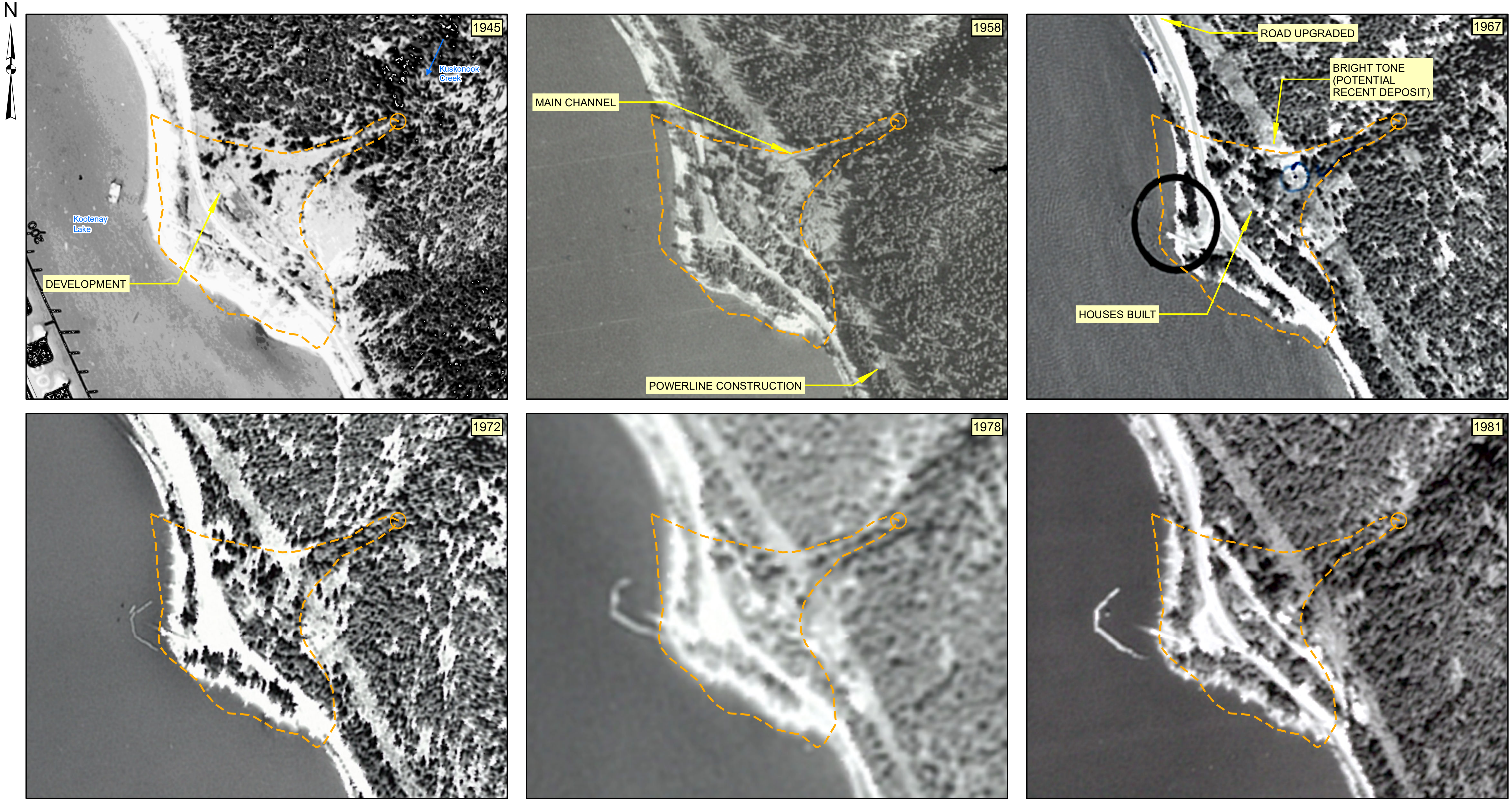

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LEGEND

APPROXIMATE FAN-DELTA BOUNDARY 2017

FAN APEX

NOTES:
1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "STEEP CREEK HAZARD AND RISK ASSESSMENT - KUSKANOOK CREEK", AND DATED MARCH 2020.
3. BASE TOPOGRAPHIC DATA BASED ON AIR PHOTOS PROVIDED BY BC AIR PHOTO LIBRARY AND NATIONAL AIR PHOTO LIBRARY.
4. THE FAN BOUNDARY AS DRAWN IS APPROXIMATE AND DELINEATES THE LANDFORM BASED ON LIDAR DATED 2017. THE BOUNDARY SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DOES IT SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
5. AIR PHOTO FROM YEAR 1967 WAS MARKED ON PHYSICAL COPIES PRIOR TO BGC'S AIR PHOTO INTERPRETATION.
