RDCK FLOODPLAIN AND STEEP CREEK STUDY

Procter Creek

Final
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TABLE OF REVISIONS

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EXECUTIVE SUMMARY

This report and its appendices provide a detailed hydrogeomorphic hazard assessment of Procter Creek. Procter Creek was chosen as a high priority creek amongst hundreds in the Regional District of Central Kootenay from a risk perspective because of its comparatively high hazards and estimated consequences from hydrogeomorphic events (debris flows and debris floods). 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 Procter Creek fan-delta. This work is the foundation for future quantitative risk assessments and/or conceptual level through to detailed design and construction of mitigation measures, if required.

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

Procter Creek is considered a hybrid (i.e., subject to debris floods and debris flows) where debris flows are considered most likely to occur following wildfires of moderate and/or high burn severity. While such wildfires also occur on the flood and debris-flood prone creeks in the RDCK, the mainstem channels of the other creeks are not sufficiently steep to convey debris flows downstream to or past the fan apex and thus affect the hazard on the fan-delta. This makes Procter Creek a particularly dangerous creek as no debris flows have been recorded in the recent past (~ 80 years) and the last wildfire occurred in 1936 thus well outside most residents' memory. The danger lies within the relative quiescence of the creek which has led to relatively unencumbered development and the perception that this creek is relatively 'harmless'. However, in BGC's opinion, Procter Creek can deliver potentially destructive debris flows into the inhabited areas.

To assess the hazards at Procter Creek, multiple hazard scenarios were developed for specific event return periods (20-, 50-, 200-, 500-year). The scenarios included bulking of flow to allow for higher organic and mineral sediment concentrations and debris flows at the 200-year and 500-year return periods.

Two numerical hydro-dynamic models (HEC-RAS 2D and FLO-2D) were employed to simulate debris flood and debris flow hazard scenarios on the fan-delta. The reason for using multiple models was to simulate a range of results as both models have their distinct advantages and shortfalls. BGC also estimated bank erosion from a physically based model for the 20- 50-, 200- and 500-year debris flood probabilities. Table E-1 provides key observations derived from the numerical modelling.

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

Process	Key Observations
Clearwater and debris-flood inundation (HEC-RAS model results for 20- and 50-year return periods)	• Both return periods produce inundation of a similar area and are summarized together in the following points. ○ Approximately 115 m upstream of the water intake weir, overbank flow occurs on both the left and right bank, with water flowing in historic channels or depressions. Much of the flow re-enters the main channel after flowing through a wooded area. ○ The water intake weir is overtopped, and a portion of the flows spills down the western side of the fan (western channel). Another portion spills east of the main channel. ○ The main channel has an avulsion at the Woodside culvert causing sheet flow to run north along Second Avenue, overtop Harrop Procter Road and flow west along the railway ditch. ○ Flow from the main channel will be diverted east at the Procter Lane culvert and inundate the downstream area within approximately 110 m of the main channel, including several properties on Jones Road. ○ The western channel is identified as the creek alignment on many maps (e.g., iMapBC), although the main channel currently flows to the center-east of the fan (See Section 4.2.1). Shallow flow spreads over Third Ave, Fourth Ave, Woodside Ave and the properties adjacent. The water flows towards Harrop-Procter Road and continues west along the ditch towards a culvert at the edge of the fan. Assuming this culvert is blocked with debris, the water will pool to a depth exceeding 1 m and overflow the road to then pool upstream of the railway. • The 50-year return period overtops the railway approximately 200 m west of Procter Creek inundating the waterfront properties along Mawdsley Lane and Jones Road with maximum water depths <0.3 m. ○ The water pooling on the upstream side of the railway could also cause the embankment to fail, which increases the maximum depth to 0.5 m in a similar inundation area along Mawdsley Lane and Jones Road. • Minor sedimentation is expected at avulsion points with flow depths of a few centimetres in unconfined sloping sections of the fan. Closed depressions will likely be filled with sediment from avulsing flows.

Process	Key Observations
Debris flow inundation (FLO-2D model results for 200- and 500-year return periods)	• The highest impacts due to sedimentation are expected from debris flows at the 200-year and 500-year return periods. • Debris flows at the 200-year and 500-year return periods are very likely to impact the entire upper fan with up to 5 to 6 m of deposition near the fan apex reducing to around 2 to 3 m at the elevation of the western portions of Woodside Avenue. • Flow velocities of debris flows will range between 6 to 8 m/s near the fan apex, reducing to 2 to 3 m/s by the time the debris flow reaches Woodside Avenue. Avulsing flow will likely decelerate quickly as it thins towards the margins with flow velocities being reduced to 1 m/s.
Bank Erosion	• In the last 90 years, less than 10 m total bank erosion has occurred. This may be partially attributable to bank reinforcement at various locations. • Predicted bank erosion at different flood return periods ranges between 4 m (20-year) and 33 m (500-year). Bank erosion potential is generally consistent from the fan apex to outlet for the 20 and 50-year event. The 200 and 500-year events experience the most erosion approximately 75 to 150 m south of Second Ave and near the outlet. • All unprotected crossing locations (culvert or bridges) are likely to be subject to bank erosion and can be isolated, eroded and partially collapse or being bypassed on either side.
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 Procter Creek will build up sediment and avulse into existing properties on either side of the creek channel north of Jones Road. • Only four debris flow scenarios were simulated (a low and high discharge scenario for the 200-year and 500-year return periods events). A large variety of other outcomes are possible dictated by different flow rheologies, or avulsion scenarios. To support a quantitative risk assessment, various other flow scenarios would need to be modelled. • It is unknown whether the railway embankment will survive debris-flow impact. In case of embankment loss, the flow behaviour will likely deviate from what has been modelled, potentially resulting in different areas inundated and at different depths.

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

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

The composite hazard rating map combines all hazard scenarios into one map and incorporates the respective 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 of the hazard ratings is attributed to specific land use prescriptions, covenants, bylaws or other limiting clauses for both existing and proposed development. The categories range from 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 Procter Creek 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 mid to distal Procter Creek fan-delta is subject to low hazards. The upper fan downstream to approximately Woodside Ave is subject to moderate to high hazards. Very high hazards are concentrated in the Procter Creek channel in the upper fan. Downstream of Woodside Ave, moderate hazards flank the channel to the Procter Creek outlet.

A review of the NHC/Thurber (1990) study which was a detailed hazard and risk assessment of Procter and other creeks in the RDCK, BGC concludes that the hazards may be somewhat higher than those estimated by NHC/Thurber as determined through BGC's assessment. This is markedly different from all other creeks where BGC assessed hazards being lower than those evaluated by NHC/Thurber. While 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, they appear to have captured the hazards and risk associated with debris flows in the upper fan.

To reduce the hazards and associated risks of debris flows on Procter Creek, a large debris basin would have to be constructed at the fan-delta apex. If this turns out to be financially infeasible or if the design event were chosen to be debris floods, channel works downstream of the fan-delta apex, bridge and culvert replacements are advisable as the creek is very constrained in its current bed and subject to avulsions.

Some uncertainties persist in this study. As with all hazard assessments and corresponding maps, they constitute a snapshot in time. Re-assessment and/or re-modelling may be warranted due to significant alterations of the fan-delta surface topography or infrastructure, such as future fan developments, debris floods, formation or reactivation of existing landslides in the watershed that could impound Procter Creek, bridge re-design or alteration to any fan infrastructure. BGC's analysis does not include breaches of Harrop Procter Road or the CP Railway embankment due to retrogressive erosion or overtopping associated with hydrogeomorphic events. Furthermore, the assumptions made on changes in runoff due to climate change and sediment bulking, while systematic and well-reasoned, will likely need to be updated occasionally as scientific understanding evolves. However, since debris flows dominate the hazard at Procter Creek, changes to clearwater flood behaviour will not significantly change the overall hazard on the fan-delta.

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

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

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1. INTRODUCTION

1.1. Summary

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

Table 1-1. List of study areas.

<table>
<tr><th>Site Classification</th><th>Geohazard Process</th><th>Hazard Code</th><th>Jurisdiction</th><th>Name</th></tr>
<tr><td rowspan="6">Floodplain</td><td rowspan="6">Clearwater Flood</td><td>340</td><td>Village of Salmo</td><td>Salmo River</td></tr>
<tr><td>372</td><td>Village of Slocan</td><td>Slocan River</td></tr>
<tr><td>393</td><td>Town of Creston</td><td>Goat River</td></tr>
<tr><td>408</td><td>RDCK Electoral Area A</td><td>Crawford Creek</td></tr>
<tr><td>375</td><td>RDCK Electoral Area K</td><td>Burton Creek</td></tr>
<tr><td>423</td><td>Village of Kaslo</td><td>Kaslo River</td></tr>
<tr><td rowspan="10">Steep Creek</td><td rowspan="7">Debris Flood</td><td>212</td><td>RDCK Electoral Area F</td><td>Duhamel Creek</td></tr>
<tr><td>252</td><td>RDCK Electoral Area F</td><td>Kokanee Creek</td></tr>
<tr><td>248</td><td>RDCK Electoral Area D</td><td>Cooper Creek</td></tr>
<tr><td>137</td><td>RDCK Electoral Area H</td><td>Wilson Creek</td></tr>
<tr><td>242</td><td>RDCK Electoral Area E</td><td>Harrop Creek</td></tr>
<tr><td>95</td><td>RDCK Electoral Area K</td><td>Eagle Creek</td></tr>
<tr><td>238</td><td>RDCK Electoral Area F</td><td>Sitkum Creek</td></tr>
<tr><td rowspan="2">Hybrid Debris Flood/Debris Flow</td><td>116</td><td>RDCK Electoral Area E</td><td>Procter Creek</td></tr>
<tr><td>251</td><td>RDCK Electoral Area E</td><td>Redfish Creek</td></tr>
<tr><td>Debris Flow</td><td>36</td><td>RDCK Electoral Area A</td><td>Kuskonook Creek</td></tr>
</table>

This report details the approach used by BGC to conduct a detailed steep creek geohazards assessment for Procter Creek, located approximately 27 km northeast of Nelson, BC in Electoral Area E. The site lies on the south side of the West Arm of Kootenay Lake and flows through the unincorporated community of Procter, BC into the lake.

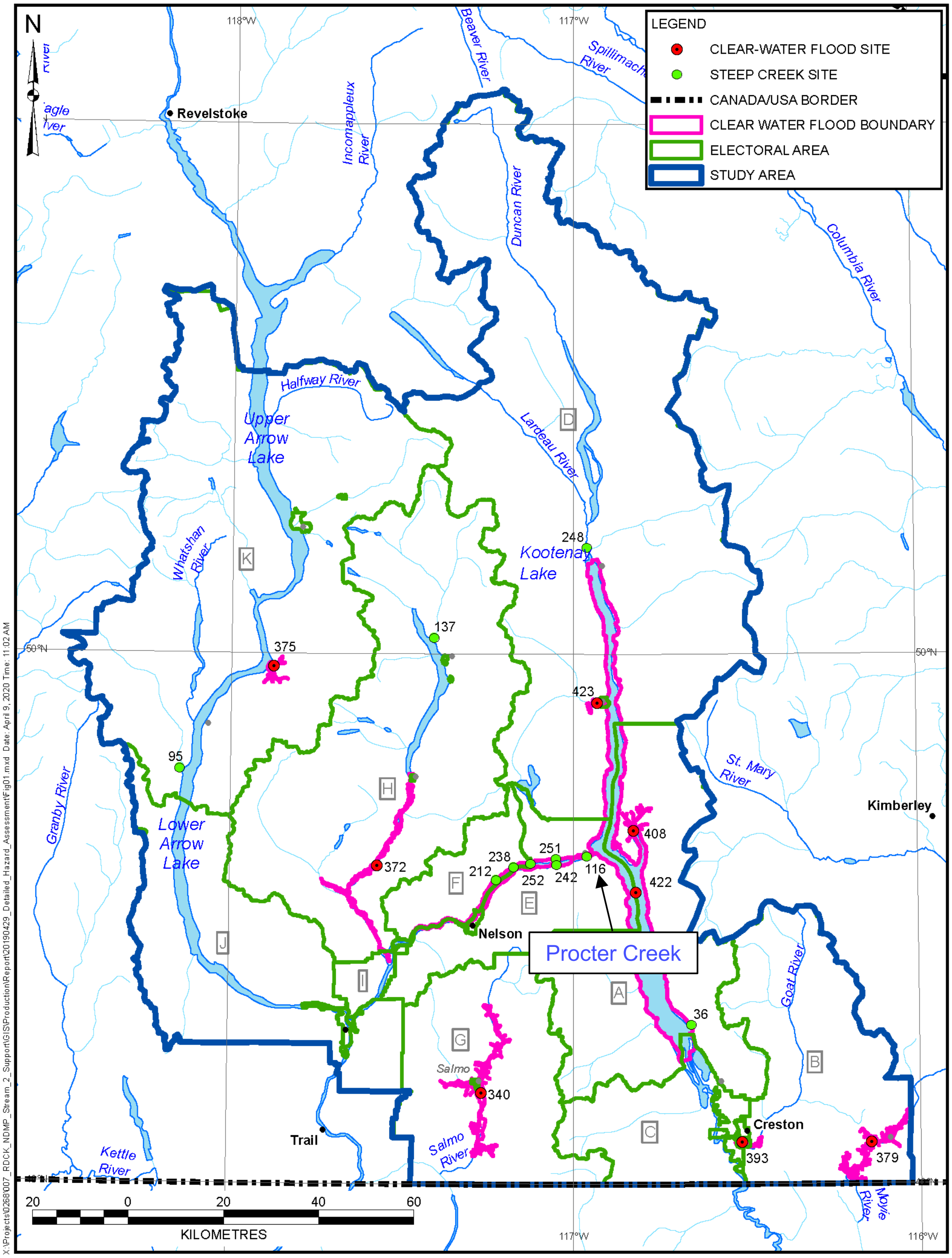

Figure 1-1. Hazard areas prioritized for detailed flood and steep creek mapping. Site labels correspond to hazard identification numbers in Cambio Communities. Procter Creek (No. 116) is labelled on the figure.

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 Procter 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 (BGC, March 31, 2020a) (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* (BGC, March 31, 2020b) (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 is being 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 Procter Creek, the scope of work included:

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

[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.

- 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 fan-delta.

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.

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 range2. 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 the BGC 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
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- Lauren Hutchinson, M.Sc., P.Eng., Intermediate Geotechnical Engineer
- Beatrice Collier-Pandya, B.A.Sc., EIT, Geological Engineer

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

- Matthias Busslinger, M.A.Sc., P.Eng., Senior Geotechnical Engineer
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Table 1-3. Study team.

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5.2	Matthias Jakob	Joseph Gartner; Lauren Hutchinson
5.3	Beatrice Collier-Pandya	Matthias Jakob; Anna Akkerman; Toby Perkins
5.4	Matthias Jakob	Beatrice Collier-Pandya; Lauren Hutchinson
5.5	Gemma Bullard	Sarah Davidson
5.6	Matthias Jakob	Beatrice Collier-Pandya; Lauren Hutchinson
6.1 – 6.2	Beatrice Collier-Pandya; Lauren Hutchinson	Matthias Jakob
6.3	Matthias Jakob; Melissa Hairabedian	Beatrice Collier-Pandya; Joseph Gartner
6.4	Beatrice Collier-Pandya; Gemma Bullard	Matthias Jakob; Toby Perkins; Anna Akkerman
6.5	Gemma Bullard; Midori Telles-Langdon,	Sarah Davidson
6.6	Beatrice Collier-Pandya; Gemma Bullard, Matthias Jakob	Lauren Hutchinson
7	Matthias Jakob	Lauren Hutchinson

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.

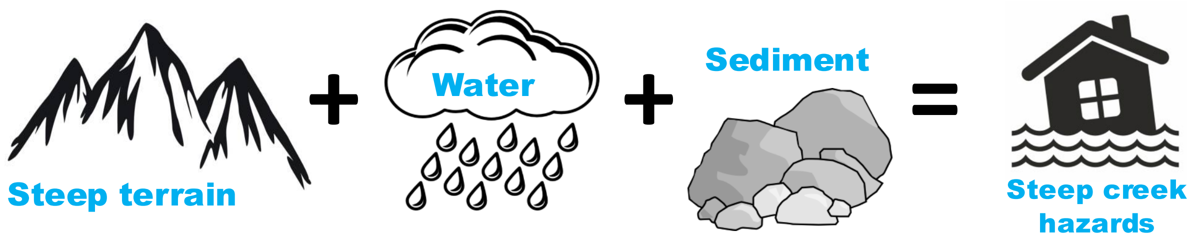


Figure 2-1. Illustration of steep creek hazards.

Steep creek hazards span a continuum of processes from clearwater flood (flood) to debris flow (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 (BGC, March 31, 2020b). Definitions of specific hazard terminology used in this report are provided in Appendix A.

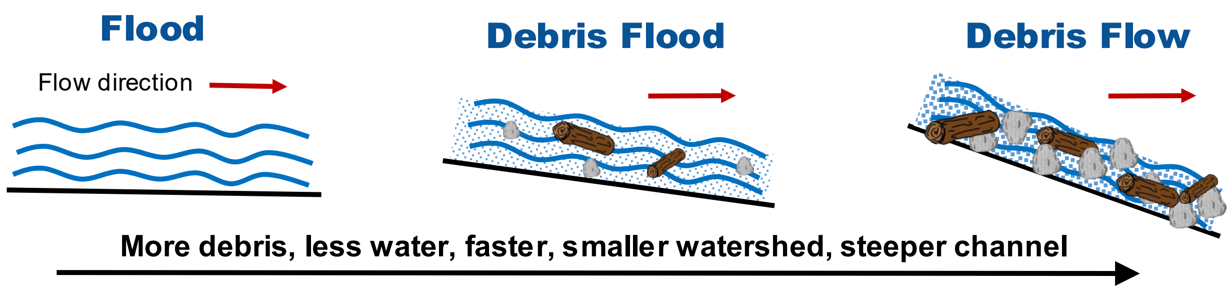


Figure 2-2. Continuum of steep creek hazards.

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) or artificial 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 or 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 a home being eroded at its foundation (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 scouring and stream 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. The latter event is of particular importance for this report because it serves as an example of a watershed steep enough for debris flow triggering and conveyance to the fan apex and beyond and also to highlight the potential for post-wildfire debris flows to be generated in this region. This applies to Procter Creek with a watershed area of 8.3 km^2 and an average channel slope above the fan apex of 23%.

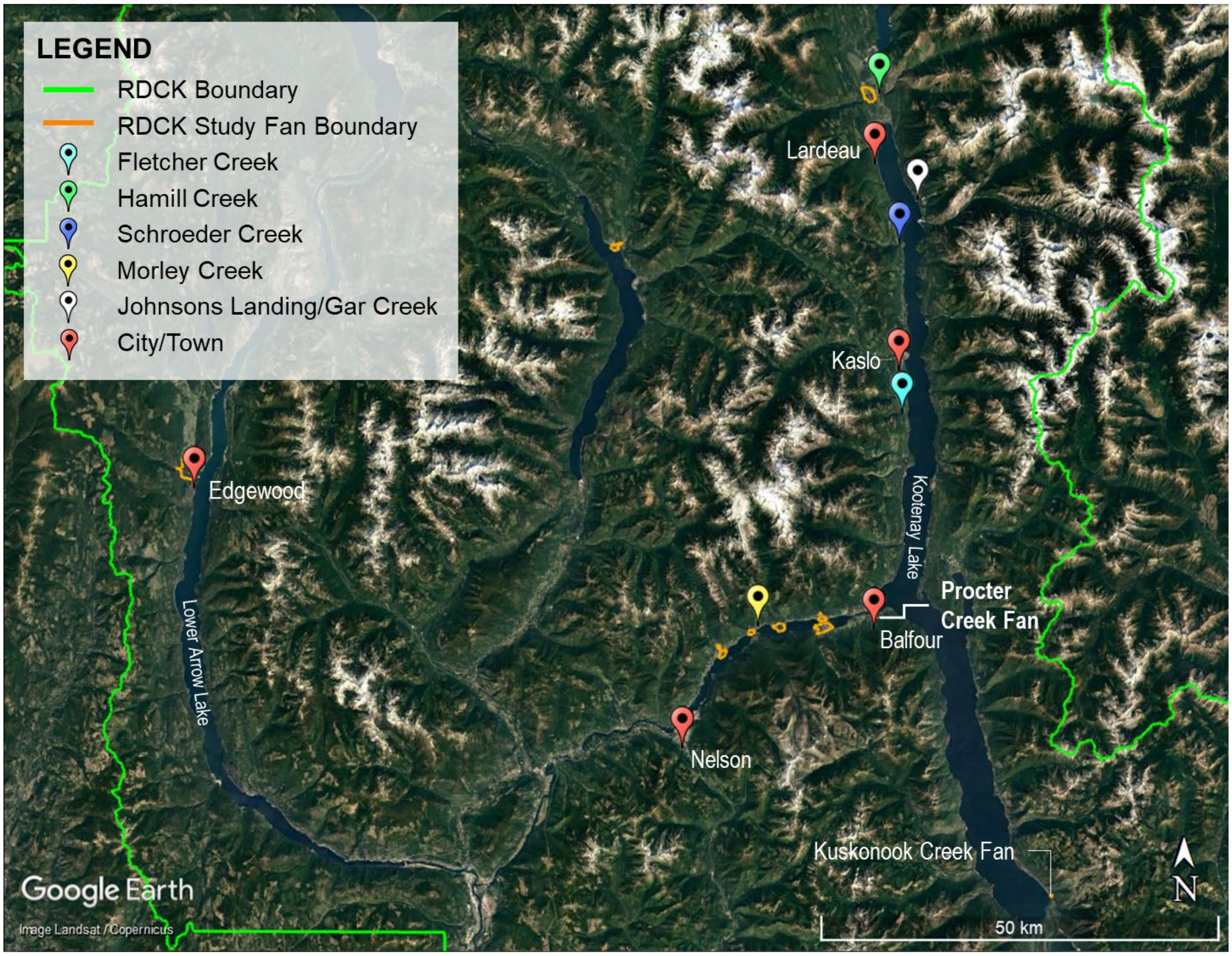


Figure 2-3. Locations of RDCK fans and recent floods, debris flows, and debris floods (Google Earth Pro, 2016).

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.

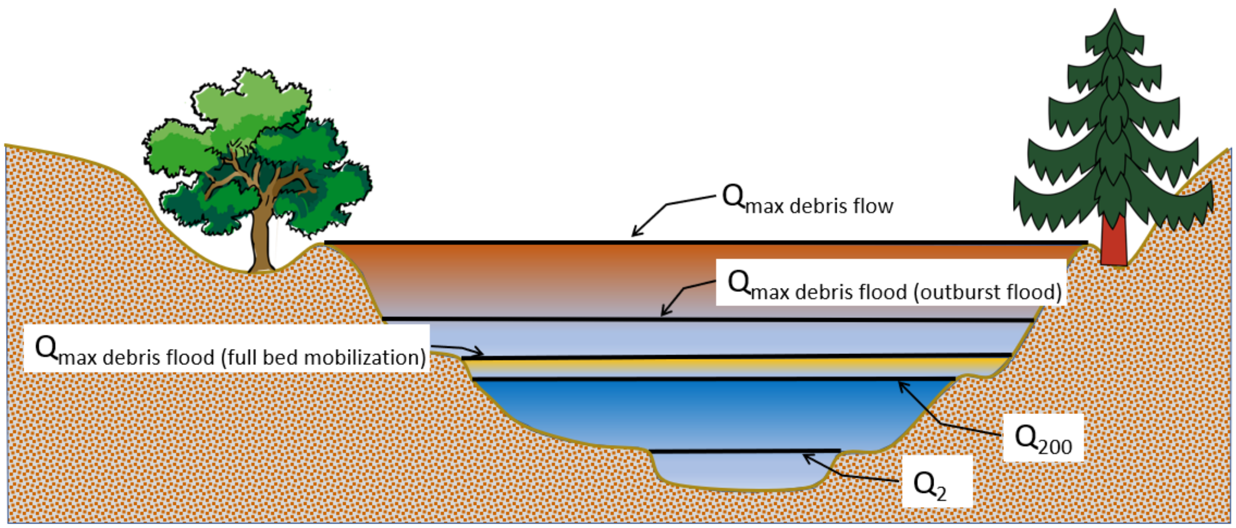


Figure 2-4. Conceptual steep creek channel cross-section showing peak discharge levels for different events. Note that for some outburst floods or debris flows the discharge may well exceed what is shown here.

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 bridge or toppled building redirects flow away from the present channel. The channel an avulsion 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 either as the main channel or in a previous avulsion. These channels differ from paleochannels because those are not expected to experience flows other than by surface runoff or groundwater flow during contemporary events. Avulsions are particularly important on Procter Creek because the creek channel is poorly incised in the surrounding fan surface and crossed by numerous structures that are likely to block leading to avulsions.

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. It is shown in dashed blue lines as avulsions only occur during severe floods. On high resolution topographic maps generated from lidar or detailed field surveys, avulsion channels are 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 hinterland. The hillsides flanking the fan apex are also preferential locations for remnants of so-called 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 it is 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.

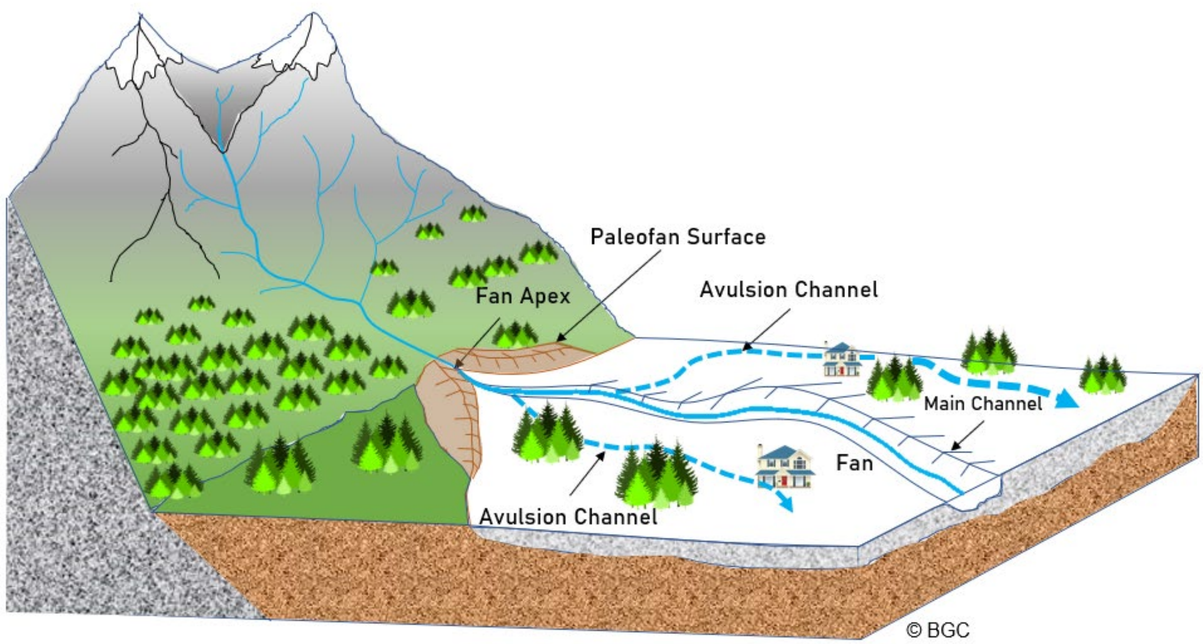


Figure 2-5. Schematic of a steep creek channel with avulsions downstream of the fan apex. Artwork by BGC.

3. STUDY AREA CHARACTERIZATION

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

3.1. Site Visit

Field work on Procter Creek was conducted on July 18, 2019, July 30, 2019 and November 18, 2019 by the following BGC personnel: Carie-Ann Lau, Kris Holm, Matthias Busslinger, Marc Olivier Trottier, Anna Akkerman and Rob Millar. Field work included channel hikes to: observe bank conditions and look for evidence of erosion and protection; locate previous creek alignments; measure grain size diameters (Wolman sampling) near the fan apex and the mouth (Appendix C); collect samples for dendrogeomorphological analysis; and, measure cross-sections at the bridge and other infrastructure crossing locations. The upper watershed was flown by helicopter on July 18, 2019 and numerous photographs were taken for later analysis of major sediment sources to the channel (Appendix B).

A topographic survey was conducted by Explore Surveys Inc. (Explore) during September 2019 and data were collected from the water intake weir near the fan apex to the creek mouth at Kootenay Lake. Cross sections were surveyed approximately every 15 m along the channel and channel details (e.g., thalweg, toe of bank) were surveyed approximately every 2 to 4 m along the channel. Bridges, culverts, weirs and other infrastructure were also surveyed and sketched by Explore.

3.2. Physiography

Procter Creek is located approximately 27 km northeast of Nelson, BC, on the south side of the West Arm of Kootenay Lake, just south of Balfour. The creek flows through the unincorporated community of Procter and into Kootenay Lake. Drawing 01 shows the watershed and fan boundaries, and Table 3-1 summarizes geomorphic parameters of the creek. Drawings 01 and 02A show the watershed and fan-delta boundaries on a shaded, bare earth digital elevation model (DEM) of the watershed, fan-delta, and surrounding terrain created from lidar data. Drawing 02B shows the fan-delta on an orthophoto. Drawing 03 shows a profile along the creek mainstem and tributaries. Representative photographs of the watershed and fan are provided in Appendix B.

The site lies in the Selkirk Mountains, which are a subgroup of the Columbia Mountains in southeastern BC. The watershed falls within the Southern Columbia Mountain ecosection of the Northern Columbia Mountains ecoregion. The ecoregion is drained by the Kootenay River and Kootenay Lake to the east and north, and by small tributaries of the Columbia River to the west (Demarchi, 2011). This ecosection is characterized by rounded mountains with few rugged peaks and serrated ridges compared to mountain ranges to the north (Holland, 1976). Precipitation in the Selkirk Mountains is associated with moisture from coastal areas that arrives from the west, resulting in a strong rainshadow effect at the eastern boundary of the range. Typical vegetation includes Engelmann Spruce and Subalpine Fir trees at lower elevations (from 500 m) and

Western Red Cedar and Western Hemlock in the uplands. The highest ridges and peaks in the Southern Columbia ecosection reach up to approximately 2400 m and are sparsely vegetated.

3.3. Geology

3.3.1. Bedrock Geology

The Procter Creek watershed is underlain by sedimentary rocks (limestone, slate, siltstone, and argillite) of the Millford Formation (Hoy et al., 1994). The formation was later intruded by granitic intrusive rock, which has been referred to as the Proctor Pluton (Moynihan & Pattison, 2013) and underlies most of the watershed. Though no faults have been mapped within the watershed, there are several northeast-trending normal and thrust faults that have been identified within 5 km, including the Midge Creek and Seeman Creek Faults (Moynihan & Pattison, 2013). These lineaments often provide preferential surface flow paths and represent locations of structural weakness. The upper reaches of Procter Creek are also oriented on a northeasterly trend, which suggests that the valley may be partially structurally-controlled. Compared to many other watersheds investigated as part of this broader study, Procter Creek watershed is underlain by more friable and fractured rock around the intrusive margins, which creates the potential for more slope instability in these areas. Moreover, the presence of slate and siltstone allows for finer-grained matrix in possible debris foods and debris flows where they originate from areas in which such rocks daylight. Fine-grained matrix typically results in higher debris flow mobility as long as there is sufficient runoff or pore water pressures in terrain being overrun by the debris flow. The bedrock geology map (Figure 3-1) shows that the vast majority (~ 90%) of the watershed is underlain by intrusive rocks. However, given the very dense vegetation covering the watershed, this conclusion may not be as accurate as in unvegetated areas.

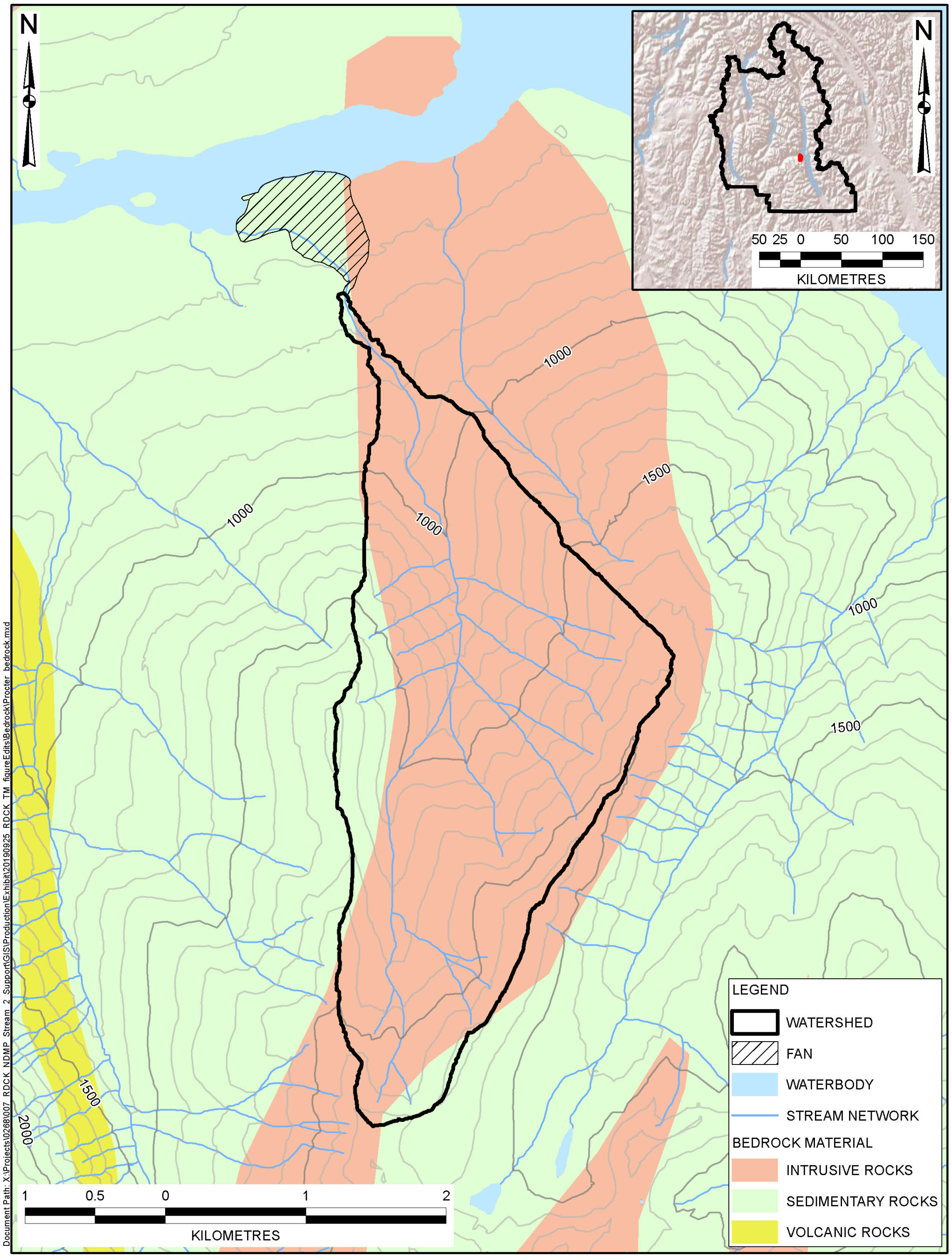


Figure 3-1. Bedrock geology of the Procter Creek watershed (Cui et al., 2017).

3.3.2. Surficial Geology

The surficial geology of the Procter Creek watershed is dominantly colluvium in the valley bottom, with some till and glaciofluvial material in the lower reaches and bedrock outcrops along steep ridges (Jungen, 1980). The abundant colluvium in the watershed indicates that the watershed is likely largely supply-unlimited, which implies a quasi-unlimited amount of sediment available in the watershed to be mobilized during extreme hydroclimatic events, especially in the case of a post-wildfire debris flow.

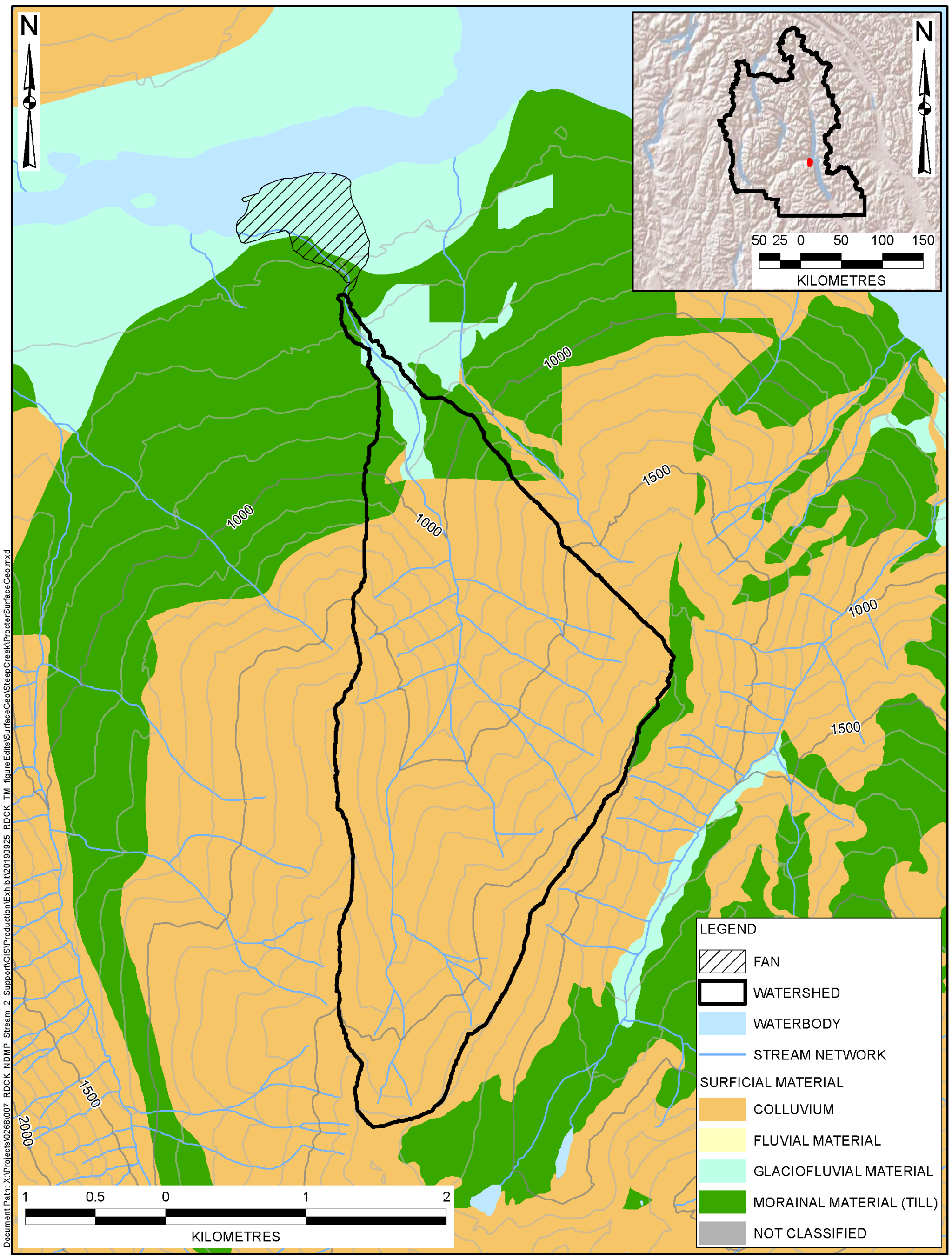


Figure 3-2. Surficial geology of the Procter Creek watershed (from Province of BC, 2016).

3.4. Geomorphology

3.4.1. Watershed

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

The headwaters of Procter Creek are the mountainous slopes of Mount Hartridge (approximate elevation of 2,270 m) at the southern edge of the watershed. The upper portions of the watershed are characterized by cirques plunging into a steep sided, V-shaped valley. The channel is steep above the fan apex (23% gradient on average, Table 3-1) with two main tributaries that join the main channel from the east (Drawing 03). The Procter Creek channel leaves the V-shaped valley approximately 1.5 km upstream of the fan apex.

In the upper watershed, two debris avalanche paths are identified (Drawing 05). In the mid-ranges of the watershed, the tributary channels are debris-flow prone on both the east and west valley walls. On the west-facing valley slopes, there is evidence of two large landslides (Figure 3-3). These landslides measure approximately 4 ha (Figure 3-3A) and 6 ha (Figure 3-3B). As shown, there is no evidence of the landslide deposits extending to the main channel at the valley bottom.

Immediately upstream, and at the fan apex, Procter Creek has incised into paleofan surfaces that are interpreted to be paraglacial terraces, i.e., terraces formed in the time following glaciation in the area. In these cases, it is very difficult to distinguish between paleofan surfaces and fluvio-glacial terraces that likely converge and interfinger with paleofan surfaces. These elevated paleo-surfaces are interpreted not to be affected by the contemporary hydrogeomorphic events investigated herein. Erosion of the terrace slopes forms a potential sediment source during hydrogeomorphic events (clearwater floods, debris floods, debris flows) (Drawing 05).

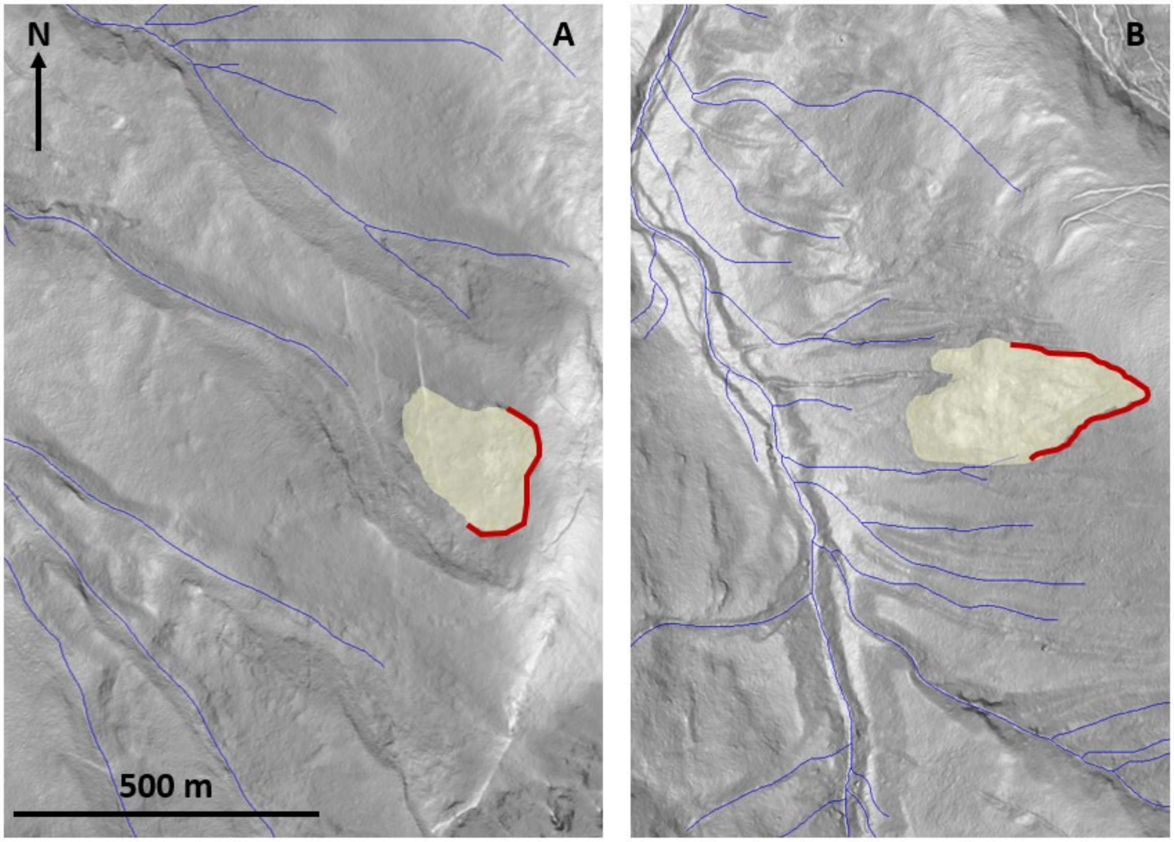


Figure 3-3. Presumed bedrock-controlled rockslides in the upper Procter Creek watershed. A) is located farther upstream, and B) is located closer to the fan apex. Note neither appears to have mobilized into a debris flow, nor connected to the channel system.

The hillslopes of the Procter Creek are densely forested. There is no record of historical logging in the watershed (FLNRORD, n.d.). There has been one recorded forest fire in the watershed in 1936 that burned 8% of the watershed area (FLNRORD, n.d.). Hence, the majority of the watershed is covered by trees aged greater than 84 years of age.

In the lower portion of the Procter between elevation 766 m and 844 m the channel of Procter Creek widens from approximately 10 m to approximately 70 m for a distance of some 400 m and has an average slope of 22% (Figure 3-4). In this reach, the channel loses confinement and it is probable that during debris flows or debris floods sediment deposition would occur here.

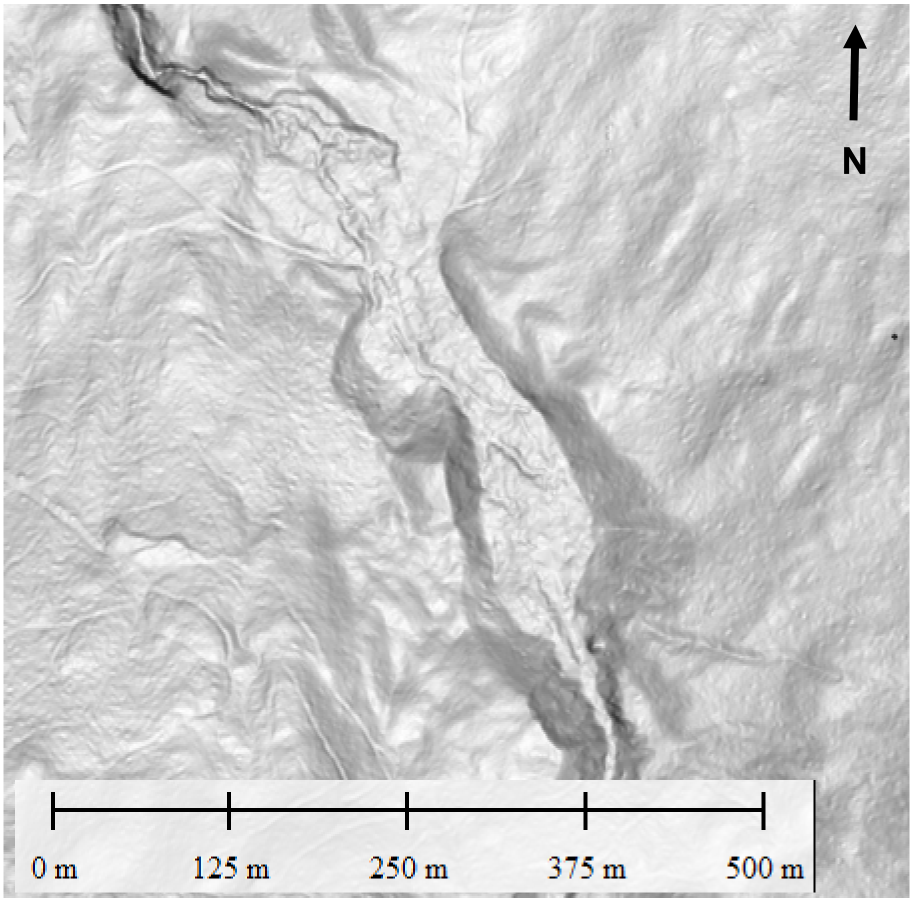


Figure 3-4. Sudden channel widening in the lower Procter Creek watershed and a likely location of intermittent debris deposition.

Table 3-1 summarizes relevant geomorphic characteristics of the Procter 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 transport 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 Procter Creek.

Characteristic	Value
Watershed area (km^2)	8.3
Fan-delta area (km^2)	0.45
Active fan-delta area (km^2)[1]	0.33
Maximum watershed elevation (m)	2,270
Minimum watershed elevation (m)	580
Watershed relief (m)	1,690
Melton Ratio (km/km)[3]	0.6
Average channel gradient of mainstem above fan apex (%)	23
Average channel gradient on fan (%)	10
Average fan gradient (%)	11

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. Procter Creek Fan-Delta

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

Procter Creek flows northernly across the fan-delta that extends into the West Arm of Kootenay Lake. The main channel across the fan-delta has been highly modified to accommodate development through channel straightening and routing as the creek passes through residential properties. The west side of the fan has also been modified by railway activity. The active channel ranges from 1 to 3 m wide on the fan. The average channel gradient on the fan is 11% (Table 3-1) with channel gradient decreasing downstream from the fan apex to the creek outlet. Figure 3-5 shows the profile of the creek channel on the fan-delta with major infrastructure (Harrop-Procter Road, CP Railway) marked. The average gradient of the fan-delta upstream of the CP railway is 11% compared to 6% downstream.

[3] Melton ratio is an indicator of the relative susceptibility of a watershed to debris flows, debris floods or floods.

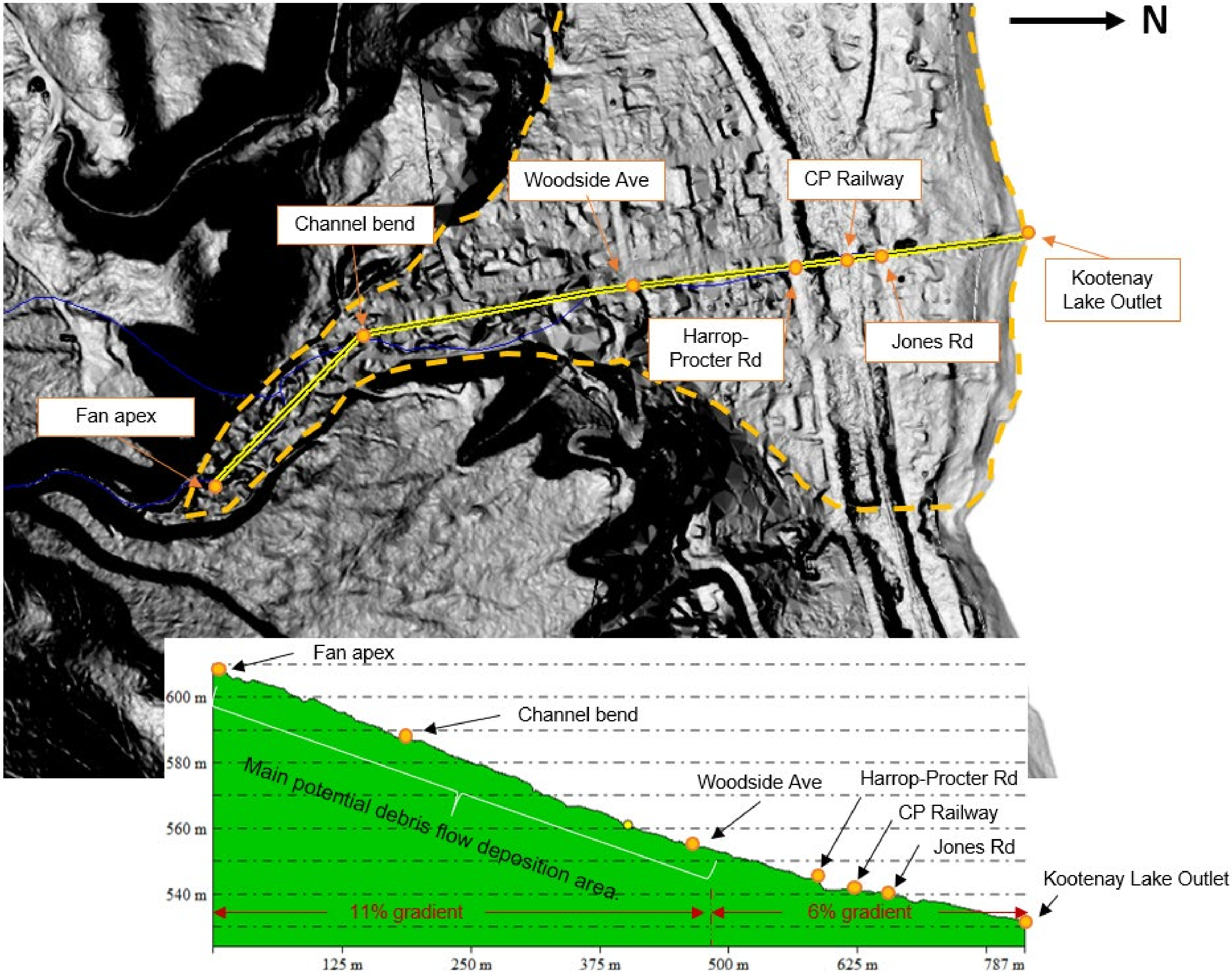


Figure 3-5. Profile along Procter Creek fan-delta. The path of the profile follows the creek channel as shown by the yellow line.

Near the fan apex, BGC identified trees with impact scars indicating boulder impact during past debris flows or debris floods (e.g., Photo 7, Appendix B). At these locations, BGC collected dendrogeomorphological samples (Drawing 02A, 02B) for analysis as discussed in Sections 5.1.2 and 6.2.2. On the left (west) side of the creek, two of the dendrogeomorphological samples were collected from trees on an approximately 1.3 m high debris levee with a boulder front (Drawing 02A, 02B).

BGC also identified a potential avulsion point on the right (east) side of the creek in the same channel reach where the bank height was only 0.2 m.

The Procter Creek fan-delta was partially submerged due to the raise of lake levels when the Corra Linn Dam (Drawing 06), located southwest of Nelson, began operation in 1938. The dam raised lake levels by approximately 2 m (Touchstone Nelson, 2007) and BGC understands that this level will be maintained. The distal portions of the fan, visible in aerial photographs (Section 6.2), were flooded by the lake level raise. The lake level rise lowered the surface water slope for the distal creek portions which in turn invites aggradation in the lower creek section. Procter Creek flows into Kootenay Lake in an approximately 10 m wide reach.

3.4.3. Steep Creek Process

BGC assessed the potential steep creek process types and hazards on Procter 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, Procter Creek plots in the data cluster prone to debris floods and debris flows (Figure 3-6) near the upper credible variation limit. This implies that for the combination of Melton Ratio and watershed length Procter Creek is unusual. 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.

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

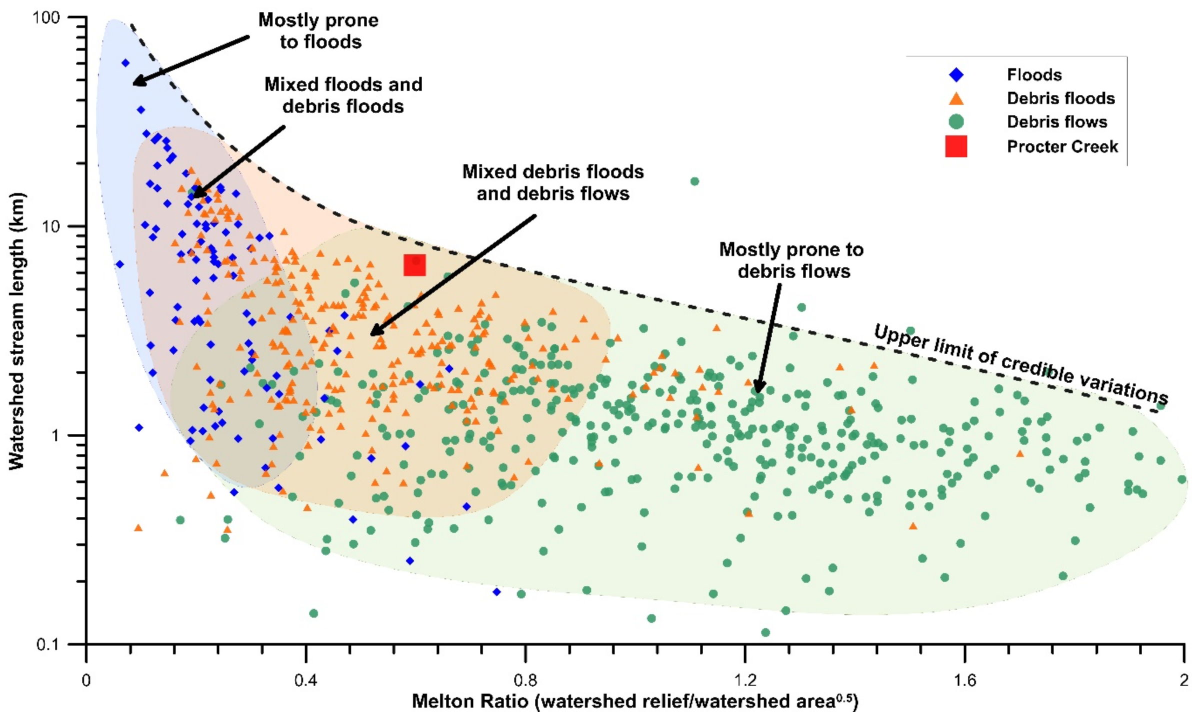


Figure 3-6. Tendency of creeks to produce floods, debris floods and debris flows, as a function of Melton Ratio and stream length (data from Holm et al., 2016 and Lau, 2017). See Section 3.2 for Procter Creek watershed data.

BGC interprets Type 1 debris floods to be the dominant hydrogeomorphic process at Procter Creek for low return periods (20- and 50-year). For the 200-year and 500-year return periods, Procter Creek is believed to be prone to debris flows which may be preferentially triggered after wildfires with moderate to severe burn intensities. This rationale is discussed further in Section 6.1.

3.5. Existing Development

Development on the Procter Creek fan-delta comprises the community of Procter (Drawing 02A, 02B) and the Canadian Pacific (CP) railway that transects the distal fan. Approximately 300 m downstream of the fan apex, there is a powerhouse 6 m east of the channel bank (Photo 8, Appendix B). A further 20 m downstream, is the water intake structure and weir that supplies water to some local households (Photo 9, Appendix B).

Downstream of the water intake, to the creek outlet at the lake, Procter Creek channel passes through the developed portion of the fan where there are numerous bridges, culverts, retaining walls and a flume (estimated 1 m wide and 1.5 m deep by BGC during site visit) installed along the channel as described in the following subsections.

In the 2016 census, the hamlet of Procter is identified as unincorporated by the name of Harrop/Procter. BGC interprets this to mean that the total population reported is for the communities of both Harrop and Procter but may also include smaller adjacent communities such as Sunshine Bay. The unincorporated communities of Harrop/Procter have a total population of approximately 600 (Statistics Canada, 2016). The estimated total improvement value of parcels intersecting the Procter Creek fan-delta based on the 2018 BC Assessment Data is $16,324,000 (BGC, March 31, 2019).

3.5.1. Bridges and Culverts

Procter Creek passes under five bridges and five culverts on the fan-delta, (Drawing 02A, Drawing 02B, Drawing 06, Figure 3-7 and Figure 3-8). Of the ten structures, only three culverts are listed in the Data Catalogue published by the Ministry of Transportation and Infrastructure (MOTI) – Construction and Maintenance (Table 3-2). BGC subcontracted Explore to survey the river channel and document the dimensions of each hydraulic structure. The survey was completed on September 5, 2019. Key dimensions are summarized in Table 3-2. Bridge and culvert locations IDs are listed in Table 3-2 and are shown on Drawing 02A, 02B. There are three wooden bridges in the upper fan upstream of Woodside Avenue. The furthest upstream is a wooden bridge (Figure 3-7A). The next bridge in the downstream direction, PRT-BR-2, is a wooden bridge installed for residential access (Figure 3-7B). Upstream and downstream of the residential bridge, the channel has been heavily modified over the course of decades with visible crib and cobbles that have been placed on the channel banks. PRT-BR-3 is a footbridge with a rotten deck (Figure 3-7C).

Downstream of PRT-BR-3, there is a galvanized steel culvert with concrete wingwalls at the inlet that conveys the flow under Woodside Avenue (PRT-CV-1, Figure 3-8A). PRT-BR-4 is a footbridge with metal railings used for house access. It sits on a concrete foundation and is made of logs and wood (Figure 3-7D). During the July site visit, BGC noted bank erosion approximately 10 m upstream of the bridge encroaching on a nearby garage.

A concrete footbridge (PRT-BR-5), which sits on a concrete wall and a log crib structure, provides access by foot to the Church of the Sacred Heart (Figure 3-7E). During the July site visit, BGC noted the poor state of the log crib structure, which may no longer provide a stable base for the footbridge. The Procter Creek channel gradient is approximately 11% from the fan apex to Procter Lane. Immediately downstream of Procter Lane, the gradient diminishes to 6% until the outlet at Kootenay Lake.

PRT-CV-2 conveys the flow under Procter Lane (alleyway) with an outlet approximately 40 m upstream of Railway Avenue. This portion of the creek is confined by a combination of concrete, metal flashing and rock to be approximately 1.5 m wide. The Railway Avenue culvert (PRT-CV-3, Figure 3-8C) is the largest of the culverts along Procter Creek. and the outlet falls 1.3 m to a plunge pool (Figure 3-8C). Twin culverts (PRT-CV-4, Figure 3-8D) convey the creek below the CP railway. Just upstream of the twin culverts at the railway is a trash rack with 18 cm spacing made from cantilevered rails cast in a concrete base. The railway is approximately 0.8 m above the left (larger) culvert and discharges into a plunge pool. The Jones Road culvert (PRT-CV-5) is the most downstream culvert on Procter Creek (Figure 3-8E).

A) PRT-BR-1. Looking downstream towards wooden vehicle bridge approximately 130 m downstream of the fan apex.

B) PRT-BR-2. Looking downstream towards a wooden bridge with metal frame.

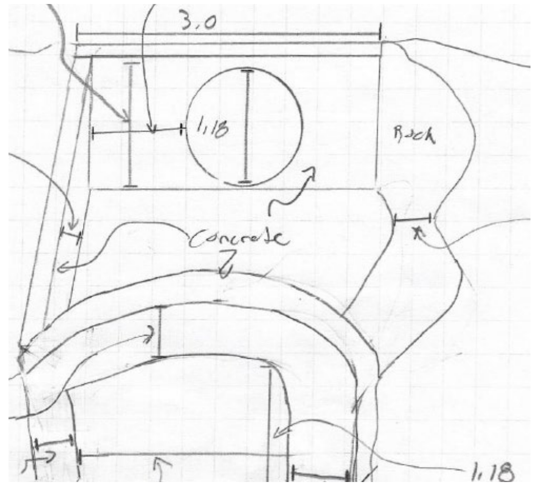
C) PRT-BR-3. Rotting footbridge over channel. Bridge is approximately 0.8 m high.

D) PRT-BR-4. Wooden footbridge with metal railing approximately 5 m wide, 1.6 m high.

E) PRT-BR-5. On right bank looking upstream at church bridge.

Figure 3-7. Procter Creek bridge structures ordered from upstream to downstream. BGC photos taken July 4, 2019.

A) PRT-CV-1. Looking upstream towards the culvert at Woodside Avenue.



B) PRT-CV-2. Procter Lane Culvert looking downstream.

C) PRT-CV-3. Looking upstream at the outlet of Railway Avenue culvert.

D) PRT-CV-4. Looking downstream at twin culverts under railway with trash rack in foreground.

E) PRT-CV-5. Looking at outflow of Jones Road culvert

Figure 3-8. Culverts on Procter Creek fan-delta. BGC photos taken on July 4, 2019.

Table 3-2. Surveyed dimensions of bridge crossings and culverts on Procter Creek fan-delta.

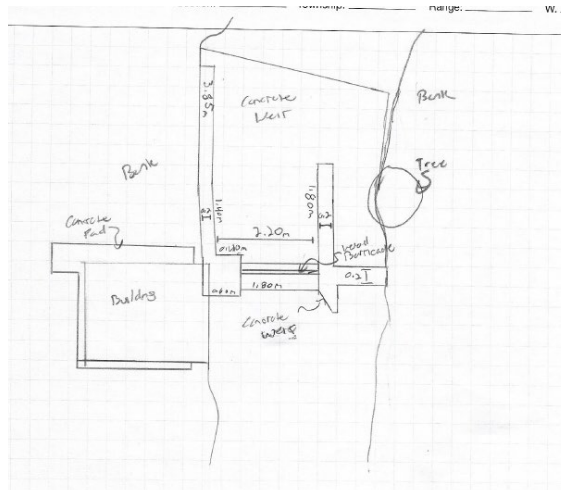
Bridge	ID	Span (m)	Height Above Channel Center (m)	Notes
Old wood vehicle bridge	PRT-BR-1	2.0	2.1	
Wood bridge	PRT-BR-2	3.67	2.5	For house access. Metal frame with wooden boards
Broken bridge	PRT-BR-3	3.3	0.9	
Woodside Avenue culvert	PRT-CV-1	9.0	1.18 m diameter	MOT culvert
Wooden bridge with metal railing	PRT-BR-4	5.15	1.0	
Church bridge	PRT-BR-5	2.12	1.42	Concrete slab with metal handrail
Procter Lane culvert	PRT-CV-2	17.9	1.18 m diameter	
Railway Ave culvert	PRT-CV-3	18.40	1.17 m diameter	MOT culvert
Railway twin culverts	PRT-CV-4	21	0.9 & 0.75 m diameter	Steel trash rack upstream of culverts
Jones Road culvert	PRT- CV-5	9.1	1.185 m diameter	MOT culvert

Note: The bridge and culvert dimensions were taken from survey measurement in the field on September 5th, 2019.

3.5.2. Other Infrastructure

Approximately 320 m downstream of the fan apex, there is a concrete weir and a water intake structure (Figure 3-9). The concrete opening is 1.8 m wide with stop logs to adjust the height of the weir. This structure is the farthest upstream point included in the survey, completed by Explore on September 5, 2019. On the date of the survey, the difference from the weir to the top concrete walls of the intake structure was measured to be 0.1 m. The channel and intake structure have a low freeboard, and this has been identified as a potential avulsion location from BGC field observation.

A) Looking upstream towards weir and water intake structure.



B) Top view sketch of Procter Creek weir

Figure 3-9. Procter Creek weir. BGC photo taken on July 4, 2019 and Explore sketch drawn on September 5, 2019.

3.5.3. Flood and Bank Protection Structures

Along the fan-delta reaches, Procter Creek banks are protected by various structures. None of the structures noted during BGC's field visit are listed on the iMapBC Flood Protection Structural Works layer. Therefore, other than the location and selective photos, the details of each structure, such as if they are designed and approved, are unknown.

At mid-fan near the church, the creek is confined by a concrete wall on the left bank and a log crib structure on the right (Figure 3-10A). The bank protection is metal flashing just upstream of Procter Lane, while downstream the creek is contained in a concrete flume (Figure 3-10B & C). Gabion baskets line the creek from the Railway Avenue culvert outlet to the railway trash grate. One gabion basket on the right bank 3 m from the Railway Avenue culvert outlet has broken and gravel material has washed out; however, the remaining baskets are all intact (Figure 3-10D). Downstream of the railway culvert, the stream is lined with a log crib structure of unknown length (Figure 3-10E).

A) Looking downstream at mid-fan near the church.

B) Metal flashing containing the creek upstream of Procter Lane

C) Looking upstream of Railway Avenue at concrete flume.

D) Looking downstream at gabion baskets lining creek from outlet of Railway Avenue towards railway.

E) Looking downstream at outlet of railway culvert showing log crib bank protection.

Figure 3-10. Select flood and bank protection structures along Procter Creek. BGC photos taken July 4, 2019. Refer to Drawing 02A, 02B for locations.

3.6. Hydroclimatic Conditions

3.6.1. Existing Conditions

Climate normal data were obtained from Environment and Climate Change Canada's (ECCC's) Kaslo station (600 m elevation), located approximately 34 km north of the Procter Creek outlet (ECCC, n.d.). Daily precipitation and temperature data are available from 1894 to 2015. Figure 3-11 shows the average monthly temperature and precipitation for this station from the 1981 to 2010 climate normals. The total annual precipitation at the Kaslo station is 886 mm, with the annual proportion of rain and snow summarized in Table 3-3. The measured historical (1981 to 2010) precipitation at the Kaslo weather station is lower than the historical (1961 to 1990) precipitation in the Procter Creek watershed, where the mountaintops extend more than 2200 m above Kootenay Lake. This difference in precipitation is due to orographic effects, which occur when an air mass is forced up over rising terrain from lower elevations. As the air mass gains altitude, it quickly cools down, and the water vapour condenses forming clouds resulting in precipitation.

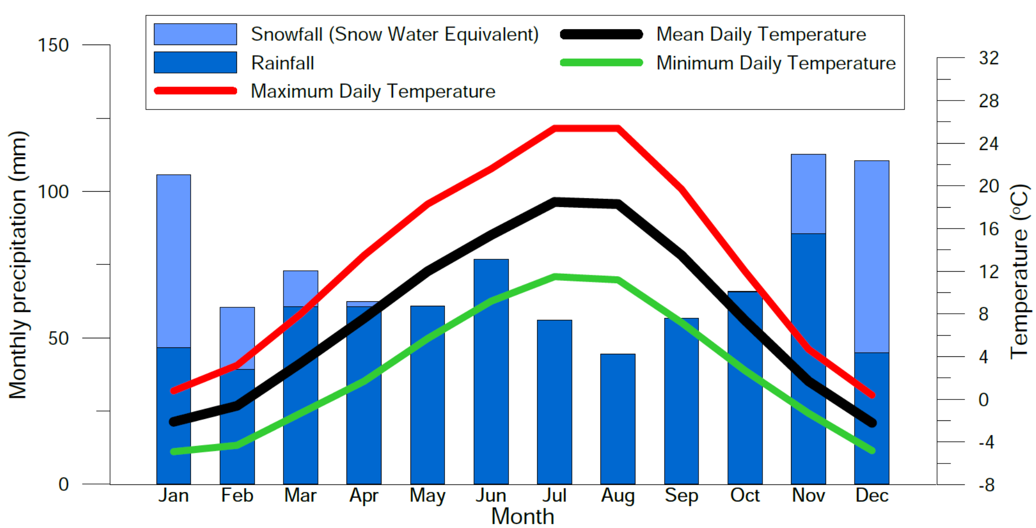


Figure 3-11. Climate normal data for Kaslo weather station from 1981 to 2010.

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

Variable	Annual Total	Percent of total annual precipitation (%)
Rainfall (mm)	698	79
Snowfall (cm)	188	21
Precipitation (mm)	886	100

To understand the regional distribution of precipitation and snowfall patterns and supplement the data from the Kaslo weather 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 1290 mm, varying as a function of elevation. The same trend is evident in the historical annual average Precipitation as Snow (PAS) where the historical average PAS is 718 mm over the watershed.

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 (Wang et al., 2016). Model results show that the mean annual temperature (MAT) in the Proctor Creek watershed is projected to increase from a historical (1961 to 1990) value of 2.6 ºC to 6.2 ºC by 2050 (2041 to 2070). The MAP is projected to increase from a historical value of 1290 mm to 1362 mm by 2050 while PAS is projected to decrease from a historical value of 718 mm to 469 mm by 2050. These projected changes in climate variables are presented in Table 3-4.

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

The substantially higher projected temperatures and declining snow cover imply that droughts will be more impactful likely changing forest ecology towards being more susceptible to wildfires. This, in conjunction with a projected severe (4-5 times) increase in extreme hourly rainfall frequency and a 20 to 30% increase in magnitude (Prein et al, 2017) suggests that the potential of post-wildfire debris flows will increase. This is especially important for Procter Creek because the watershed is interpreted to be subject to debris flows.

Wildfire frequency and size in southern BC are increasing due to climate change and the estimated return period of a 200 km^2 fire has decreased from 100 years to 20 years (Kirchmeier-Young et al., 2019). For example, severe wildfire in Cariboo forests (located further to the north of the Merritt, BC area) have return periods ranging from about 25 to 50 years (UBC, 2019). The

2017 wildfires in BC were unprecedented in terms of the amount of land burned and the subsequent 2018 wildfires continued this trend and burned over 1.3 million ha of land (Government of BC, 2019).

Table 3-4. Projected change (RCP 8.5, 2050) from historical (1961 to 1990) conditions for the Proctor Creek watershed based on ClimateNA model (Wang et. al, 2016).

Climate Variable	Projected Change
Mean Annual Temperature (MAT)	+3.6 ºC
Mean Annual Precipitation (MAP)	+72 mm
Precipitation as Snow (PAS)	-249 mm

4. SITE HISTORY

4.1. Introduction

Procter Creek flows through the community of Procter and into Kootenay Lake. Residents have lived on the fan-delta since the late 1800s. The community has served as an important railway link on the south side of the West Arm of Kootenay Lake. BGC notes that the town name is also spelled “Proctor” in several reports. The community has also been known as “Kootenay City” and “Procter’s Landing”.

4.2. Document Review

In developing a flood, mitigation, and development history for Procter Creek, BGC reviewed a number of documents, including:

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

BGC’s review of the above work is not meant 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 nor rejecting the findings of those studies, as this was not the scope of the present study.

The following subsections provide a brief description of relevant study findings from a selection of the previous reports available that are pertinent to the present study.

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

Year	Month/Day	Source	Purpose
1972	June	Water Resources Branch (BC Government)	Flood survey report
1990	April	Northwest Hydraulic Consultants Ltd. and Thurber Consultants Ltd.	Hazard Assessment
1998	February 23	Klohn-Crippen	Terrain Stability Inventory
2004	February 16	WSA Engineering Ltd.	Precondition for Building Permit
2004	May 12	Deverney Engineering Services Ltd.	Precondition for Subdivision
2011	April 18	Deverney Engineering Services Ltd.	Precondition for Site-specific Exemption
2011	July 13	Masse Environmental Consultants Ltd.	Environmental Impact Assessment
2011	October 17	Perdue Geotechnical Services Ltd.	Precondition for Subdivision
2013	November 12	Perdue Geotechnical Services Ltd.	Precondition for Building Permit
2014	May 31	Lasca Group Technical Services	Precondition for Building Permit

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 creeks were also prioritized for detailed study by BGC.

NHC/Thurber identified natural debris levees that partially confined the channel and several lobes of deposited debris near the fan apex of Procter Creek. However, there was no specific mention of the process that had deposited the observed levees. Because debris levees are characteristic of debris flows, this process was perhaps implied. A detailed comparison of the NHC/Thurber study with the present work is included in Section 6.6.1.

4.2.2. WSA Engineering (2004)

WSA Engineering Ltd. (WSA) completed a geotechnical hazard assessment of property on the south side of Harrop-Procter Road approximately 60 m west of Procter Creek as a prerequisite for a Building Permit for a mobile home on the property. WSA assessed Procter Creek to be 'significantly undersized' for its 'current gully and fan.' WSA also assessed that avulsions of the channel are unlikely. In the event of an extreme hydrologic event, WSA assessed that the intake structure on the upstream side of Woodside Avenue could be overtopped with overflow along Second Avenue. They interpreted the potential for impacts west of Second Avenue to be low and that any flow would be 'thoroughly dispersed' by existing infrastructure (WSA, 2004).

4.2.3. Deverney Engineering Services (2004)

In 2004, Deverney Engineering Services Ltd. (Deverney) completed a geotechnical evaluation of 246 Third Avenue in support of an evaluation of the feasibility of modifications to the Procter Community Hall (Deverney, 2004). The property is located on the south side of Harrop-Procter Road. In reviewing the geomorphological evidence, Deverney provided qualitative ratings of the hazard to the property associated with different process types without providing the basis for the qualitative ratings in their report. Deverney assessed the 'debris torrent' and debris flow hazard to the property to be very low, and the flooding hazard associated with overbank flows including channel erosion and shifting to be moderate. Deverney estimated the annual risk of exposure to an avulsion/flooding hazard to be 'in the order of' 1/1,000 to 1/1,200. They estimated that overland flow velocities would be 'in the order of'1.5 to 2.0 m/s and depth of flow to be less than 0.5 m. The basis for the risk of exposure, flow velocity and flow depth estimates was not provided. Given that the intended use of the proposed building was not for residential occupancy, Deverney assessed the risk to life at the property to be very low.

4.2.4. Perdue Geotechnical Services (2011)

In 2011, Perdue Geotechnical Services (Perdue) completed a geotechnical assessment of a property located north of the CP Railway on the northwest side of the fan, west of Third Avenue in support of an application for lot subdivision. Perdue described evidence of historic events in the form of minor channel avulsions, debris lobes and levees in the upper reach of the Procter Creek fan-delta. Perdue inferred that the most recent event occurred more than 100 years ago as it pre-dated the existing, mature stand of trees. Perdue noted that no evidence of deposition was noted more than 400 m downstream of the fan apex but recognized that existing development may have altered the landscape such that indicators are no longer visible. Given the Melton ratio and channel and fan morphometrics, Perdue assessed that the likelihood of a debris flood or debris flow adversely affecting the property was less than the acceptable level of safety (1 in 475) mandated by MoTI at that time. Moreover, Perdue assessed the probability of a potentially damaging flood event adversely affecting the property to be less than the acceptable risk suggested by MoTI at the time (1 in 200).

4.2.5. Lasca Group Technical Services (2014)

Lasca Group Technical Services completed a geotechnical engineering site visit to 239 First Ave in 2014 (Lasca, 2014). The property is located approximately 50 m east of Procter Creek south of Procter Lane. Lasca indicated that, at the time of the site visit, there was no indication of pooling of water on the land. Lasca also indicated that there was no indication of erosional features anywhere in Procter and, given the high concentration of cobbles and sand in the soil, flooding was not a concern as they assessed that much of the creek water becomes groundwater. Lasca assessed there to be no debris flow hazards, contradicting some of the earlier studies. Further Lasca indicated that the property is not in a floodplain as Procter Creek 'has had no historic flooding' (Lasca, 2014).

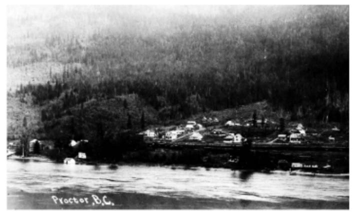
4.3. Historic Timeline

Figure 4-1 provides a timeline summary of floods and mitigation history for Procter Creek. For location references, refer to Drawings 01 and 02. 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 four notable hydrogeomorphic events have occurred in recorded history. These flood events occurred during freshet (snowmelt) conditions. BGC interprets that at least the 1956 event could be classified as a damaging debris flood, given the record of extensive erosion and avulsion.
- The 1939 air photograph suggests a debris flow or debris flood in that year or a few years prior evidenced by light colours indicative of sediment deposition. Note that no historical information has been identified that described this event and the air photo is of relatively poor quality, so the interpretation of the air photos is somewhat speculative.
- Historical flood and debris flood events have caused channel aggradation and culvert blockages.
- The channel has been substantially modified to constrain the channel through the townsite and under the highway and railway culverts. BGC suspects that the channel was straightened prior to the earliest aerial photograph in 1929, and possibly in 1914 when the town was surveyed, and roads constructed. Additional channel flood hazard mitigation measures were likely installed after the 1956 event to prevent bank erosion.
- Procter Creek previously occupied a channel on the western fan boundary.
- The watershed has never been logged.
- The Procter Creek fan-delta was partially submerged due to the raise of lake levels when the Corra Linn Dam began operation in 1938. The dam raised lake levels by approximately 2 m.

Geohazard History

August 2017 - Lightning-caused Harrop Creek wildfire initiated evacuation alerts for Procter and other local communities



Procter, 1914 (Image D-03381 courtesy of the Royal BC Museum and Archives)

The Outlet, Procter, BC, 1911 (Image B-06660 courtesy of the Royal BC Museum and Archives)

June 1974 - Snow melt resulted in flooding and damage to property

June 2, 1972 - Flooding blocked highway and railway culverts

June 1956 - Flash flooding along Procter Creek washed away a portion of the CPR lines in Procter; bank erosion resulted; flooding possibly associated with a slide in the watershed

June 9, 1948 - Heavy rainstorm resulted in swollen, debris-filled creeks flooding railway and blocking two bridges

1936 - Lightning-caused wildfire burned approximately 60 ha in upper watershed

June 1914 - Local newspaper notes Procter Creek being diverted, however, does not provide detail on location

1901 - Forest fires destroyed much of what is now the Harrop-Procter Community Forest

2020 2010 2000 1990 1980 1970 1960 1950 1940 1930 1920 1910 1900 1890

Mitigation

1974 - Gravel cleared out of channel after flood

June 1914 - Procter Creek diverted

Development

1999 - Harrop-Procter Community Forest established, covering 11,300 ha of Provincial Forest Crown land

July 12, 1995 - West Arm Provincial Park established, adjacent to the Harrop-Procter community watershed

1966 - Outlet Hotel demolished in Procter

1947 - Balfour became the cross-Kootenay Lake ferry port and service withdrawn from Procter

1938 - Corra Linn Dam activated downstream of Procter Creek on Kootenay Lake

1931 - CPR opened rail line up the west side of Kootenay Lake from Kootenay Landing to Procter

June 1914 - Road building and road raising completed in town of Procter

1908 - Railway barge slip and piers re-built

1891 - Town of Procter named after early landowner and hotelier, Thomas Gregg Procter

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

Figure 4-1. Summary of recorded geohazard, mitigation, and development history at Procter Creek.

5. METHODS

The overall assessment methodology applied to the nine flood and debris flood-prone steep creeks in the RDCK is summarized in the Methodology Report (BGC, March 31, 2020b). Figure 5-1 shows the workflow to develop frequency-magnitude (F-M) relationships for Procter Creek and other flood and debris flood prone creeks in the RDCK. This section summarizes the overall workflow as well as any specific deviations from the steep creek methodology applied at Procter Creek. Relative to other reports, it provides additional detail on the methodology as Procter Creek is considered subject to debris flows at the 200-year and 500-year return periods.

The field investigation at Procter Creek did not include test trenching as most of the fan is densely developed.

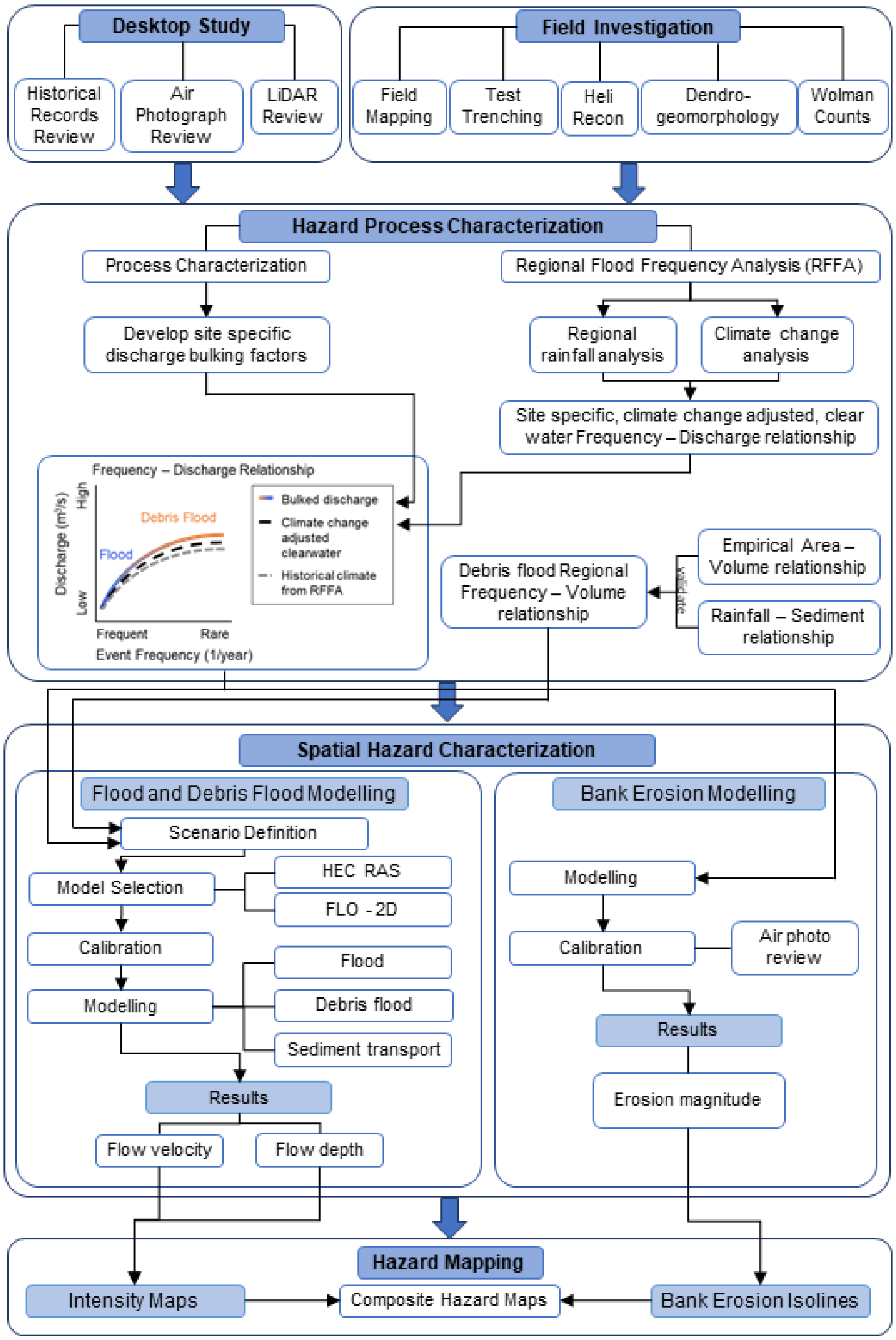


Figure 5-1. Flood and debris flood prone steep creeks workflow used for developing frequency-magnitude relationships, modelling, and preparing hazard maps.

5.1. Debris-Flood and Debris-Flow Frequency Assessment

5.1.1. Air Photo Interpretation

At Procter Creek, air photo interpretation was used to estimate debris-flood frequencies. Air photos dated between 1929 and 2017 were examined for evidence of past sediment transport events on Procter Creek. A complete list of the air photos reviewed is included in Appendix D.

Hydrogeomorphic events were identified from the appearance of bright areas and disturbed vegetation indicative of transported/ and or deposited sediment since the 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 be captured. Air photo interpretation was supplemented by historical records of past events (Section 4).

5.1.2. Dendrogeomorphology

Ten tree core samples were collected for dendrogeomorphological analysis from Procter Creek (Drawings 02A, 02B). Of the ten samples collected, eight were analysed. Characteristics of the analysed samples including the tree type, minimum establishment date[4], and features that indicate physical damage to the tree are presented in the results section (Section 6.2.2). The presence of features indicating a tree sustained damage in a given year can supplement the historical records and air photo interpretation in the development of a record of historical events, as well as the extents of such events

5.2. 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[5], and discharge and sediment volume are used as the measures of magnitude. For more background on F-M, the reader is referred to the Methodology Report (BGC, March 31, 2020b).

BGC assessed Procter Creek for the 20-, 50-, 200-, and 500-year return periods for floods, debris floods and debris flows. At these return periods, the dominant hydrogeomorphic process was identified as debris flood up to the 50-year return period and debris flows for the 200 and 500-year return periods based on stream morphometrics, site observations (Section 6.1) and considerations of post-wildfire debris-flow activity (Section 6.3.2).

5.2.1. Debris Floods

Debris-flood events carry sediment and woody debris, therefore the climate adjusted clearwater discharges need 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 runout 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.

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4 The minimum establishment date refers to oldest tree ring identified in the sample. The samples do not always hit the earliest tree rings so this year is taken as the minimum date the tree could have established itself.

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

Therefore, a regional frequency-volume relationship was applied in addition to the numerical model (Jakob et al., 2016; Jakob et al., submitted). The inundation areas were then divided by the predicted sediment volumes to arrive at likely average deposition depths across the inundated areas. A detailed discussion of the methodology is provided in Section 2 of the Methodology Report (BGC, March 31, 2020b).

5.2.1.1. Clearwater Peak Discharge Estimation

There are no hydrometric stations on Proctor Creek, therefore peak discharges (flood quantiles) were estimated using a regional flood frequency analysis (Regional FFA) and compared with the results from previous studies. The regionalization of floods procedure was completed using the index-flood method. For this project, the mean annual flood was selected as the index-flood and dimensionless regional growth curves were developed from Water Survey of Canada (WSC) data to scale the mean annual flood to other return periods. The index-flood for each creek is determined from catchment characteristics. The index-flood was estimated using a regional and provincially based ensemble of multiple regression models. The peak discharge estimates were compared with historical estimates published by previous studies (e.g., NHC, 1990; KCB, 2008; and PGS, 2012). Based on its catchment characteristics, the Proctor Creek watershed was assigned to the '4 East hydrologic region for watersheds less than 500 km^2'. Details of the Regional FFA are presented in Section 3 of the Methodology Report (BGC, March 31, 2020b).

5.2.1.2. 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 Proctor 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 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).

Note that this does not apply to the estimation of debris flow peak discharges which are discussed in Section 5.2.2.3.

5.2.1.3. 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).

5.2.2. Debris Flows

BGC assessed the dominant hydrogeomorphic process on Procter Creek at the 200-year and 500-year return periods to be debris flows. This interpretation is based on the steep gradient of the watershed and upper fan, observations of large (> 1 m diameter) boulders near the fan apex, and observations of past debris flow deposits from air photos. Furthermore, wildfire occurred in the watershed in 1936. Wildfire is well documented to increase the frequency and magnitude of debris flows in a watershed (e.g., Cannon & Gartner, 2005). After wildfires, debris flow frequency and magnitude can change. Post-wildfire landscapes are subject to two primary debris flow initiation processes, as summarized by Cannon and Gartner (2005):

1. Runoff-dominated erosion by surface overland flow.
2. Infiltration-triggered landslide mobilization.

Runoff-dominated erosion has triggered the vast majority of debris flows in burned areas in the western U.S. within the first two years after a wildfire (Cannon & Gartner, 2005). Infiltration-triggered landslide mobilization is more frequent two to 10 years after a wildfire (DeGraff et al., 2015).

5.2.2.1. Post-Wildfire Debris-Flow Frequency

There is no direct evidence of a post-wildfire debris flow in the Procter Creek watershed to calibrate an estimate of post-wildfire debris flow probability. However, during BGC excavations on the distal reaches of Harrop Creek fan, located 6 km west of Procter Creek, abundant charcoal was found overlying sandy or gravelly flood units indicating that post-wildfire erosion and transport does occur in the region.

Post-wildfire debris flow frequencies can be estimated by combining the probability of a wildfire occurring with that of a potential debris flow triggering storm occurring in the critical post-wildfire period, which is about 2 years (Cannon & Gartner, 2005). For example, in a region with a 100-year fire frequency, the post-wildfire debris flow probability of a watershed impacted by a storm with a 10-year return period within the first two years after the fire would be 0.002 (which is equivalent to a 500-year return period).

Regional analysis for southeastern BC indicates that the historic frequency of a stand-replacing wildfire ranges between 35 years (at lower elevation) and 200 years (higher elevation) (Blackwell, Grey and Compass, 2003). Only one wildfire has occurred in the Procter Creek watershed in the air photo record (60 ha burned in 1936), which implies roughly a 1:100-year fire frequency. However, the frequency of wildfire will likely increase at Proctor Creek in the future due to progressive warming and loss of winter snowpack (Kirchmeier-Young et al., 2019; Westerling et al., 2006).

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

5.2.2.2. Post-Wildfire Debris-Flow Volume

Empirical models for predicting post-wildfire debris-flow volumes (e.g., Cannon et al., 2010; Gartner et al., 2014) can be used to assess hazards posed by debris flows following wildfires. These models predict volumes of material that may flow past a given point along a debris flow channel. The Gartner et al. (2014) model is currently used by the U.S. Geological Survey (USGS) for emergency assessments of post-wildfire debris flow hazards (available online at https://landslides.usgs.gov/hazards/postfire_debrisflow/). The inputs for the model include the contributing watershed area burned at moderate and high severity[6], the relief of the contributing watershed area, and the storm rainfall intensity measured over a 15-minute duration. The model is applicable for up to two years following the wildfire, after which plant re-growth and/or source area sediment depletion render it less reliable.

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

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

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

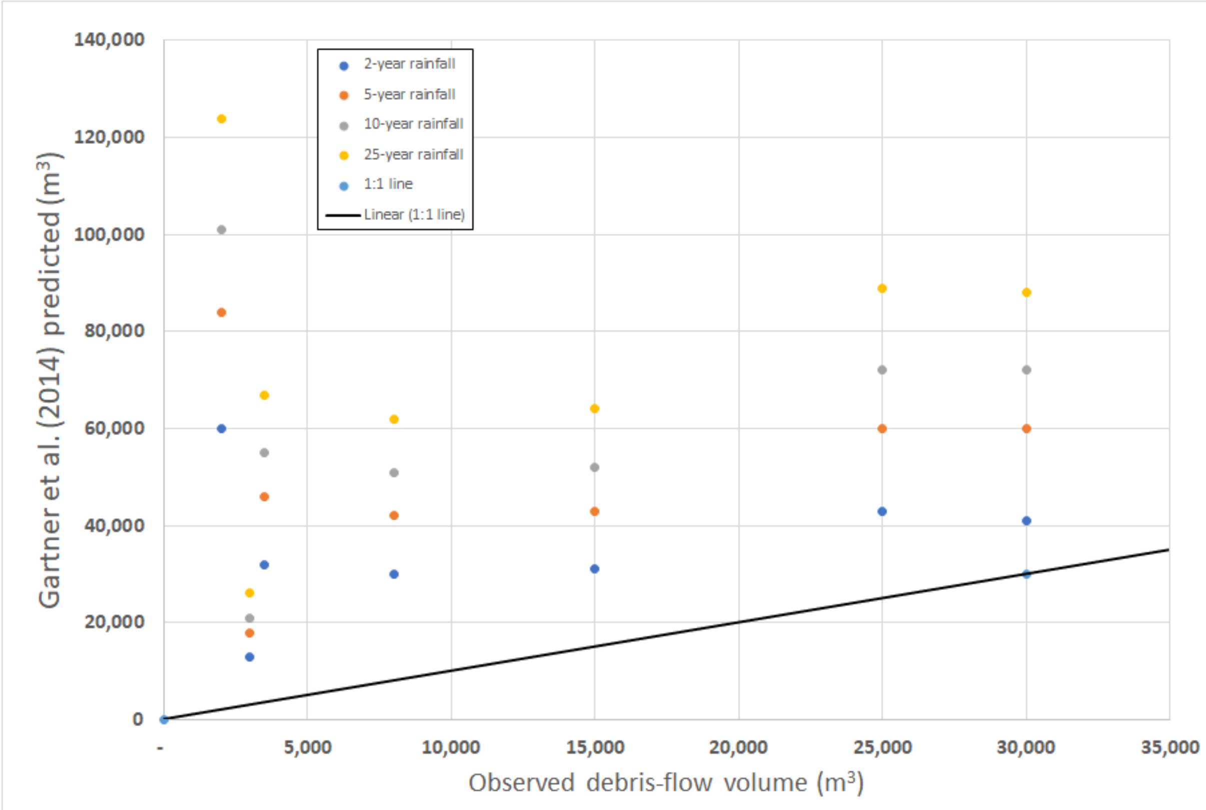

Figure 5-2. Correlation between observed (Jordan, 2015) and Gartner et al.'s (2014) model debris flow volume predictions. Note the outlying Ingersoll 10 data (far left dataset). The black line is a 1:1 line and values above this line are overpredicted.

The comparisons shown in Figure 5-2 demonstrate that the Gartner et al. (2014) model overpredicts the available debris flow dataset in southeastern BC by at least a factor of 2. Because the occurrence of post-wildfire debris flows is much less frequent in southeastern BC than southern California, it is not surprising that the Gartner et al., (2015) model, which is based on data from southern California, would overpredict debris flow magnitudes in southeastern BC. However, since the return periods of individual debris flows contained in the Jordan (2015) database are unknown, it is not possible to draw further conclusions. Nonetheless, BGC considers it reasonable to apply a multiplier of 0.5 to the Gartner et al. (2015) model results when applying this model to southeastern BC watersheds.

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

The "emergency assessment model" from Gartner et al. (2014) is applicable for two years post-wildfire. In that two-year period, BGC investigated what debris flow volumes would be generated from rainfall events with intensities corresponding to 5-year and 10-year return periods (annual probabilities ranging from 0.2 to 0.1). Rainfall intensities were obtained from the IDF curves for Creston, located approximately 70 km southeast of Procter Creek.

Section 6.3.2 summarizes the results from this analysis.

5.2.2.3. Post-Wildfire Debris-Flow Peak Discharge

Debris-flow peak discharge was then estimated using a method developed by Bovis and Jakob (1999), who provide empirical correlations between peak discharge and debris-flow volume based on observations of 33 debris flow basins in southwestern British Columbia (Figure 6-1). This relationship was constructed for “muddy” debris flows and “granular” debris flows. Muddy debris flows are those with a relatively fine-grained matrix as found from volcanic source areas or fine-grained sedimentary rocks, while granular debris flows are those typical for granitic source areas with large clasts embedded in the flow which slow the flow through friction thus creating large surge fronts. For many (not all) post-wildfire debris flows, the initiation occurs via progressive bulking of flows (Cannon & Gartner, 2005 quote some 75% bulked by runoff-dominated erosion). This occurs via rilling and gullying in recently burned terrain and sometimes hydrophobic (water repellent) soils have developed. The peak discharge of debris flows initiated by runoff-dominated erosion contrasts debris flows initiated by infiltration-triggered landslide mobilization. The latter results in comparatively higher peak flows.

It is not known whether the muddy or granular debris flow equation would be most applicable to Procter Creek. Therefore, BGC examined the V-Q relationship for Kuskonook Creek, a 4.6 km^2 watershed that experienced a post-wildfire debris flow in 2004. VanDine et al. (2005) estimated the volume of this event at 20,000 m^3 to 30,000 m^3 (VanDine et al., 2005). Solving the muddy and granular equations in Figure 6-1 for Q, one obtains:

$$Q_{muddy} = 0.03 \cdot V^{1.01} \qquad \text{[Eq. 5-1]}$$

$$Q_{granular} = 0.04 \cdot V^{0.9} \qquad \text{[Eq. 5-2]}$$

Equation 5-1 yields a peak flow estimate on Kuskonook Creek for the 20,000 and 30,000 m^3 range quoted by VanDine et al. (2005) of 70 to 100 m^3/s, while Equation 5-2 yields a peak discharge of (rounded) 300 and 430 m^3/s. VanDine reports a back-calculated discharge range of 200 to 480 m^3/s for the 2004 Kuskonook Creek debris flow which would indicate that this debris flow had more granular than muddy characteristics. However, the debris-flow initiation was described to be a channel bed and bank failure at a point where the channel slope increased (VanDine, 2005; Jordan 2015. This initiation by bed and bank failure and the resultant peak discharge may be more similar to a debris flow initiated by infiltration triggered landslide mobilization than a debris flow initiated by runoff dominated erosion following a wildfire. Given this uncertainty, BGC estimated peak discharges on Procter Creek using both Equation 5-1 and 5-2, resulting in a range of values.

5.3. Numerical Debris Flood Modelling

Debris flood numerical modelling of Procter Creek was completed for 20- and 50-year return periods. Details of the numerical modelling techniques are summarized in Section 2 of the

Methodology Report (BGC, March 31, 2020b). The hydraulic model HEC-RAS (Version 5.0.7) was used for debris flood modelling. HEC-RAS is a public domain one-dimensional and two-dimensional hydraulic modelling program developed and supported by the United States Army Corps of Engineers (Brunner & CEIWR-HEC, 2016).

Table 5-1 summarizes the key numerical modelling inputs selected for the HEC-RAS model. Further details on modelling methods are presented in Section 2 of the Methodology Report (BGC, March 31, 2020b). In contrast to the standard DEM generation methods described in the Methodology Report, a site survey was conducted at Procter Creek because the channel is small and not well resolved by the lidar data. Survey details are presented in Section 3.1. These survey data were merged with the lidar data to generate the model terrain. Despite this, it should be noted that the terrain data (survey and lidar) and model computational grid resolution may not accurately resolve all terrain features that may impact flow conditions. This limitation is noted in Section 2 of the Methodology Report (BGC, March 31, 2020b), but reiterated here due to the small size of Procter Creek and the potential for this limitation to affect if, when and where overbank flow occurs.

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). Because Kootenay Lake level is regulated by dam operation, high flows in Procter Creek may not be concurrent with high lake levels. Additionally, water levels drop along the West Arm from Kootenay Lake to Corra Linn Dam. For the purpose of modelling fluvial conditions, a Kootenay Lake level of 534.6 m was assumed.

Table 5-1. Summary of numerical modelling inputs.

Variable	HEC-RAS
Topographic Input	Lidar (2017)
Grid cells	Variable (1- 2 m)
Manning' n	0.1 (channel), 0.02 (main roads), 0.1 (fan)
Upstream boundary condition	Steady Flow (Q_{20} and Q_{50})
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 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 Procter Creek as presented in Appendix E. Modelling scenarios include different return periods (principal scenario), different bulking scenarios, 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. Modelling results show inundation areas for various return periods. Each scenario assumes the flood protection structures remain intact for all return periods

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

5.4. Numerical Debris Flow Modelling

Debris flow modelling was completed using FLO-2D (Version 19.07.21). 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).

Both the 200-year and 500-year debris flows were modelled. Two peak discharges for each return period were modelled as it is not possible to firmly ascertain that either (muddy vs. granular) applies.

5.4.1. Basic Setup and Input Parameters

The debris flow models were run on a grid created from a DEM constructed from lidar dated 2017. Grid spacing was set at 5 m so as not to exceed about 30,000 cells to ensure reasonable processing times for the models. This means that an elevation is averaged for each cell from the DEM.

Appropriate boundaries and boundary conditions were selected to best show how the flows would interact with the topography and development. Manning's n values were input for all cells depending whether the cell was in the channel, on a road or on the fan-delta. A hydrograph for the inflow cell at the apex of the fan-delta was specified depending on the return period being modelled.

Table 5-2 summarizes the basic input parameters that were used to set up the models. BGC conservatively assumed that there is negligible infiltration on fan-deltas.

Table 5-2. FLO-2D basic input parameters for debris flow models.

Parameter		Value
Manning's n	Fan-delta	0.1
	Streets	0.02
	Channel	0.06
Floodplain limiting Froude number	Debris flows	2
Sediment concentration (by volume)	Debris flows	50%
Surface detention[7]		0.03 m

[7] The surface detention parameter limits the minimum flow depth of modelled flow. It is intended to account for flow storage in shallow depressions.

Area reduction factors, used to facilitate modelling flows through urban environments, were not used as development is not dense enough to employ this feature and impact forces on the upper fan-delta are high enough to fully destroy structures.

5.4.2. Sediment Model Setup and Calibration

In FLO-2D, sediment and water inputs are defined using inflow hydrographs, which can be assigned to grid cells at the fan-delta apex. The peak discharge of the hydrograph is changed between model scenarios to model different event sediment volumes. The debris-flow input hydrographs use a constant hydrograph shape and sediment concentration (50%), and the length of the hydrograph is adjusted to match the estimated sediment volume and peak discharge. In general, because of the high peak discharges, the hydrographs are very short (<10 minutes). The inflow hydrograph parameters are summarized in Table 6-4. The sediment volumes and peak discharges were calculated as outlined in Section 5.2.2.2 and 5.2.2.3 above.

Debris-flow modelling also requires the definition of rheological parameters, which inform the flow behaviour of the water and debris slurry. In FLO-2D, the main rheological parameters are viscosity and yield stress. These parameters can be modified during model calibration in order to achieve the best possible match with the behaviour of known events. Neither variable is directly measured from observed events.

For Procter Creek, the 2004 event on Kuskonook Creek[8] was used for calibration. BGC used the event delineations and field observations from VanDine et al. (2005) to calibrate the model. The rheology was estimated iteratively until the modelled debris flow extent was similar to the observed runout and deposit depths as mapped in the field on Kuskonook Creek. The resulting rheological parameters are presented in Table 5-3.

Table 5-3. Rheological parameters for FLO-2D modelling.

Viscosity Coefficient	Viscosity Exponent	Yield Stress Coefficient	Yield Stress Exponent
0.00102	27.6	0.05	22.3

These parameters are modified from Rickenmann (1999) and have been used on other debris flow creeks in BC by BGC.

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 seven creek cross-sections between the fan apex and the mouth of the creek. For bank erosion modelling, debris floods were assumed up to the 500-year event as debris floods are considered to be more efficient in eroding banks than debris flows. The assessment methods are outlined in Section 2 of the Methodology Report (BGC, March 31, 2020b). 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

8 This creek is also the subject of a detailed hazard assessment by BGC.

Drawing 02A, 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, BGC prepared two types of steep creek hazard maps for Procter Creek: debris flood model (scenario) result maps and a composite hazard rating map. The model result maps support emergency planning and risk analyses, and the composite hazard rating map supports communication and policy implementation, as described further below.

5.6.1. Debris-Flood and Debris-Flow Model Result Maps

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

1. The hazard intensity and extent of inundated areas from both HEC-RAS and FLO-2D modelling.
2. Areas of sediment deposition extracted from FLO-2D debris flow 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.

5.6.2. Composite Hazard Rating Map

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

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

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

$$IIF = v^2 \times \rho_f \times d_f \times P(H) \quad \text{[Eq. 5-3]}$$

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

Equation 5-3 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 5-3).

A further area designated a "very low" hazard, is also presented as areas likely to not be affected by any of the modelled scenarios up to the 500-year return period debris flows, but which are not free of hazard. Very low hazard areas 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 for some creeks. Figure 5-3 displays a wider range of return periods and intensities than are relevant to debris flood and debris flow hazards on Procter 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.

Return Period Range (years)	Representative Return Period (years)	Geohazard Intensity				
		Very Low	Low	Moderate	High	Very High
1 - 3	2					
10 - 30	20					
30 - 100	50					
100 - 300	200					
300 - 1000	500					

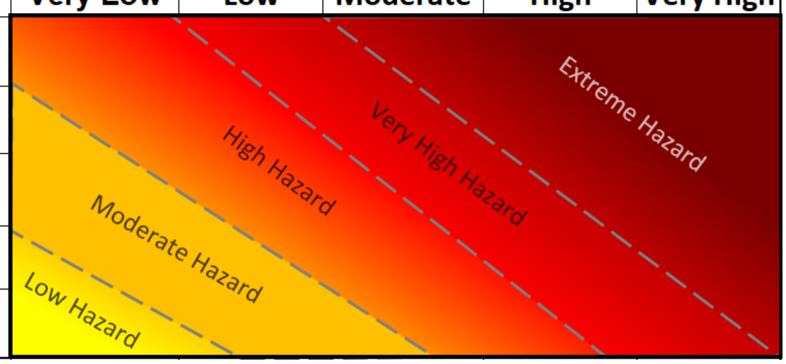

Figure 5-3. Simplified geohazard impact intensity frequency matrix.

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

Interpreted hazard maps showing *IIF* values were developed for each return period class at all locations within the study area. For the individual hazard scenario maps that are added to the Cambio web application, the raw (no interpretation nor zone homogenization) impact force modelling results are presented. For the composite hazard rating map, the different intensities were interpreted by BGC to homogenize zones into easily identifiable polygons that are likely to fall into the range of intensity bins reported above. In some cases, individual properties may have been artificially raised and are thus less prone to 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.

6. RESULTS

6.1. Hydrogeomorphic Process Characterization

Figure 3-6 indicates that Procter Creek is prone to debris floods and debris flows. This result is consistent with the following evidence:

- The average channel gradient above the fan apex is 23% (Drawing 03), which is sufficient for sustained debris flow transport.
- Tributaries upstream of the fan apex are debris-flow prone (Drawing 05).
- The average fan gradient of 10% is typical of creeks prone to debris floods.
- Large (> 1 m diameter) boulders, indicative of debris-flow transport, were observed near the fan apex.
- The west side of the fan has an avulsion channel which was the main flow channel in the early 1900s (Drawings 04A and 06).
- Historical records of past hydrogeomorphic events on the fan-delta (Section 4) suggest past avulsions and bank erosion consistent with debris floods. However, the evidence in the air photo record to support these historical records is limited (Section 6.2.1).

Together, this evidence indicates that Procter Creek is subject to supply-unlimited Type 1 debris floods for low return periods (20- and 50-year). For the 200- and 500-year return periods, post-wildfire debris flows are believed to be dominant. Debris flows can inject substantial volumes of debris leading to surging flow and higher sediment concentrations compared to Type 1 debris floods.

6.2. Debris-Flood and Debris-Flow Frequency Assessment

6.2.1. Air Photo Interpretation

Debris-flood and debris-flow frequency was assessed using historic air photos and historical accounts. BGC reviewed air photos from 1929 to 2017 (Appendix D). Drawings 04A and 04B show air photos with observed changes demarcated. The 1939 air photograph suggests a debris flow or debris flood in that year or a few years prior evidenced by light colours indicative of sediment deposition. Note that no historical information has been identified that described this event and the air photo is of relatively poor quality, so the interpretation of the air photos is somewhat speculative. Given the low image quality, BGC was not able to interpret deposition areas or characteristics of this or other hydrogeomorphic events identified from historical records (Figure 4-1). The reasons why the 1948, 1956, 1972, and 1974 events were not identified in the air photo record include that the events could have been well confined to the creek channel with limited evidence of bank erosion, avulsion, or sediment deposition, the timing of the events relative to the next available air photo such that the evidence is no longer visible, vegetation and residential development cover the affected areas.

6.2.2. Dendrogeomorphology

Results for the eight dendrogeomorphological samples analyzed on Procter Creek are presented in Table 6-1 and tree locations are shown on Drawings 02A, 02B.

Table 6-1. Summary of Procter Creek dendrogeomorphology sample features.

Sample[1]	Tree Type	Minimum Establishment Date (first ring)	Features[2]
Procter-01	Cedar	1972	Pith not reached due to rot in centre of tree
Procter -02	Cedar	1979	Pith not reached due to rot in centre of tree
Procter -03	Cedar	1962	Pith not reached due to rot in centre of tree
Procter -04	Cedar	1969	Pith not reached due to rot in centre of tree
Procter -05	Cedar	1975	Pith not reached due to rot in centre of tree
Procter -06	Cedar	1972	Strong TRDs in 1976
Procter-08a	Cedar	1998	Pith not reached due to rot in centre of tree
Procter-09	Cedar	1989	Pith not reached due to rot in centre of tree

Notes:
1. Sample locations are shown on the Fan-Delta Overview Map (Drawings 02A, 02B).
2. Traumatic resin ducts (TRDs) are small circles that appear within the wood, which indicate that the tree sustained physical damage during that year (similar to a scar tissue).

One sample had strong TRDs in 1976. There are known events in 1972 and 1974 (Figure 4-1) that the TRDs could potentially be associated with. Several trees showed impact scars pre-dating the 1970s but with an unknown impact date as those trees were all subject to core-rot that did not allow a more accurate estimate.

6.2.3. Summary

Based on historical records, notable flood or Type 1 debris floods have occurred approximately every 10 to 20 years on Procter Creek (Table 6-2); however, there have been no known events since 1974. These events have not led to significant damage that could be observed in the air photo record (Drawings 04A, 04B). The channel location on the Procter Creek fan shifted from the western fan boundary to the present location (Drawing 04A); however, the date and mechanism of the shift are unknown. A local newspaper noted the channel was diverted in 1914. NHC/Thurber (1990) similarly noted this shift and likewise could not verify the shift with historic air photos. There appears to be occasional flow in this west channel as evidenced by the presence of culverts along its path (Drawing 02A, 02B); however, this is no longer the main Procter Creek channel. During the 2019 site visit, BGC observed that the channel was vegetated.

Along the main (east) Procter Creek channel, there is significant anthropogenic modification channel with the construction of footbridges and training works through the developed portion of the fan. These measures likely reduce the potential for bank erosion and channel avulsions unless blocked.

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

Event Year	Description
1939	Possible event on the western channel downstream of the fan-delta apex
1948	Heavy rainstorm resulted in flooding along the CP Railway and blocking of two bridges.
1956	Flash flooding reported to have washed away a portion of the CPR lines resulting in bank erosion.
1972	Flooding blocked the highway and railway culverts.
1974	Snowmelt resulted in flooding and damage to property.

6.3. Frequency-Magnitude Relationship

6.3.1. Debris Floods

6.3.1.1. Debris-Flood Volume

BGC used two independent approaches to create a frequency-volume relationship for Procter Creek debris floods: an empirical sediment transport equation (Rickenmann, 2001), and application of regional relationships for fan area – sediment volume and watershed area – sediment volume (Jakob et al., 2016; Jakob et al., submitted). Air photo interpretation did not identify sediment deposits that could be used to support the development of a frequency-volume relationship.

Debris volume results from the regional relationship and Rickenmann sediment transport equation are shown in Table 6-3. The volume estimates from the Rickenmann (2001) empirical equation are approximately double the regional relationship for return periods up to the 50-year return period. These sediment volumes are associated with Type 1 debris floods.

Table 6-3. 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 (2001)
20	6,000	11,000
50	8,000	19,000

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

The confidence in the debris flood sediment volumes is relatively low as there are very few reliable bedload transport measurements on comparable creeks in BC or elsewhere. Moreover, a significant proportion of this sediment could have been discharged into Kootenay Lake in the past and thus not be accumulated in the channel. Irrespective, the volume of sediment for debris floods is of secondary importance to modeling which relies primarily on peak flows.

6.3.1.2. Debris-Flood Peak Discharge

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 6-5 and Figure 6-2. With respect to these results, the reader should note the following:

- Because there are no hydrometric stations on Procter Creek, historical peak discharges (flood quantiles) were estimated using a Regional FFA. The provincial index-flood model was selected because it produced slightly higher peak discharges than the regional model.
- The historic peak discharge estimates were adjusted by 20% to account for the projected 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 debris flood numerical modelling.

6.3.2. Debris Flows

6.3.2.1. Debris-Flow Frequency-Volume

The magnitude of the 200-year return period debris flow was estimated by assuming a 5-year return period rainstorm (15-minute rainfall intensity = 12.2 mm/hr) in combination with a 100-year return period wildfire. This frequency was multiplied by 2 to account for post-wildfire susceptibility that is most likely for the first two years following the fire. The result is an approximate return period of 250 years for this scenario, which was considered a proxy for the 200-year return period event. The 200-year return period post-wildfire debris flow volume was estimated to be 49,000 m^3.

The 500-year return period event was estimated by applying the 50% increase in debris-flow volumes from the regional debris-flow F-M approach (Jakob et al., submitted) between the 200-year and 500-year events. This yielded a debris-flow volume of approximately 75,000 m^3.

6.3.2.2. Debris-Flow Peak Discharge

As discussed in Section 5.2.2.3, it is not possible to predict, with certainty, if a debris flow becomes muddy or granular, though post-wildfire debris flow experience suggests that most have a muddy appearance (Gartner, pers. comm. 2020). BGC chose to model both the muddy and granular types as per Table 6-4 and Figure 6-1 and carry the results into development of the composite hazard rating map.

Table 6-4. Assumed 200-year and 500-year debris-flow peak discharges for Procter Creek and corresponding peak discharges for muddy and granular debris flows.

Return Period (years)	Volume (m^3)	Q_{max} (muddy) (m^3/s)	Q_{max} (granular) (m^3/s)
200	49,000	160	670
500	75,000	250	980

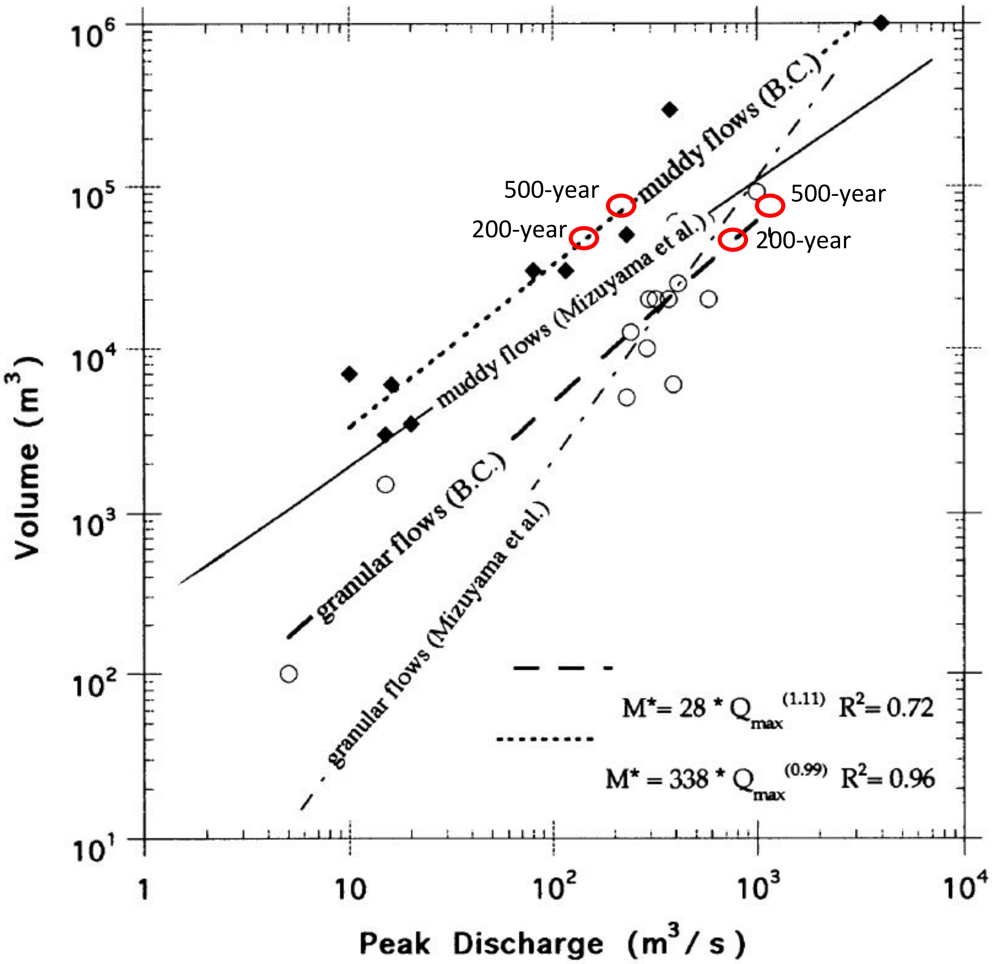

Figure 6-1. Bovis and Jakob (1999) relationship between peak discharge and volume for British Columbia, with comparison regressions computed by Mizuyama et al. (1992).

The resulting peak discharges for both debris floods and debris flows are shown graphically in Figure 6-2 and summarized in Table 6-5.

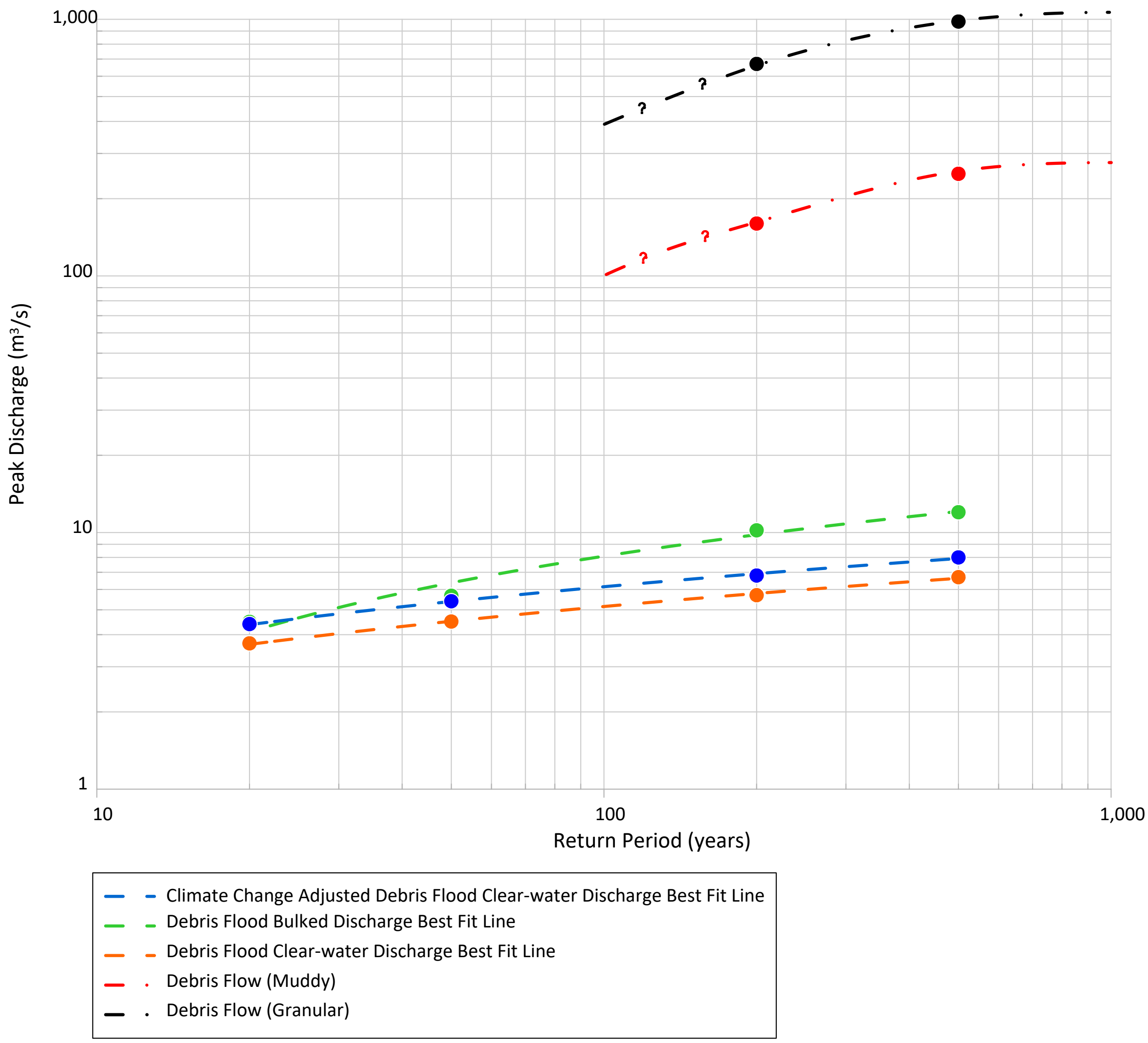

Figure 6-2. Frequency-discharge relationship for Procter Creek for debris floods and debris flows.

Table 6-5. 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	4	4	1.02	4	1	Few active landslides in lower 20% watershed
50	0.02	5	5	1.05	6	1	Landslide activity increases to “several” active landslides in lower 20%
200	0.005	6	7	N/A	160 to 670	Debris Flow	Assuming a wildfire with a 100-year return period burns 2/3rd of the watershed at high and moderate severity and post-wildfire debris flows are triggered by runoff dominated erosion during a 5-year storm that occurs within two years of a wildfire.
500	0.002	7	8	N/A	250 to 980	Debris Flow	Assuming a wildfire with a 100-year return period burns 2/3rd of the watershed at high and moderate severity and post-wildfire debris flows are triggered by runoff dominated erosion during a 10-year storm that occurs within two years of a wildfire.

Note:
1. Refer to Section 2 of the Methodology Report (BGC, March 31, 2020b) for details on bulking method.
2. Only bulked, debris-flow peak discharges were modelled for the 200- and 500-year return periods to be included in the composite hazard rating map.

6.4. Numerical Modelling

6.4.1. Results

A summary of the key observations from the debris flood and debris flow modelling is included in Table 6-6. Drawing 07 provides representative modelling results for model scenario PRC-3 (Appendix E): a 200-year debris flow with a peak discharge of 160 m^3/s to 670 m^3/s, where the maximum impact force from either model is displayed in each cell. Other model scenario results are presented in Cambio Communities. A Cambio user guide is included in the Summary Report (BGC, March 31, 2020a).

Table 6-6. Summary of modelling results.

Process	Key Observations
Clearwater and debris-flood inundation (HEC-RAS model results for 20- and 50-year return periods)	• Both return periods produce inundation of a similar area and are summarized together in the following points. ○ Approximately 115 m upstream of the water intake weir, overbank flow occurs on both the left and right bank, with water flowing in historic channels or depressions. Much of the flow re-enters the main channel after flowing through a wooded area. ○ The water intake weir is overtopped, and a portion of the flows spills down the western side of the fan (western channel). Another portion spills east of the main channel. ○ The main channel has an avulsion at the Woodside culvert causing sheet flow to run north along Second Avenue, overtop Harrop Procter Road and flow west along the railway ditch. ○ Flow from the main channel will be diverted east at the Procter Lane culvert and inundate the downstream area within approximately 110 m of the main channel, including several properties on Jones Road. ○ The western channel is identified as the creek alignment on many maps (e.g., iMapBC), although the main channel currently flows to the center-east of the fan (See Section 4.2.1). Shallow flow spreads over Third Ave, Fourth Ave, Woodside Ave and the properties adjacent. The water flows towards Harrop-Procter Road and continues west along the ditch towards a culvert at the edge of the fan. Assuming this culvert is blocked with debris, the water will pool to a depth exceeding 1 m and overflow the road to then pool upstream of the railway. • The 50-year return period overtops the railway approximately 200 m west of Procter Creek inundating the waterfront properties along Mawdsley Lane and Jones Road with maximum water depths <0.3 m. ○ The water pooling on the upstream side of the railway could also cause the embankment to fail, which increases the maximum depth to 0.5 m in a similar inundation area along Mawdsley Lane and Jones Road.

Process	Key Observations
	• Minor sedimentation is expected at avulsion points with flow depths of a few centimetres in unconfined sloping sections of the fan. Closed depressions will likely be filled with sediment from avulsing flows.
Debris flow inundation (FLO-2D model results for 200- and 500-year return periods)	• The highest impacts due to sedimentation are expected from debris flows at the 200-year and 500-year return periods. • Debris flows at the 200-year and 500-year return periods are very likely to impact the entire upper fan with up to 5 to 6 m of deposition near the fan apex reducing to around 2 to 3 m at the elevation of the western portions of Woodside Avenue. • Flow velocities of debris flows will range between 6 to 8 m/s near the fan apex, reducing to 2 to 3 m/s by the time the debris flow reaches Woodside Avenue. Avulsing flow will likely decelerate quickly as it thins towards the margins with flow velocities being reduced to 1 m/s.
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 Procter Creek will build up sediment and avulse into existing properties on either side of the creek channel north of Jones Road. • Only four debris flow scenarios were simulated (a low and high discharge scenario for the 200-year and 500-year return periods events). A large variety of other outcomes are possible dictated by different flow rheologies, or avulsion scenarios. To support a quantitative risk assessment, various other flow scenarios would need to be modelled. • It is unknown whether the railway embankment will survive debris-flow impact. In case of embankment loss, the flow behaviour will likely deviate from what has been modelled, potentially resulting in different areas inundated and at different depths.

6.4.2. Model Check

Griswold and Iverson (2008) developed an empirical correlation between the planimetric area inundated by non-volcanic debris flows and the associated deposited volume. The modelled surface inundation areas for each return period (red triangles in Figure 6-3) plot somewhat above the expected best fit line, but are not considered outliers with respect to the selected debris flow volumes.

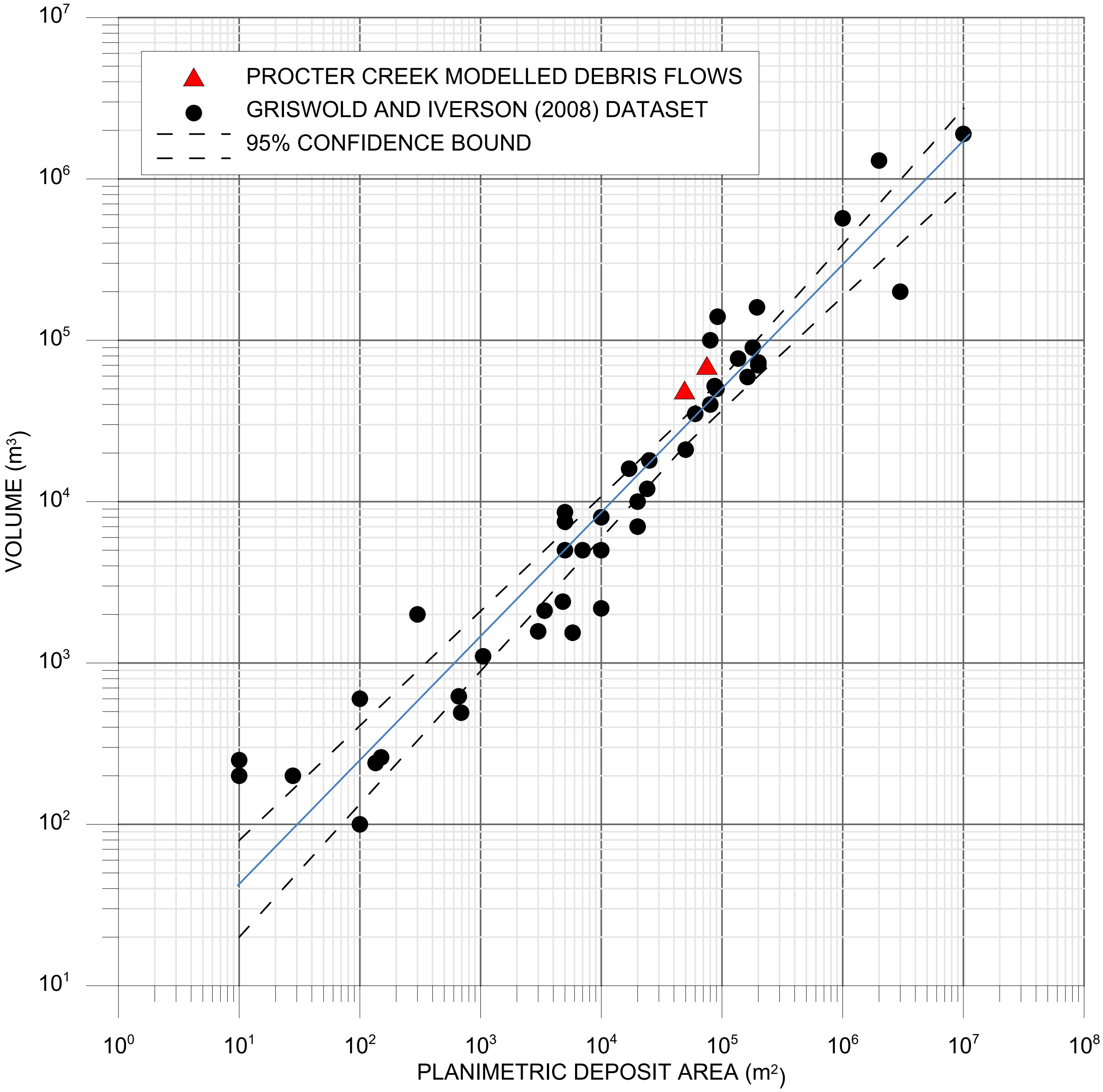

Figure 6-3. Modelled event volumes for Procter Creek (red) in comparison to typical non-volcanic debris flow dataset (black) developed by Griswold and Iverson (2008).

This independent check verifies that the modelled debris-flow inundated areas for the input volumes appear reasonable.

6.5. Bank Erosion Assessment

The bank erosion model could not be calibrated with air photos as the channel is too small to be viewed in aerial imagery at any of the seven cross-sections considered in the bank erosion assessment (see Drawing 02A, 02B for cross-section locations). However, it can be concluded that less than 10 m of observed erosion has occurred since 1929.

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. Note that for the 200 and 500-year return periods, debris flows will dominate which will result largely in channel infill rather than bank erosion.

Return Period (years)	Minimum Erosion (m)	Average Erosion (m)	Maximum Erosion (m)
20	2	3	4
50	4	6	8
200	12	21	29
500	24	29	33

Bank erosion estimates are particularly challenging where there are numerous artificial alterations to banks including stone walls, masonry, or concrete. Therefore, the above erosion values should not be interpreted as precise or applicable, necessarily to the entire creek alignment on the fan-delta reaches. Some homogenization was required to simplify the composite hazard rating map.

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 6-4 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). For the 500-year event the erosion peaks at cross-section 3 and for all other return periods at cross-section 2 (see Drawing 02A, 02B).

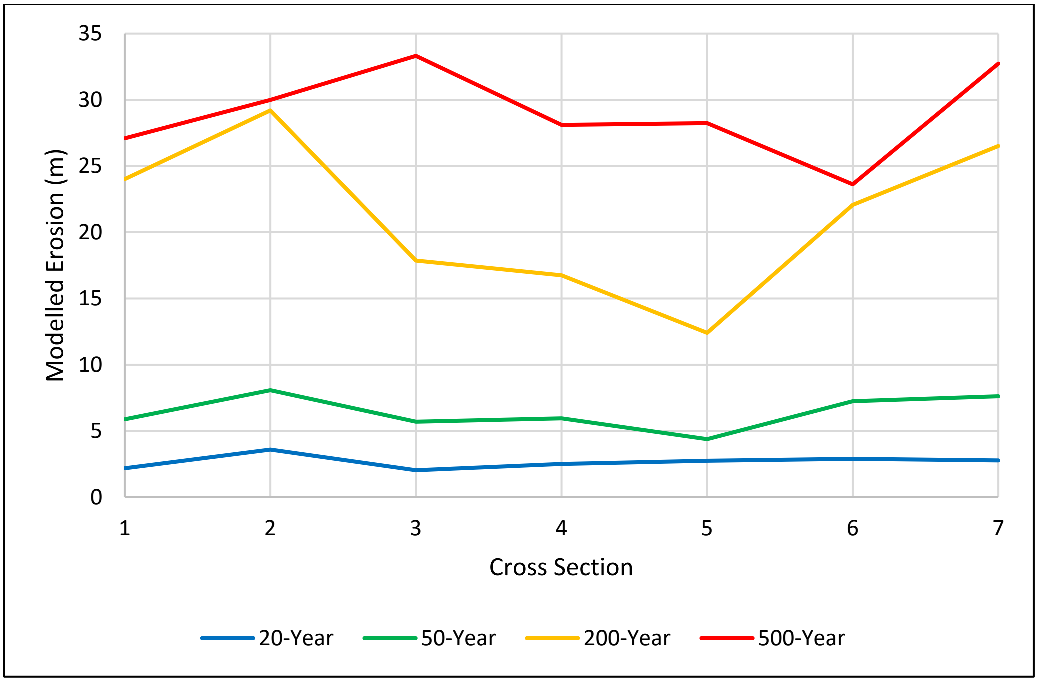

Figure 6-4. Procter Creek 50th percentile bank erosion model results at each cross-section.

There are a few properties and buildings very close to the creek, which fall within the improbable corridor for all return period event. Longer-term progressive erosion could also impact buildings along the creek. All unprotected crossing locations (culvert or bridges) are likely to be subject to bank erosion and can be isolated, eroded and partially collapse or being bypassed on either side.

6.6. Hazard Mapping

Drawing 07 provides a representative example of the model results for the 200-year return period. Drawing 08 provides a composite hazard rating map showing the maximum extent of all hazard scenarios.

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

The composite hazard rating map demonstrates that the hazards of hydrogeomorphic events are dominated by the 200-year and 500-year debris flows as those results in much higher peak flows and thus higher intensities than the clearwater floods. The upper fan of Procter Creek is colour-coded in red implying a high hazard with orange areas extended well into the developed area. This implies that for those areas debris flows will likely result in substantial building damage or destruction.

6.6.1. Comparison with NHC/Thurber (1990)

As outlined in Section 4.2.1, a detailed study of creeks on the West Arm of Kootenay Lake 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.

6.6.1.1. Methodological Differences

The NHC/Thurber (1990) assessment considered debris torrents[9], avulsions or channel shifts, and inundation. For each fan investigated, hazard areas were 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, their hazard maps provided information on relative levels of risk. Specific risk zones were defined as those where individual life loss risk exceeds or falls below specified values. Areas with a hazard (risk) code of 3 or higher were interpreted to have a significant threat to loss of life defined as the annual probability of death of a select individual of > 1:20,000. Figure 6-5 shows the NHC/Thurber risk map for Procter Creek.

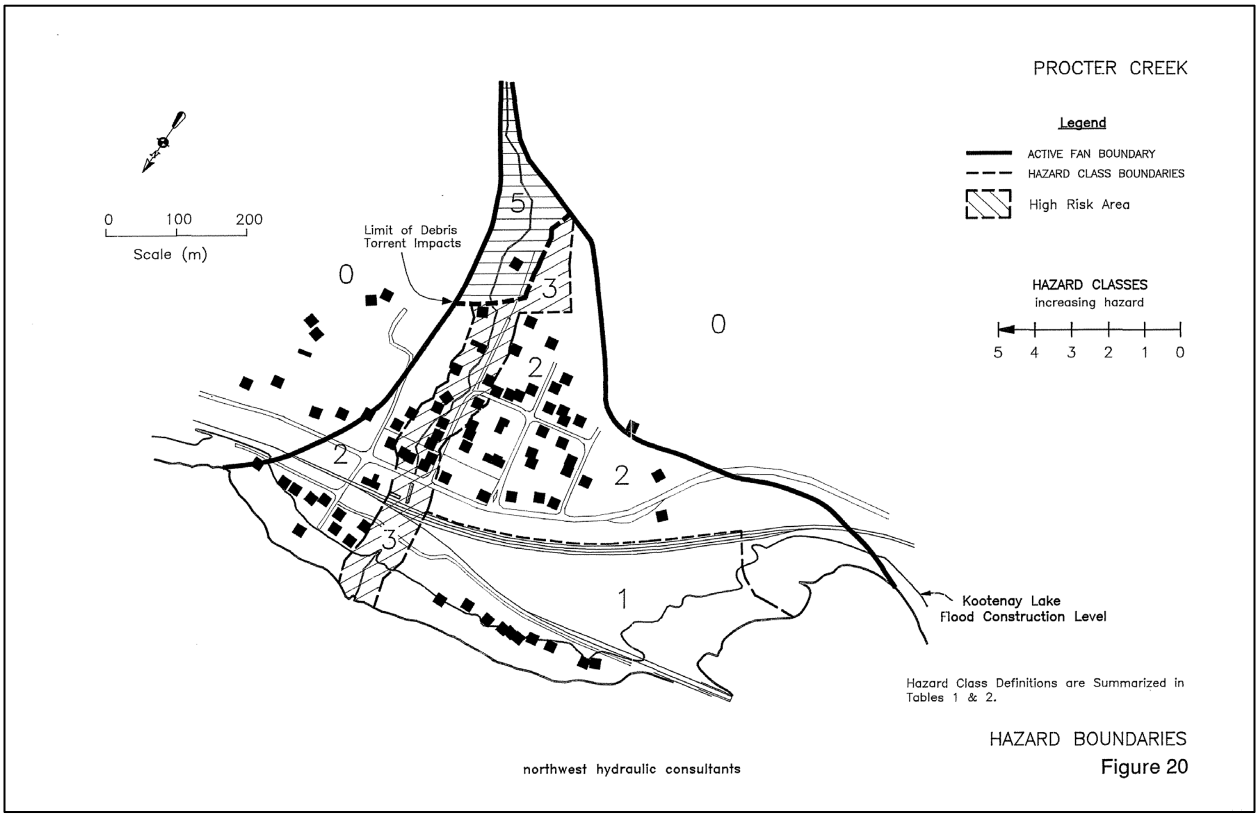

Figure 6-5. NHC/Thurber's (1990) Procter Creek individual life risk map. Class 4 and 5 imply individual life loss risk values exceeding 1:10,000. Class 3 1:10,000 to 1:20,000. Class 0, 1 and 2 < 1:20,000.

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

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

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 intensity
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 and an empirical sediment transport equation	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*. Note that those were estimated, not modelled.	Based on modelled flow velocity, depth and fluid density	The key difference 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.

Note: * See Table 6-9

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.
			>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.

6.6.1.2. Procter Creek Specifics

NHC/Thurber (1990) identified natural debris levees that partially confine the channel and several lobes of deposited debris near the fan apex. The age of these deposits is unknown; however, NHC/Thurber estimated the age of the trees in the vicinity as 80 to 100 years (now 30 years older).

NHC/Thurber assessed there to be an elevated potential for avulsion at Procter Creek near the fan apex due to construction of weirs resulting in the channel bed level aggrading. The estimated bankfull capacity of the creek was assessed to be less that the peak discharge of a 200-year clearwater flood indicating that the Procter Creek fan would be susceptible to overbank flooding even without sediment bulking.

The hazard classification at Procter Creek was highest in the proximal fan and along the main channel. In total 19% of the fan was classified as hazard code 3 or 5. Of all the creeks studied by NHC/Thurber, Procter had the overall lowest risk.

6.6.1.3. Summary

After careful review of the NHC/Thurber (1990) work, BGC concludes that the hazards may be somewhat higher than those estimated by NHC/Thurber as determined through BGC's assessment. This is markedly different from all other creeks where BGC assessed hazards being lower than those evaluated by NHC/Thurber. While 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, they appear to have captured the hazards and risk associated with debris flows in the upper fan.

BGC believes that the current work is a credible representation of hazards on Procter Creek up to the 500-year return period scenarios considered.

7. SUMMARY AND RECOMMENDATIONS

7.1. Introduction

This report provides a detailed hazard assessment of the Procter Creek fan-delta. Procter Creek was chosen as a high priority creek amongst hundreds in the RDCK due to its comparatively high risk as estimated during the prioritization level. This high risk is further exacerbated by the assumed susceptibility of Procter Creek to debris flows at high (200-year and 500-year) return periods. These debris flows are assumed to be preferentially triggered after stand-replacing wildfires.

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 Procter Creek.

A variety of analytical desktop and field-based tools and techniques were combined to decipher Procter 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, Procter Creek is subject to supply-unlimited Type 1 debris floods for the 20- and 50-year return periods. For the 200-year return period, and 500-year return periods, debris flows are believed to be the dominant hydrogeomorphic hazard.

7.2.2. Air Photo Interpretation

Air photo interpretation was completed to gain an understanding of watershed and channel changes on the fan-delta and help with the construction of an F-M relationship. Evidence of possible event can be seen on the 1939 air photo on the western channel downstream of the fan-delta apex. Though it was difficult to note a specific year, a major channel shift from the western fan-delta boundary to the present east channel can be seen between the 1929 and 2017 air photos. This observation is consistent with a documented channel re-alignment in 1914.

7.2.3. Dendrogeomorphology

Dendrogeomorphological analysis was completed to support the development of an F-M relationship by assisting in dating observed impacts to trees potentially associated with sediment transport events. Of the samples analyzed, only one sample provided evidence of a past event in the mid-1970s. Several trees showed impact scars pre-dating the 1970s but with an unknown impact date as those trees were all subject to core-rot that did not allow a more accurate estimate. It is possible that this impact event is attributable to a late 1930s event that has been interpreted from the 1939 air photos.

7.2.4. Peak Discharge Estimates

In recognition of the impacts of climate change and potential bedload and suspended sediment loads, the clearwater flows estimated from a regional 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 discharges was adopted as per Section 4 of the Methodology Report (BGC, March 31, 2020b).
- The climate-change adjusted peak discharges for Proctor Creek range from 3.7 m^3/s (20-year flood) to 6.7 m^3/s (500-year flood).
- Sediment bulking factors of 1.02 (2% increase for the 20-year debris flood) and 1.05 (5% increase for the 50-year debris flood) were adopted as input to numerical modelling.
- For the 200- and 500-year return periods, BGC assumed post-wildfire debris flows with peak discharges of up to 670 and 980 m^3/s, respectively. Those dominate the hazard on Procter Creek.

7.2.5. Frequency-Volume Relationships

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

Table 7-1. Procter Creek debris flood and debris-flow frequency-volume relationship.

Return Period (years)	Peak Discharge (m^3/s)	Event Volume (m^3)
20	4	
50	6	
200	160 to 670	49,000
500	250 to 980	75,000

Note that for the 200- and 500-year return period debris flow, the range indicated reflects the muddy (lower) and granular (upper) debris flow types. Event volumes for the 20 and 50-year return periods were not added as those were not included in numerical modeling, and a significant portion is likely to reach Kootenay Lake.

7.2.6. Modelling

Two numerical models were employed to simulate the chosen hazard scenarios on the Procter 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 6-6 provides key observations derived from the numerical modelling.

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

7.2.7. Bank Erosion Assessment

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

- The bank erosion model was calibrated based on the lack of a visible channel in the air photo analysis by ensuring the predicted 50-year erosion is less than 10 m at all cross-section locations.
- The improbable modelled erosion ranges from 4 m in a 20-year event to 33 m in a 500-year event. The likely erosion ranges from 3 m to 29 m during the 20-year to 500-year events.
- Bank erosion is likely to affect infrastructure along Procter Creek including all bridge structures (see Drawing 02A, 02B).

7.2.8. Hazard Mapping

Model results are cartographically expressed in two ways:

- The individual debris flood model results (hazard scenarios) are captured through an index of impact force that combines flow velocity, bulk density and flow depth flow path. These maps are useful for assessments of development proposals and emergency planning. These hazard scenarios are shown on Cambio Communities and a representative example is shown on Drawing 07.
- A composite hazard rating map (impact intensity frequency map) that combines the debris flood and debris flow intensity (impact force) and frequency up to the 500-year return period event. This map is useful to designate hazard zones and is included as Drawing 08.

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

7.3. Limitations and Uncertainties

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

- Future fan development
- Substantial flood, debris-flood or debris-flow events
- Development of landslides in the watershed with the potential to impound Procter Creek
- Bridge or culvert re-design and/or further channel modification in the developed portion of the Procter Creek fan
- Substantial changes to Kootenay Lake levels.

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 climate impacts on hydrogeomorphic processes evolves.

BGC recognizes that all hazard processes display some chaotic behaviour and therefore not all hazards or hazard scenarios can be adequately modelled. For example, unforeseen log jams or ice jams may alter flow directions and create avulsions into areas not specifically considered in the individual hazard scenarios. Similarly, high bank landslides triggered by bank erosion can divert the creek into pre-existing paleochannels or scour can create new channels. Due to the small size of the Procter Creek channel, the available terrain data (site survey and lidar) may not accurately represent the channel geometry and seemingly small changes (e.g., constriction by landowner activities, vegetation growth) may affect if, when and where overbank flow occurs. This is only relevant for flooding or debris floods. For debris flows, the channel will be entirely overwhelmed and likely not be recognizable after such an event. Despite these limitations and uncertainties, BGC believes that a credible hazard assessment has been achieved on which land use decisions can be made.

7.4. