RDCK FLOODPLAIN AND STEEP CREEK STUDY

Duhamel Creek

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TABLE OF REVISIONS

ISSUE	DATE	REV	REMARKS
DRAFT	March 31, 2020		Interim draft.
FINAL	March 31, 2020		Final issue

LIMITATIONS

EXECUTIVE SUMMARY

This report and its appendices provide a detailed hydrogeomorphic hazard assessment of Duhamel Creek. This creek was chosen as a high priority creek amongst hundreds in the Regional District of Central Kootenays from a risk perspective because of its comparatively high hazards and perceived consequences from debris floods. It is the most densely developed fan-delta along the West Arm of Kootenay Lake with the highest asset values.

Duhamel 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 and Duhamel creeks); those by debris flows (Kuskonook Creek); and hybrids (Procter and Redfish creeks).

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 Duhamel Creek fan-delta. This work is the foundation for possible future quantitative risk assessments or conceptualization and eventual design and construction of mitigation measures.

Multiple hazard scenarios were developed for specific event return periods. This included bulking of flow to allow for higher organic and mineral sediment concentrations. Various bridge blockage scenarios were also considered. This is especially important for Duhamel Creek because the fan-delta is crossed by numerous highway and pedestrian bridges some of whose capacity is jeopardized at various return period flood or debris flood events.

Two numerical hydro-dynamic models were employed to simulate debris flood 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. BGC also estimated bank erosion from a physically-based model for different debris flood probabilities. Table E-1 provides key observations derived from the numerical modelling.

Table E-1. Key findings from numerical modelling of Duhamel Creek debris floods.

Process	Key Observations
Clearwater inundation (HEC-RAS model results for all return periods)	• For all return period debris floods, at the log crib bifurcation structure, water flows over the left bank and follows paleochannel channels downstream to pool in the upstream ditch of Highway 3A. • Water overtops the stretch of highway in between the east channel and Barnes Road and continues to flow overland towards the lake inundating several private properties. • Water flows southwest toward the lake in the Highway 3A ditch and as sheet flow along the highway for the 50, 200 and 500-year return period. • The area in between the west and east channels and north of Lower 6 Mile Road in inundated for the 50, 200 and 500-year return periods. For the 50-year event, water avulses from the diversion channel approximately 50 m downstream of the Highway 3A West Bridge. For the 200 and 500-year events, the water flooding this area is largely from overtopping Highway 3A section of Lower 6 Mile Road (from approximately 50 m to 200 m northeast of the east channel) experiences shallow flow for the 20- and 50-year return periods. • A section of Lower 6 Mile Road (from approximately the diversion channel to 320 m northeast of the east channel) experiences shallow flow for all return periods. • The west channel stays relatively confined until just downstream of elementary school, École des Sentiers-Alpins, where there is a small avulsion over the left bank and a much larger one for the 20-year flood immediately upstream of Lower 6 Mile Road. This results in shallow water flow along the stretch of road in between the east and west channels for approximately 145 m for the 20- and 50- year return periods. • For the 200 and 500-year events, there are multiple very small avulsions for the 500-year return period) approximately 50 m upstream of the Highway 3A bridge as well as in between the Highway 3A bridge and Lower 6 Mile Rd over the right channel bank. This causes flooding for several properties along the roadways, including the trailer park along Duhamel Beech Rd. • Water overtops the Lower 6 Mile Road flooding several properties for all return periods.
Sedimentation	• For the 200- and 500-year return period debris floods, it is likely that one or both of the channels at the bifurcation structure could block due to aggradation and all flow would be diverted down either channel, causing avulsions of debris similar to the clearwater models out of each channel as it reaches its capacity and berms are damaged. • Sedimentation associated with debris floods can occur across all parts of the active fan as the flow spreads as it leaves the channel in numerous locations of low confinement. The average sediment deposition depths across the inundation area could be between 0.1 to 0.2 m for the 200-year and 500-year debris floods. • Sedimentation associated with debris floods could reach up to 3 m thickness in the channel and up to 1.5 m outside the channel, in localized low-lying areas.

Process	Key Observations
Bank Erosion	• Average bank erosion ranges between 1 m (20-year) and 19 m (500-year) with maxima ranging between 3 m (20-year) and 32 m (500-year). Bank erosion potential generally increases downstream. • Bank erosion may affect the abutments of Highway 3A and Lower 9 Mile bridges during a high return period event, or by progressive erosion over time. During a 500-year return period event, properties located south of Highway 3A along Duhamel Creek may be impacted.
Auxiliary Hazards	• As with other debris-flood prone creeks in the study area that end in lakes, during high lake levels there is a substantial chance that the lower portions of Duhamel Creek will build up sediment and avulse east or west of the active channels downstream of the Lower 6-Mile Road. • All modeling results demonstrate overtopping of Highway 3A. Experience on other fans in BC and Alberta has demonstrated that such overtopping can lead to scour on the downstream (lake) side, followed by pavement undermining and collapse. This may lead to preferential flow paths not captured in the numerical modeling, resulting in higher flow velocities and flow depths than modeled. Flow will concentrate in paleochannels, for example, halfway between the east channel and Barnes Road. • Barnes Road and Duhamel Creek Road which run parallel to Duhamel Creek would likely either be eroded (Duhamel Creek Road) or convey water at high flow velocities (Barnes Road). In this case, water in the ditches on either side of the road would likely create deep furrows which deepen the more water they convey, and eventually undercut the asphalt. The result is that neither Barnes nor Duhamel Creek Road would likely be passable during, and immediately after, a major flood or debris flood. • The west channel of Duhamel Creek upstream of Highway 3A flows along the 40 to 45 m high paleofan surface. Bank erosion along this reach could lead to slope failures from the paleofan complex. Halfmoon-shaped embayments visible on lidar imagery suggest that sluffs or slumps have happened in the past. Such bank erosion and associated slope failures could affect properties perched along the eastern edge of the paleofan surface and possibly deflect the creek into hitherto unrecognized avulsion paths.

The multiple process numerical modelling ensemble approach demonstrates the key hazards and associated risks stem from avulsions at the bifurcation structure and at the Highway 3A and Six Mile Road bridge crossings. These are attributable to exceeding bridge capacity in association with channel bed aggradation or log jams. Such avulsions are likely to affect the majority of the active fan.

Model results are cartographically expressed in two ways: 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. It 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 debris flood 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 hazard zone is attributed to specific land use prescriptions, covenants, bylaws or other limiting clauses for both existing and proposed development. The categories range from very low to very high hazard. Very low hazard is defined as areas likely to not be affected by any of the modeled scenarios up to the 500-year return period debris floods, but which are not free of hazard. Very low hazard zones could be impacted by flows of higher return periods, or if, over time, the channel bed of Duhamel Creek aggrades, or the channel or fan surface is artificially altered. All other hazard categories are classified via the impact force intensity. The composite hazard rating map shows that the majority of the Duhamel Creek fan-delta is subject to low hazards. Moderate and high hazards are concentrated along the main channels and where avulsions of Duhamel Creek were identified through numerical modelling.

A review of the NHC/Thurber (1990) study which was a detailed hazard and risk assessment of Duhamel and other creeks in the RDCK, BGC concludes that the hazards and likely (as BGC did not quantify risks) the risks to loss of life are substantially lower than presumed in the NHC/Thurber report. NHC/Thurber did not benefit from lidar topography, detailed numerical modelling, and an additional 30 years of data that have accrued since their study and the present. In absence of such detailed information and analysis, it was likely justified to err on the conservative spectrum.

While not comprehensive or quantitative, BGC provides several considerations for creek hazard management. These include (from the top of the fan delta to the bottom): A debris basin to capture sediment that could be installed in several different locations; increasing the capacity of the Highway 3A and Lower 6 Mile Road bridges on both channels; and deflection berms upstream of Highway 3A and upstream of Lower 6 Mile Road on the west channel to prevent avulsions. Drainage and toe erosion of the slopes adjacent to the fan-delta should be assessed. If necessary, the appropriate mitigative actions could be taken to prevent slope failures onto the fan-delta. In addition to physical mitigation, other measures should be considered such as development restrictions.

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 surface topography or scenario assumptions, such as future fan developments, debris floods, formation of large landslides in the watershed that could impound Duhamel Creek, bridge re-design or alteration to the existing dikes and berms. Breaches of the Highway 3A or Lower 6 Mile Road embankments due to retrogressive erosion associated with overtopping could result in inundation and rapid sedimentation not reflected on BGC's individual hazard scenarios or composite hazard rating map. Similarly, the re-occupation and erosion of inactive channels on the fan delta could result in higher flow depths as modeled. Erosion of Barnes Road or Duhamel Creek Road could result in preferred flow paths with some deviations from BGC's model results. Slope failures from steep embankments along the paleofan surfaces on the west and east side of the fan-delta could result in temporary creek impoundments and deflections of creek water with avulsions occurring at locations not specifically modeled by BGC.

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.

Not all hazards can be adequately modelled as each process displays some chaotic behaviour. 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.

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

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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 for Duhamel Creek, located approximately 15 km northeast of Nelson, BC, in Electoral Area F. The site lies on the north side of the West Arm of Kootenay Lake and flows through the unincorporated community of Six Mile, BC into the lake.

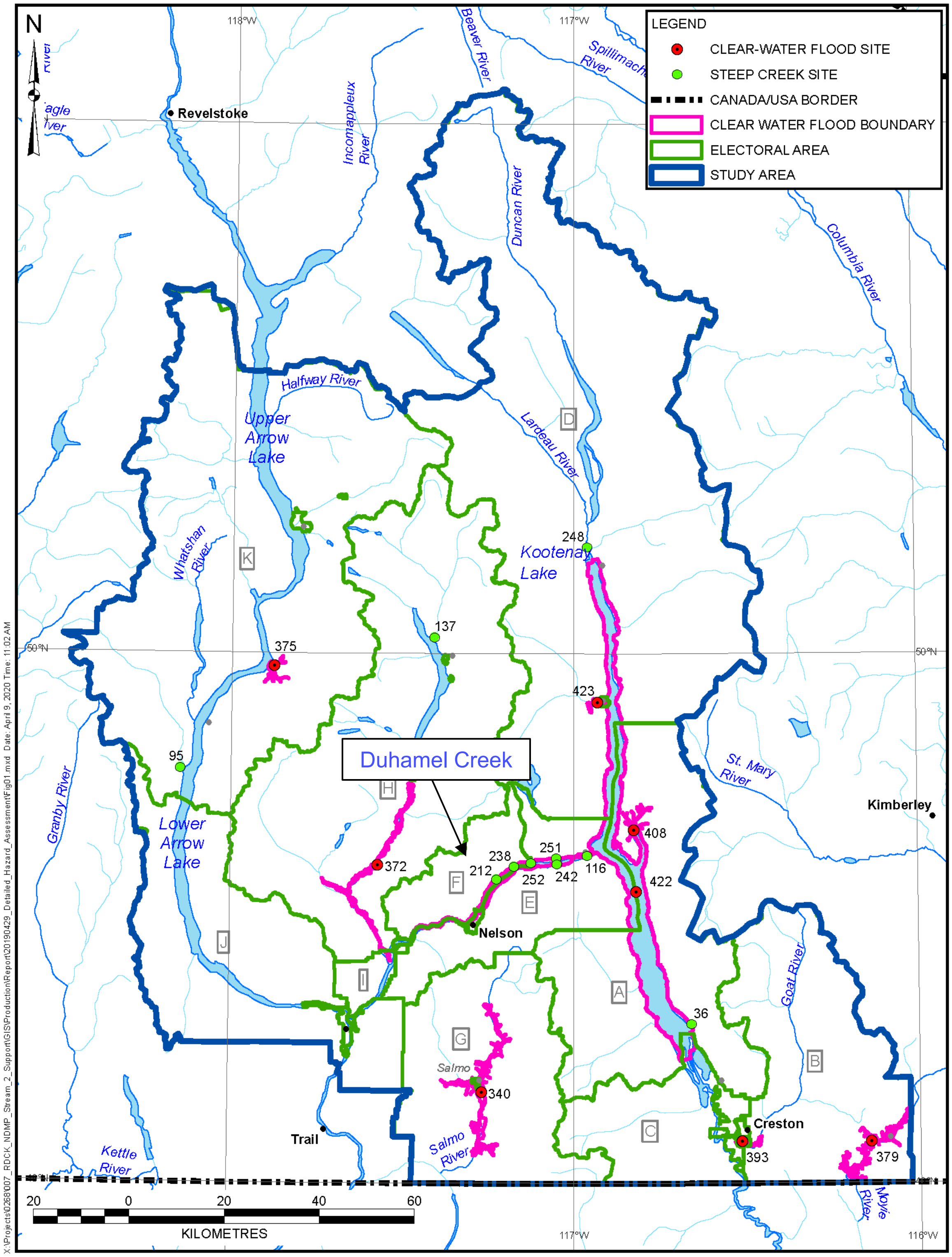

Figure 1-1. Hazard areas prioritized for detailed flood and steep creek mapping. Site labels correspond to hazard identification numbers in Cambio Communities. Duhamel Creek (No. 212) is labelled on the figure.

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 Duhamel 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 Duhamel Creek, the scope of work included:

- Characterization of the study area including regional physiography and hydroclimate, and local watershed characteristics, geology, steep creek process, and fan and creek characteristics.
- Development of a comprehensive site history of floods 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.
- Consideration of processes specific to fan-deltas (backwater effect during times of high lake levels and high peak discharges).
- 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 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 (BGC, March 31, 2020a). As outlined in Section 1.1, the report is best read with the Summary Report (BGC, March 31, 2020a) and Methodology Report (BGC, March 31, 2020b).

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
- Carie-Ann Lau, M.Sc., P.Geo., Intermediate Geoscientist

[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.

- Jack Park, B.A.Sc., EIT, GIT, Junior Geological Engineer
- Hilary Shirra, B.A.Sc., EIT, Junior Hydrotechnical Engineer
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- Sarah Davidson, Ph.D., P.Geo. Intermediate Geoscientist
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- 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.

Project Director	Kris Holm	
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Overall Technical Reviewer(s)	Matthias Jakob Hamish Weatherly	
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2	Beatrice Collier-Pandya	Matthias Busslinger; Lauren Hutchinson
3	Jack Park	Matthias Busslinger; Anna Akkerman; Carie-Ann Lau
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5.1	Beatrice Collier-Pandya	Matthias Busslinger; Matthias Jakob
5.2	Melissa Hairabedian	Matthias Jakob
5.3	Beatrice Collier-Pandya; Lauren Hutchinson	Matthias Busslinger
5.4	Beatrice Collier-Pandya; Gemma Bullard	Lauren Hutchinson; Toby Perkins; Anna Akkerman
5.5	Gemma Bullard; Midori Telles-Langdon	Sarah Davidson
5.6	Matthias Jakob	Lauren Hutchinson
6.1 – 6.2	Beatrice Collier-Pandya; Lauren Hutchinson	Matthias Jakob
6.3	Melissa Hairabedian	Matthias Jakob
6.4	Lauren Hutchinson; Matthias Busslinger	Matthias Jakob
6.5	Gemma Bullard; Beatrice Collier-Pandya	Lauren Hutchinson; Toby Perkins; Anna Akkerman
6.6	Gemma Bullard; Midori Telles-Langdon,	Sarah Davidson
6.7	Beatrice Collier-Pandya; Gemma Bullard; Matthias Jakob	Lauren Hutchinson
7	Lauren Hutchinson	Matthias Jakob

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.

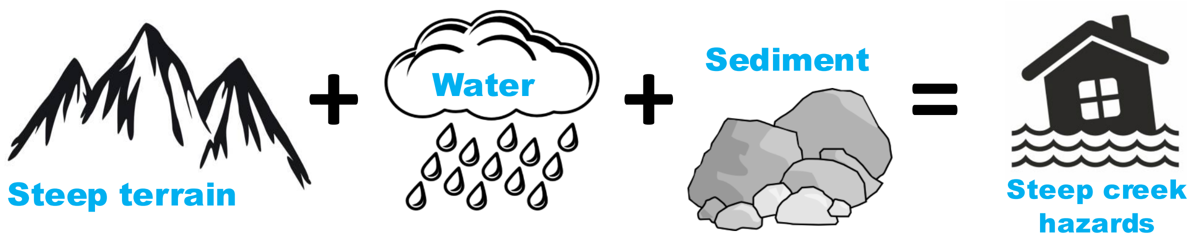

Figure 2-1. Illustration of steep creek hazards.

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.

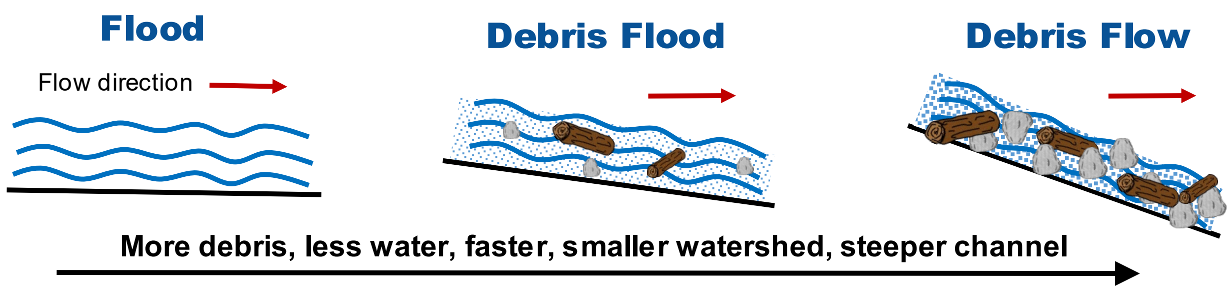

Figure 2-2. Continuum of steep creek hazards.

2.2. Clearwater 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 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.

Debris flows 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.

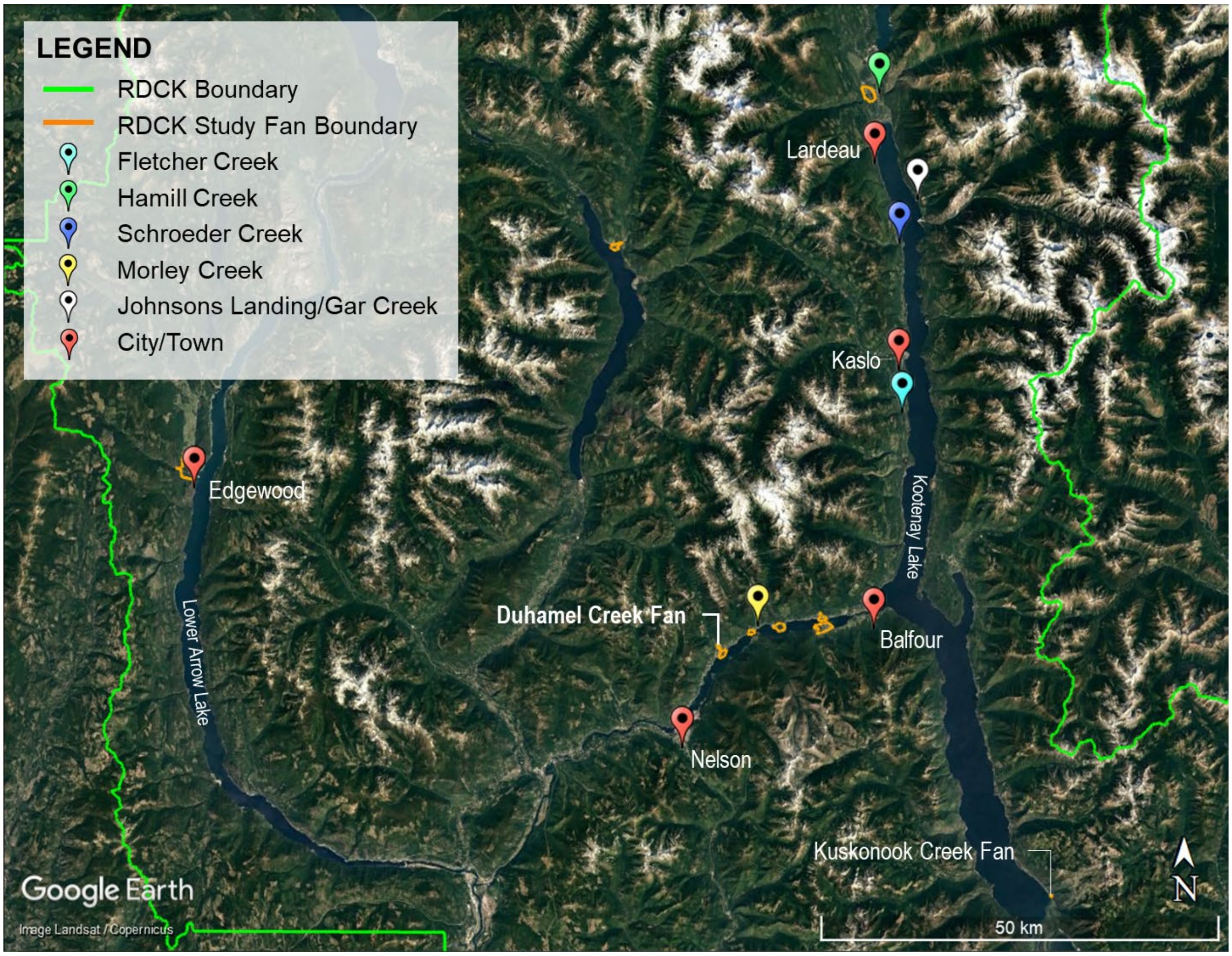

Figure 2-3. Locations of RDCK fans and recent floods, debris flows, and debris floods (Google Earth Pro, 2016).

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 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.

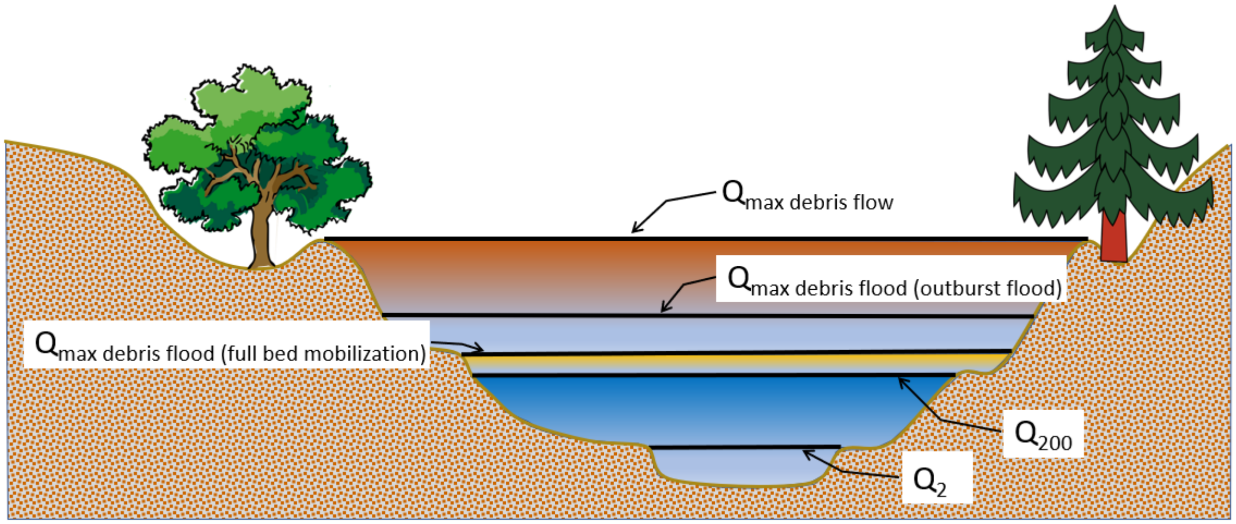

Figure 2-4. Conceptual steep creek channel cross-section showing peak discharge levels for different events. Note that for some outburst floods or debris flows the discharge may well exceed what is shown here.

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. 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.

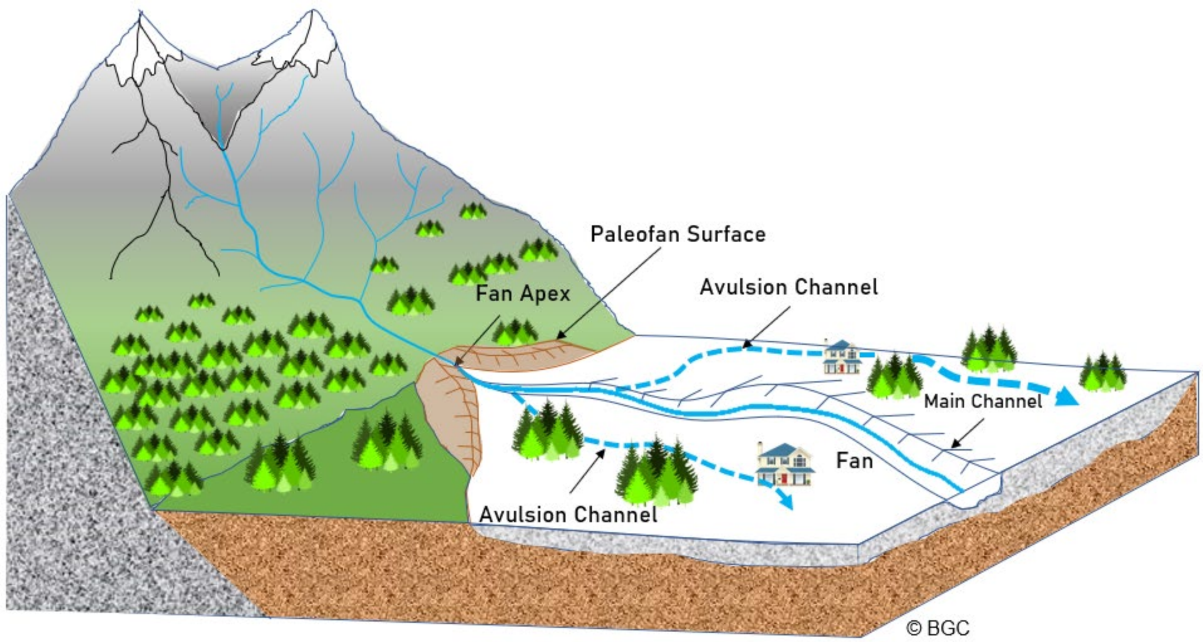

Figure 2-5. Schematic of a steep creek channel with avulsions downstream of the fan apex. Artwork by BGC.

3. STUDY AREA CHARACTERIZATION

The following section provides a characterization of the study area including physiography, geology, a description of the Duhamel Creek watershed (Drawing 01) and existing development on the fan (Drawings 02A and 02B), as well as hydroclimatic conditions and projected impacts of climate change.

3.1. Site Visit

Field work on Duhamel Creek was conducted on July 5, 8, 24, 27 to 29, 2019, and on November 19, 2019 by BGC personnel (Marc Olivier Trottier, Anna Akkerman, Rob Millar, Matthias Busslinger, Matthias Jakob, Kris Holm, Carie-Ann Lau, Beatrice Collier-Pandya and Hilary Shirra). Field work included channel hikes to look for evidence of high-water marks; assess bank erosion and previous creek alignments; measure grain size diameters (Wolman sampling) (Appendix C); and, measure cross-sections at the bridges and other infrastructure crossing locations. Fieldwork focused on the active channels on the fan-delta and recent overflow channels as a preliminary steep creek process assessment for Duhamel Creek indicated the dominant process type was clearwater flooding (Stream 1 Study (BGC, March 31, 2019)).[3] 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).

3.2. Physiography

Duhamel Creek is located approximately 11 km northeast of Nelson, BC, on the north shore of the West Arm of Kootenay Lake. The site lies within the Selkirk Mountains, which are a subgroup of the Columbia Mountains in southeastern BC. Most of the creek catchment falls within the Central Columbia Mountain ecosection of the Northern Columbia Mountains ecoregion, which is drained by numerous streams that flow into Kootenay Lake, the Slocan River, and the Arrow Lake reservoir (Demarchi, 2011). The ecosection is characterized by long, uniformly steep slopes that terminate at sharp ridges and mountain peaks sculpted by cirque glaciers with mostly narrow valleys (Holland, 1976). Precipitation is high in the Central Columbia ecosection, as moisture from coastal areas arrives from the south and west, bringing high humidity and rain in summer, and deep snow in winter (Demarchi, 2011). Typical vegetation includes Western Red Cedar and Western Hemlock trees at lower elevations (from 500 m) and Engelmann Spruce and Subalpine Fir trees along the mid-mountain slopes. The highest peaks in the Central Columbia ecosection reach up to approximately 3200 m and consist of barren rock.

3.3. Geology

3.3.1. Bedrock Geology

The Duhamel Creek watershed is underlain by granodioritic intrusive rocks of the Nelson Batholith, which formed in the Mid-Jurassic Period. The catchment is situated in the approximately 1500 km^2, northern portion of the batholith (i.e., intrusive igneous rock), where subvertical to

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3 Upon further analysis, it was concluded that Kokanee Creek is also subject to debris floods at return periods in excess of 20 years.

west-dipping foliation has been mapped north of the West Arm of Kootenay Lake (Vogl & Simony, 1992). Though there have been no faults mapped within the watershed, the linear nature of the creek suggests that its path is structurally controlled (Apex Geoscience, 2015).

3.3.2. Surficial Geology

Along Duhamel Creek, the prevailing surficial material consists mostly of colluvium in the upper watershed and glaciofluvial in the lower reaches (Figure 3-1). The valley walls and ridges are composed of thin veneers of sandy, blocky colluvium overlying bedrock, while bare rock outcrops are only on the highest peaks (Jungen, 1980). The abundant colluvium in the watershed, which is subject to mobilization via debris avalanches and debris flow into the mainstem, indicates that the watershed is likely largely supply unlimited. This implies a quasi-unlimited amount of sediment available in the watershed to be mobilized during extreme hydroclimatic events.

3.4. Geomorphology

3.4.1. Watershed

Geomorphological analysis of Duhamel Creek included characterization of the watershed and fan characterization 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 03 shows a channel profile for the watershed with annotations of reaches and representative channel gradients. Drawing 05 shows geomorphic features of the watershed.

The headwaters of Duhamel Creek are the mountainous slopes of Mount Cornfield (approximate elevation of 2362 m) to the north and Mount Grohman (approximate elevation of 2299 m) to the west, although the watershed divide at the top of the valley near Six Mile Lakes is low (approximately elevation 1100 m). The main reach of the watershed is characterized by a steep sided, V-shaped valley that runs directly north-south, perpendicular to the West Arm. Several small lakes (Six Mile Lakes, Photo 9 in Appendix B) are present on the upper flatter portions of the main channel (Drawing 03). With approximately 7 km^2 catchment area each, Tributary A and Tributary B are the largest tributaries and join Duhamel Creek approximately 3 and 9 km upstream of the lake outlet (Locations A and B, Drawing 03). The fan apex is located 2.0 km upstream of the lake outlet.

The steep-sided valley has many avalanche and debris flow-prone tributaries that deposit sediment fans into the main channel and push the creek alignment back and forth across the valley bottom (Drawing 05). Particularly about 4 km upstream of the fan apex on the east side of the valley the debris flow-prone tributaries are closely spaced at about 300 m. The main channel has incised into thick (> 10 m) glaciofluvial deposits along the valley bottom from the fan apex to approximately 8.5 km upstream from the Kootenay Lake outlet.

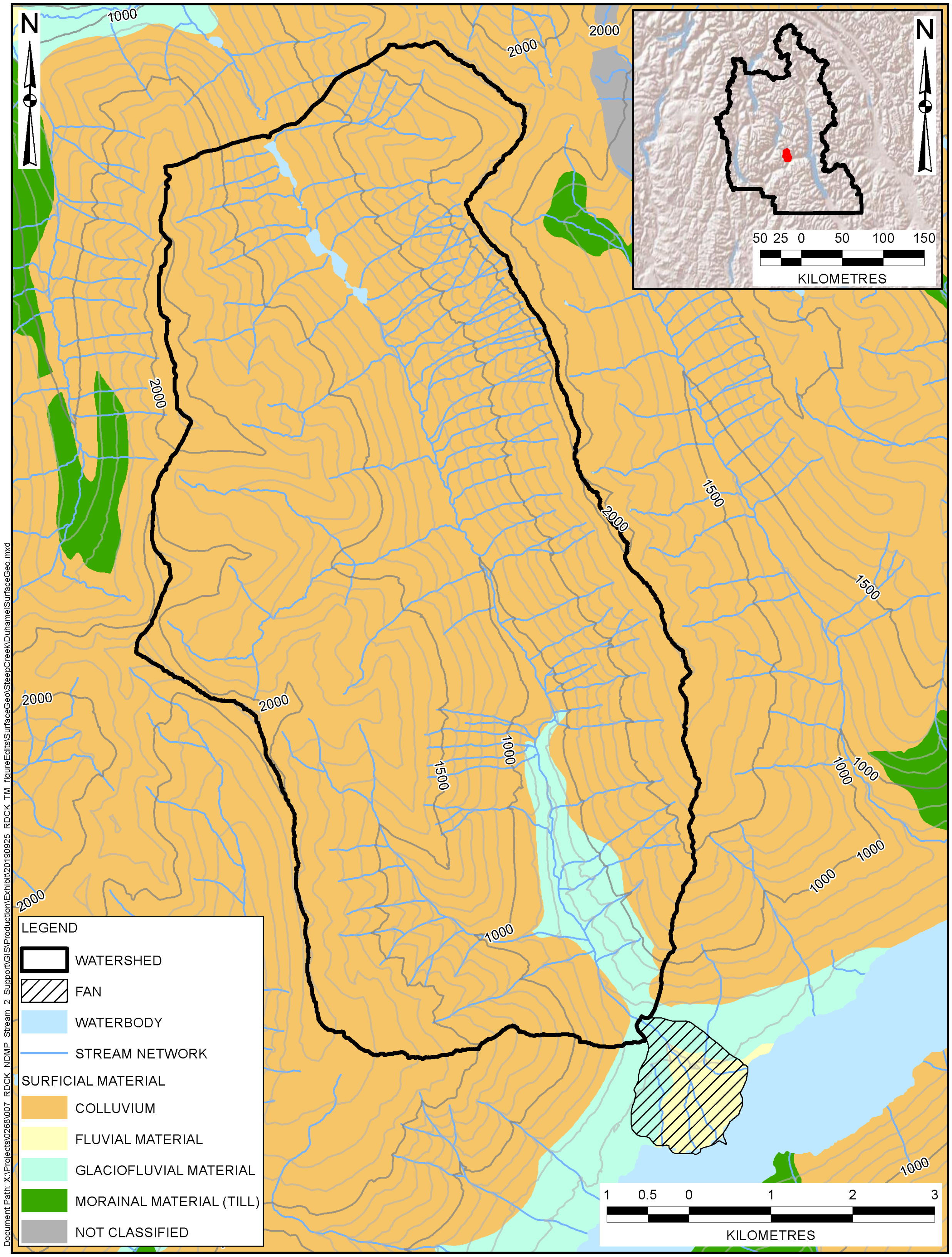

Figure 3-1. Surficial geology of the Duhamel Creek watershed (from Province of BC, 2016).

The Six Mile Lakes appear to have been shaped and in places blocked by fans of the steep unnamed tributaries. Further downstream, a dendritic drainage network with deeply incised gullies (Photo 10 in Appendix B) has formed on the east valley slope in the area that approximately coincides with the 1924 burn (Drawing 05). Debris flow and debris avalanche paths were mapped in these tributaries. Fans of the tributaries draining the 1924 burn area appear to be larger than the fans on the opposite valley side. The relatively large size of these fans indicates that ample sediment is supplied to Duhamel Creek.

A series of lineaments is present on the Kokanee Range ridge on the east side of the valley. These lineaments can be seen in Drawing 05 at elevations 1580 to 1730 m along the ridge crest. These lineaments may be related to the west dipping foliation mentioned in Section 3.3.1.

The extents of historically burned and logged areas are shown in Drawing 05. Extensive logging occurred on the west side of the watershed and 9% of the entire watershed area has been logged since 1900 (FLNRORD, 2019b). 21% of the total watershed has burned since 1919, with the largest forest fire on record in 2015 (FLNRORD, 2019a). Photos 11 and 12 in Appendix B show burned areas. BGC notes that the records in the FLNRORD (2019a) and (2019b) datasets may not be complete in the early years, the first cut block is reported for 1969 and the first fire for 1920.

Areas of logging and forests fires are important from a geomorphic perspective, as they can be significant sources of sediment. Photo 11 in Appendix B shows the 2015 burn area on the eastern slope above Duhamel Creek (Drawing 05), while Photo 12 shows the surficial erosion and riling occurring in the burn area. On the west side of the valley numerous debris avalanches are mapped (Drawing 05). Most of these debris avalanches occur in the vicinity of clear cuts or logging roads (e.g., Photo 8 in Appendix B).

Table 3-1 summarizes relevant geomorphic characteristics of the Duhamel Creek watershed, which are indicators of the process type and anticipated behaviour of the watershed in response to high runoff. The Melton Ratio (watershed relief divided by square root of watershed area) and channel gradient both assist in determining if a creek is susceptible to flood, debris flood, or debris-flow processes (Section 3.5). The channel gradient above the fan apex provides an indication of whether transportation of sediment is likely, and the fan gradient approximates the angle where sediment deposition of larger flows from the watershed generally ensues.

Table 3-1. Watershed characteristics of Duhamel Creek.

Characteristic	Value
Watershed area (km^2)	56
Fan-delta area (km^2)	1.73
Active fan-delta area (km^2)[1]	0.7
Maximum watershed elevation (m)	2,362
Minimum watershed elevation (m)	630
Watershed relief (m)	1,732
Melton Ratio[2]	0.23
Average channel gradient of mainstem above fan-delta apex (%)	10
Average channel gradient on fan-delta (%)	5.7
Average fan-delta gradient (%)	7.7

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. Duhamel Creek Fan-Delta

An overview of the Duhamel Creek fan-delta is shown in Drawings 02A and 02B, while Drawing 06 shows geomorphic features of the fan. Overview photos are provided in Appendix B (Photos 1, 2, 3 and 4). Locations referred to in the text below are labelled on these drawings. The fan-delta areas delineated in the drawings have been interpreted by BGC based on lidar and field data; however, the extents of the fan-delta beyond the lidar data limits at Kootenay Lake are difficult to define due to changing lake levels.

Duhamel Creek flows southeasterly across the fan that extends into the West Arm of Kootenay Lake. The channel leaves a confined valley where the channel width is approximately 7 to 10 m and widens to approximately 15 to 18 m wide as it enters the fan. Approximately 1 km downstream of the fan apex, a bifurcation structure splits flow down two channels (Photos 4 and 5 in Appendix B). This structure is discussed in detail in Section 3.5.2. The western channel is the main channel currently receiving most of the flow. It flows along a 40 to 45 m high paleosurface upstream of Highway 3A. The active channel ranges from 10 to 15 m wide on the western channel and 2 to 5 m wide on the eastern channel. The average channel gradient decreases from approximately 11% (6°) at the fan apex to approximately 7% (4°) near the channel outlets into the lake. At the lake outlet, beaver dams have been reported (Dwain Boyer, email attachment, personal communication, April 22, 2020).

Remnants of a paraglacial fan are present as raised surfaces on either side of the upper fan (Drawing 06). The western channel is eroding into the paraglacial fan bank to the west of the current fan. There is an elevated surface on the northeastern side of the active fan that likely represents a more recent inactive fan portion (i.e., in the vicinity of Worley Road).

The Duhamel Creek fan-delta has been slightly modified by the raise of lake levels in 1932 by construction of the Corra Linn Dam, southwest of Nelson. The dam raised the lake levels by approximately 2 m and aims to keep this level relatively steady with the use of upstream dam management as well. The distal portions of the fan, visible in air photos (Section 6.2), were flooded by the lake level raise. Duhamel Creek flows into Kootenay Lake in an approximately 55 m wide reach on the western channel (Photo 6 in Appendix B) and an approximately 30 m wide reach on the eastern channel.

3.4.3. Steep Creek Process

BGC assessed the potential steep creek process types and hazards on Duhamel 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, Duhamel Creek plots in the data cluster prone to debris floods and floods (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.

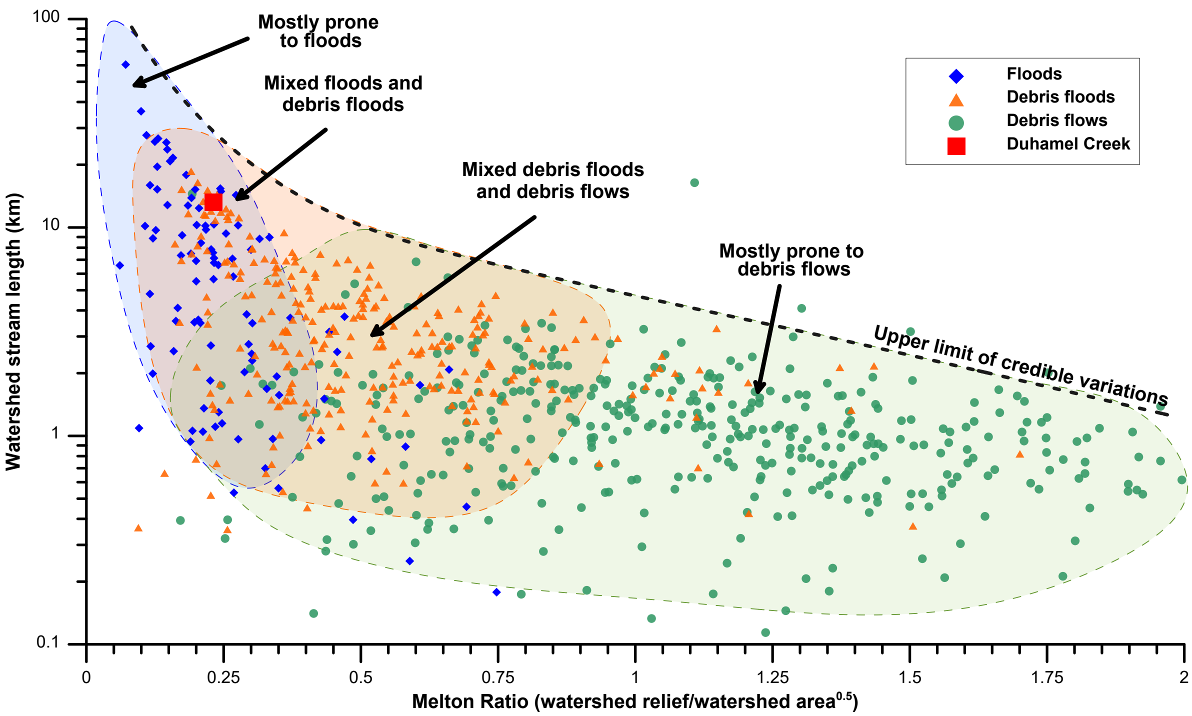

Figure 3-2. Tendency of creeks to produce floods, debris floods and debris flows, as a function of Melton Ratio and stream length (data from Holm et al., 2016 and Lau, 2017). See Section 3.2 for Duhamel Creek watershed data.

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). 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 Type 1 debris floods to be the dominant hydrogeomorphic process at Duhamel Creek for low return periods (20- and 50-year), while Type 2 debris floods dominate at the higher return periods (200-, and 500-year) that were studied. This rationalization is discussed further in Section 6.1.

3.5. Existing Development

Development on the Duhamel Creek fan-delta comprises the unincorporated community of Six Mile. Highway 3A, petroleum infrastructure and communications infrastructure transect the mid-fan-delta. BGC notes that the community of Six Mile is elsewhere referred to as McDonalds Landing or Willow Point; for consistency, the name Six Mile is used in this report. There are several businesses located on the fan-delta, including the Duhamel Store, Hellman Canoes and Kayaks, Kokanee Glacier Resort, and Sweet Mountain Pottery Studio and Gallery, all located on the distal end of the fan-delta. 6 Mile RV and Storage is a business located on the mid fan-delta. An elementary school, École des Sentiers-Alpins, is located south of Highway 3A, east of the western channel.

The 2016 census does not have a population estimate for Six Mile and instead groups the community into the RDCK electoral area (Statistics Canada, 2016). BGC's estimate of the fan-delta population developed as part of the Stream 1 study was 161 (BGC, March 31, 2019). This estimate should be treated as a minimum as it does not account for all population sources. The estimated total improvement value of parcels intersecting the Duhamel Creek fan-delta based on the 2018 BC Assessment Data is approximately $27 million (BGC, March 31, 2019).

There are fourteen water intakes along Duhamel Creek upstream of Highway 3A, one at the Highway 3A crossing, and an additional five downstream of the Highway (Active Water Rights – Licenses available on iMapBC and shown on Drawings 02A and 02B).

3.5.1. Bridges

Bridge locations are shown in Drawings 02A, 02B and 06, and bridge dimensions are provided in Table 3-2.

Moving downstream from the fan-delta apex, the first bridge on Duhamel Creek is the Old Log Bridge (Figure 3-3A). The second bridge is a resident driveway bridge to 2898 Duhamel Creek Road (Figure 3-3B), approximately 300 m upstream of Highway 3A.

A) Old Log Bridge.

B) Looking downstream at Driveway Bridge 1.

Figure 3-3. Duhamel Creek bridges upstream of bifurcation structure: A) Old Log Bridge, B) Driveway Bridge. BGC photos taken July 2019.

Table 3-2. Estimated dimensions of bridge crossings on Duhamel Creek fan-delta, heading downstream by creek channel.

Bridge	Channel	Span (m)	Height Above Channel Center (m)	Notes
Old Log Bridge	Main	-	-	Near fan-delta apex. Dimensions were not obtained.
Driveway Bridge 1	Main	9	2.5	Single lane access to home (2898 Duhamel Creek Road)
Bifurcation Bridge	Western	6	2.2	On Duhamel Creek Road
Duhamel Highway 3A West Bridge	Western	9.6	2.1	Highway 3A, paved 2-lane road
Lower 6 Mile Road West Bridge	Western	11	1.4	Paved 2-lane road
Duhamel Highway 3A East Bridge	Eastern	3.3	1.3	Highway 3A, paved 2-lane road
Pedestrian Bridge 1	Eastern	10	1.3	Wooden footbridge
Driveway Bridge 2	Eastern	9	1.6	
Lower 6 Mile Road East Bridge	Eastern	7.7	1.5	Paved 2-lane road
Pedestrian Bridge 2	Eastern	-	-	Dimensions were not obtained.

Note: The bridge dimensions were either obtained in the field or estimated from site photographs from typical dimensions for the size of road.

At the bifurcation structure (Drawings 02A, 02B and 06), Duhamel Creek splits into a main (western) channel and an eastern channel. The western channel passes under three bridges: the Bifurcation Bridge at the bifurcation structure (Figure 3-4A and B), Duhamel Highway 3A West Bridge (Figure 3-4C), and Lower 6 Mile Road West Bridge (Figure 3-4D).

A) On the upstream right bank looking downstream at the bifurcation structure in the centre and Bifurcation Bridge on the right.

B) Looking downstream (towards western channel) underneath Bifurcation Bridge at the bifurcation structure (see also Photos 4 and 5 in Appendix B for aerial view of bridge).

C) On upstream left bank looking at right bank riprap armouring under Duhamel Highway 3A West Bridge crossing the western channel.

D) Looking downstream at Lower 6 Mile Road West Bridge over western channel.

Figure 3-4. Duhamel Creek bridges on western channel. BGC photos taken July 2019.

Downstream of the bifurcation structure, the eastern channel passes through Duhamel Highway 3A East Bridge (Figure 3-5A and B) and Pedestrian Bridge 1 (Figure 3-5C) located approximately 50 m downstream of Highway 3A, while Driveway Bridge 2 (Figure 3-5D) is 100 m downstream. Further downstream, the eastern channel passes through the Lower 6 Mile Road East Bridge (Figure 3-5E) and approximately 70 m downstream, Pedestrian Bridge 2 (Figure 3-5 F).

The two Highway 3A bridges are located approximately at mid-fan. The channel gradient decreases from approximately 6.5% upstream of the bridges to approximately 4% on the downstream side of the channels. During the site visit in July 2019, BGC noted the limited capacity (see Figure 3-5A and B) of the Duhamel Highway 3A East Bridge and identified the potential for overland flooding that may affect properties in the event of a blockage. This potential was investigated with numerical models (Section 6.5).

A) Looking downstream at Duhamel Highway 3A East Bridge.

B) Looking upstream through opening of Duhamel Highway 3A East Bridge opening on the eastern channel.

C) Looking downstream at Pedestrian Bridge 1 approximately 50 m downstream of Duhamel Highway 3A East Bridge on the eastern channel.

D) Looking upstream at Driveway Bridge 2 approximately 100 m downstream of Duhamel Highway 3A East Bridge on the eastern channel.

E) Looking downstream at the clearance of the Lower 6 Mile Road East Bridge across the eastern channel.

F) Pedestrian Bridge 2, approximately 70 m downstream of Lower 6 Mile Road East Bridge.

Figure 3-5. Duhamel Creek bridges on eastern channel. BGC photos taken July 2019.

3.5.2. Flood Protection Structures

There are fifteen identified flood protection structures on Duhamel Creek fan-delta. Five structures are listed in the BC Flood Protection Works Database[4]. These five structures are formed from contiguous segments as outlined in Table 3-3. Attributes of all flood protection structures are listed under Table 3-3 and shown on Drawings 02A, 02B, and 06.

The first three structures (DHL-FP-01, 02, and 03) are located near the channel bifurcation, approximately 230 m upstream of the Duhamel Highway 3A East Bridge (Figure 3-6). DHL-FP-01 and 02 are log crib bank protection structures reconstructed in 1968 (Section 4.3), both extending for approximately 75 m. The log cribbing at the upstream end of DHL-FP-01 tapers to the creek bank and approximately 1.5 to 2.5 m of rounded boulders and cobbles have been placed on top of the cribbing, making DHL-FP-01 approximately 1 to 2 m higher than DHL-FP-02. DHL-FP-03 is a V-shaped log crib with metal sheeting. DHL-FP-01 was the only structure listed in the Government of British Columbia's (2020) list of dikes by river/watercourse. The list states that this structure has "no local authority" as Owner/Administrator, rendering it an orphan dike[5] based on the nomenclature applied by the government (i.e., a flood protection structure which is not maintained by a diking authority).

BGC's scope of work did not include the evaluation of specific mitigation works. The following descriptions are therefore meant to alert the readers of this report but are not meant as a comprehensive evaluation of the said structures. This would require specialist input. Irrespective, all three structures (DHL-FP-01, 02 and 03) show signs of damage and some logs have slipped out of their original alignment in places. Bushes and small trees are growing along the edge of DHL-FP-01 and in places, in the log cribbing. Erosion behind the structures as well as deposition of gravel against the structures was observed at DHP-FP-03. The metal sheeting at DHP-FP-03 is attached with two canvas ratchet tie-down straps. Riprap has been placed at the end of DHP-FP-03 on the western (main) channel and angular material, approximately 1 m in diameter, was observed in the creek channel, downstream of the bank protection structure (Figure 3-6F).

The flow split at the bifurcation structure will likely vary with water elevation and deposition at the entrance to the eastern channel. At the time of fieldwork in July 2019, the flow split was estimated to be 75% in the western (main) channel and 25% in the eastern channel. At the entrance to the eastern channel, the slope of the bed was gradual while the western channel dropped approximately 1 m to 2 m under the Duhamel Creek Road Bridge (Figure 3-6A). This difference in bed slope will affect flow split during moderate flows. If future deposition occurs at the entrance to the eastern channel, the portion of flow entering this channel will be reduced. The logs forming

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4 BC Flood Protection Works Database was accessed through iMapBC: https://www2.gov.bc.ca/gov/content/data/geographic-data-services/web-based-mapping/imapbc

5 The Government of British Columbia (2020) states the following with respect to Orphan Dikes: "There are over 100 flood protection works in B.C. which are not maintained by a diking authority. As many of these works were constructed under emergency conditions, they generally lack adequate planning and engineering design. Local emergency plans should address any specific risks that may be associated with these works."

the bifurcation structure are rotting and are deteriorating (Dwain Boyer, email attachment, personal communication, April 22, 2020).

Along the western (main) channel, between the bifurcation structure and Highway 3A, both banks have flood protection structures (DHL-FP-04 and 05) (Figure 3-7). The left bank berm (DHL-FP-04) extends for the full length (360 m) between the bifurcation and Highway 3A. This structure appears to be mainly placed bed material with some short sections of log cribbing and concrete block wall and varies in height along its length (Figure 3-7A and B). In some sections, vegetation and trees are growing in and along the berm material, while others appear to be maintained. Several water intakes were observed along the edge of the berm. The right bank berm (DHL-FP-05) is located upstream of Highway 3A for approximately 80 m. This structure appeared to be mainly placed bed material with large trees growing along the berm and was approximately 1 m to 2 m lower than DHL-FP-04.

Between Highway 3A and Lower 6 Mile Road along the western (main) channel, both banks are paralleled by berms (DHL-FP-06 and 07) for its full length of about 270 m (Figure 3-8). Approximately 80 m upstream of Lower 6 Mile Road, low spots in both berms were observed by BGC, where there is a potential for flow to overtop (Figure 3-8C and E).

Downstream of Lower 6 Mile Road along the western (main) channel, both the left and right banks are diked (DHL-FP-08 and 09) for 220 m and 160 m (Figure 3-9). Along DHL-FP-08, approximately 60 m downstream of Lower 6 Mile Road, a low spot in the dike was noted (Figure 3-9C) where the owners of the property indicated that they plan to place material to raise the height of the dike (personal communication, July 29, 2019). A channel was visible to the east of the DHL-FP-08 on private property and the owners said it was fed from seepage through the dike year-round (personal communication, July 29, 2019). Along the opposite bank (DHL-FP-09) approximately 30 m downstream of Lower 6 Mile Road, swampy ground was noted on the west side of the dike where water likely flows through the 2-3 m tall dike (Figure 3-9 A). This indicates water leaves the channel through the both banks and bed and resurfaces in adjoining properties.

A) Looking downstream (south) at DHL-FP-01 (on the left) and DHL-FP-03 (bifurcation structure "V") with Duhamel Creek Road Bridge on the right.

B) Looking upstream (north) at bifurcation with DHL-FP-01 (right), DHL-FP-02 (left), and DHL-FP-03 (center, "V") with Duhamel Creek Rd seen on upper left.

C) Looking at the right bank (west) at the DHL-FP-02 and Duhamel Creek Rd Bridge on the left.

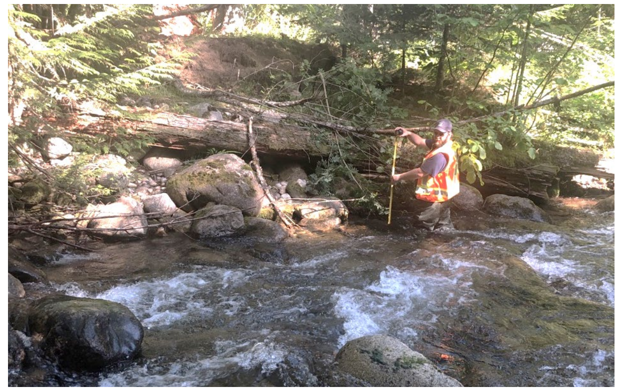
D) Looking downstream (south) at beginning of the eastern channel with DHL-FP-01 (left), DHL-FP-03 (right).

E) Looking upstream (east) at the end of DHL-FP-02 (on the left) and DHL-FP-03 (on the right) with Duhamel Creek Rd Bridge along the top.

F) Looking at the left bank (south) at end of DHL-FP-03 with Duhamel Creek Rd seen on upper left.

Figure 3-6. Flood protection structures at bifurcation. BGC photos taken July 2019. Refer to Table 3-3 for attributes and Drawings 02A, 02B, and 06 for locations.

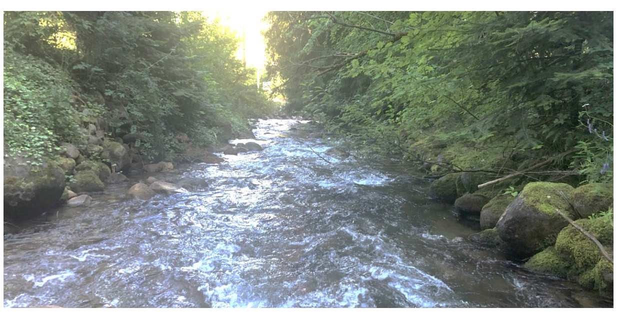
A) DHL-FP-04: Rounded creek bed material on left bank with trees growing through berm, approximately 50 m downstream of bifucation structure.



B) DHL-FP-04: Log berm 1 m high on left bank, approximately 140 m downstream of bifucation structure.

C) DHL-FP-04: Placed creek bed material on left bank approximately 180 m upstream of Highway 3A.

D) DHL-FP-04: Placed creek bed material on left bank approximately 130 m upstream of Highway 3A. Concrete brick wall and water intake visible in the distance



E) Looking downstream at placed creek bed material in DHL-FP-04 (left bank) and DHL-FP-05 (right bank) approximately 70 m upstream of Highway 3A.

F) Looking downstream at DHL-FP-04 (left bank) and DHL-FP-05 (right bank) approximately 20 m upstream of Highway 3A. Bridge visible in the distance.

Figure 3-7. Flood protection structures on western (main) channel downstream of bifurcation and upstream of Highway 3A. BGC photos taken July 2019. Refer to Table 3-3 for attributes and Drawings 02A, 02B, and 06 for locations.

A) DHL-FP-06: Berm constructed of sub-rounded cobbles and boulders approximately 1.5 m to 2 m high on left bank, approximately 50 m downstream of Highway 3A.

B) DHL-FP-07: Berm constructed of sub-rounded cobbles on the right bank approximately 50 m downstream of Highway 3A.

C) DHL-FP-06: Berm constructed of sub-rounded cobbles and old concrete foundation approximately 1.5 m high on left bank approximately 80 m upstream of Lower 6 Mile Road on the western channel.

D) DHL-FP-06: Berm constructed of sub-rounded cobbles and old concrete foundation approximately 40 m upstream left bank of Lower 6 Mile Road on the western channel.

E) DHL-FP-07: Low point on the right bank approximately 80 m upstream of Lower 6 Mile Road on the western channel.

Figure 3-8. Flood protection structures on western (main) channel downstream of Highway 3A and upstream of Lower 6 Mile Road. BGC photos taken July 2019. Refer to Table 3-3 for attributes and Drawings 02A, 02B, and 06 for locations.

A) DHL-FP-09: Standing on right (west) bank, approximately 30 m downstream of Lower 6 Mile Road looking across at dike on left bank (DHL-FP-08).

B) DHL-FP-08: On mid channel bar approximately 60 m downstream of Lower 6 Mile Road, looking at left bank (east).

C) DHL-FP-08: Looking at left bank (east), approximately 70 m downstream of Lower 6 Mile Road. Additional berm material visible in the background.

D) DHL-FP-08: Standing in the channel looking upstream (north), approximately 100 m downstream of Lower 6 Mile Road.

E) DHL-FP-09: Standing in the channel, approximately 100 m downstream of Lower 6 Mile Road, looking west at right bank.

F) DHL-FP-08: Looking east at the left bank dike, approximately 150 m downstream of Lower 6 Mile Road.

Figure 3-9. Flood protection structures on western (main) channel downstream of Lower 6 Mile Road. BGC photos taken July 2019. Refer to Table 3-3 for attributes and Drawings 02A, 02B, and 06 for locations.

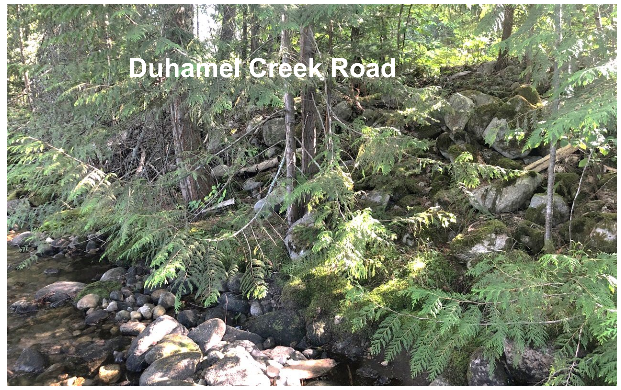
Along the eastern channel, between the bifurcation structure and Highway 3A, bed material has been sporadically placed on the channel banks (Figure 3-10) for flood protection (DHL-FP-10 and 11). Sections of the channel have no protection on either bank, so these structures have been classified as discontinuous (Table 3-3). Bank height varies along the length of the channel; however, in most sections the left bank (DHL-FP-11) along Duhamel Creek Road is approximately 0.5 m to 1 m higher than the right bank (DHL-FP-10). A short 5 m section of DHL-FP-10 just downstream of the bifurcation structure has been reinforced with concrete (Figure 3-10A).

Both banks immediately downstream of Highway 3A have bank protection (DHL-FP-12 and 13) extending down to Pedestrian Bridge 1 (Figure 3-11A and B). Approximately 200 m downstream of Highway 3A, a shorter 20 m flood protection (DHL-FP-14) is located on the right bank (Figure 3-11C). The remainder of the channel has vegetated sloping banks without obvious flood protection (Figure 3-11D).

Between Lower 6 Mile Road and Pedestrian Bridge 2, both banks are lined with placed creek bed material, approximately 2 m to 2.5 m tall, extending approximately 60 m (Figure 3-12A to C). On both banks downstream of Pedestrian Bridge 2, there are indications from the lidar imagery that the banks have been raised; however, this was not able to be confirmed during BGC's July 2019 field visit due to heavy vegetation cover (Figure 3-12D).

The majority of flood mitigation works along Duhamel Creek do not appear to be designed to withstand specific design events, to a consistent height above creek bed, or with appropriate materials. This implies that such structures will likely suffer variable damage during floods and debris floods. In particular, debris floods are likely to mobilize berms constructed from in-bed cobbles as those have already been transported by floods and debris floods. The placement of such cobbles as berms may somewhat delay damage but will not be able to prevent it. BGC made several assumptions as to the mitigation works which are listed in the methods report (BGC, March 31, 2020b).

A) DHL-FP-10: Concrete wall on left bank, approximately 30 m downstream of bifurcation structure looking downstream.



B) DHL-FP-11: Looking at rounded boulders and cobbles along right bank, approximately 70 m downstream of bifurcation structure, looking downstream.

C) DHL-FP-10 & 11: Approximately 110 m downstream of bifurcation looking upstream. Minimal protection on either bank

D) DHL-FP-11: Approximately 80 m upstream of Highway 3A looking at left bank with 1 m boulders. Similar sized material was observed on right bank (DHL-FP-10).

E) DHL-FP-10: Looking at left bank, approximately 70 m upstream of Highway 3A.

F) DHL-FP-11: Approximately 40 m upstream of Highway 3A looking at left bank with rounded cobbles and small boulders.

Figure 3-10. Flood protection structures on eastern channel downstream of bifurcation to Highway 3A. BGC photos taken July 2019. Refer to Table 3-3 for attributes and Drawings 02A, 02B, and 06 for locations.

A) DHL-FP-12: In the channel looking at left bank immediately downstream of Highway 3A.

B) DHL-FP-13: In the channel looking at right bank immediately upstream of Pedestrian Bridge 1 (left side of photo).

C) DHL-FP-14: Looking at right bank approximately 130 m upstream of Lower 6 Mile Road Bridge.

D) In the channel looking upstream, approximately 80 m upstream of Lower 6 Mile Road

Figure 3-11. Flood protection structures on eastern channel downstream of Highway 3A to Lower 6 Mile Road. BGC photos taken July 2019. Refer to Table 3-3 for attributes and Drawings 02A, 02B, and 06 for locations.

A) DHL-FP-15 & 16: In the channel, approximately 40 m downstream of Lower 6 Mile Road, looking upstream. Berms on both banks are approximately 2 m to 2.5 m tall.

B) DHL-FP-15: Looking at left bank, just upstream of Pedestrian Bridge 2 (right side of photo).

C) DHL-FP-16: Looking at right bank, just upstream of Pedestrian Bridge 2 (left side of photo).

D) Approximately 110 m downstream of Pedestrian Bridge 2, looking south at heavy vegetation cover.

Figure 3-12. Flood protection structures on eastern channel downstream of Lower 6 Mile Road. BGC photos taken July 2019. Refer to Table 3-3 for attributes and Drawings 02A, 02B, and 06 for locations.

Table 3-3. Flood protection structure attributes along Duhamel Creek.

Attribute	Flood Protection Structure															
BGC ID	DHL-FP-01	DHL-FP-02	DHL-FP-03	DHL-FP-04	DHL-FP-05	DHL-FP-06	DHL-FP-07	DHL-FP-08	DHL-FP-09	DHL-FP-10	DHL-FP-11	DHL-FP-12	DHL-FP-13	DHL-FP-14	DHL-FP-15	DHL-FP-16
No. of Structures	1	1	1	1	1	2 contiguous	5 contiguous	2 contiguous	2 contiguous	1	1	1	1	1	1	1
Source[1,2]	iMapBC	BGC Field Observation	BGC Field Observation	BGC Field Observation	BGC Field Observation	iMapBC	iMapBC	iMapBC	iMapBC	BGC Field Observation	BGC Field Observation	BGC Field Observation	BGC Field Observation	BGC Field Observation	BGC Field Observation	BGC Field Observation
Type	Protection	Berm	Berm	Berm	Berm	Protection/ Dike	Protection/ Dike	Dike	Dike	Berm	Berm	Berm	Berm	Berm	Berm	Berm
Orphan (Y/N)[3]		-	-	-	-					-	-	-	-	-	-	-
Comments	Log crib and river rock	Log crib	Bifurcation "V" structure. Log crib and metal sheeting			River rock	River rock			Dis-continuous	Dis-continuous					
Survey Year(s)	2004	-	-	-	-	2004	2004	2004	2004	-	-	-	-	-	-	-
Channel	Main/ Eastern	Main/ Western	Eastern/ Western	Western	Western	Western	Western	Western	Western	Eastern	Eastern	Eastern	Eastern	Eastern	Eastern	Eastern
Erosion Protection Side	Left	Right	Left/Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Right	Left	Right
Length (m)	74	74	28	357	81	278	259	218	161	193	203	48	69	20	57	58

Notes:
1. iMapBC data downloaded from Flood Protection Structural Works layer on March 3, 2020.
2. BGC Field Observation made on July 27-29, 2019.
3. Only the structure within iMapBC data was classified as an orphan structure.

3.6. Hydroclimatic Conditions

3.6.1. Existing Conditions

Climate normal[6] data were obtained from Environment and Climate Change Canada's South Slocan station (457 m), located approximately 25 km west of the Duhamel Creek outlet (Environment and Climate Change Canada, n.d.). Daily precipitation and temperature data are available from 1940 to 2008. Figure 3-13 shows the average temperature and precipitation for this station from the 1971 to 2000 climate normals. Precipitation (rain and snow) peaks in November due to cold winter air temperature with average rainfall in May and June only slightly lower. Table 3-4 provides the total annual precipitation and proportion thereof falling as rain and snow respectively. The measured precipitation at the South Slocan weather station is lower than the actual precipitation in the Duhamel Creek watershed, where the mountaintops extend more than 1800 m above Kootenay Lake. This 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.

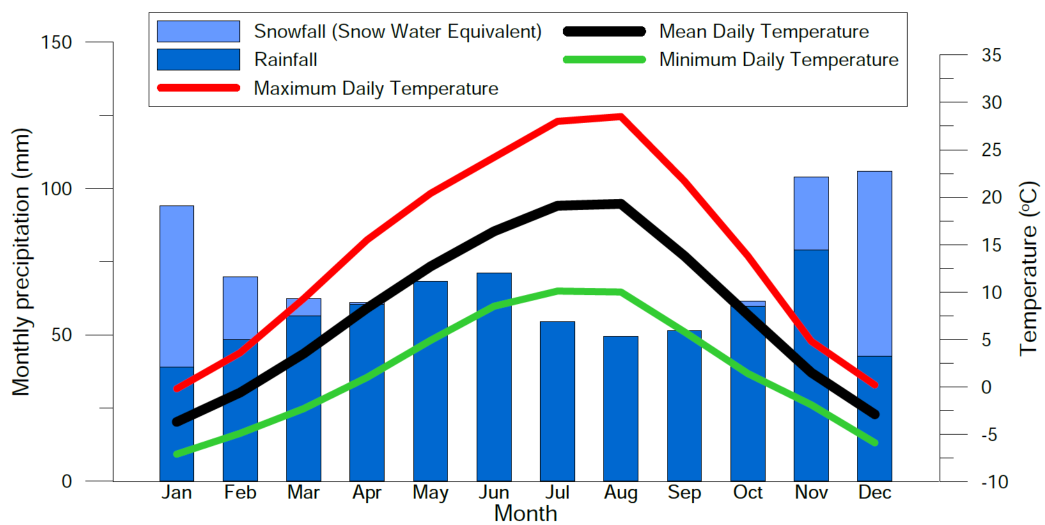


Figure 3-13. Climate normal data for South Slocan station from 1971 to 2000.

[6] Climate normal are long-term (typically 30 years) averages used to summarize average climate conditions at a particular location.

Table 3-4. Annual total of climate normal data for South Slocan weather station from 1971 to 2000.

Variable	Annual Total	Percent of total annual precipitation (%)
Rainfall (mm)	680	80
Snowfall (cm)	173	20
Precipitation (mm)	853	100

To understand the regional distribution of precipitation and snowfall patterns and supplement the data from the Kaslo station, BGC obtained climate data based on the CRU-TS 3.22 dataset (Mitchell & Jones, 2005) for the period 1961-1990. 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 1300 mm, varying as a function of elevation. The same trend is evident in the historical annual average Precipitation as Snow (PAS) over the watershed where the historical average PAS is 691 mm. The PAS increases at the higher elevations; therefore, Duhamel Creek watershed accumulates greater precipitation falling as snow over the entire watershed compared to the South Slocan weather station.

3.6.2. Climate Change Impacts

The watershed lies within the Southern Columbia Mountain 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., 2011).

The Climate NA model provides downscaled climate projections for future conditions (RCP 8.5) (Wang et al., 2016) and indicates that the mean annual temperature (MAT) in the Duhamel Creek watershed is projected to increase from 3.1ºC (historical period 1961 to 1990) to 6.7 ºC by 2050 (average for projected period 2041 to 2070). The MAP is projected to increase from 1300 mm to 1376 mm while precipitation as snow (PAS) is projected to decrease from 691 mm to 437 mm by 2050 in the Duhamel Creek watershed for RCP 8.5. Projected change in climate variables from historical conditions for the Duhamel Creek watershed are presented in Table 3-5.

Table 3-5. Projected change (RCP 8.5, 2050) from historical (1961 to 1990) conditions for the Duhamel Creek watershed (Wang et. al., 2016).

Climate Variable	Projected Change
Mean Annual Temperature (MAT)	+3.6 ºC
Mean Annual Precipitation (MAP)	+76 mm
Precipitation as Snow (PAS)	-254 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).

4. SITE HISTORY

4.1. Introduction

Duhamel Creek flows through the “Six Mile” community and into Kootenay Lake at Willow Point. Residents have lived on the alluvial fan since the late 1800s. BGC notes that the community has been previously named “Willow Point” and is also referred to as “McDonalds Landing” and the creek has also been referred to as “Six Mile Creek”. Historically, the Duhamel Creek watershed was explored and developed for mineral exploration and mining.

4.2. Document Review

In developing a flood, mitigation, and development history for Duhamel 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-fire, etc.).
- Reports provided to BGC by Ministry of Forests, Lands, Natural Resource Operations and Rural Development (MFLNRORD) (Table 4-1)
- Research articles (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
  - Accounts from Duhamel Creek residents.
- Historical wildfire perimeters (MFLNRORD, n.d.)
- Cut block perimeters (MFLNRORD, n.d.)

BGC’s review of the above work is not aimed as a critique but rather a brief summary of the findings of each report. Each scientific or engineering/geoscientific study builds on the preceding one benefitting from the added knowledge. By summarizing aspects of the studies listed below, BGC is neither endorsing or rejecting the findings of those studies, as this was not the scope of the present study.

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

Year	Month/Day	Source	Purpose
1972	June	Water Resources Branch (BC Government)	Flood survey report
1974	October 2	Ministry of Forests, Lands, Natural Resources Operations	Hazard Assessment
1974	November 15	Ministry of Forests, Lands, Natural Resources Operations	Hazard Assessment
1975	September 25	Ministry of Forests, Lands, Natural Resources Operations	Hazard Assessment with Mitigation Recommendations
1989	January	Ministry of Environment	Hazard Assessment (Flood Hazard Rating)
1990	April	Northwest Hydraulic Consultants Ltd. and Thurber Consultants Ltd.	Hazard Assessment
1991	November 18	N/A[1]	Precondition for Subdivision
1997	June 3	Nelson Forest Region, Ministry of Environment	Hazard Assessment
1997	October 20	EBA Engineering Consultants Ltd.	Precondition for Building Permit
1998	January 27	EBA Engineering Consultants Ltd.	Geotechnical Assessment
1998	February 23	Klohn-Crippen Consultants Ltd.	Terrain Stability Inventory
1998	May 12	Klohn-Crippen Consultants Ltd.	Flood and debris hazard assessment
1998	May 29	Klohn-Crippen Consultants Ltd.	Flood and debris hazard assessment
2003	March 11	Intermountain Engineering & Surveying Ltd.	Precondition for Building Permit
2004	April 14	Intermountain Engineering & Surveying Ltd.	Precondition for Building Permit
2004	July 15	Integrated Hydropedology Ltd. and Ground Stability Consulting Inc.	Precondition for Building Permit
2005	May 3	Integrated Hydropedology Ltd.	Precondition for Subdivision
2005	October 13	Intermountain Engineering & Surveying Ltd.	Precondition for Building Permit
2005	November 21	Intermountain Engineering & Surveying Ltd.	Precondition for Building Permit
2006	April 5	Intermountain Engineering & Surveying Ltd.	Precondition for Building Permit
2006	November 10	Intermountain Engineering & Surveying Ltd.	Precondition for Building Permit
2008	July 23	Perdue Geotechnical Services Ltd.	Precondition for Building Permit
2009	January 13	Intermountain Engineering & Surveying Ltd.	Precondition for Building Permit
2011	September 1	Integrated Hydropedology Ltd.	Precondition for Building Permit
2012	April 14	Perdue Geotechnical Services Ltd.	Precondition for Building Permit
2012	June 8	Apex Geoscience Consultants Ltd.	Precondition for Building Permit
2012	August 2	Perdue Geotechnical Services Ltd.	Precondition for Building Permit
2014	April	Forest Practices Board	Timber Harvesting Hazard Assessment
2014	September 19	Lasca Group Technical Services Ltd.	Precondition for Building Permit
2015	January 26	Apex Geoscience Consultants Ltd.	Hydrogeomorphic Assessment
2015	September 22	Ministry of Forest, Lands, and Natural Resources Operations	Post-Wildfire Risk Analysis, Fire N70261
2016	February 16	Lasca Group Technical Services Ltd.	Precondition for Site-specific Exemption

Note:
1. Incomplete application notice, as the applicant did not provide an engineer's report.

4.2.1. NHC/Thurber (1990)

In 1990, a detailed report was authored by a team of Northwest Hydraulic Consultants Ltd (NHC) and Thurber Consultants (Thurber), titled: Alluvial Fan Hazard Assessment, Regional District of Central Kootenay Electoral Area "E" & "F". This report includes Duhamel, Sitkum, Kokanee, Redfish, Laird, Harrop, Narrows, and Procter creeks. Except from Laird and Narrows creeks, those same creeks were prioritized for detailed study by BGC. The NHC/Thurber (1990) study is highlighted and discussed separately as it is the key detailed study now being superseded by this report. A detailed comparison of the NHC/Thurber study with the present work is included in Section 6.7.1.

4.2.2. Post-Wildfire Hazard Analysis

In 2015, Jordan completed a post-wildfire risk analysis (Jordan, 2015). Burn extents of the 2015 fire are shown on Drawing 05. Jordan concluded that given the high burn severity in the gullies and rocky ridges between the gullies, it was likely that the 2015 wildfire would affect the debris flow likelihood on tributaries in the Duhamel Creek watershed.

4.2.3. Assessments to Support Building Permit and Subdivisions

Numerous reports prepared to support applications for building permits and subdivision were provided by the RDCK to BGC (Table 4-1). A selection of these that provide relevant information to the present work or highlight assessments that differ from the present work are summarized in the coming subsections. Note that this is not a full selection of the background material reviewed as summarized above and in Table 4-1.

The main findings from the assessments completed to support building permit and subdivision applications listed in Table 4-1 that are pertinent to this study are that Duhamel Creek has a history of instability on the fan, and that prevention of debris accumulation upstream of the bifurcation structure is important to reduce the risk of channel avulsion resulting from blockage at the bifurcation structure.

4.2.3.1. Integrated Hydropedology (2005)

Integrated Hydropedology (IHP) completed an assessment in support of an application to subdivide part of a lot north of Heddle Road on the eastern side of the fan (Part of Lot 4, Plan 12528, except Lots A and B, Plan 18613). IHP assessed a range of hazards including gullying, snow avalanches, debris slides, debris torrents, rockfalls and rockslides for the entire Duhamel Creek watershed. On the fan-delta, IHP reviewed potential avulsion and re-entry points. IHP re-iterated the findings from previous assessments (e.g., NHC/Thurber, 1990, Salway & Mordhorst, 2004) that the risk of avulsion on the Duhamel Creek fan is highest at the bifurcation if debris accumulates in the reaches upstream of the bifurcation structure and mobilization in an event leads to a blockage. In these instances, flow is expected on Tees and Barnes Roads (IHP, 2005).

4.2.3.2. Intermountain Engineering & Surveying (2005)

Intermountain Engineering & Surveying Ltd. (Intermountain) completed a property assessment in support of a building permit at 2776 Lower Six Mile Road. The property is located south of Lower Six Mile on the east side of the eastern channel. Intermountain assessed the potential for a "debris torrent" to be 'quite unlikely' due to the location of the property on the fan and the gentle slope of the fan. The hazard of overland flow was also assessed to be 'slight' as it was interpreted that Lower Six Mile Road would deflect significant overland flow. BGC's model results are presented in Section 6.5.

4.2.3.3. Integrated Hydropedology (2011)

Integrated Hydropedology Ltd. (IHP) completed a hazard assessment as a precondition for a building permit application for 1888 Barnes Rd located immediately south of Highway 3A on the east side of Barnes Road. The assessment referred to a 1995 terrain survey of Duhamel Creek watershed by the same firm. This survey identified geomorphic processes including snow avalanche, debris slide, and the potential for debris flows and "torrents"[7] on the tributaries of the creek. Further, they noted that geomorphic activity was anticipated to increase with further timber harvesting in the watershed. With this, IHP identified the importance of ensuring debris does not accumulate in the main channel increasing the risk of an avulsion.

4.2.3.4. Perdue (2012)

Perdue Geotechnical Services (2012) completed a geotechnical assessment as a precondition for a building permit application at Lot 1, Plan EPP14453 and Lot 29, Plan 1329. These properties are located on the eastern side of the junction of Highway 3A and Lower Six Mile Road approximately 50 m west of the main channel at its closest point, and as with the majority of the Duhamel Creek fan-delta had a Ministry of Environment (MoE) Non-Standard Flood and Erosion Rating (NSFER) of "E"[8]. As part of the review, Perdue described the bifurcated creek channel indicating that the west (main) channel accommodates the majority of the flow while the lesser (east) channel accommodates overflow volumes. At the time of the assessment Perdue reported that both channels were well-confined with no significant accumulation of sediment or coarse woody debris. Perdue (2012) acknowledged the existence of two abandoned channels: one between the two active channels and one northeast of Barnes Road that were previously identified by Woods (1974) and indicated that during field review no recent surface flow was observed.

Perdue assessed the probability of a debris flow adversely affecting the properties as unlikely, and similarly that the likelihood of the property being affected by moderate to high velocity flows to be low; however, it was indicated that the property could experience shallow inundation.

[7] Interpreted to refer to debris floods
[8] An NSFER rating of E indicates that flooding and erosion from high velocity flows, avulsions, debris flows or bank stability problems are possible

4.2.3.5. Lasca (2014)

Lasca Group completed a geotechnical engineering site investigation as a precondition for a building permit application at 2808 Lower Six Mile Road, located on the distal fan approximately 85 m northeast of the east channel (Lasca, 2014). In test trenches (1.5 m depth) on the property, Lasca identified three stratigraphic units; topsoil (12 cm depth), Kootenay Lake beach sand, and minor stream material. Lasca refers to ages of organic material in the topsoil as 8,000 years ago and thus concludes there has been no alluvial activity on the property in over 8,000 years. Note that the source of the dates is not provided and thus it is unclear if the dates are based on glacial history or radiocarbon dating.

4.2.3.6. Lasca (2016)

Lasca Group completed a geotechnical engineering site investigation of 2836 Lower Six Mile Road, located on the distal fan approximately 240 m northeast of the east channel (Lasca, 2016). In test trenches on the property, Lasca identified a charcoal layer interpreted to be from an ancient forest fire approximately 50 cm below ground surface. The author estimated that the property last experienced a flood event 1400 years ago but does not provide the basis for this assessment. Overall, Lasca assessed the likelihood of a flood event impacting this property to be low given the distance (230 m) from the bermed east channel of Duhamel Creek. The definition for low was not provided.

4.2.4. Geomorphic Assessments

In 2014, in response to complaints from community members, the Forest Practices Board reviewed logging practices in the Duhamel Creek watershed. Concerns were raised in relation to the occurrence of landslides in the watershed, the potential associated impacts to water quality and public safety associated with landslides in the watershed. Furthermore, questions were asked as to who would take responsibility for remediation works, should there be downstream impacts on the Duhamel Creek fan-delta. The Board recommended an update to the 2004 hydrologic assessment that had concluded that “forestry activities situated on the lower elevation slopes of the watershed will not increase the existing hazard of flooding or avulsion on the fan of Duhamel Creek” (Forest Practices Board, 2014).

In 2015, Apex Geoscience Consultants Ltd. (Apex) completed a hydrogeomorphic assessment of the Duhamel watershed to provide guidance for forest management considering both cut blocks and forest roads. The report was intended to assess the likelihood of adverse effects in terms of water quality and quantity associated with harvesting in the watershed. Apex (2015) provides a detailed description of the channel reaches upstream of the fan apex. On the fan, Apex observed an abandoned channel near the fan apex and interpreted that the channel had shifted laterally during a flood event estimated to have occurred 40 to 50 years ago. As a result, a cobble/boulder levee approximately 1.3 to 1.5 m higher than the existing banks was deposited along the eastern bank. Apex also described Duhamel Creek Trib A (Drawing 03) as being debris flood/ debris flow prone with an estimated return period of 20- to 50-years.

Apex (2015) completed a risk assessment but only considered the water intake and did not consider other development on the fan downstream of the water intake. Apex found that the level of forest harvesting at the time of writing (~10%) had a low likelihood of increasing debris flood frequency on Duhamel Creek. They recommended that logging activities on Trib A should be limited to only 5% of the watershed and limited to south aspect or low elevation slopes to limit the potential for increased debris flood frequency.

4.3. Historic Timeline

Figure 4-1 provides a timeline summary of floods and mitigation history for Duhamel 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:

- At least eight notable hydrogeomorphic events have occurred in recorded history. BGC interprets that the 1948, 1955/1956, 1968, and 1971 floods can be classified as a damaging debris flood events, given the record of extensive erosion and avulsion. Two historical events in 1990, 1996 were associated with icing/ice jams[9] in the channel, the latter was indicated that icing threatened to result in a flood on the creek.
- Historical flood events have caused significant bank erosion, channel aggradation, and destroyed several bridges.
- Historically, the channel flowed across the alluvial fan in several channels. Development has significantly modified the channel into its current configuration of a dominant western channel and a secondary eastern channel divided by a bifurcation structure near the top of the fan.
- Based on aerial photographs, the eastern channel appeared to be the dominant main channel prior to a major flood in 1948.
- The channel has been dredged (i.e., cleared with equipment) several times since the construction of the bifurcation structure in 1948.
- Logging has occurred in the watershed and some logging road-related landslides have occurred.
- A wildfire in 2015 burned a large area of the eastern side of the watershed near the fan apex.
- Water levels at the toe of the fan are influenced by the reservoir levels on Kootenay Lake.

[9] Engineers and Geoscientists of British Columbia (EGBC) indicate that “in rivers that are subject to significant winter ice formation, high water levels may be caused by ice jams.” (EGBC, 2018 pg. 61)

Geohazard History

Duhamel Creek gullies, 2015 (Copyright Province of British Columbia. All rights reserved. Reproduced with permission from the Province of British Columbia)

Flood damage to building and highway bridge, 1956 (Fred and Audrey Heddle Collection)

July 4, 2015 - Wildfire in Duhamel, Sitkum, and Ainsley Creek watersheds burned approximately 7 km^2

2012 - Largest flood on limited record (1995 to present) at Duhamel Creek gauge

2011 - Slope failure on Duhamel Heights FSR; sediment entered channel and impacted water intake

2010 - Slope failure on Duhamel Heights FSR; limited sediment entered channel

May 15, 1997 - Landslide off Duhamel Heights FSR

February 1, 1996 - Creek threatened to flood due to icing

December 29, 1990 - Flooding due to icing

1983 - Approximate date of debris flood event in Duhamel Creek tributary

June 1972 - Creek flooded and avulsed on lower end of western channel; water seeped through dike on western channel and flooded mobile home

May 13, 1971 - Creek flooded and washed out highway bridge

June 3, 1968 - Creek flooded, avulsed at bifurcation, A.I. Collinson School closed, water mains damaged, highway and lower bridges nearly washed out

May 1955 or 1956 - Creek flooded and damaged restaurant, home, and summer camp; highway and lower bridges washed out

1948 - Creek flooded and avulsed in multiple locations, flowing west and crossing highway in seven locations; two bridges and orchards destroyed

1917 - Survey shows creek channel within existing eastern channel

1907 - Survey shows channel on east side of fan (outside of existing channels)

Early Development History - Duhamel Creek flowed across the fan in unconfined channel

1880s - West Arm drainage areas burned in search of mineral deposits

Wildfire
Flood
Landslide
Debris flow or debris flood
Channel location
Mitigation
Development event

Mitigation

March 2000 - East channel cleared at bifurcation

December 1990 - Channel cleared during flood

1984 - Highway bridge over western channel replaced; channel cleared

1981 - Private bridge constructed above bifurcation

1974 - Channel cleared; aggradation noted near lower bridge

1972 - Department of Highways removed accumulated debris at bifurcation

1971 - Highway bridge over western channel washed out and replaced. Flow re-established into two channels, banks repaired

1968 - Bridges saved from flood. Timber control structure at bifurcation ("Y") destroyed by flood and reconstructed, banks repaired

1955 - Creek channelization after flooding

1948 - Highway bridges over the two channels washed out and replaced. Timber control works constructed at bifurcation ("Y"), channels restored, banks repaired

Early Development History - Residents slowly dig out Duhamel Creek channel

Development

Late 2000s to Mid 2010s - Logging in upper watershed

2007 - Forestry licensee reactivates Duhamel Heights FSR

2003 - SBFEP deactivates Duhamel Heights FSR

1995 - Duhamel Creek designated community watershed

1990s - Small Business Forest Enterprise Program (SBFEP) builds Duhamel Heights Forest Service Road (FSR) into watershed on western side of valley

Late 1960s to Early 1970s - Logging in upper watershed.

1963 - A.I. Collinson School opens

1938 - Corra Linn Dam activated downstream of Duhamel Creek on Kootenay River

Early Development History - Duhamel Creek was populated primarily by summer homes

1902 - Duhamel Creek School opened

1901 - Community named "Willow Point" by Charles W. West

August 12, 1897 - Henry Duhamel receives Crown Grant for 212 acres of land in Six Mile

Late 1890s to early 1900s - Road to Nelson constructed; logging in watershed

Figure 4-1. Summary of recorded geohazard, mitigation, and development history at Duhamel 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. This section summarizes the overall workflow as well as any specific deviations from the steep creek methodology applied at Duhamel Creek. Table 5-1 shows the workflow to develop frequency-magnitude (F-M) relationships for Duhamel Creek and other flood and debris flood prone creeks.

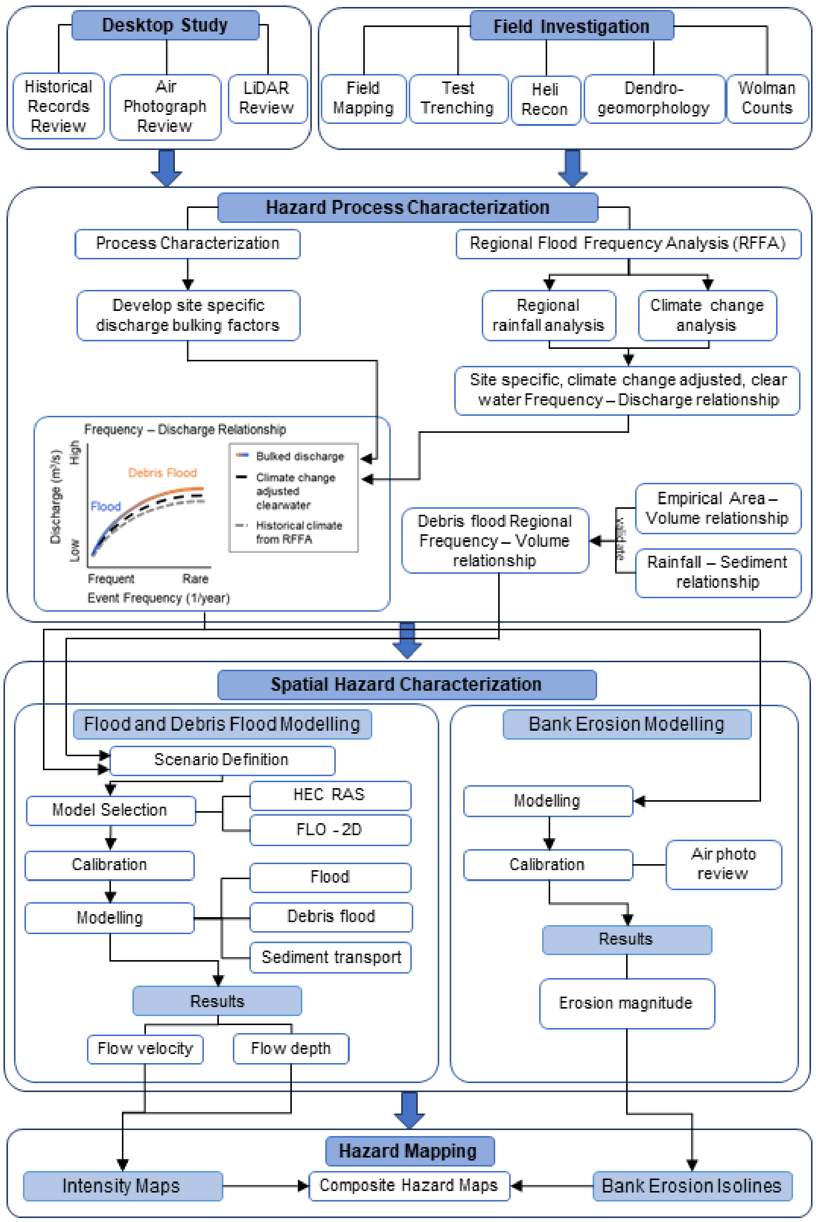


Figure 5-1. Flood and debris flood prone steep creeks workflow used for developing frequency-magnitude relationships, modelling, and preparing hazard maps.

5.1. Debris Flood Frequency Assessment

This section combines the methods established to estimate debris flood frequencies from remote sensing and field methods on Duhamel Creek: air photo interpretation and dendrogeomorphological assessment.

5.1.1. Air Photo Interpretation

Air photos dated between 1929 and 2017 were examined for evidence of past sediment transport events on Duhamel Creek. A complete list of the air photos reviewed is included in Appendix D. Events were identified from the appearance of bright areas and disturbed vegetation relative to previous air photos. 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 not captured. Air photo interpretation was supplemented by historical records of past events (Figure 4-1).

5.2. Peak Discharge Estimates

5.2.1. Clearwater Peak Discharge Estimation

Peak discharge (flood quantile) estimates were calculated using a station flood frequency analysis (FFA) because historical streamflow data are recorded at the *Duhamel Creek Above Diversions* (08NJ026) hydrometric station maintained by the Water Survey of Canada. The peak discharge estimates calculated at the hydrometric station were applied directly to the Duhamel Creek watershed because the hydrometric station is located approximately at the outlet. The peak discharge estimates for Duhamel Creek were compared to results using a regional FFA based on the index-flood method and with historical estimates published by previous studies (e.g., IHL, 2005; MoE, 1989; Apex, 2015; PGS, 2012, and Intermountain, 2009). For the regional FFA, the Duhamel Creek watershed was assigned to the 4 East hydrologic region for watersheds less than 500 km^2 based on its watershed characteristics. The peak discharge estimates calculated at the hydrometric station (08NJ026) were selected for Duhamel Creek. The methodology for the regional FFA as well as the estimation of peak discharge at the hydrometric station are described in Section 3 of the Methodology Report (BGC, March 31, 2020b).

5.2.2. 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 Duhamel 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).

5.2.3. Sediment Concentration Adjusted Peak Discharges

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 (BGC, March 31, 2020b). The concept of bulking is described in Sections 2.2 and 2.3 as it pertains to debris floods and debris flows, respectively.

5.3. 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[10], and discharge is used as the measure of magnitude. For more background on F-M the reader is referred to the Methodology Report.

BGC assessed Duhamel Creek for the 20-, 50-, 200-, and 500-year return periods. At these return periods, the hydrogeomorphic process was identified as debris flood based on climate adjusted peak discharges and stream morphometrics. Because the debris-flood events will carry sediment and woody debris, the climate adjusted clearwater discharge needs to be bulked accordingly. To produce a bulked frequency-discharge relationship, a bulking factor was applied to the peak discharge for each return period, based on sediment availability and debris-flood process type. The bulked frequency-discharge relationship was then used in numerical modelling.

Another measure for magnitude is sediment volume. While sediment volume is less useful as input to numerical modelling, it is helpful to verify sediment deposition predicted by the model. Therefore, a regional frequency-volume relationship was created to compare to numerical modelling results. A detailed discussion of the methodology is provided in Section 2 of the Methodology Report.

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

5.4. Numerical Debris Flood Modelling

BGC modelled the 20-, 50-, 200- and 500-year return periods debris floods. Details of the numerical modelling techniques are summarized in Section 2 of the Methodology Report. Two numerical models were used, HEC-RAS 2D (Version 5.0.7) and FLO-2D (Version 19.07.21). HEC-RAS is a public domain hydraulic modelling program developed and supported by the United States Army Corps of Engineers (Brunner & CEIWR-HEC, 2016). It was used to model clearwater floods with climate-change adjusted and bulked flows.

FLO-2D is a two-dimensional, volume conservation hydrodynamic model that supports sediment transport and mudflow processes (FLO-2D Software Inc., 2017). It is a Federal Emergency Management Agency (FEMA) approved model that has shown reasonable results when compared to other debris flow models (Cesca & D'Agostino, 2008). It was used to model sediment transport when a return period event had a predicted sediment concentration of 10% to 25% by volume. Debris flood events with a sediment concentration of 30% or greater were modelled with rheological parameters to represent mudflow.

The sediment transport equation outlined in Section 2 of the Methodology Report (BGC, March 31, 2020b), Ackers-White (Ackers & White, 1973), was initially modelled on Duhamel Creek. However, BGC found that the use of this empirical equation resulted in sediment accumulating directly downstream of the fan apex, up to 20 m deep, which was deemed not possible and happened on this creek for unknown reasons. Instead, the Zeller-Fullerton equation was used for sediment transport modelling (Zeller & Fullerton, 1983). Although Duhamel Creek does not fit all the selection criteria for use of the Zeller-Fullerton equation, sensitivity runs on other creeks in this study have shown that results using the Zeller-Fullerton and Ackers-White equations are comparable.

Table 5-1 summarizes the key numerical modelling inputs selected for the HEC-RAS and FLO-2D models. Further details on modelling methods are presented in Section 2 of the Methodology Report. Different Manning's n values were used between the HEC-RAS and FLO-2D models as during modelling execution each model treats roughness in a different way, further details are provided in Section 2 of the Methodology Report. The impacts of Kootenay Lake level on the communities bordering the lake are investigated in the Kootenay Lake Flood Impact Analysis (BGC, January 15, 2020).

Table 5-1. Summary of numerical modelling inputs.

Variable	HEC-RAS	FLO-2D
Topographic Input	Lidar (2017)	Lidar (2017)
Grid cells	Variable (1- 2 m)	5 m
Manning' n	0.08 (channel), 0.02 (main roads), 0.1 (fan)	0.06 (channel), 0.02 (main roads), 0.1 (fan)
Upstream boundary condition	Steady Flow (Q_{20} and Q_{50})	Steady Flow (Q_{200} and Q_{500})
Downstream boundary condition	Steady stage at Kootenay Lake (534.6 m)	

Note: The downstream boundary condition is Intermediate scenario between BC Hydro's minimum and maximum flood scenarios; and 0.1 m above the approximate peak recorded reservoir level (July 4, 2012) since commissioning of the Libby Dam (BGC, January 15, 2020).

A series of modelling scenarios were developed for Duhamel Creek as presented in Appendix E. Modelling scenarios include different return periods (principal scenario), different bulking scenarios, erosion of flood protection structures and assumed bridge blockage scenarios (sub-scenarios). The latter were based on comparisons between the bridge conveyance and the bulked and climate-change adjusted peak discharges.

Dikes were removed from topography when the bank erosion was predicted to reach the dike footprint and the critical shear stress to shear stress ratio reached or exceeded two ($\tau/\tau_c \geq 2$). For Duhamel Creek, the following flood protection structures were assumed eroded away for all modelled return periods: DHL-FP-01, DHL-FP-06, DHL-FP-07, DHL-FP-08, and DHL-FP-09. BGC did not include any beaver dams in the model scenarios as it is anticipated that peak flows associated with beaver dam breaches would be lower than the peak flows associated with the return periods investigated as part of this study. (Table 1-2).

Modelling results show inundation areas for various return periods and scenarios, while FLO-2D also provides approximate sediment deposition areas and depths that are compared to the regional frequency-volume relationship.

More than one sub-scenario was modeled for some return periods. Not all possible avulsion scenarios were modelled given the nature of debris floods, which sometimes result in unpredictable outcomes. The scenarios selected are believed to form a representative example of credible scenarios given present conditions on the fan. Further limitations are outlined in Section 7.3. As the objective of this study was a hazard assessment, BGC did not assign conditional probabilities to the occurrence of one sub-scenario versus another. Those would need to be estimated for a quantitative risk assessment which would support the choice and scale of mitigation measures.

5.5. Bank Erosion Assessment

A bank erosion assessment was conducted using a physically-based model calibrated to the erosion observed in historical air photos, as calculated at eleven creek cross-sections between the fan apex and the mouth of the creek of both the main channel and eastern diversion channel. The assessment methods are outlined in Section 2 of the Methodology Report. Sediment size sample results used as inputs to the modelling are included in Appendix C. The location of each bank erosion cross-section is delineated on Drawings 02A and 02B. Refer to Appendix D for the full list of air photos consulted during the calibration process.

5.6. Hazard Mapping

BGC prepared hazard maps based on the combined results from the numerical debris flood modelling and bank erosion assessment. Specifically, two types of steep creek hazard maps for Duhamel Creek were developed: debris flood model result maps (i.e., model scenarios) 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. Debris Flood Model Result Maps

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

1. The hazard intensity and extent of inundated areas from both HEC-RAS and FLO-2D modelling.
2. Areas of sediment deposition extracted from FLO-2D modelling.
3. Potential bank erosion extents.

FLO-2D and HEC-RAS 2D model outputs include grid cells showing the velocity, depth, and extent of debris flood 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 ankle-deep muddy water) need to be designated very differently 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. The hazard maps are provided as a geospatial data package and displayed on Cambio Communities. A representative example of a hazard scenario for the 200-year return period is included as a static map (Drawing 07).

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 rating 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:

$$IIF = v^2 \times \rho_f \times d_f \times P(H) \qquad \text{[Eq. 5-1]}$$

where v is flow velocity (m/s), ρ_f is the fluid density (kg/m^3) and d_f is the fluid’s flow depth (m), to obtain a unit of force per metre flow width for the three left terms in Equation 5-1. $P(H)$ 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 5-1 and the concordant mapping is new in Canada.

Equation 5-1 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 5-2).

A further area designated a “very low” hazard, is also presented as areas likely to not be affected by any of the modeled scenarios up to the 500-year return period debris floods, but which are not free of hazard. Very low hazard zones could be impacted by flows of higher return periods, or if, over time, the channel bed aggrades, or the channel or fan surface is artificially altered. This designation is not classified using impact force and frequency. These fan surfaces are designated as 'inactive' which is distinct from 'paleosurfaces'.

Paleosurfaces within the approximate fan area are interpreted as not being affected by contemporary hazardous geomorphic processes considered in this study (e.g., debris floods, debris flows, bank erosion) and have no hazard rating on the composite hazard rating maps. Surface flow on paleo surfaces has not been assessed in this study. Over steepened banks along paleofan surfaces can be subject to landsliding especially when undercut by streamflow. This process has been highlighted on the fan-delta geomorphology map (Drawing 06).

Figure 5-2 displays a wider range of return periods and intensities than are relevant to debris flood hazard on Duhamel Creek. The intention is to provide a range that can be consistently applied to a broad spectrum of hazards, including landslides, as part of a long-term geohazard risk management program.

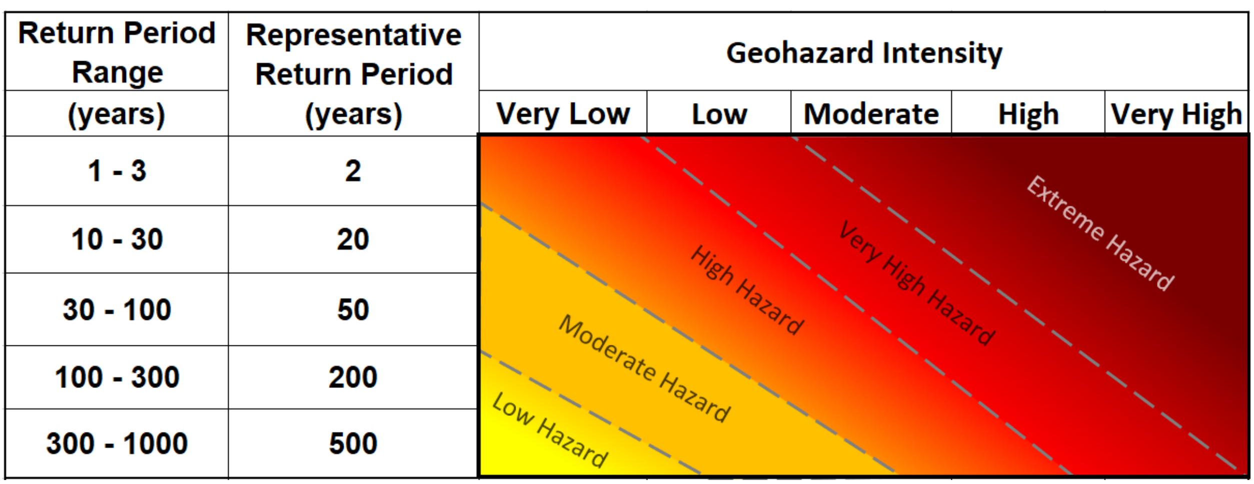


Figure 5-2. Simplified geohazard impact intensity frequency matrix.

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, the raw (no interpretation nor zone homogenization) impact force modelling results are presented. For the composite hazard rating maps, 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 flood or debris flood 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. Note that for debris floods, red and dark red zones will be confined to the channel where the highest flow depths and flow velocities will be encountered. Overbank flows associated with debris floods will have much lower flow depths and velocities.

6. RESULTS

6.1. Hydrogeomorphic Process Characterization

Figure 6-1 indicates that Duhamel Creek is prone to floods and debris floods. This result is consistent with the following evidence:

- The average channel gradient upstream of the fan apex is 10% (Drawing 03 and (Table 3-1) which cannot sustain debris-flow transport. Tributary A has an overall gradient of 24% before it meets Duhamel Creek 1.2 km above the fan apex. From there to the fan apex the gradient is only about 9%.
- The average fan gradient of 8% is typical of creeks prone to debris floods.
- Accounts of previous flood events and analyses of historic air photos (see Section 4.3) are consistent with debris-flood activity due to associated erosion and observed movement of sediment in air photos. In particular, the 1948 event on Duhamel Creek exhibited typical debris flood behaviour; e.g., it avulsed in multiple locations, and during the 1948 event the dominant main channel switched from the eastern to the western channel.

Together, this evidence indicates that Duhamel Creek is subject to supply-unlimited Type 1 debris floods for low return periods (20- and 50-year), while Type 2 (debris-flow transitional) debris floods dominate in the higher return periods (200-, and 500-year). Type 2 debris floods are suggested by the numerous tributaries, such as Tributary A, that are prone to debris flows. While a debris flow discharging into the mainstem of Duhamel Creek would quickly lose momentum due to lower channel gradients, it would still transport substantial volumes of debris leading to surging flow and higher sediment concentrations compared to Type 1 debris floods. Type 3 debris floods are also conceivable from upstream landslides in the thick presumably glacio-fluvial deposits flanking the creek. It could also be facilitated by large stand-replacing moderate to high intensity fire in the watershed which may lead to an abundance of shallow landslides if followed by high intensity rainstorms or rapid snowmelt. This potential scenario ought to be considered in the context of a detailed post-fire hazard assessment which BGC has not attempted. The return period for Type 3 debris floods with discharges in excess of the climate-change adjusted bulked peak flows is unknown.

6.2. Debris Flood Frequency Assessment – Air Photo Interpretation

Debris flood frequency was assessed using historic air photos and historical accounts. Two notable hydrogeomorphic events that are easily discernible in air photos (1955/56, 1968) have occurred since 1929 as identified from the air photo interpretation. The 1972 event is visible, but the event volume was too small to delineate accurately. Additional flood or debris flood events that occurred in 1948, 1971, 1990, 1991, and 2012 are known from historical records (Figure 4-1) but were not delineated in the air photos. The 1990 and 1991 flood events were associated with icing in the channel. Drawings 04A and 04B show air photos with events delineated. The interpreted deposition area and characteristics of the sediment transport events observed in the air photos are described in Table 6-1. BGC interprets that all the noted events are likely Type 1 or Type 2 debris flood events due to the erosion and observed movement of sediment in air photos. No distinct damming event was identified during the air photograph analysis.

Table 6-1. Summary of Duhamel Creek sediment transport events in air photo record (1929-2017).

Event Year[1]	Air Photo Year	Deposition Area (m^2)	Estimated Event Volume (m^3)	Event Characteristics
1955/1956	1968	43,200	21,000	Fresh sediment in channel from fan apex to channel outlets.
1968	1968	67,200	41,000	Fresh sediment in channel from fan apex to channel outlets. A small bank erosion failure on the main (west) channel upstream of Highway 3A observed.
1972	1979	-	-	Deposit in main channel. Event volume too small to delineate accurately

Note:
1. Event year interpreted from air photo dates and historical records. Where the exact date is unknown, the decade or time period between successive air photos is indicated.

In summary, notable flood or Type 1 debris floods have occurred , on average, every 10 years on Duhamel Creek (Table 6-2). BGC interprets that the 1948, 1955/1956, 1968, and 1971 floods can be classified as a damaging debris flood events, given the record of extensive erosion and avulsion (Drawings 04A, 04B).

Table 6-2. Summary of past flood and debris flood events on Duhamel Creek.

Event Year	Description
1948	Creek flooded and avulsed in multiple locations. Two bridges destroyed. Creek flowed west along highway and orchards were destroyed.
1955/1956	Creek flooded and damaged properties. Highway and lower bridges washed out.
1968	Creek flooded and avulsed at bifurcation. Water mains damaged, highway and lower bridges nearly washed out.
1971	Creek flooded and washed out highway bridge
1972	Creek flooded and avulsed on lower end of watershed channel. A mobile home was flooded after water seeped through a dike on the western channel.
1990	Flooding due to icing
1996	Creek threatens to flood due to icing
2012	Largest flood on limited record (1995 to present) at Duhamel gauge.

6.3. Peak Discharge Estimates

Peak discharges for different return periods were estimated to serve as input to the numerical modelling. The workflow entailed an estimate of clearwater peak discharges, followed by a climate-change adjustment, and finally an adjustment for sediment bulking. Results of the analysis are presented in Table 6-3 and Figure 6-1. With respect to these results, the reader should note the following:

- Historical peak discharges are based on an FFA at the hydrometric station (08NJ026).
- The historic peak discharge estimates were adjusted by 20% to account for the impacts of climate change as per Section 4 of the Methodology Report (BGC, March 31, 2020b).
- The climate-adjusted, bulked peak discharges were used in the numerical modelling of debris floods.

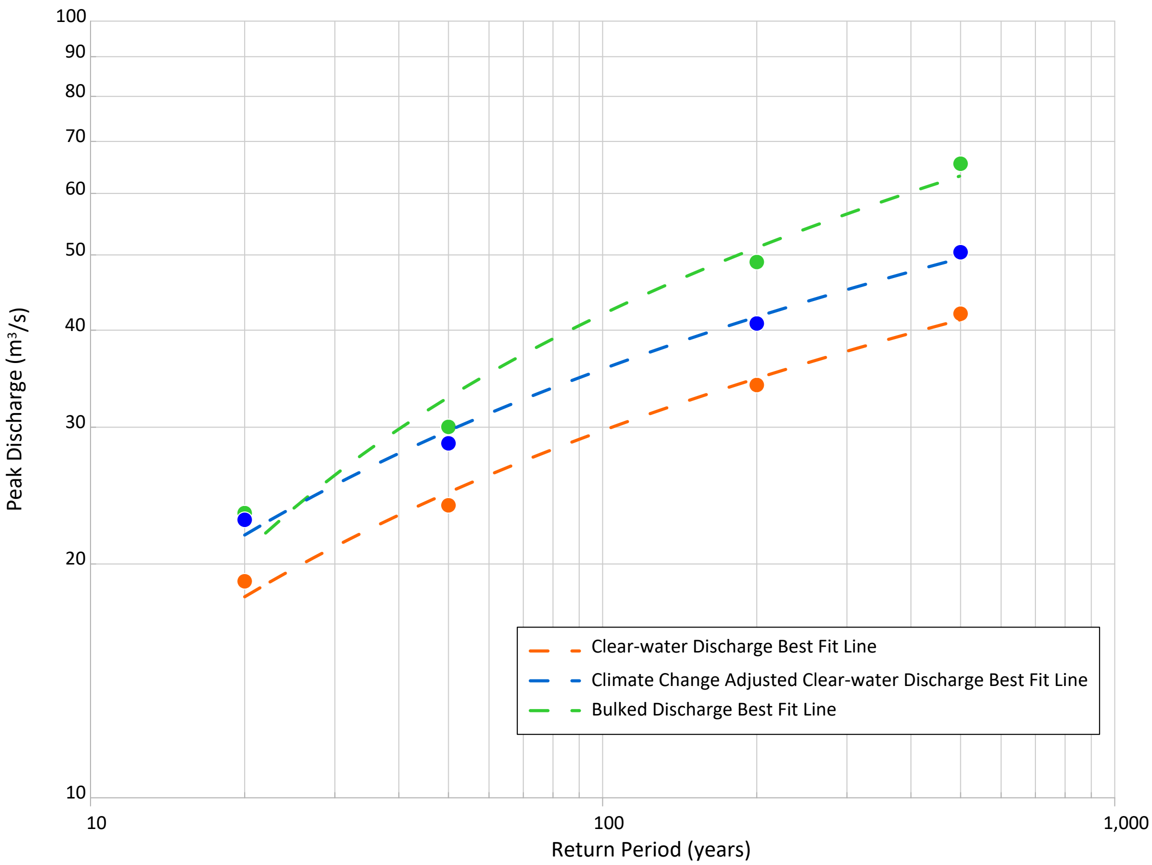


Figure 6-1. Frequency-discharge relationship for Duhamel Creek.

Table 6-3. Peak discharges for selected return period events.

Return Period (years)	AEP	Non-adjusted Peak Discharge (m^3/s)	Climate-adjusted Peak Discharge (m^3/s)	Bulking Factor	Bulked Peak Discharge (m^3/s)	Key Considerations	
						Debris Flood Type	Comments
20	0.05	20	25	1.02	25	1	Few active landslides in lower 20% watershed
50	0.02	25	30	1.05	30	1	Few active landslides in lower 20% watershed
200	0.005	35	40	1.2	50	2	Tributary A enters channel from the west approximately 1.2 km upstream of fan apex.
500	0.002	40	50	1.3	65	2	Several debris flow tributaries in the lower 10 km upstream of the fan apex.

Note:

1. Refer to Section 2 of the Methodology Report (BGC, March 31, 2020b) for details on bulking method.

6.4. Frequency-Volume Relationship

6.4.1. General

BGC used several independent approaches to create a frequency-volume relationship for Duhamel Creek. These included air photo analysis of sediment deposits, sediment transport equations, and application of regional relationships for fan area – sediment volume and watershed area – sediment volume. The different methods were compared.

Debris volume results from the air photo analysis are shown in Table 6-1 and the results of the regional relationship and empirical sediment transport equation are shown in Table 6-4. Volume estimates using the Rickenmann (2011) equation are not considered credible given that events greater than approximately 40,000 m^3 do not appear in the air photo record and are 2 to 4.6 times higher than those obtained from the regional F-M analysis. This overestimate could be attributable to either BGC's hydrographs not being representative, or the critical discharge being underestimated (Section 2 of Methodology Report). Therefore, for numerical modelling, the regional relationships were applied as they are similar to the air photo record and appear to provide more reasonable results.

Table 6-4. Summary of event volumes for each return period based on the regional frequency-volume curve.

Return Period (years)	Event Volume (m^3)	
	Regional Frequency Volume	Rickenmann (2011)
20	33,000	68,000
50	43,000	117,000
200	57,000	230,000
500	67,000	318,000

Note: this relationship was specifically developed for modelling results verification only. It is not suitable to inform mitigation design.

6.4.2. Wildfire Effects on Debris-Flood Sediment Volumes

The effect of wildfires on debris-flood hazards is extremely complex and cannot be solved deterministically. Regional climate change projections indicate that there will be an increase in the hourly intensity of extreme rainfall and increase in frequency of events (Prein et al., 2017). Changes to short duration (one hour and less) rainfall intensities are particularly relevant for post-fire situations in debris flow and debris flood generating watersheds. Within the year to a few years after a wildfire affecting large portions of a given watershed, short duration and high intensity rainfall events are much more likely to trigger debris flows or debris floods, than prior to a wildfire event.

- The elevation of the fires in the watersheds is important as it could either increase peak discharges through melt at higher elevation occurring simultaneously with lower elevation, or vice versa, in which case a wildfire may have little effect on the frequency and magnitude of runoff.

- The ratio of the total watershed area to the burned area (i.e., the lower this ratio, the higher the runoff effect).
- The burn severity (i.e., the higher the burn severity, the greater the hydrological and geomorphic response).
- The debris-flow response in tributaries (i.e., if there are post-fire debris flows discharging into the main channel, the geomorphic response of the main channel will be amplified).
- The type of system, as supply-unlimited basins will respond with high volumes every time after a wildfire, whereas supply-limited basins may respond with reduced volumes depending on their respective recharge rates.

As the location, size and severity of a wildfire cannot be predicted, neither can the associated streamflow response post-wildfire. A method to evaluate more fully would be to stochastically examine a suite of scenarios and their respective fluvial and geomorphic response. By doing so, the most likely model scenario could be selected immediately after a wildfire to link the expected discharge and bulking scenario to a runout model. This would prevent the substantial lag time between the wildfire occurring and having tangible results for emergency planning.

The results of this study should not be relied upon to predict post-wildfire behaviour in the Duhamel Creek watershed, especially for large moderate to high burn severity wildfires.

6.5. Numerical Debris Flood Modelling

A summary of the key observations from the debris flood modelling is included in Table 6-5. The model results are shown on Cambio Communities and a representative scenario map is included as Drawing 07.

A Cambio user guide is included in the Summary Report (BGC, March 31, 2020a).

Table 6-5. Summary of modelling results.

Process	Key Observations
Clearwater inundation (HEC-RAS model results for all return periods)	• For all return period debris floods, at the log crib bifurcation structure, water flows over the left bank and follows paleochannel channels downstream to pool in the upstream ditch of Highway 3A. • Water overtops the stretch of highway in between the east channel and Barnes Road and continues to flow overland towards the lake inundating several private properties with a maximum depth and velocity ranging from 0.2 m at 1 m/s for the 20-year return period to 0.5 m at 1.5 m/s for the 500-year return period. • Water flows southwest toward the lake in the Highway 3A ditch and as sheet flow (<0.1 m depth) along the highway for the 50, 200 and 500-year return period. • The area in between the west and east channels and north of Lower 6 Mile Road in inundated for the 50, 200 and 500-year return periods. For the 50-year event, water avulses from the diversion channel approximately 50 m downstream of the Highway 3A West Bridge. For the 200 and 500-year events, the water flooding this area is largely from overtopping Highway 3AA section of Lower 6 Mile Road (from approximately 50 m to 200 m northeast of the east channel) experiences shallow (<0.1 m) flow for the 20- and 50-year return periods. • A section of Lower 6 Mile Road (from approximately the diversion channel to 320 m northeast of the east channel) experiences shallow (<0.1 m) flow for all return periods. • The west channel stays relatively confined until just downstream of elementary school, École des Sentiers-Alpins, where there is a small avulsion (<1 m^3/s) over the left bank and a much larger one (~7 m^3/s) for the 20-year flood immediately upstream of Lower 6 Mile Road. This results in shallow water flow along the stretch of road in between the east and west channels for approximately 145 m for the 20- and 50- year return periods. • For the 200 and 500-year events, there are multiple very small avulsions (<0.3 m^3/s for the 500-year event) approximately 50 m upstream of the Highway 3A bridge as well as in between the Highway 3A bridge and Lower 6 Mile Rd over the right channel bank. This causes nuisance flooding (<0.1 maximum depth) for several properties along the roadways, including the trailer park along Duhamel Beech Rd. • Water overtops the Lower 6 Mile Road flooding several properties with approximately 0.6 m flow depth and a velocity of approximately 1 m/s for the all return periods.

Process	Key Observations
Sedimentation	• For the 200- and 500-year return period debris floods, it is likely that one or both of the channels at the bifurcation structure could block due to aggradation and all flow would be diverted down either channel, causing avulsions of debris similar to the clearwater models out of each channel as it reaches its capacity and berms are damaged. • Sedimentation associated with debris floods can occur across all parts of the active fan as the flow spreads as it leaves the channel in numerous locations of low confinement. The average sediment deposition depths across the inundation area could be between 0.1 to 0.2 m for the 200-year and 500-year debris floods. • Sedimentation associated with debris floods could reach up to 3 m thickness in the channel and up to 1.5 m outside the channel, in localized low-lying areas.
Auxiliary Hazards	• As with other debris-flood prone creeks in the study area that end in lakes, during high lake levels there is a substantial chance that the lower portions of Duhamel Creek will build up sediment and avulse east or west of the active channels downstream of the Lower 6-Mile Road. • All modeling results demonstrate overtopping of Highway 3A. Experience on other fans in BC and Alberta has demonstrated that such overtopping can lead to scour on the downstream (lake) side, followed by pavement undermining and collapse. This may lead to preferential flow paths not captured in the numerical modeling resulting in higher flow velocities and flow depths than modeled. Flow will concentrate in paleochannels, for example, halfway between the east channel and Barnes Road. • Barnes Road and Duhamel Creek Road which run parallel to Duhamel Creek would likely either be eroded (Duhamel Creek Road) or convey water at high flow velocities (Barnes Road). In this case, water in the ditches on either side of the road would likely create deep furrows which deepen the more water they convey and eventually undercut the asphalt. The result is that neither Barnes nor Duhamel Creek Road would likely be passable during, and immediately after, a major flood or debris flood. • The west channel of Duhamel Creek upstream of Highway 3A flows along the 40 to 45 m high paleofan surface. Bank erosion along this reach could lead to slope failures from the paleofan complex. Halfmoon-shaped embayments visible on lidar imagery suggest that sluffs or slumps have happened in the past. Such bank erosion and associated slope failures could affect properties perched along the eastern edge of the paleofan surface and possibly deflect the creek into hitherto unrecognized avulsion paths.

6.6. Bank Erosion Assessment

BGC compared air photos from a subset of available air photos between 1945 to 2006 to determine the historical changes in channel width at the eleven cross-sections considered in the bank erosion assessment (see Drawings 02A and 02B for cross-section locations). Table 6-6 summarizes the maximum channel width change between successive pairs of air photos at the cross-section at which it was observed. The maximum observed change in channel width between two successive air photos on Duhamel Creek was 9 m, between 1958 and 1968 at cross-section 6. To provide context for these values, the average current bankfull width is 14 m at the cross sections analyzed. Potential error or uncertainty in these measurements may be introduced by shadows from vegetation, poor image quality, or distortion during rectification. BGC estimates the total error associated with the above factors is less than 5 m.

Table 6-6. Summary of channel width change for each air photo.

Air Photo Interval	Maximum Channel Width Change Between Photos (m)	Cross-Section of Maximum Channel Width Change (Drawings 02A, 02B)
1945-1952	3	2
1952-1958	-2	-
1958-1968	9	6
1968-1979	2	3
1979-1982	0	2
1982-1988	6	6
1988-1994	1	2
1994-2000	0	2
2000-2006	3	-

A summary of the bank erosion model results by return period is outlined in Table 6-7. This table displays the minimum, maximum, and average erosion modelled across all cross-sections considered at each of the four return periods modelled. Cambio Communities shows bank lines indicating the 50% exceedance probability of the modelled erosion (i.e., the bank erosion that is predicted to be exceeded in 50% of the model runs) for each return period as two corridors: the likely erosion corridor and the potential/improbable erosion corridor.

Table 6-7. Summary of bank erosion model results by return period.

Return Period (years)	Minimum Erosion (m)	Average Erosion (m)	Maximum Erosion (m)
20	0	1	3
50	0	4	9
200	2	10	18
500	6	19	32

The potential/improbable erosion corridor shows the corridor outlining the full modelled erosion if it were applied to both banks. The likely erosion corridor scales the predicted erosion on either side of the channel based on the elevation of the surrounding terrain; if the elevation of the surrounding terrain is high relative to the channel elevation, for example, then the predicted erosion distance decreases to account for the larger volume of material that would need to be eroded (Section 2 of Methodology Report (BGC, March 31, 2020b)). Both the potential/improbable and likely erosion corridors account for the inherent uncertainty in assigning erosion to a particular bank.

Figure 6-2 and Figure 6-3 shows the 50% percentile modelled bank erosion at each cross-section. The predicted erosion differs between cross-sections based on the cross-section characteristics (e.g., channel geometry, channel slope, D_{84} grain size). Erosion peaks at cross-section 6 for the 20-year return period and at cross-section 1 for all other higher return periods (see Drawings 02A, 02B). Abutments of the Highway 3A and Lower 6 Mile bridges may be impacted by erosion during a rare (high return period) event or by progressive erosion over time. Several existing buildings may be impacted as they fall within the improbable erosion corridor for the 500-year return period.

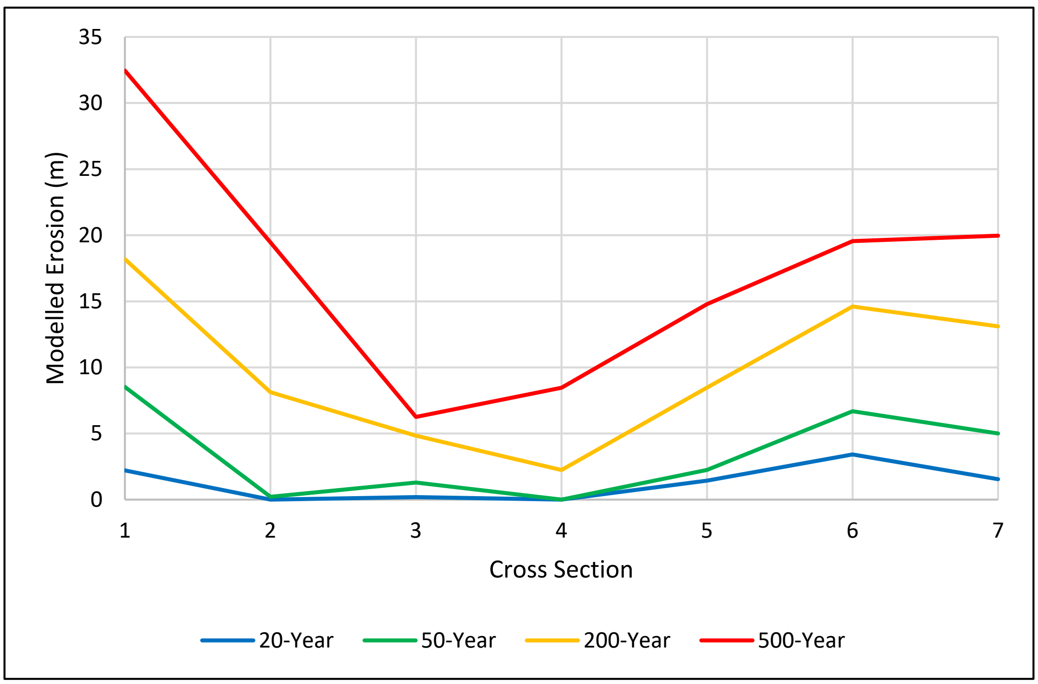


Figure 6-2. Duhamel Creek 50th percentile bank erosion model results at main channel cross-sections (1 to 7).

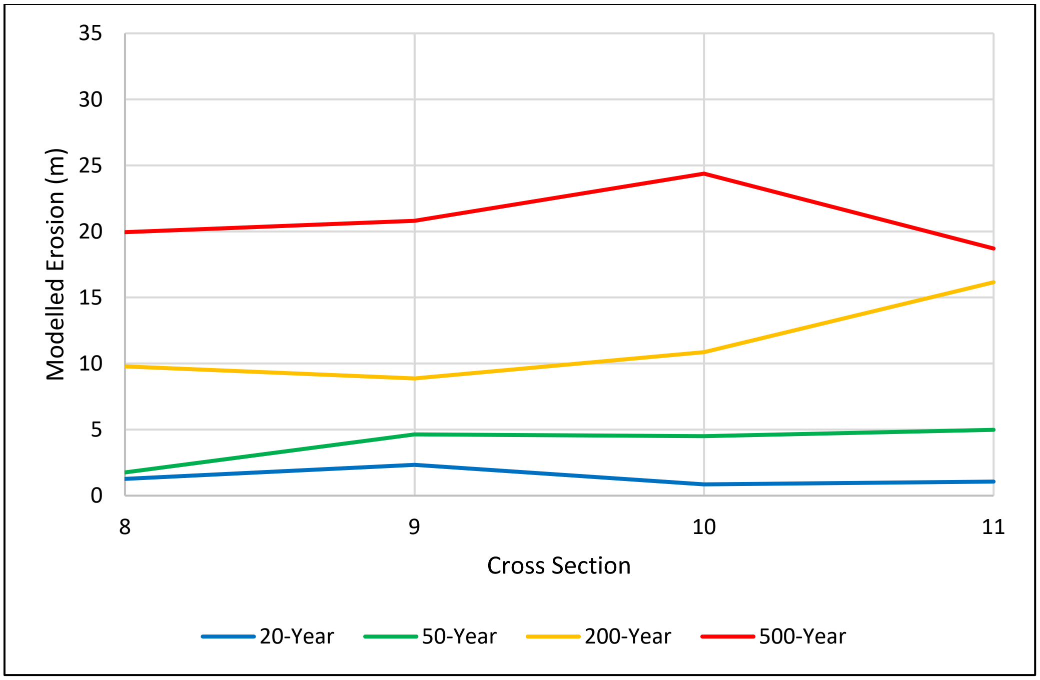


Figure 6-3. Duhamel Creek 50th percentile bank erosion model results at diversion channel cross-sections (8 to 11).

Non-engineered berms are currently present paralleling the east and west channels of Duhamel Creek downstream of Highway 3A. As the date of construction of the berms is unknown, it is not clear whether the erosion used to calibrate the model (i.e., the change in width from 1958-1968) occurred prior to, or following, berm construction. Furthermore, any armouring on the berms is not accounted for in the grain size measurements (D_{84}) for each modelled cross-section. As a result, the modelled erosion estimates are likely conservative.

6.7. Hazard Mapping

Drawing 07 provides a representative debris flood model result map for the 200-year return period. The full debris flood model results maps are presented on Cambio Communities. Drawing 08 provides a composite hazard rating map showing the maximum extent of all hazard scenarios.

As noted in Section 5.6, hazard 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.

6.7.1. Comparison with NHC/Thurber (1990)

As outlined in Section 4.2.1, a detailed study of creeks on the Kootenay Lake West Arm was completed in 1990 by NHC/Thurber. The NHC/Thurber (1990) study is highlighted and discussed separately as it is the key detailed study now being superseded by this report.

6.7.1.1. Methodological Differences

The NHC/Thurber (1990) assessment considered debris torrents[11], avulsions or channel shifts, and inundation. For each fan investigated, hazard areas are codified between 0 (lowest hazard) and 5 (highest hazard). However, since NHC/Thurber (1990) also included loss of life consequences as a second dimension in their hazard mapping, it renders their hazard maps into individual life loss risk maps. Specific risk zones are defined as those where individual life loss risk for people inside buildings exceeds or falls below specified values. Figure 6-4 shows the NHC/Thurber risk map for Duhamel Creek.

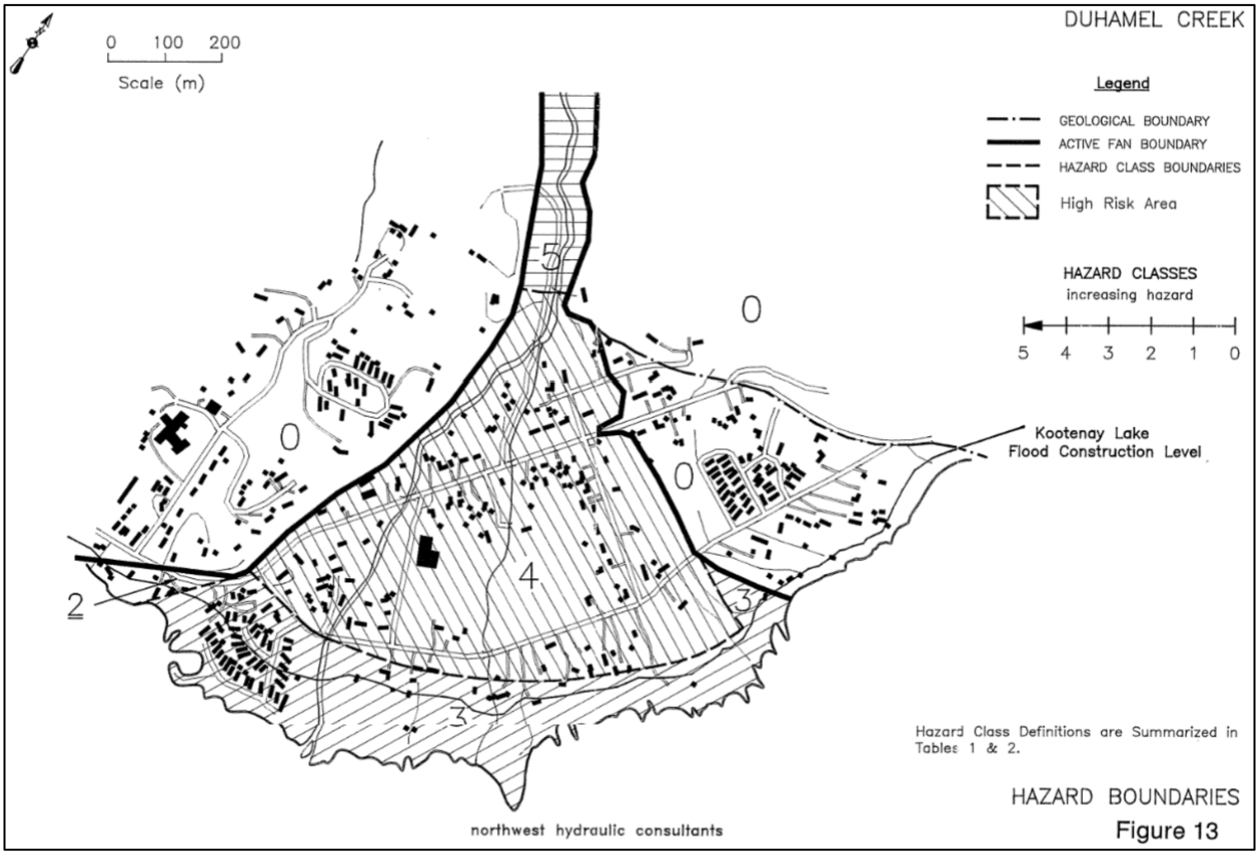


Figure 6-4. NHC/Thurber's (1990) Duhamel Creek individual life risk map. Class 4 and 5 imply individual life loss risk values exceeding 1:10,000. Class 3 1:10,000 to 1:20,000. Class 0, 1 and 2 < 1:20,000.

This section compares BGC's and NHC/Thurber's approaches because the hazard maps of the two reports differ significantly with NHC/Thurber's hazards and concordant risks being generally much higher than those of BGC[12]. The principal differences are highlighted in Table 6-8. For convenience NHC/Thurber (1990) is abbreviated in Table 6-8 to N/T.

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[11] In the NHC/Thurber (1990) report, debris torrent is used to describe a debris flow and is sometimes used interchangeably with debris flood. Section 2 and Appendix A provide definitions of these terms as used in this report.

[12] Note that BGC has not calculated risk to individuals, however, from hazard modeling and comparable studies by BGC it is apparent that PDI risk in yellow (low) and very low (yellow hatched) zones does not result in PDI risk exceeding 1:10,000.

Table 6-8. Method comparison between NHC/Thurber (1990) and this report (BGC (2020)).

Technique/Data	NHC/Thurber (1990)	BGC (2020)	Comment
Process	Debris torrents (debris flows and debris floods)	Debris floods	BGC did not encounter evidence for debris flows on the fans at the return periods considered
Process Severity	Classification into debris floods, indirect and direct impacts	Impact quantified and independent of process	BGC (2020) is a more comparable and transparent approach to evaluate impact
Topography	2 m contours	Lidar DEM	Substantially higher resolution in BGC (2020)
Fan activity designation	Into “active” and “inactive”	Into “paleofans” and “active”	Given the better DEM resolution, BGC’s classification is a refinement to N/T
Return Periods Considered	<100, 100-1000, >1000	20, 50, 200, 500	Return periods greater than 500 years are associated with very high uncertainties and were thus not included in BGC (2020)
Frequency Estimates	Historical air photos, maps, records, watershed characteristics	As N/T, but also 30 years more historical data, flood and debris flood frequency analysis.	Substantially greater effort by BGC (2020) compared to N/T, thus higher confidence in BGC (2020)
Magnitude Estimates	Relative assessments of sediment supply, hydraulic modelling of clearwater flows in main channels	Two types of sediment transport calculations, regional F-M sediment volume relationships, empirical relationships between peak discharges and sediment volumes	Substantially greater effort by BGC (2020) compared to N/T, thus higher confidence in BGC (2020)
Probability of Avulsion	Method by Dawdy (1979) to determine probability of avulsion based on historical information and geomorphology	Numerical modelling-assisted with assumptions of bridge and/or culvert blockages at critical locations based on capacity exceedances	Lesser reliance on expert judgement for BGC (2020) and hence more replicable and transparent than N/T.
Impact Intensity	Based on flow velocity and depth (Table 6-9). Note that those were estimated, not modelled.	Based on flow velocity, depth and fluid density	The key is the association of given impact intensity groupings to severity of impact.
Hazard Mapping	Classification into 5 groups based on hazard type, frequency and severity	Based on frequency and impact force (severity) including bank erosion	More transparent approach based on numerical modelling rather than pure expert judgement
Risk to Loss of Life	Calculated via standard probability of loss of life for an individual formula	No loss of life risk calculations	In N/T, risk to loss of life calculations were reported under hazard mapping. Risk and hazard are distinctly different. BGC’s (2020) did not attempt to calculate risk to loss of life.

Table 6-9. Comparison of NHC/Thurber (1990) and this report (BGC, 2020) hazard mapping methods. Note that the categories of flow depth and flow velocity of NHC/Thurber (1990), do not exactly match the impact force as determined by BGC (2020).

NHC/Thurber (1990)			BGC (2020)	
Flow Depth (m)	Flow Velocity (m/s)	Severity	Impact Force (kN/m)	Severity
< 0.5	1.5-2	Low, lives rarely threatened, little structural damage	< 1	Slow flowing shallow and deep water with little or no debris. High likelihood of water damage. Potentially dangerous to people in buildings, in areas with high water depths
0.5 to 1.0	1.5-2	Moderate, threshold conditions which can result in loss of life and structural damage	1-10	(1-3): Mostly slow flowing shallow or deep flow with minor debris. High likelihood of sedimentation and water damage. Potentially dangerous to people in buildings, or in areas with higher water depths. (3-10): Potentially fast flowing but mostly shallow water with debris. Moderate likelihood of building damage and high likelihood of major sediment and/or water damage. Potentially dangerous to people on the first floor or in the basement of buildings without elevated concrete footings.
>1	>2	High, considerable potential of loss of life, significant structural damage	10-100	Fast flowing and debris. High likelihood of structural building damage and severe sediment and water damage. Dangerous to people on the first floor or in the basement of buildings. Replacement of unreinforced buildings likely required.
n/a	n/a	n/a	>100	Fast flowing debris. High likelihood of severe structural building damage and severe sediment damage. Unreinforced building replacement required. Very dangerous to people in buildings irrespective of floor.

6.7.1.2. Duhamel Creek Specifics

At Duhamel Creek, NHC/Thurber (1990) indicated that the creek had a long history of channel instability and thus, assessed a high probability of avulsion during future hydrogeomorphic events. Further, NHC/Thurber assessed that the potential for channel aggradation and bank erosion associated with extreme events necessitated the construction of flood control works. NHC/Thurber also suggested that to provide long term flood protection to existing developments between the east and west channels, that the existing bifurcation should be removed, and a series of river training structures constructed to maintain the flow within the west branch.

During helicopter reconnaissance, NHC/Thurber observed little evidence of accumulated debris upstream of the fan and assessed the potential for debris torrents on the creek to be low. In comparison with the other creeks studied, NHC/Thurber estimated that potential flood damages would be highest at Duhamel due to the history of channel instability and density of development. In total 78% of the fan is classified as hazard code 3, 4, or 5.

6.7.1.3. Summary

After reviewing the NHC/Thurber (1990) work, BGC concludes that the hazards and likely (as BGC did not quantify risks) the risks to loss of life are substantially higher for the NHC/Thurber report than estimated in this report by BGC. The main reason for this discrepancy is that NHC/Thurber did not benefit from lidar topography, detailed numerical modelling, and an additional 30 years of data that have accrued since their study and the present. In absence of such detailed information and analysis, it was likely justified to err on the conservative spectrum.

BGC believes that the current work is a credible representation of hazards on the detailed study creeks including Duhamel Creek up to the 500-year return period scenarios considered in this study.

7. SUMMARY AND RECOMMENDATIONS

7.1. Introduction

This report and appendices provide a detailed hazard assessment of the Duhamel Creek fan-delta. This 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 mitigation measures should those be found to be required for Duhamel Creek.

A variety of analytical desktop and field-based tools and techniques were combined to decipher Duhamel 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, Duhamel Creek is subject to supply-unlimited Type 1 debris floods for 20- and 50-year return periods. For higher return periods (200- and 500-year), Type 2 debris floods are believed to be the dominant process. Type 3 debris floods are plausible, especially after stand-replacing wildfires in the larger Duhamel Creek tributaries. Those were not modeled by BGC.

7.2.2. Air Photo Interpretation

Air photos were interpreted to gain an understanding of watershed and channel changes on the fan-delta and help with the construction of an F-M relationship. Some highlights from these analyses are:

- Significant debris flood events occurred in 1948, 1955/56, 1968 and 1971 based on air photo records.
- Notable flood events also occurred in 1972, 1990, 1996, and 2012. The 1990 and 1996 events were associated with icing in the channel.
- The largest debris flood is interpreted to be the event in 1968. The 1968 air photo shows an area of freshly deposited debris of approximately 67,200 m^2.

7.2.3. Peak Discharge Estimates

In recognition of the impacts of climate change and potential bedload and suspended sediment loads, the clearwater flows estimated from the station FFA were adjusted. There are no reliable methods to predict sediment concentrations for streams in which those variables have not been measured, and hence sediment concentration estimates are associated with substantial uncertainty. 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 clearwater peak discharges for Duhamel Creek range from 25 m^3/s (20-year flood) to 50 m^3/s (500-year flood).
- Sediment bulking factors of 1.02 (2% increase for the 20-year debris flood) to 1.3 (30% increase for the 500-year return period event) were adopted as input to numerical modelling.
- Consideration of climate change and sediment bulking increase the non-adjusted clearwater discharge estimate from 20 to 25 m^3/s for the 20-year debris flood, and from 40 to 65 m^3/s for the 500-year event.

7.2.4. Frequency-Magnitude Relationships

Frequency-magnitude relationships were constructed for peak discharges associated with those events as summarized in Table 7-1.

Table 7-1. Duhamel Creek debris flood frequency-magnitude relationship.

Return Period (years)	Adjusted Peak Discharge (m^3/s)
20	25
50	30
200	50
500	65

7.2.5. Numerical Flood and Debris Flood Modelling

Two numerical models were employed to simulate the chosen hazard scenarios on the Duhamel Creek fan-delta. The two models were complimentary, in that results could be compared to facilitate flexibility in the interpretation of results in consideration of the advantages and shortcomings of the individual models. Table 6-5 provided key observations derived from the numerical modelling.

The multiple process numerical modelling ensemble approach demonstrates that the key hazards and associated risks at Duhamel Creek stem from the multiple avulsion paths as the main channel's capacity is exceeded at higher return periods and allows the flow to spread over most of the active fan surface.

7.2.6. Bank Erosion Assessment

A bank erosion assessment was completed because debris floods can be highly erosive. The key findings from the bank erosion assessment are:

- The bank erosion model was calibrated based on the air photo analysis by comparing the predicted 50-year erosion to the maximum measured erosion in the reach. The highest erosion estimated from consecutive air photos was 9 m. Note that this is not a single event erosion amount, which could have been higher or lower.
- The maximum modelled erosion ranges from 3 m in a 20-year event to 32 m in a 500-year event. The likely erosion ranges from 1 m to 19 m during the 20-year to 500-year events.

- Bank erosion may affect the abutments of Highway 3A and Lower 9 Mile bridges during a high return period event, or by progressive erosion over time. During a 500-year return period event, properties located south of Highway 3A along Duhamel Creek may be impacted.

7.2.7. 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 shown as debris flood model results. A representative example is included in Drawing 07 and full results are presented in Cambio Communities.
- A composite hazard rating map (impact intensity frequency map) that combines the debris flood 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 impact intensity frequency map serve as decision-making tools to guide subdivision and other development permit approvals.

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 Duhamel Creek represent a snapshot in time. Future changes to the Duhamel Creek watershed or fan-delta including the following may warrant re-assessment and/or re-modelling:

- Future fan development and substantial flood or debris-flood events
- Development of large landslides in the watershed with the potential to impound Duhamel Creek or significant wildfires
- Bridge re-design and/or alteration to the existing dikes that parallel the creek
- Changes to the bifurcation structure
- Significant aggradation of the channel or bank erosion that increases the potential for avulsions
- Substantial changes to Kootenay Lake levels
- A channel blockage on the upper fan could erode the western Duhamel Creek bank into the western paleosurface delineated on Drawing 06.

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

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 or ice 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 as they pertain to all studied RDCK creeks. This section notes Duhamel Creek-specific issues that could be considered 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 flooding would be considered intolerable by the District. It would also require discussions with other stakeholders with assets on the Duhamel Creek fan-delta.

As for all steep creeks with high sediment transport potential, the following key considerations ought to be acknowledged when trying to achieve successful risk reduction for existing and future developments:

1. Stopping organic and mineral debris near the fan apex to avoid downstream aggradation and concordant avulsions. Note that this strategy, while being effective, is expensive and requires regular maintenance. Stream downcutting downstream of the structure can be avoided by allowing some grains to pass through the structure. This will also be beneficial for downstream fish habitat.
2. Most creeks on fans and fan-deltas tend to be wide and laterally unstable. Forcing the creek in between berms flanking the creek is undesirable. Deepening the channel through excavation will invariably be followed by infill causing a cycle of expensive and disruptive gravel excavations. This is being done at the Resort Municipality of Whistler on Fitzsimmons Creek at a cost of several hundred thousand dollars per year. Instead, setback berms that provide maximum room for the creek to shift and build up sediment is preferred. However, setback berms, for example paralleling the creek at the 50th percentile bank erosion line would severely infringe in people’s properties. The berms would have to be owned and operated by local government which will requires access easements. Given the length of the fan delta from the bifurcation structure (almost 2000 m for the east and west channels), such setback berms would also be very expensive and would still require occasional sediment removal.

Duhamel Creek fan-delta hosts the highest value of assets of the steep creek fan-deltas studied in detail (Table 1-1). Hence, while likely expensive, Option 1 may be viable at Duhamel Creek. With reference to Figure 7-1, the following specific mitigation measures could be considered to reduce hazards and risks on Duhamel Creek:

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

Option	Description	Effect on Flood Hazard Reduction
(a-1)	Debris basin downstream of the fan apex with single outlet structure	Reduction in debris load, reduced chance of downstream avulsions. Minor flow attenuation.
(a-2)	Debris basin immediately upstream of the bifurcation with outlet structures into the east and west channels	As above and avoidance of outflanking of bifurcation structure.
(a-3)	Debris basin immediately downstream of the bifurcation with outlet structures into the east and west channels	As above but requires deflection berm on east side to prevent outflanking of bifurcation structure.
(b-1)	Highway 3A East Bridge replacement (high priority)	Avoidance of bridge blockage and upstream avulsions; avoidance of bridge damage or destruction
(b-2)	Highway 3A West Bridge replacement	
(c-1)	Lower 6 Mile Road East Bridge replacement	
(c-2)	Lower 6 Mile Road West Bridge replacement (high priority)	
(d)	Deflection berm upstream of Highway 3A on west channel	Avoidance of avulsion onto far western fan-delta segments
(e)	Deflection berm upstream of Lower 6 Mile Road on east side of west channel	Avoidance of avulsions to the east and downstream of Lower 6 Mile Road

In addition to the mitigation considerations listed above, several other measures are conceivable:

- Enforcement of channel erosion-related construction setbacks from top of bank to avoid undercutting of building foundations during debris floods.
- Establishment and enforcement of construction recommendations based on the composite hazard rating map and RDCK engineering guidelines for construction on alluvial fans. These could be fan-segment specific but would have to be refined for all new building permit applications by qualified professionals.
- Developments east of Greenwood Road and Harlow Road that are close to the edge of the paleofan terrace (Drawings 02A, 02B, 06) require careful roof and property drainage management (Option (f)). Uncontrolled water release down the eastern slopes towards the west channel are to be avoided as those could lead to slope instabilities. Debris slides or slumps from the paleofan terrace could block or divert the west channel leading to forced avulsions towards the east which have not been specifically modeled.
- Similar to the above bullet, developments along the western portion of Heddle Road near the steep escarpment above Duhamel Creek require careful drainage management to avoid slope failures that could impound or deflect Duhamel Creek near the northern end of Duhamel Creek Road (Option (g)).
- The outlets of Six Mile Lakes in the upper watershed of Duhamel Creek could become blocked by log debris or debris flows with commensurate increases in lake level. Should such blockages be noted, the blockages should be carefully removed to avoid outburst floods.

Given that funding for any of the measures listed in Table 7-2 is presently uncertain, the above five bullets could be implemented immediately irrespective of any future funding for more elaborate mitigation measures.

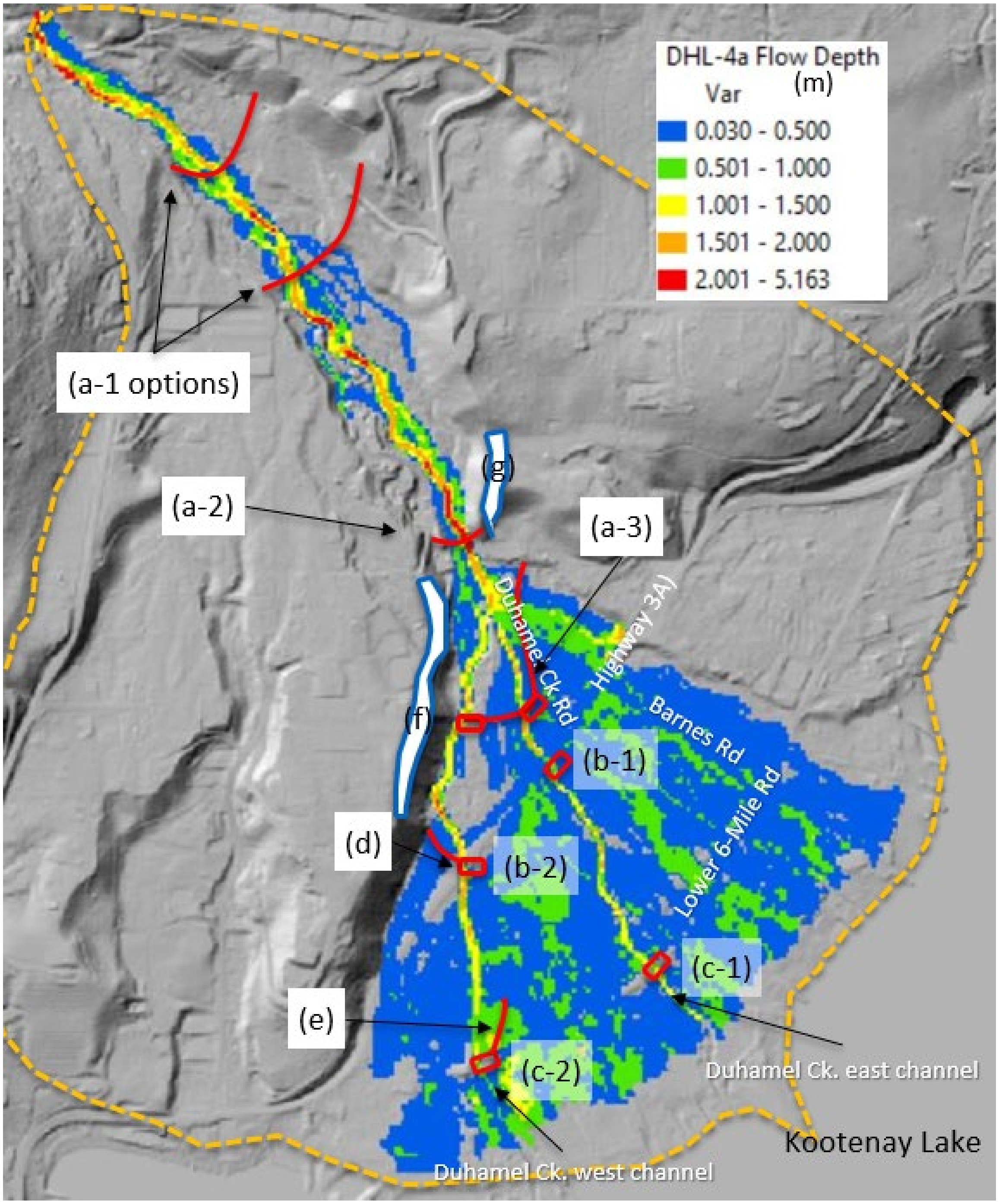

Figure 7-1. Debris-flood inundation map showing flow depths for a 500-year return period debris flood on Duhamel Creek from FLO-2D modeling with no specific bridge blockages. The figure shows conceptual-level mitigation options for Duhamel Creek fan-delta. Note that these options have not been tested 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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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

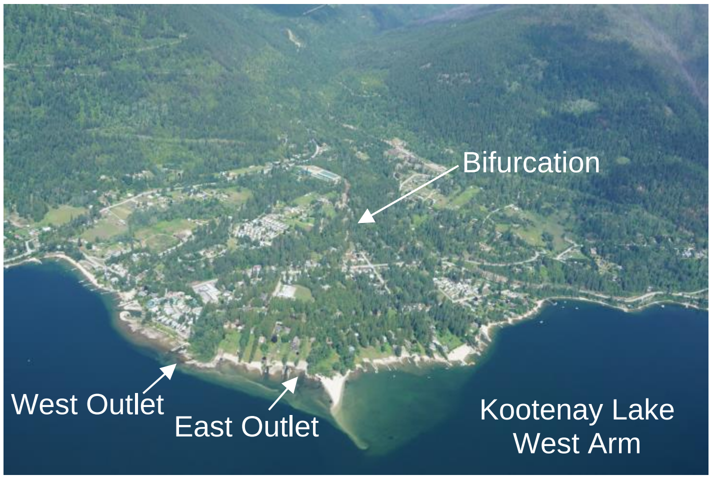


Photo 1.

Overview photo taken during helicopter overflight looking northwest at Duhamel Creek fan. A bifurcation structure divides Duhamel Creek into a West and East Channel draining into Kootenay Lake West Arm. Photo: BGC, July 6, 2019.

Photo 2.

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

Photo 3.

Overview photo taken during helicopter overflight looking north at the Duhamel Creek fan. Both the east and west outlets of Duhamel Creek to Kootenay Lake are visible. Photo: BGC, July 6, 2019.

Photo 4.

Overview photo taken during helicopter overflight looking south at Duhamel Creek fan, with the bifurcation structure in the foreground dividing Duhamel Creek into a West and East Channel draining into Kootenay Lake. Photo: BGC, July 6, 2019.

Photo 5.

Overview photo taken during helicopter overflight looking down at Duhamel Creek Road Bridge spanning the West Channel and the bifurcation structure Photo: BGC, July 6, 2019.

Photo 6.

Overview photo taken during helicopter overflight looking down at the western Duhamel Creek outlet to Kootenay Lake. Photo: BGC, July 6, 2019.

Photo 7.

Overview photo taken during helicopter overflight looking west and down towards Duhamel Creek approximately 3.5 km upstream of lake outlet. Photo: BGC, July 6, 2019.

Photo 8.

Overview photo taken during helicopter overflight looking west and down at recent debris avalanches (indicated with arrows) upslope of Duhamel Creek approximately 8.5 km upstream of lake outlet. Photo: BGC, July 6, 2019.

Photo 9.

Overview photo taken during helicopter overflight looking south at Six Mile Lakes in foreground and Duhamel Creek in background. Photo: BGC, July 6, 2019.

Photo 10.

Collage of overview photos taken during helicopter overflight looking east at upper parts of tributaries that burned in 1924 on eastern slope of Duhamel Creek, located near Six Mile Lakes. Photo: BGC, July 6, 2019.

Photo 11.

Overview photo taken during helicopter overflight looking southeast at forest that burned in 2015 on eastern slope of Duhamel Creek, approximately 6 km upstream of lake outlet. Photo: BGC, July 6, 2019.

Photo 12.

Overview photo taken during helicopter overflight looking east at forest that burned in 2015 on eastern slope of Duhamel Creek, approximately 3.8 km upstream of lake outlet. Note the surficial erosion and erosion riling in the burned area, and the man-made firebreak to the right of the photo. Photo: BGC, July 6, 2019.

Photo 13.

Debris piled up on the Duhamel Creek banks approximately 100 m upstream of the east outlet to Kootenay Lake. Photo: BGC July 27, 2019.

Photo 14.

Standing on the right bank of Duhamel Creek at the west outlet to Kootenay Lake looking upstream (north). Photo: BGC, July 8, 2019.

APPENDIX C
SEDIMENT SIZE SAMPLING

C.1. SAMPLING LOCATIONS

At Duhamel Creek, three Wolman Samples were taken, one upstream of the fan apex, one upstream of the west Highway 3A bridge, and one at the outlet to Kootenay Lake. The sampling locations (referred to as Duhamel 1, Duhamel 2 and Duhamel 3) are shown in Figure C-1 and in Table C-1. Bed material conditions at each site are shown on Figure C-2, Figure C-3, and Figure C-4.

Table C-1. Wolman sampling locations.

Site Name	Duhamel 1	Duhamel 2	Duhamel 3
Location	Upstream of fan apex	Upstream of west Highway 3A Bridge	Near outlet to Kootenay Lake
Longitude	117°14'16.89"W	117°13'40.02"W	117°13'20.89"W
Latitude	49°35'5.25"N	49°34'28.97"N	49°34'17.81"N
Number of stones measured	101	98	116

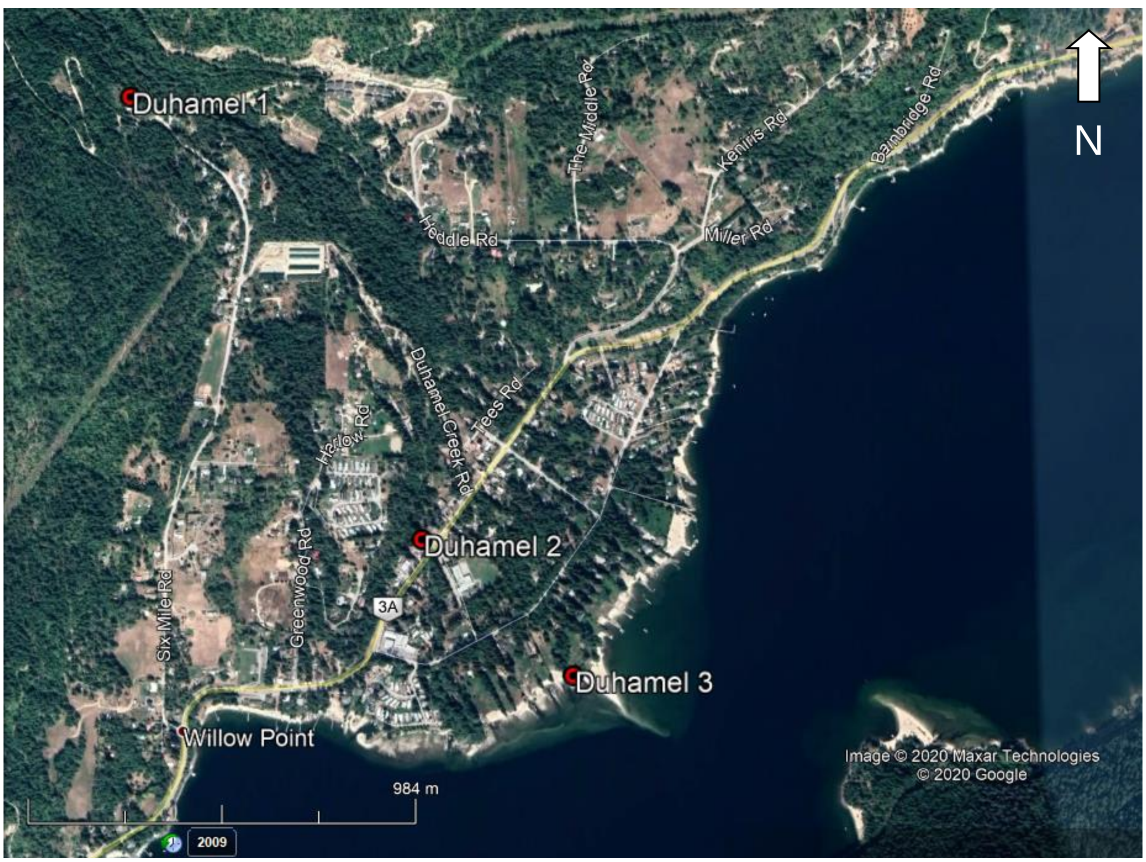


Figure C-1. Wolman sampling locations along Duhamel Creek. Google Earth image of September 3, 2018.

Figure C-2. Photograph taken of Wolman sampling location Duhamel 1. BGC photograph of November 19, 2019.

Figure C-3. Photograph taken of Wolman sampling location Duhamel 2. BGC photograph of November 19, 2019.

Figure C-4. Photograph taken of Wolman sampling location Duhamel 3. BGC photograph of July 27, 2019.

C.2. RESULTS

Results of the Wolman counts are shown in Table C-2 and on Figure C-5, Figure C-6 and Figure C-7.

Table C-2. Duhamel Creek sediment distribution from Wolman Count Data.

Grain Size	Duhamel 1	Duhamel 2	Duhamel 3
D_{95} (mm)	214	>256	113
D_{84} (mm)	151	145	77
D_{50} (mm)	74	62	39
D_{15} (mm)	31	19	<2
D_{5} (mm)	16	3	<2

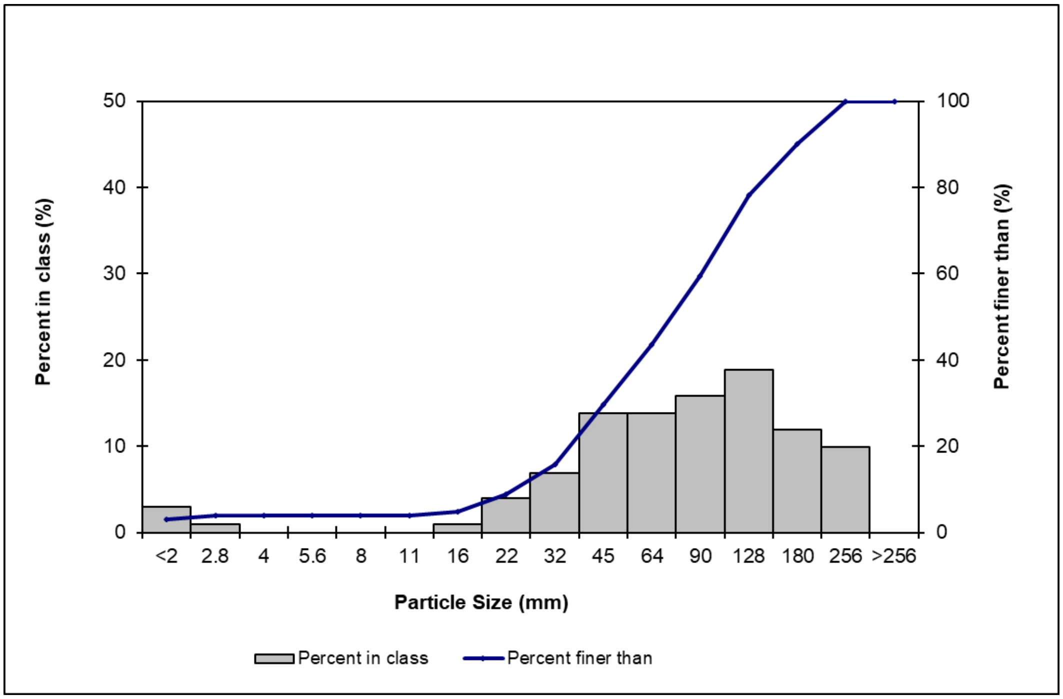


Figure C-5. Duhamel Creek grain size distribution at Duhamel 1 (upstream of fan apex) from Wolman count.

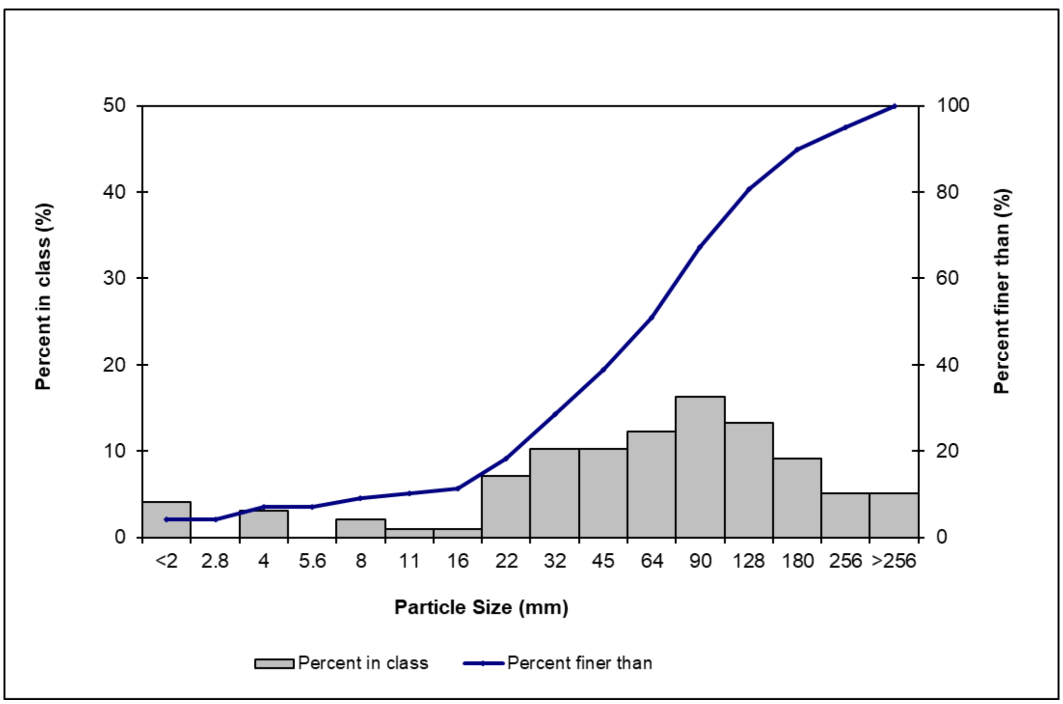


Figure C-6. Duhamel Creek grain size distribution at Duhamel 2 (upstream of west Highway 3A bridge) from Wolman count.

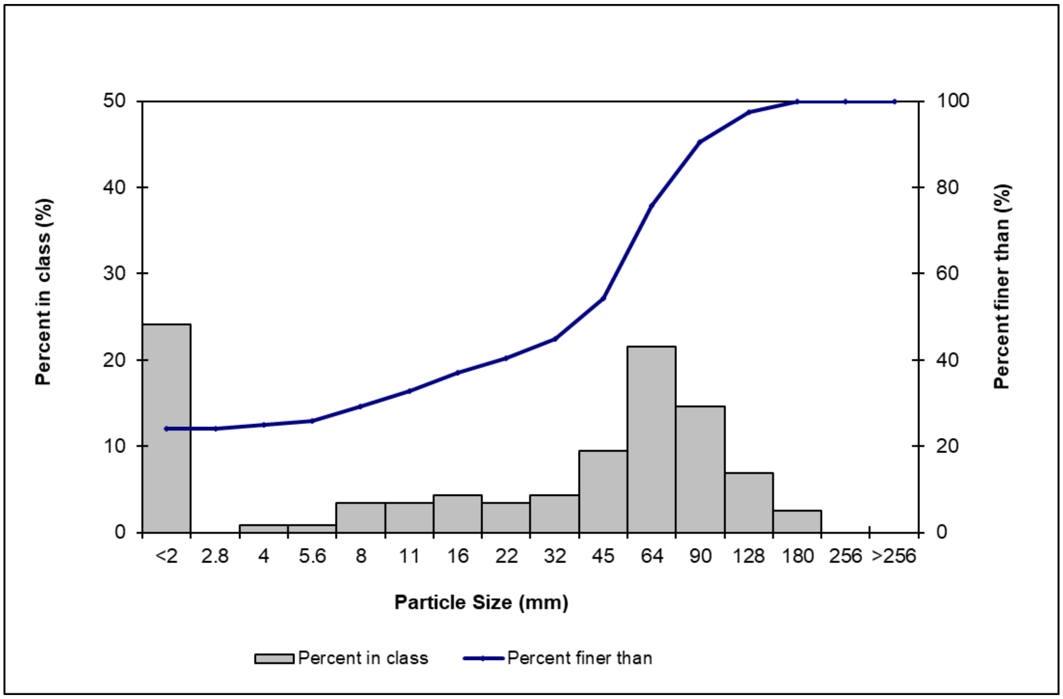


Figure C-7. Duhamel Creek grain size distribution at Duhamel 3 (near outlet to Kootenay Lake) from Wolman count.

As expected, given the reduction in channel gradient, bed material size decreases in a downstream direction along the fan. In order to predict sediment size distributions at locations not sampled, linear interpolation between the D_{84} values collected at the sampling locations and distance from fan apex was used.

APPENDIX D
AIR PHOTO RECORDS

Table D-1 presents air photo records from the Duhamel 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 D-1. Duhamel Creek air photo records.

Year	Date	Roll Number	Photo Number	Scale
2006	7/21/2006	BCC06061	42-44	20,000
2000	9/17/2000	BCB00038	68-71, 129-132	15,000
1997	8/22/1997	BCB97047	105-107, 171-173	15,000
1994	5/31/1994	BCB94016	51-54	15,000
	5/9/1994	BCB94011	169-175, 107-111, 166-168, 137-141	5,000
	5/9/1994	BCB94007	139-145, 184-187	5,000
1988	7/22/1988	BC88090	6-8	15,000
1986	7/20/1986	BC86059	1-6, 20-23, 39-42	16.000
1982	8/27/1982	BC82036	108	54,000
	8/23/1982	BC82031	200-203	20,000
1981	6/25/1981	BC81028	238-242	5,000
1979	8/2/1979	BC79134	106-110	10,000
1968	8/31/1968	BC7109	26-28	16,000
1982	8/31/1968	BC7108	213-216	16,000
1958	7/24/1958	BC2477	64-66	15,840
	7/24/1958	BC2475	96, 99	15,840
1952	6/14/1952	BC1455	96-97	31,680
	6/14/1952	BC1458	31	31,680
1945	6/5/1945	A7735	77-78	25,000
1939	6/17/1939	BC144	20-22	31,680
1929	4/17/201	A1014	84-86	10,000

APPENDIX E
MODELLING SCENARIOS

E.1. MODELLING SCENARIOS

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

Table E-1. Modeling scenario summary for Duhamel Creek.

Scenario Name	Return Period (yrs)	Process Type	Bulking Factor	Bulked Peak Discharge (m^3/s)	Conveyance Structures			Flood Protection Structures				
					Name	Estimated Capacity (m^3/s)	Assumption	Name	Type	Bank Erosion Encroaching	τ/τc ≥ 2	Assumption
DHL-1	20	Debris Flood (Type 1)	1.02	23	Old Log Bridge	-	In disrepair, assumed to be washed away when at capacity	DHL-FP-01	Log crib bank erosion, orphaned.	Y	Y	Removed from topography, assumed to fail
					Driveway Bridge 1	50	Functioning as intended	DHL-FP-06	Left bank erosion protection, not orphaned.	Y	Y	Removed from topography, assumed to fail
					Bifurcation Bridge	30	Functioning as intended	DHL-FP-07	Right bank erosion protection, orphaned.	Y	Y	Removed from topography, assumed to fail
					Duhamel Highway West Bridge	60	Functioning as intended	DHL-FP-08	Left bank dike, not orphaned.	Y	Y	Removed from topography, assumed to fail
					Lower 6 Mile Rd West Bridge	25	Functioning as intended	DHL-FP-09	Right bank dike, orphaned.	Y	Y	Removed from topography, assumed to fail
					Duhamel Highway East Bridge	10	Functioning as intended					
					Pedestrian Bridge 1	25	Functioning as intended					
					Driveway Bridge 2	30	Functioning as intended					
					Lower 6 Mile Rd East Bridge	30	Functioning as intended					
					Pedestrian Bridge 2	-	Lightweight bridge, assumed to be washed away when at capacity					
DHL-2a	50	Debris Flood (Type 1)	1.05	30	Old Log Bridge	-	In disrepair, assumed to be washed away when at capacity					
					Driveway Bridge 1	50	Functioning as intended					

Scenario Name	Return Period (yrs)	Process Type	Bulking Factor	Bulked Peak Discharge (m³/s)	Conveyance Structures			Flood Protection Structures				
					Name	Estimated Capacity (m³/s)	Assumption	Name	Type	Bank Erosion Encroaching	τ/τc ≥ 2	Assumption
					Bifurcation Bridge	30	Functioning as intended	DHL-FP-01	Log crib bank erosion, orphaned.	Y	Y	Removed from topography, assumed to fail
					Duhamel Highway West Bridge	60	Functioning as intended	DHL-FP-06	Left bank erosion protection, not orphaned.	Y	Y	Removed from topography, assumed to fail
					Lower 6 Mile Rd West Bridge	25	Functioning as intended	DHL-FP-07	Right bank erosion protection, orphaned.	Y	Y	Removed from topography, assumed to fail
					Duhamel Highway East Bridge	10	Functioning as intended	DHL-FP-08	Left bank dike, not orphaned.	Y	Y	Removed from topography, assumed to fail
					Pedestrian Bridge 1	25	Functioning as intended	DHL-FP-09	Right bank dike, orphaned.	Y	Y	Removed from topography, assumed to fail
					Driveway Bridge 2	30	Functioning as intended					
					Lower 6 Mile Rd East Bridge	30	Functioning as intended					
					Pedestrian Bridge 2	-	Lightweight bridge, assumed to be washed away when at capacity					
DHL-2b	50	Debris Flood (Type 1)	1.05	30	Old Log Bridge	-	In disrepair, assumed to be washed away when at capacity	DHL-FP-01	Log crib bank erosion, orphaned.	Y	Y	Removed from topography, assumed to fail
					Driveway Bridge 1	50	Functioning as intended	DHL-FP-06	Left bank erosion protection, not orphaned.	Y	Y	Removed from topography, assumed to fail
					Bifurcation Bridge	30	Functioning as intended	DHL-FP-07	Right bank erosion protection, orphaned.	Y	Y	Removed from topography, assumed to fail
					Duhamel Highway West Bridge	60	Functioning as intended	DHL-FP-08	Left bank dike, not orphaned.	Y	Y	Removed from topography, assumed to fail
					Lower 6 Mile Rd West Bridge	25	Blocked	DHL-FP-09	Right bank dike, orphaned.	Y	Y	Removed from topography, assumed to fail
					Duhamel Highway East Bridge	10	Blocked					
					Pedestrian Bridge 1	25	Functioning as intended					

Scenario Name	Return Period (yrs)	Process Type	Bulking Factor	Bulked Peak Discharge (m³/s)	Conveyance Structures			Flood Protection Structures				
					Name	Estimated Capacity (m³/s)	Assumption	Name	Type	Bank Erosion Encroaching	τ/τc ≥ 2	Assumption
					Driveway Bridge 2	30	Functioning as intended					
					Lower 6 Mile Rd Bridge East	30	Functioning as intended					
					Pedestrian Bridge 2	-	Lightweight bridge, assumed to be washed away when at capacity					
DHL-3a	200	Debris Flood (Type 2)	1.2	49	Old Log Bridge	-	In disrepair, assumed to be washed away when at capacity	DHL-FP-01	Log crib bank erosion, orphaned.	Y	Y	Removed from topography, assumed to fail
					Driveway Bridge 1	50	Functioning as intended	DHL-FP-06	Left bank erosion protection, not orphaned.	Y	Y	Removed from topography, assumed to fail
					Bifurcation Bridge	30	Functioning as intended	DHL-FP-07	Right bank erosion protection, orphaned.	Y	Y	Removed from topography, assumed to fail
					Duhamel Highway West Bridge	60	Functioning as intended	DHL-FP-08	Left bank dike, not orphaned.	Y	Y	Removed from topography, assumed to fail
					Lower 6 Mile Rd West Bridge	25	Functioning as intended	DHL-FP-09	Right bank dike, orphaned.	Y	Y	Removed from topography, assumed to fail
					Duhamel Highway East Bridge	10	Functioning as intended					
					Pedestrian Bridge 1	25	Functioning as intended					
					Driveway Bridge 2	30	Functioning as intended					
					Lower 6 Mile Rd Bridge East	30	Functioning as intended					
					Pedestrian Bridge 2	-	Lightweight bridge, assumed to be washed away when at capacity					
DHL-3b	200	Debris Flood (Type 2)	1.2	49	Old Log Bridge	-	In disrepair, assumed to be	DHL-FP-01	Log crib bank erosion, orphaned.	Y	Y	Removed from topography, assumed to fail

Scenario Name	Return Period (yrs)	Process Type	Bulking Factor	Bulked Peak Discharge (m^3/s)	Conveyance Structures			Flood Protection Structures				
					Name	Estimated Capacity (m^3/s)	Assumption	Name	Type	Bank Erosion Encroaching	τ/τc ≥ 2	Assumption
							washed away when at capacity					
					Driveway Bridge 1	50	Functioning as intended	DHL-FP-06	Left bank erosion protection, not orphaned.	Y	Y	Removed from topography, assumed to fail
					Bifurcation Bridge	30	Functioning as intended	DHL-FP-07	Right bank erosion protection, orphaned.	Y	Y	Removed from topography, assumed to fail
					Duhamel Highway West Bridge	60	Functioning as intended	DHL-FP-08	Left bank dike, not orphaned.	Y	Y	Removed from topography, assumed to fail
					Lower 6 Mile Rd West Bridge	25	Over capacity, blocked	DHL-FP-09	Right bank dike, orphaned.	Y	Y	Removed from topography, assumed to fail
					Duhamel Highway East Bridge	10	Over capacity, blocked					
					Pedestrian Bridge 1	25	Functioning as intended					
					Driveway Bridge 2	30	Functioning as intended					
					Lower 6 Mile Rd Bridge East	30	Functioning as intended					
					Pedestrian Bridge 2	-	Lightweight bridge, assumed to be washed away when at capacity					
DHL-3c	200	Debris Flood (Type 2)	1.2	49	Old Log Bridge	-	In disrepair, assumed to be washed away when at capacity	DHL-FP-01	Log crib bank erosion, orphaned.	Y	Y	Removed from topography, assumed to fail
					Driveway Bridge 1	50	Functioning as intended	DHL-FP-06	Left bank erosion protection, not orphaned.	Y	Y	Removed from topography, assumed to fail
					Bifurcation Bridge	30	Block east channel	DHL-FP-07	Right bank erosion protection, orphaned.	Y	Y	Removed from topography, assumed to fail
					Duhamel Highway West Bridge	60	Functioning as intended	DHL-FP-08	Left bank dike, not orphaned.	Y	Y	Removed from topography, assumed to fail
					Lower 6 Mile Rd West Bridge	25	Over capacity, blocked	DHL-FP-09	Right bank dike, orphaned.	Y	Y	Removed from topography, assumed to fail

Scenario Name	Return Period (yrs)	Process Type	Bulking Factor	Bulked 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
					Duhamel Highway East Bridge	10	Functioning as intended					
					Pedestrian Bridge 1	25	Functioning as intended					
					Driveway Bridge 2	30	Functioning as intended					
					Lower 6 Mile Rd Bridge East	30	Functioning as intended					
					Pedestrian Bridge 2	-	Lightweight bridge, assumed to be washed away when at capacity					
DHL-3d	200	Debris Flood (Type 2)	1.2	49	Old Log Bridge	-	In disrepair, assumed to be washed away when at capacity	DHL-FP-01	Log crib bank erosion, orphaned.	Y	Y	Removed from topography, assumed to fail
					Driveway Bridge 1	50	Functioning as intended	DHL-FP-06	Left bank erosion protection, not orphaned.	Y	Y	Removed from topography, assumed to fail
					Bifurcation Bridge	30	Block west channel	DHL-FP-07	Right bank erosion protection, orphaned.	Y	Y	Removed from topography, assumed to fail
					Duhamel Highway West Bridge	60	Functioning as intended	DHL-FP-08	Left bank dike, not orphaned.	Y	Y	Removed from topography, assumed to fail
					Lower 6 Mile Rd West Bridge	25	Functioning as intended	DHL-FP-09	Right bank dike, orphaned.	Y	Y	Removed from topography, assumed to fail
					Duhamel Highway East Bridge	10	Over capacity, blocked					
					Pedestrian Bridge 1	25	Functioning as intended					
					Driveway Bridge 2	30	Functioning as intended					
					Lower 6 Mile Rd Bridge East	30	Functioning as intended					

Scenario Name	Return Period (yrs)	Process Type	Bulking Factor	Bulked 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
					Pedestrian Bridge 2	-	Lightweight bridge, assumed to be washed away when at capacity					
DHL-4a	500	Debris Flood (Type 2)	1.3	66	Old Log Bridge	-	In disrepair, assumed to be washed away when at capacity	DHL-FP-01	Log crib bank erosion, orphaned.	Y	Y	Removed from topography, assumed to fail
					Driveway Bridge 1	50	Functioning as intended	DHL-FP-06	Left bank erosion protection, not orphaned.	Y	Y	Removed from topography, assumed to fail
					Bifurcation Bridge	30	Functioning as intended	DHL-FP-07	Right bank erosion protection, orphaned.	Y	Y	Removed from topography, assumed to fail
					Duhamel Highway West Bridge	60	Functioning as intended	DHL-FP-08	Left bank dike, not orphaned.	Y	Y	Removed from topography, assumed to fail
					Lower 6 Mile Rd West Bridge	25	Functioning as intended	DHL-FP-09	Right bank dike, orphaned.	Y	Y	Removed from topography, assumed to fail
					Duhamel Highway East Bridge	10	Functioning as intended					
					Pedestrian Bridge 1	25	Functioning as intended					
					Driveway 2	30	Functioning as intended					
					Lower 6 Mile Rd Bridge East	30	Functioning as intended					
					Pedestrian Bridge 2	-	Lightweight bridge, assumed to be washed away when at capacity					
DHL-4b	500	Debris Flood (Type 2)	1.3	66	Old Log Bridge	-	In disrepair, assumed to be washed away when at capacity	DHL-FP-01	Log crib bank erosion, orphaned.	Y	Y	Removed from topography, assumed to fail
					Driveway Bridge 1	50	Functioning as intended	DHL-FP-06	Left bank erosion protection, not orphaned.	Y	Y	Removed from topography, assumed to fail

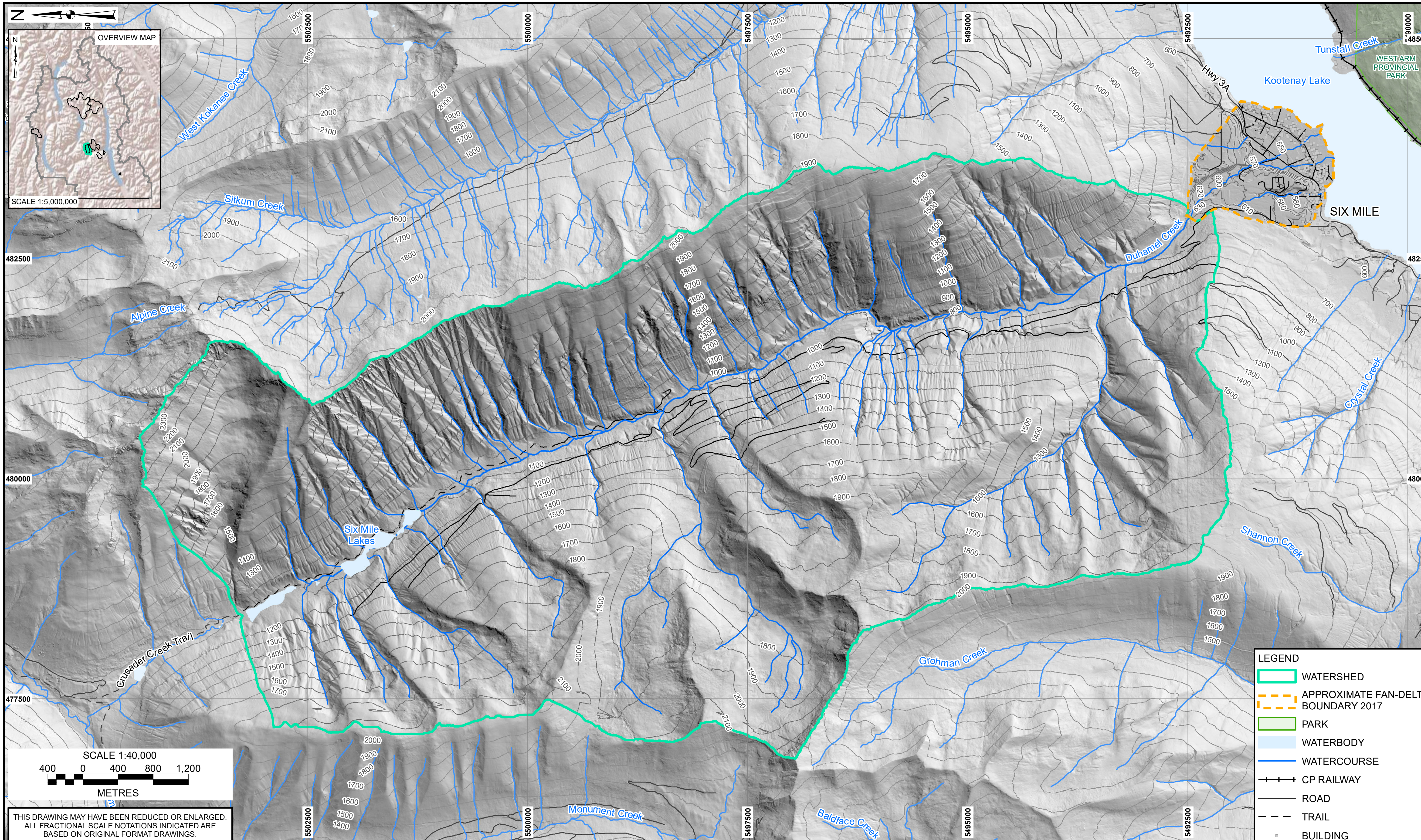
Scenario Name	Return Period (yrs)	Process Type	Bulking Factor	Bulked Peak Discharge (m^3/s)	Conveyance Structures			Flood Protection Structures				
					Name	Estimated Capacity (m^3/s)	Assumption	Name	Type	Bank Erosion Encroaching	τ/τc ≥ 2	Assumption
					Bifurcation Bridge	30	Functioning as intended	DHL-FP-07	Right bank erosion protection, orphaned.	Y	Y	Removed from topography, assumed to fail
					Duhamel Highway West Bridge	60	Functioning as intended	DHL-FP-08	Left bank dike, not orphaned.	Y	Y	Removed from topography, assumed to fail
					Lower 6 Mile Rd West Bridge	25	Over capacity, blocked	DHL-FP-09	Right bank dike, orphaned.	Y	Y	Removed from topography, assumed to fail
					Duhamel Highway East Bridge	10	Over capacity, blocked					
					Pedestrian Bridge 1	25	Functioning as intended					
					Driveway Bridge 2	30	Functioning as intended					
					Lower 6 Mile Rd Bridge East	30	Functioning as intended					
					Pedestrian Bridge 2	-	Lightweight bridge, assumed to be washed away when at capacity					
DHL-4c	500	Debris Flood (Type 2)	1.3	66	Old Log Bridge	-	In disrepair, assumed to be washed away when at capacity	DHL-FP-01	Log crib bank erosion, orphaned.	Y	Y	Removed from topography, assumed to fail
					Driveway Bridge 1	50	Functioning as intended	DHL-FP-06	Left bank erosion protection, not orphaned.	Y	Y	Removed from topography, assumed to fail
					Bifurcation Bridge	30	Block east channel	DHL-FP-07	Right bank erosion protection, orphaned.	Y	Y	Removed from topography, assumed to fail
					Duhamel Highway West Bridge	60	Functioning as intended	DHL-FP-08	Left bank dike, not orphaned.	Y	Y	Removed from topography, assumed to fail
					Lower 6 Mile Rd West Bridge	25	Over capacity, blocked	DHL-FP-09	Right bank dike, orphaned.	Y	Y	Removed from topography, assumed to fail
					Duhamel Highway East Bridge	10	Functioning as intended					
					Pedestrian Bridge 1	25	Functioning as intended					

Scenario Name	Return Period (yrs)	Process Type	Bulking Factor	Bulked Peak Discharge (m^3/s)	Conveyance Structures			Flood Protection Structures				
					Name	Estimated Capacity (m^3/s)	Assumption	Name	Type	Bank Erosion Encroaching	τ/τc ≥ 2	Assumption
					Driveway Bridge 2	30	Functioning as intended					
					Lower 6 Mile Rd Bridge East	30	Functioning as intended					
					Pedestrian Bridge 2	-	Lightweight bridge, assumed to be washed away when at capacity					
DHL-4d	500	Debris Flood (Type 2)	1.3	66	Old Log Bridge	-	In disrepair, assumed to be washed away when at capacity	DHL-FP-01	Log crib bank erosion, orphaned.	Y	Y	Removed from topography, assumed to fail
					Driveway Bridge 1	50	Functioning as intended	DHL-FP-06	Left bank erosion protection, not orphaned.	Y	Y	Removed from topography, assumed to fail
					Bifurcation Bridge	30	Block west channel	DHL-FP-07	Right bank erosion protection, orphaned.	Y	Y	Removed from topography, assumed to fail
					Duhamel Highway West Bridge	60	Functioning as intended	DHL-FP-08	Left bank dike, not orphaned.	Y	Y	Removed from topography, assumed to fail
					Lower 6 Mile Rd West Bridge	25	Functioning as intended	DHL-FP-09	Right bank dike, orphaned.	Y	Y	Removed from topography, assumed to fail
					Duhamel Highway East Bridge	10	Over capacity, blocked					
					Pedestrian Bridge 1	25	Functioning as intended					
					Driveway Bridge 2	30	Functioning as intended					
					Lower 6 Mile Rd Bridge East	30	Functioning as intended					
					Pedestrian Bridge 2	-	Lightweight bridge, assumed to be washed away when at capacity					

Note:

1. Estimated bridge capacity was derived from field and lidar measurements as a preliminary screening tool for model scenario development. They should not be treated as design capacity values.

DRAWINGS



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 - DUHAMEL 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. RAILWAY DATA FROM GEOBASE NATIONAL RAILWAY NETWORK.
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BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT: REGIONAL DISTRICT CENTRAL KOOTENAY

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: DUHAMEL CREEK SITE LOCATION MAP

PROJECT No.: 0268007

DWG No: 01

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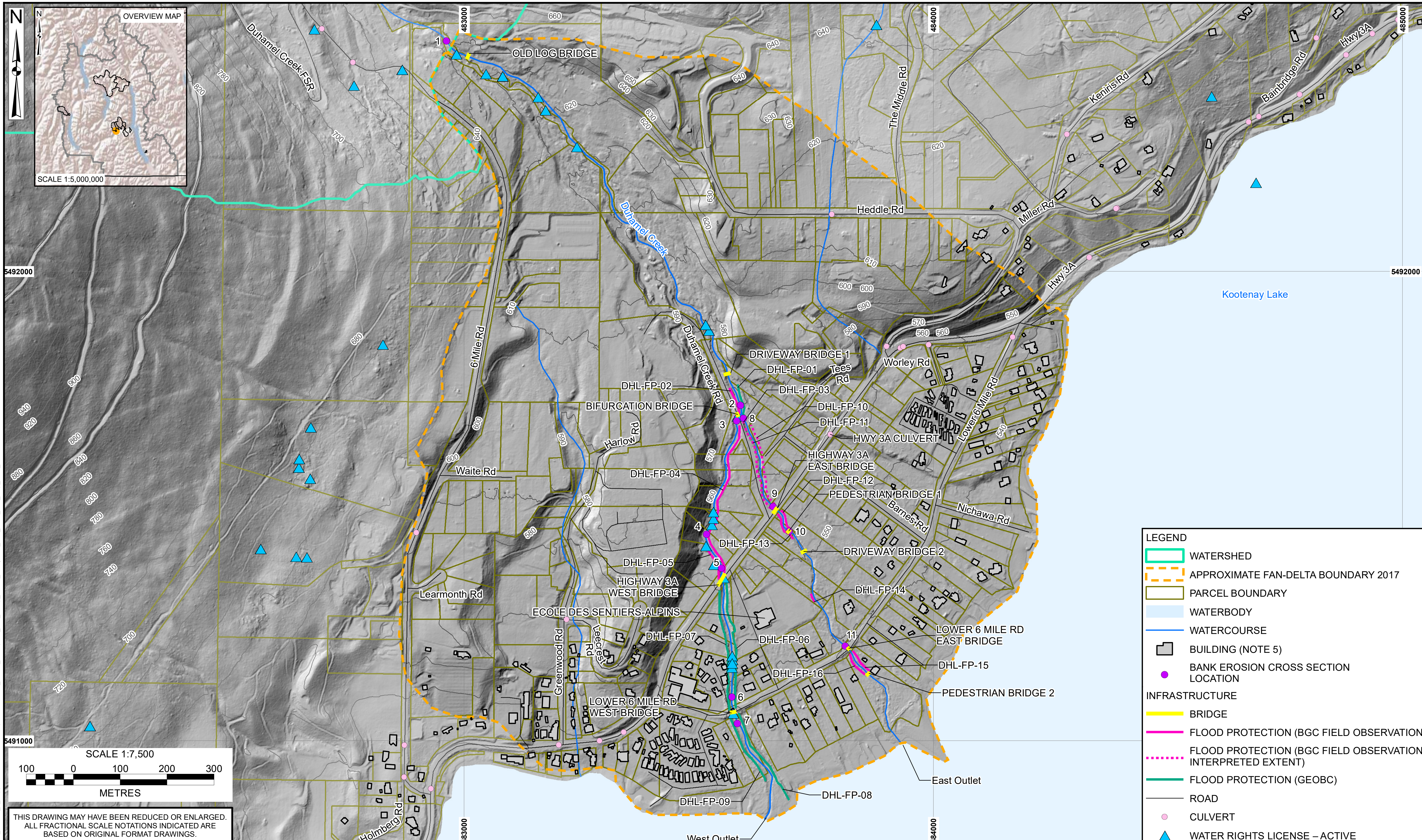

NOTES:

1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
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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. FLOOD PROTECTION DATA FROM GEOBC AND BGC FIELD OBSERVATIONS (APPROXIMATE). ROADS DATA FROM BC DIGITAL ROAD ATLAS. WATER RIGHTS LICENSE DATA FROM GEOBC. PARCELS FROM PARCELMAP BC.
6. PROJECTION IS NAD 1983 UTM ZONE 11N.
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CLIENT:

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: DUHAMEL CREEK FAN-DELTA SITE MAP

PROJECT No.: 0268007

DWG No: 02A

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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 REPORT TITLED "RDCK FLOODPLAIN AND STEEP CREEK STUDY - DUHAMEL 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. FLOOD PROTECTION DATA FROM GEOBC AND BGC FIELD OBSERVATIONS (APPROXIMATE). ROADS DATA FROM BC DIGITAL ROAD ATLAS. WATER RIGHTS LICENSE DATA FROM GEOBC. PARCELS FROM PARCELMAP BC.
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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DATE:	MAR 2020
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CHECKED:	JJHP
APPROVED:	HW

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

PROJECT:
RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE:
DUHAMEL CREEK
FAN-DELTA SITE MAP

PROJECT No.:	DWG No:
0268007	02B

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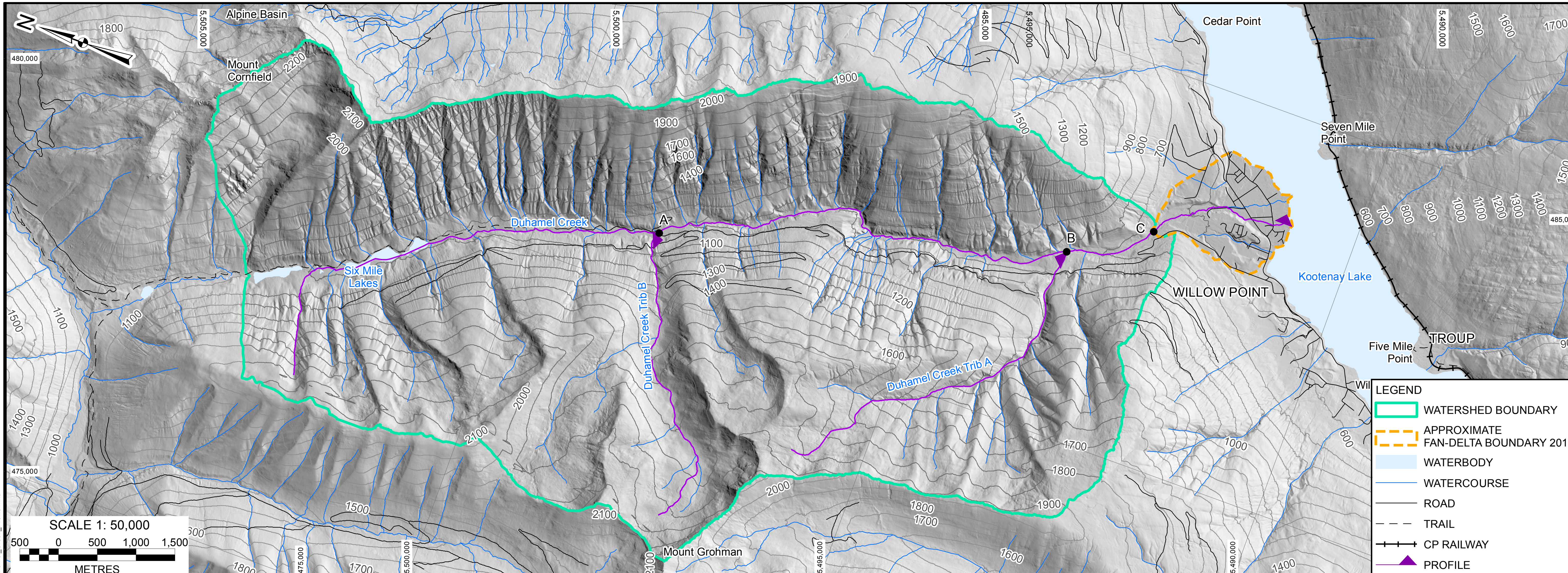

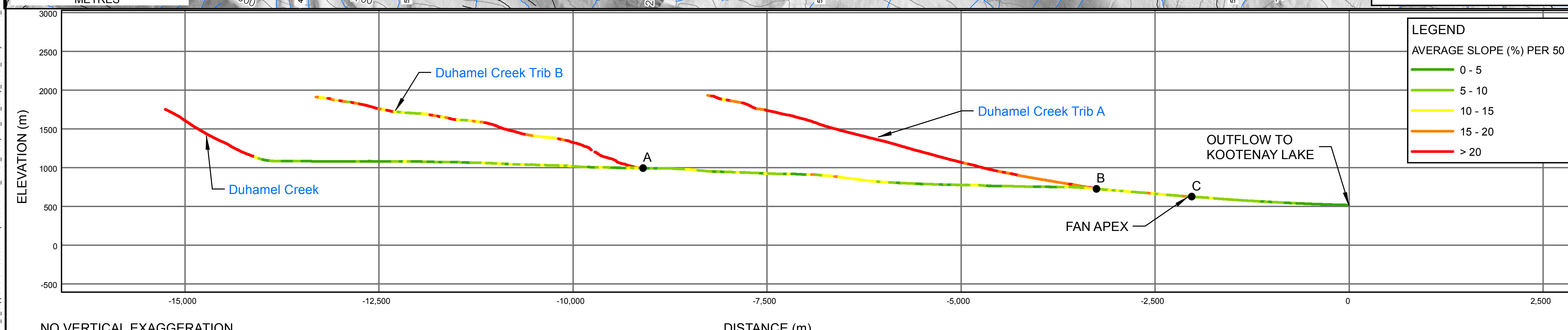

NOTES:

1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "RDCK FLOODPLAIN AND STEEP CREEK STUDY – DUHAMEL CREEK", AND DATED MARCH 2020.
3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY RDCK DATED 2017. CONTOUR INTERVAL IS 20m.
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. RAILWAY DATA FROM GEOBASE NATIONAL RAILWAY NETWORK.
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 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:	HW

BGC ENGINEERING INC.
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CLIENT:

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: DUHAMEL CREEK PROFILE

PROJECT No.: 0268007

DWG No: 03

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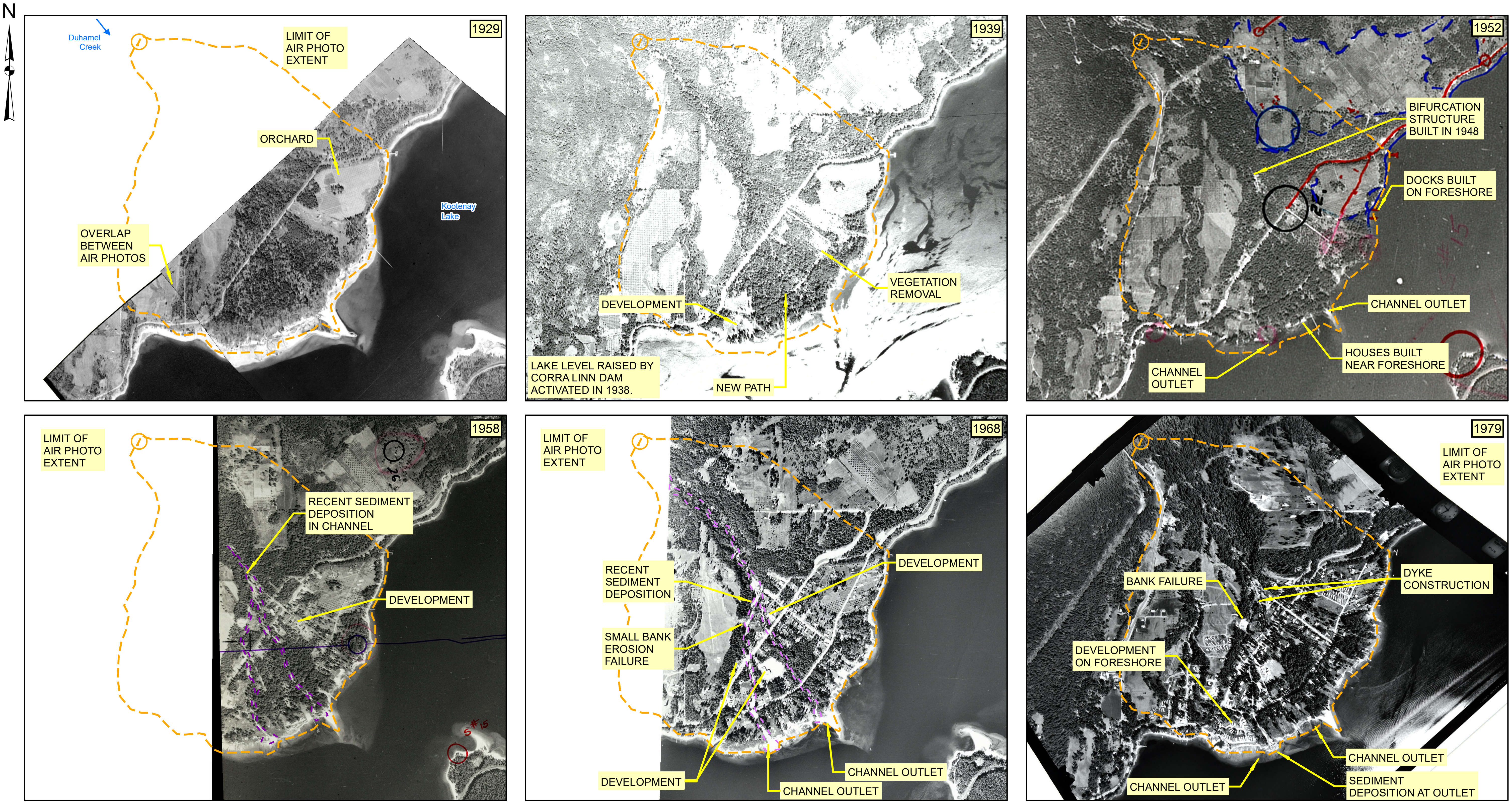

SCALE 1:20,000

200 0 200 400 600

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
- FAN APEX
- APPROXIMATE EXTENT OF 1956 EVENT
- APPROXIMATE EXTENT OF 1968 EVENT

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 - DUHAMEL 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 YEARS 1952 AND 1958 WERE MARKED ON PHYSICAL COPIES PRIOR TO BGC'S AIR PHOTO INTERPRETATION.
6. LAKE LEVEL RAISED BY CORRA LINN DAM ACTIVATED IN 1938.
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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DATE:	MAR 2020
DRAWN:	MIB, LL
CHECKED:	JJHP, LCH
APPROVED:	MJ

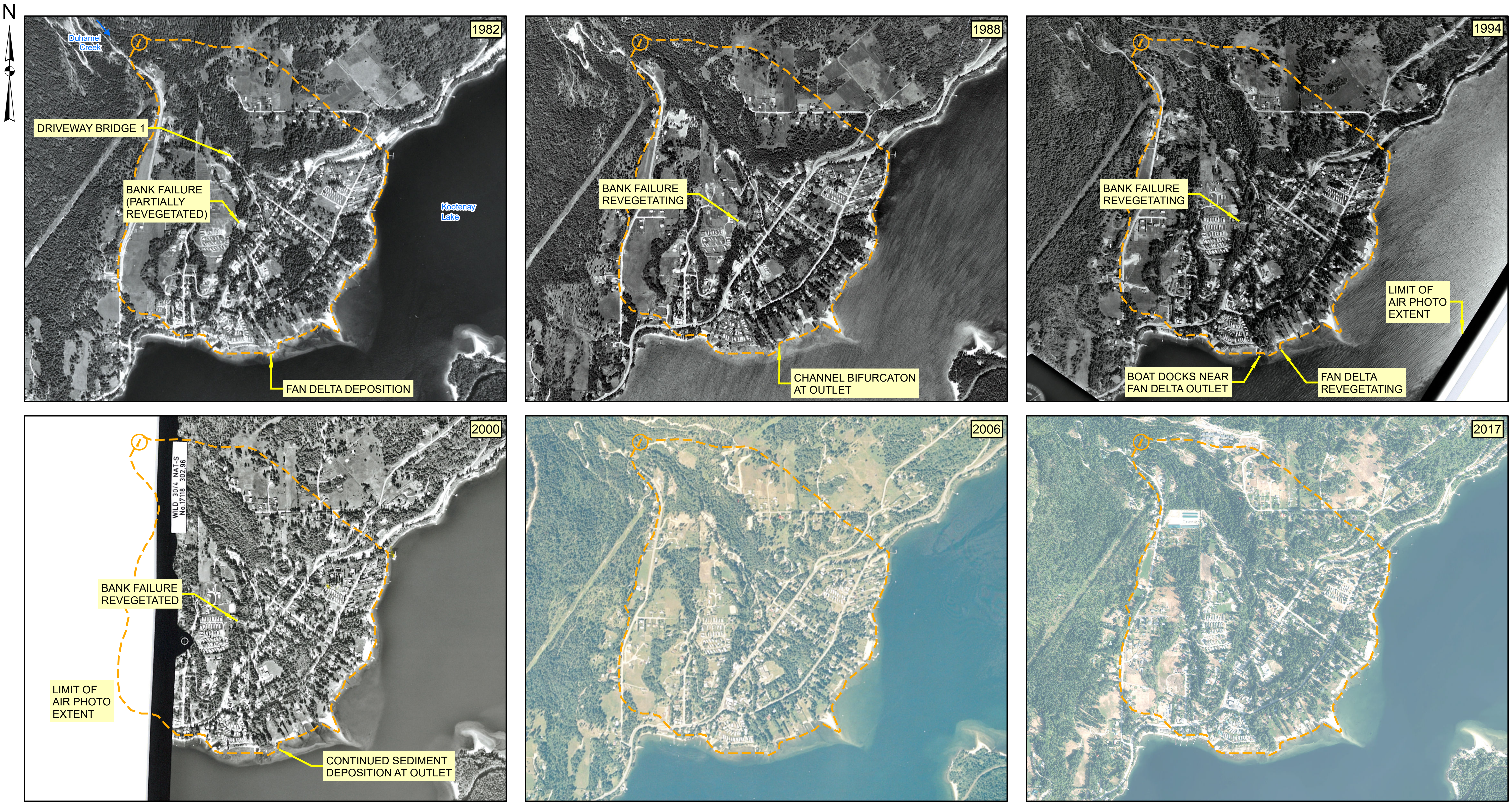
BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

PROJECT:
RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE:
DUHAMEL CREEK
AIR PHOTO COMPARISON

PROJECT No.:	DWG No:
0268007	04A



SCALE 1:20,000

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METRES

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

DRAFT

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 - DUHAMEL 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 PHOTOS WITH NO LABELS INDICATE NO MAJOR DEVELOPMENT OR CHANGE IN CHANNEL FEATURES COMPARED TO PREVIOUS AIR PHOTO.
6. COORDINATE SYSTEM IS UTM ZONE 11 NAD 1983. VERTICAL DATUM IS UNKNOWN.
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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DATE:	MAR 2020
DRAWN:	MIB, LL
CHECKED:	JJHP, LCH
APPROVED:	HW

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: DUHAMEL CREEK AIR PHOTO COMPARISON

PROJECT No.: 0268007

DWG No: 04B

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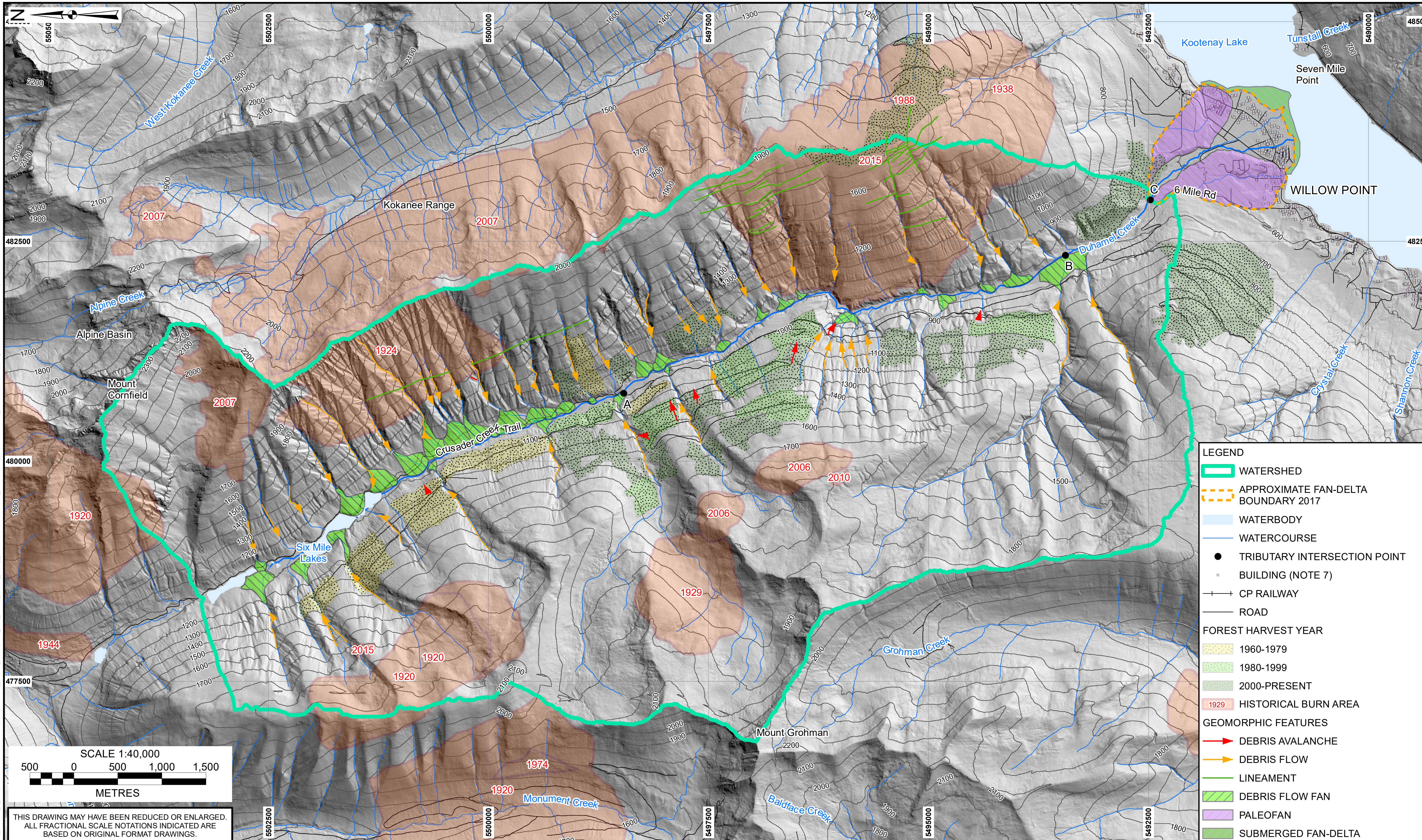

NOTES:

1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "RDCK FLOODPLAIN AND STEEP CREEK STUDY - DUHAMEL 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.
8. PROJECTION IS NAD 1983 UTM ZONE 11N.
9. 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:	HW

BGC ENGINEERING INC.
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CLIENT: REGIONAL DISTRICT CENTRAL KOOTENAY

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: DUHAMEL CREEK WATERSHED GEOMORPHOLOGY

PROJECT No.: 0268007

DWG No.: 05

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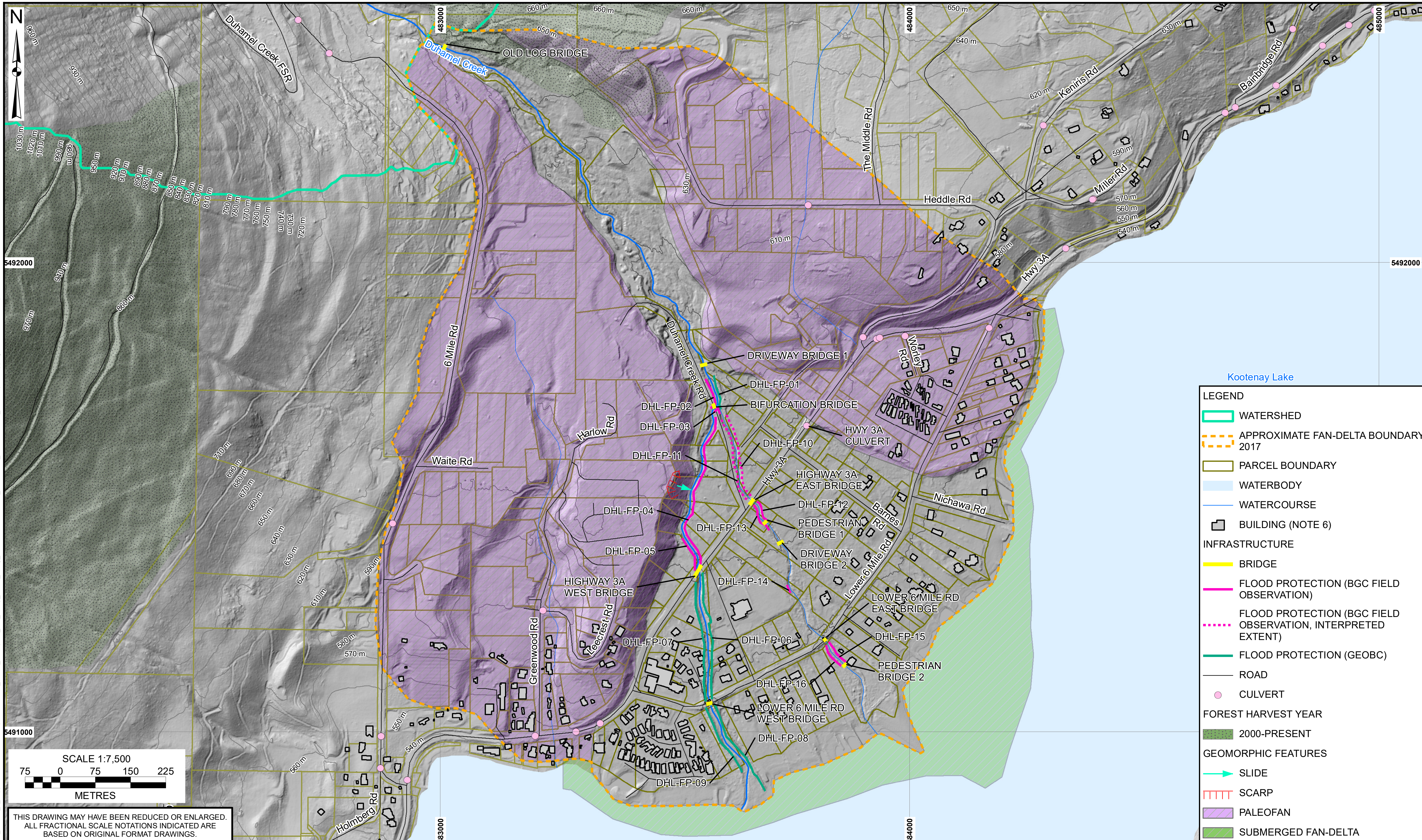

NOTES:
1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "RDCK FLOODPLAIN AND STEEP CREEK STUDY - DUHAMEL CREEK", AND DATED MARCH 2020.
3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY RDCK DATED 2017. CONTOUR INTERVAL IS 10m.
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.
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.
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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BGC ENGINEERING INC.
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CLIENT:

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: DUHAMEL CREEK FAN-DELTA GEOMORPHOLOGY

PROJECT No.: 0268007

DWG No: 06

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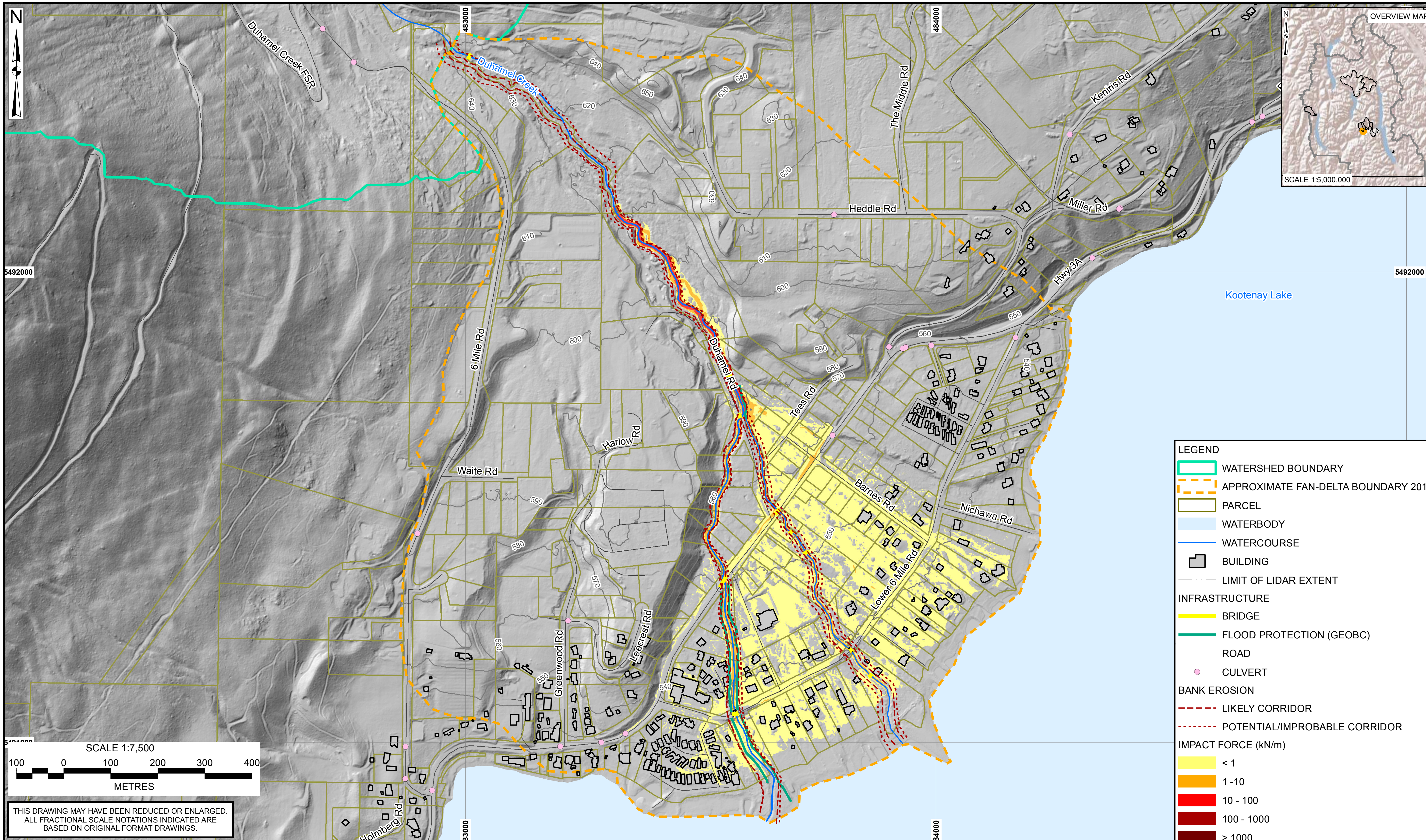

NOTES:

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 - DUHAMEL 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. MODELLED BANK EROSION IS SHOWN AS A LIKELY CORRIDOR (DIVIDED BETWEEN CHANNEL BANKS BASED ON CHANNEL GEOMETRY) AND POTENTIAL/IMPROBABLE CORRDIOR (APPLIED EQUALLY TO BOTH BANKS).
5. BUILDING FOOTPRINTS DIGITIZED BY BGC. ROADS DATA FROM BC DIGITAL ROAD ATLAS. BANK PROTECTION FROM GEOBC AND BGC FIELD OBSERVATIONS. PARCEL MAP FROM PARCELMAP BC.
6. SCENARIO MAP SHOWS CLEARWATER IMPACT FORCE BASED ON HEC-RAS 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.
7. THIS MAP REPRESENTS A SNAPSHOT IN TIME. FUTURE CHANGES (DEVELOPMENT, DEBRIS FLOOD MITIGATION, GEOHAZARD EVENTS) MAY WARRANT RE-DRAWING OF CERTAIN AREAS.
8. PROJECTION IS NAD 1983 UTM ZONE 11N. VERTICAL DATUM IS UNKNOWN.
9. 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:	LCH
APPROVED:	HW

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT: REGIONAL DISTRICT CENTRAL KOOTENAY

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: DUHAMEL CREEK 200 YEAR MODEL SCENARIO DHL-3a

PROJECT No.: 0268007

DWG No: 07

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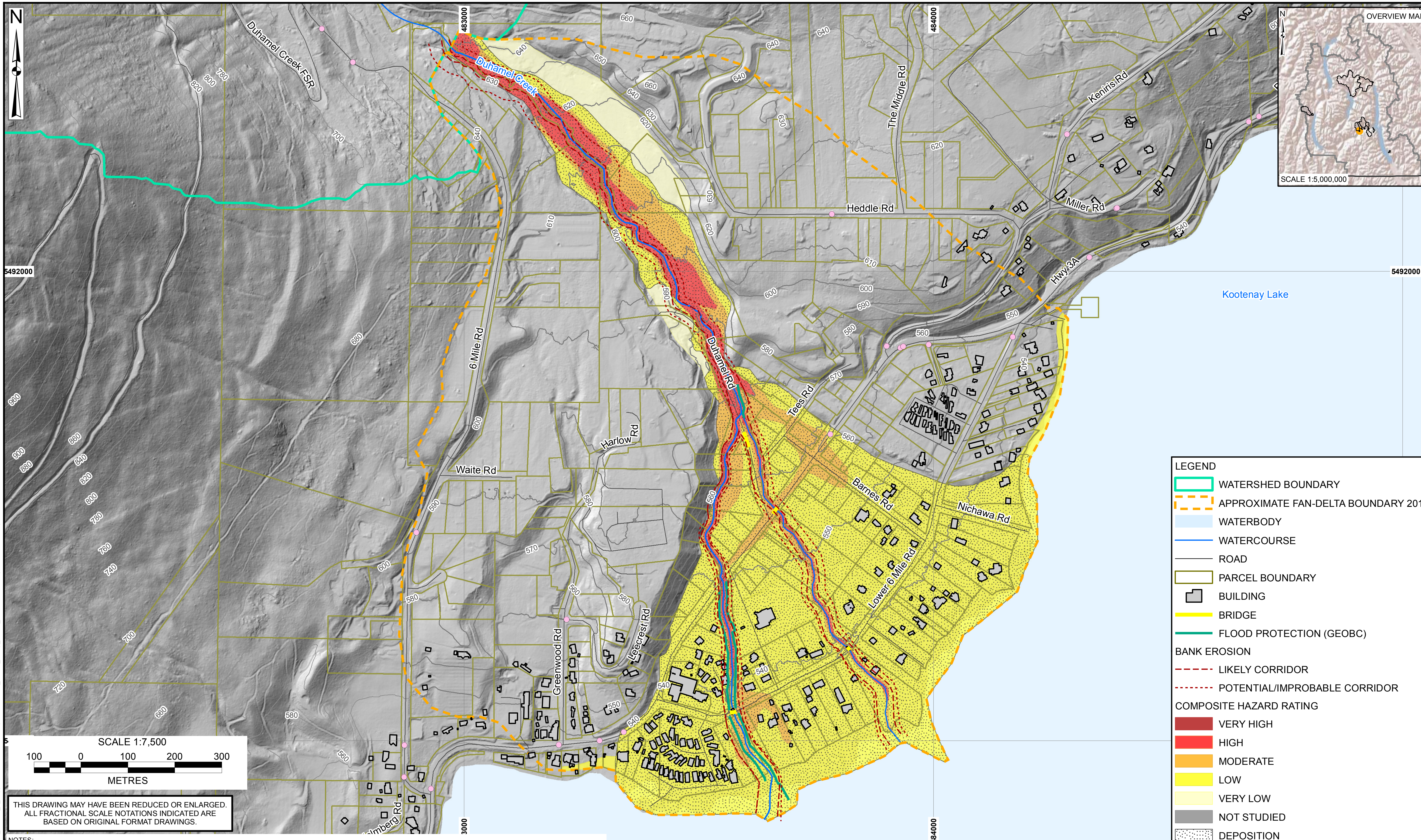

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NOTES:
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3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY RDCK, DATED 2017. CONTOUR INTERVAL IS 20 m AND 10 m ON FAN. THE FAN BOUNDARY AS DRAWN IS APPROXIMATE AND DELINEATES THE LANDFORM BASED ON LIDAR DATED 2017.
4. COMPOSITE HAZARD RATINGS PORTRAYED ON THIS DRAWING ONLY REPRESENT HAZARDS STUDIED WITHIN THE FAN-DELTA BOUNDARY.
5. SURFACE FLOW ON PALEO SURFACES WITHIN THE FAN-DELTA BOUNDARY HAVE NOT BEEN ASSESSED IN THIS STUDY.
6. MODELLED BANK EROSION IS SHOWN AS A LIKELY CORRIDOR (DIVIDED BETWEEN CHANNEL BANKS BASED ON CHANNEL GEOMETRY) AND POTENTIAL/IMPROBABLE CORRDIOR (APPLIED EQUALLY TO BOTH BANKS).
7. THIS MAP REPRESENTS A SNAPSHOT IN TIME. FUTURE CHANGES (DEVELOPMENT, DEBRIS FLOOD MITIGATION, GEOHAZARD EVENTS) MAY WARRANT RE-DRAWING OF CERTAIN AREAS.
8. BUILDING FOOTPRINTS DIGITIZED BY BGC. ROADS DATA FROM BC DIGITAL ROAD ATLAS. BANK PROTECTION FROM GEOBC AND BGC FIELD OBSERVATIONS. PARCEL MAP FROM PARCELMAP BC
9: PROJECTION IS NAD 1983 UTM ZONE 11N.
10. 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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DATE:	MAR 2020
DRAWN:	STT, LL, MIB
CHECKED:	LCH
APPROVED:	HW

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CLIENT:

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: DUHAMEL CREEK COMPOSITE HAZARD RATING MAP

PROJECT No.:	DWG No:
0268007	08

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