6. AIR PHOTOS WITH NO LABELS INDICATE NO MAJOR DEVELOPMENT OR CHANGE IN CHANNEL FEATURES COMPARED TO PREVIOUS AIR PHOTO.
7. COORDINATE SYSTEM IS UTM ZONE 11 NAD 1983. VERTICAL DATUM IS UNKNOWN.
8. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED OR USED FOR ANY PURPOSE OTHER THAN THE PURPOSE FOR WHICH BGC GENERATED IT. BGC SHALL HAVE NO LIABILITY FOR ANY DAMAGES OR LOSS ARISING IN ANY WAY FROM ANY USE OR MODIFICATION OF THIS DOCUMENT NOT AUTHORIZED BY BGC. ANY USE OF OR RELIANCE UPON THIS DOCUMENT OR ITS CONTENT BY THIRD PARTIES SHALL BE AT SUCH THIRD PARTIES' SOLE RISK.

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CHECKED:	JJHP, LCH
APPROVED:	MJ

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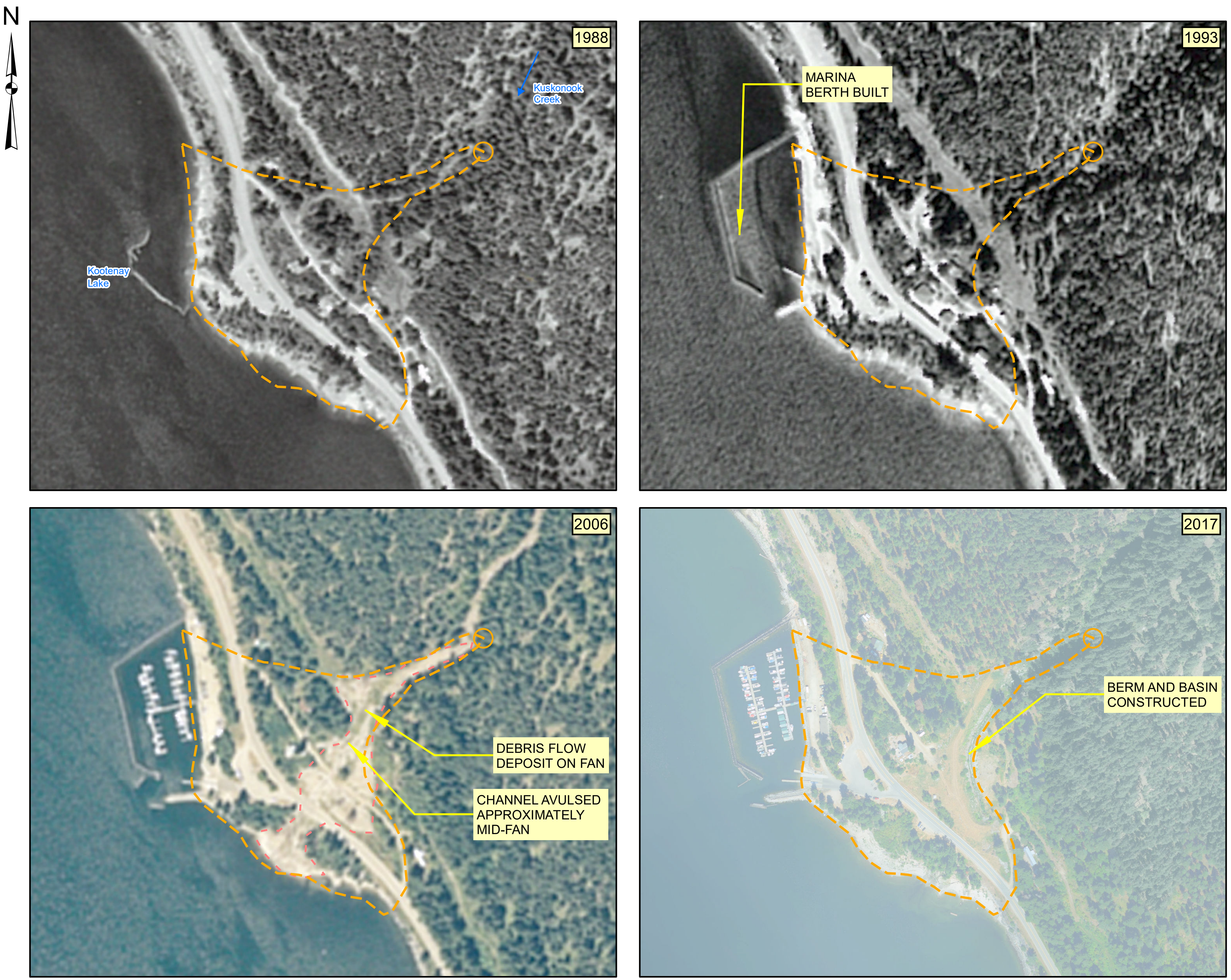
CLIENT:

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: KUSKONOOK CREEK AIR PHOTO COMPARISON

PROJECT No.: 0268007

DWG No: 04A



SCALE 1:5,000

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METRES

THIS DRAWING MAY HAVE BEEN REDUCED OR ENLARGED. ALL FRACTIONAL SCALE NOTATIONS INDICATED ARE BASED ON ORIGINAL FORMAT DRAWINGS.

LEGEND

- APPROXIMATE FAN-DELTA BOUNDARY 2017
- APPROXIMATE EXTENT OF 2004 EVENT
- FAN APEX

NOTES:
1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "STEEP CREEK HAZARD AND RISK ASSESSMENT - KUSKANOOK CREEK", AND DATED MARCH 2020.
3. BASE TOPOGRAPHIC DATA BASED ON AIR PHOTOS PROVIDED BY BC AIR PHOTO LIBRARY AND NATIONAL AIR PHOTO LIBRARY.
4. THE FAN BOUNDARY AS DRAWN IS APPROXIMATE AND DELINEATES THE LANDFORM BASED ON LIDAR DATED 2017. THE BOUNDARY SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DOES IT SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
5. COORDINATE SYSTEM IS UTM ZONE 11 NAD 1983. VERTICAL DATUM IS UNKNOWN.
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APPROVED:	MJ

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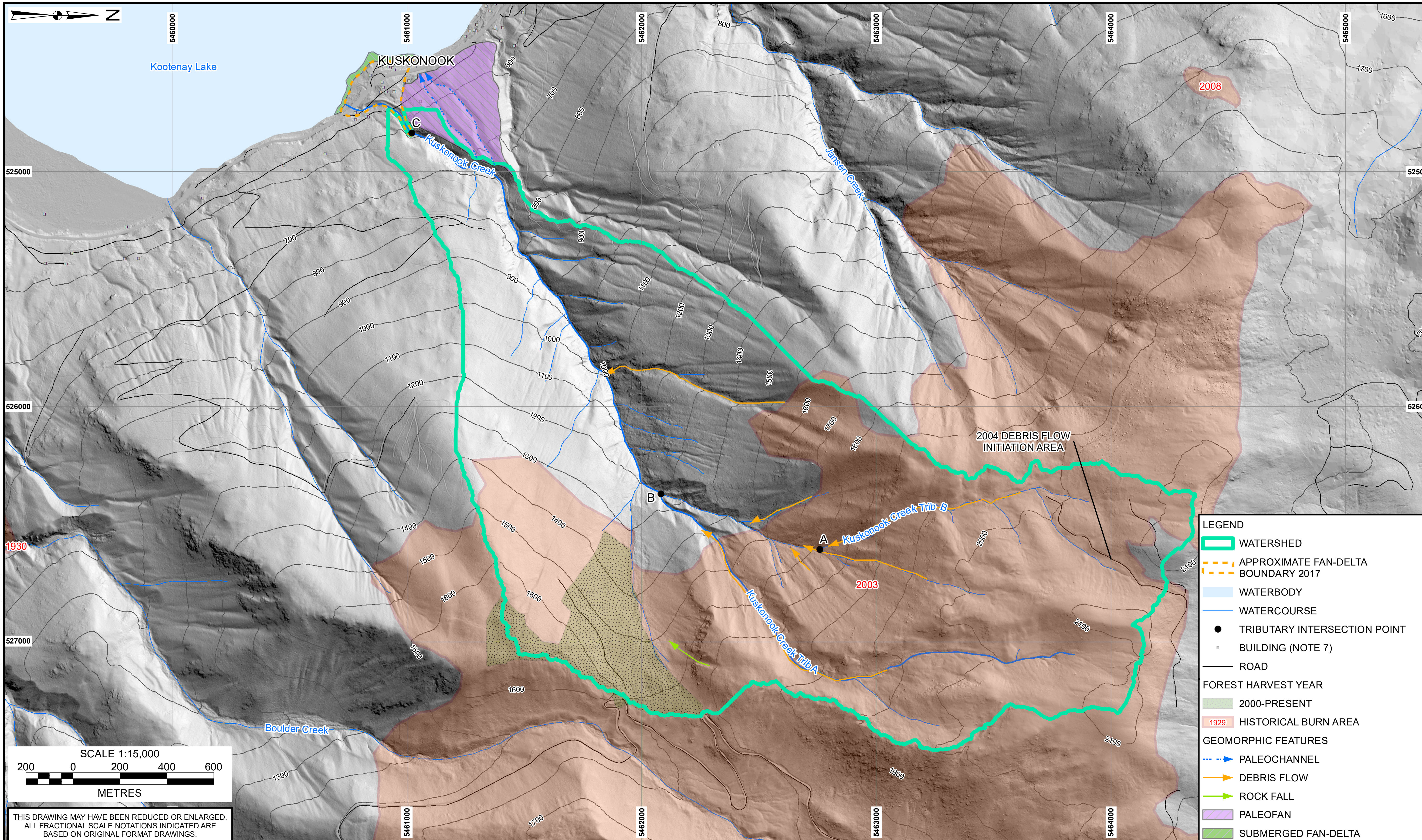
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

PROJECT:
RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE:
KUSKONOOK CREEK
AIR PHOTO COMPARISON

PROJECT No.:	DWG No:
0268007	04B



NOTES:
1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "RDCK FLOODPLAIN AND STEEP CREEK STUDY - KUSKONOOK CREEK", AND DATED MARCH 2020.
3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY RDCK DATED 2017, AND GEOBASE CDED. CONTOUR INTERVAL IS 100m.
4. THE WATERSHED AND FAN-DELTA BOUNDARY AS DRAWN ARE APPROXIMATE AND DELINEATE THE LANDFORMS BASED ON LIDAR DATED 2017. THE BOUNDARIES SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DO THEY SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
5. HISTORICAL CUT BLOCK DATA ONLY REPRESENTATIVE OF AREAS THAT INTERSECT WATERSHED BOUNDARY.
6. SUBMERGED FAN-DELTA DELINEATED BASED ON LAKE LEVEL FROM LIDAR DATED 2017.
7. BUILDING FOOTPRINTS DIGITIZED BY BGC BASED ON LIDAR AND REPRESENT ONLY A SUBSET OF TOTAL BUILDINGS ON THE FAN-DELTA. ROADS DATA FROM BC DIGITAL ROADS ATLAS. RAILWAY DATA FROM GEOBASE NATIONAL RAILWAY NETWORK.
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APPROVED:	MJ

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: KUSKONOOK CREEK WATERSHED GEOMORPHOLOGY

PROJECT No.:	DWG No.:
0268007	05

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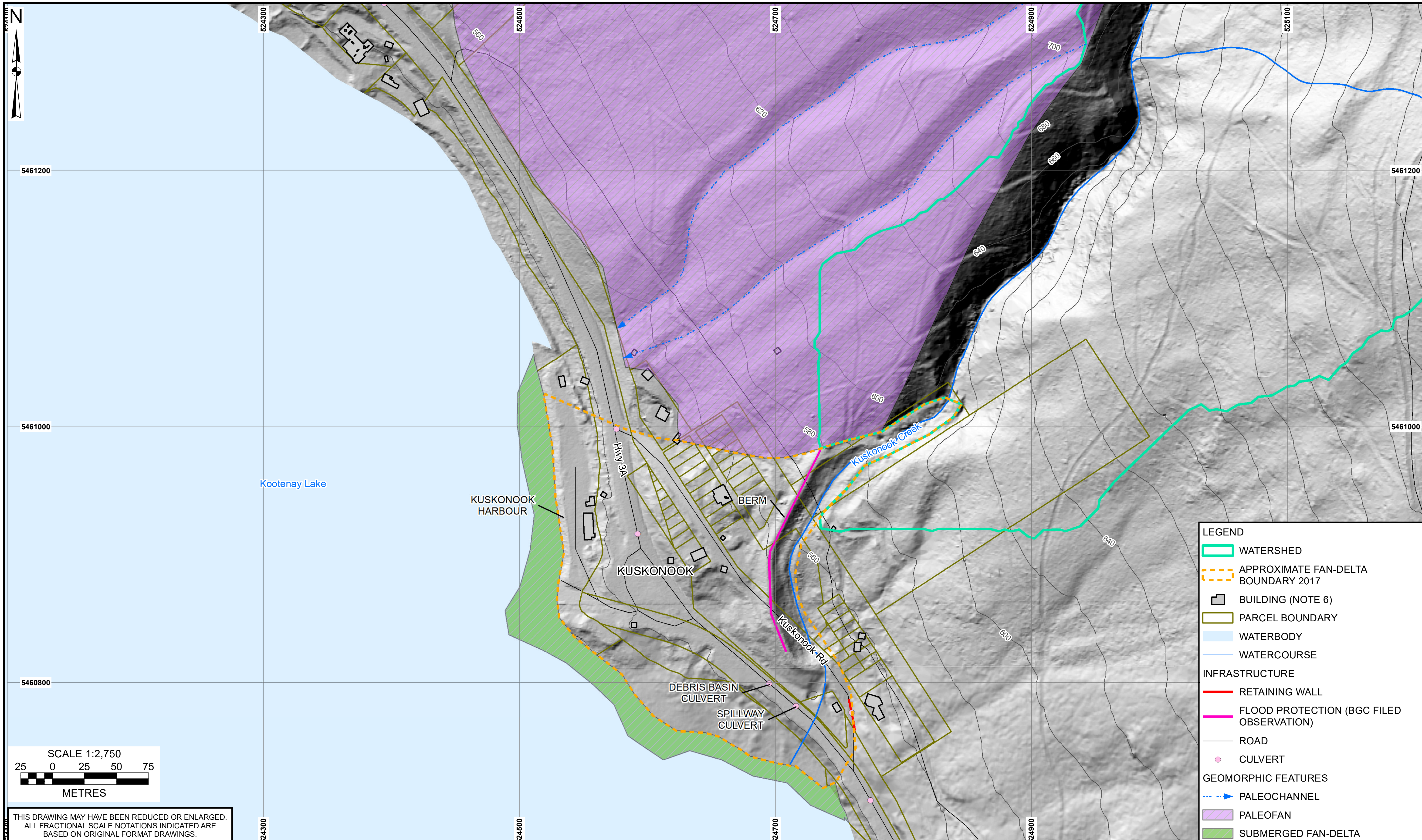

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3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY RDCK DATED 2017. CONTOUR INTERVAL IS 10m.
4. THE WATERSHED AND FAN-DELTA BOUNDARY AS DRAWN ARE APPROXIMATE AND DELINEATE THE LANDFORMS BASED ON LIDAR DATED 2017. THE BOUNDARIES SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DO THEY SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
5. SUBMERGED FAN-DELTA DELINEATED BASED ON LAKE LEVEL FROM LIDAR DATED 2017. WATER DATA FROM CANVEC, UPDATED BASED ON BGC FIELD OBSERVATIONS, WHERE APPLICABLE.
6. CULVERT LOCATIONS FROM BC MINISTRY OF TRANSPORTATION. ROADS DATA FROM BC DIGITAL ROAD ATLAS. PARCELS FROM PARCELMAP BC. BUILDING FOOTPRINTS DIGITIZED BY BGC BASED ON LIDAR AND REPRESENT ONLY A SUBSET OF TOTAL BUILDINGS ON THE FAN-DELTA. HISTORICAL CUT BLOCK DATA ONLY REPRESENTATIVE OF AREAS THAT INTERSECT WATERSHED BOUNDARY. RETAINING WALL FROM MINISTRY OF TRANSPORTATIN DATASET DATED 2012.
7. PROJECTION IS NAD 1983 UTM ZONE 11N.
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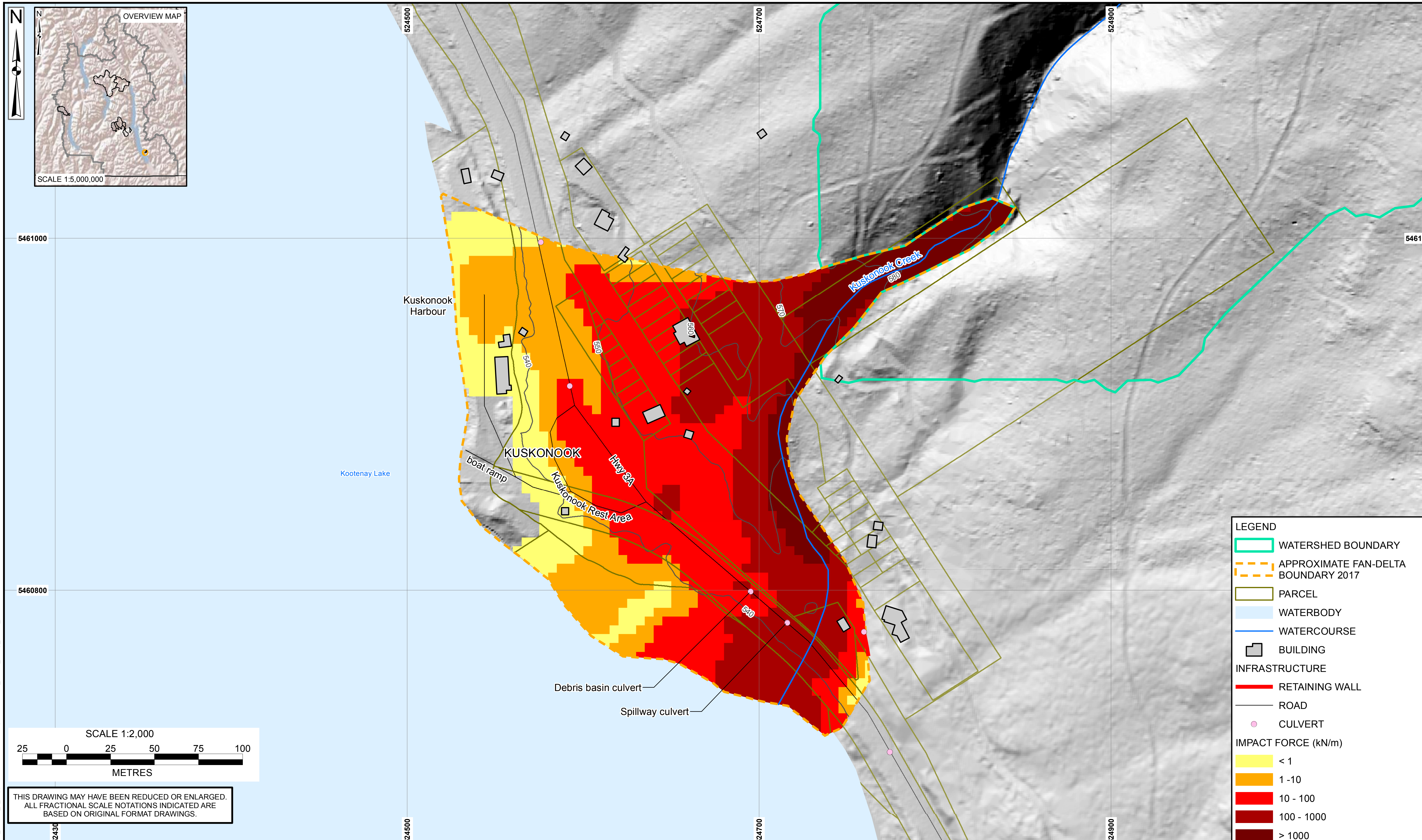
CLIENT:

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: KUSKONOOK CREEK FAN-DELTA GEOMORPHOLOGY

PROJECT No.:	DWG No.:
0268007	05



THIS DRAWING MAY HAVE BEEN REDUCED OR ENLARGED. ALL FRACTIONAL SCALE NOTATIONS INDICATED ARE BASED ON ORIGINAL FORMAT DRAWINGS.

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NOTES:
1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORTS TITLED "RDCK FLOODPLAIN AND STEEP CREEK STUDY - KUSKONOOK CREEK", AND DATED MARCH 2020.
3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY RDCK, DATED 2017. CONTOUR INTERVAL IS 20 m AND 10 m ON FAN.
4. BUILDING FOOTPRINTS DIGITIZED BY BGC BASED ON LIDAR AND REPRESENT ONLY A SUBSET OF TOTAL BUILDINGS ON THE FAN-DELTA. ROADS DATA FROM BC DIGITAL ROAD ATLAS.
5. SCENARIO MAP SHOWS DEBRIS-FLOW IMPACT FORCE BASED ON DAN3D MODEL RESULTS FOR THE 200-YEAR RETURN PERIOD COMPLETED BY BGC. THIS IS A REPRESENTATIVE MAP AND DOES NOT SHOW THE FULL SUITE OF MODELLED SCENARIOS. SCENARIO DETAILS ARE OUTLINED IN BGC REPORT.
6. THIS MAP REPRESENTS A SNAPSHOT IN TIME. FUTURE CHANGES (DEVELOPMENT, DEBRIS FLOOD MITIGATION, GEOHAZARD EVENTS) MAY WARRANT RE-DRAWING OF CERTAIN AREAS.
7. PROJECTION IS NAD 1983 UTM ZONE 11N. VERTICAL DATUM IS UNKNOWN.
8. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED OR USED FOR ANY PURPOSE OTHER THAN THE PURPOSE FOR WHICH BGC GENERATED IT. BGC SHALL HAVE NO LIABILITY FOR ANY DAMAGES OR LOSS ARISING IN ANY WAY FROM ANY USE OR MODIFICATION OF THIS DOCUMENT NOT AUTHORIZED BY BGC. ANY USE OF OR RELIANCE UPON THIS DOCUMENT OR ITS CONTENT BY THIRD PARTIES SHALL BE AT SUCH THIRD PARTIES' SOLE RISK.

SCALE:	1:2,000
DATE:	MAR 2020
DRAWN:	LL, MIB, STT
CHECKED:	LCH
APPROVED:	MJ

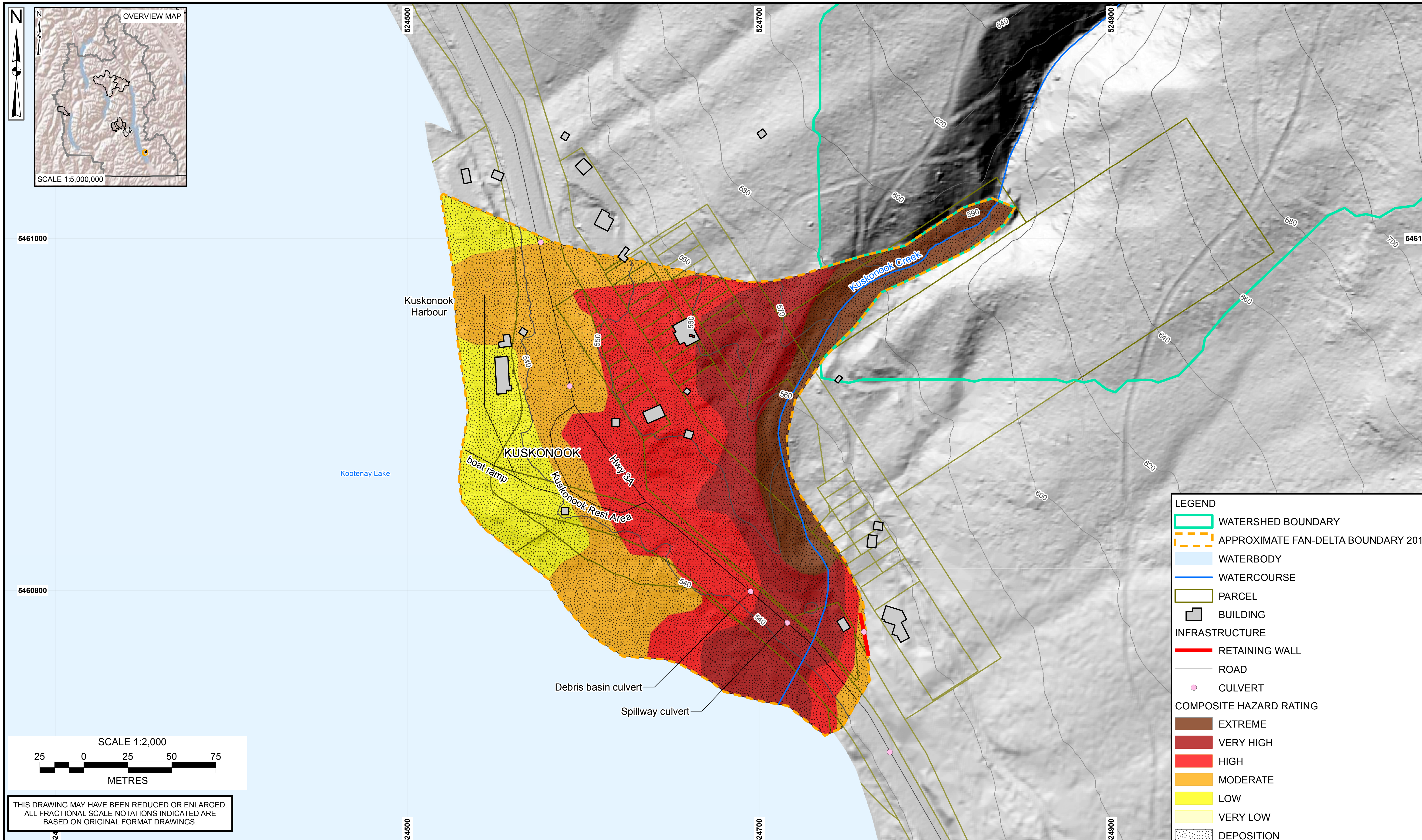
BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

PROJECT:
RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE:
KUSKONOOK CREEK 200 YEAR MODEL SCENARIO KSK-3

PROJECT No.:	DWG No:
0268007	07



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NOTES:
1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORTS TITLED "RDCK FLOODPLAIN AND STEEP CREEK STUDY - KUSKONOOK CREEK", AND DATED MARCH 2020.
3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY RDCK, DATED 2017. CONTOUR INTERVAL IS 20 m AND 10 m ON FAN. THE FAN BOUNDARY AS DRAWN IS APPROXIMATE AND DELINEATES THE LANDFORM BASED ON LIDAR DATED 2017.
4. COMPOSITE HAZARD RATINGS PORTRAYED ON THIS DRAWING ONLY REPRESENT HAZARDS STUDIED WITHIN THE FAN-DELTA BOUNDARY.
5. THIS MAP REPRESENTS A SNAPSHOT IN TIME. FUTURE CHANGES (DEVELOPMENT, DEBRIS FLOOD MITIGATION, GEOHAZARD EVENTS) MAY WARRANT RE-DRAWING OF CERTAIN AREAS.
6. BUILDING FOOTPRINTS DIGITIZED BY BGC BASED ON LIDAR AND REPRESENT ONLY A SUBSET OF TOTAL BUILDINGS ON THE FAN-DELTA. ROADS DATA FROM BC DIGITAL ROAD ATLAS. PARCEL MAP FROM PARCELMAP BC.
7. PROJECTION IS NAD 1983 UTM ZONE 11N.
8. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED OR USED FOR ANY PURPOSE OTHER THAN THE PURPOSE FOR WHICH BGC GENERATED IT. BGC SHALL HAVE NO LIABILITY FOR ANY DAMAGES OR LOSS ARISING IN ANY WAY FROM ANY USE OR MODIFICATION OF THIS DOCUMENT NOT AUTHORIZED BY BGC. ANY USE OF OR RELIANCE UPON THIS DOCUMENT OR ITS CONTENT BY THIRD PARTIES SHALL BE AT SUCH THIRD PARTIES' SOLE RISK.

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CLIENT:

PROJECT:
RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE:
KUSKONOOK CREEK
COMPOSITE HAZARD RATING MAP

PROJECT No.:	DWG No:
0268007	08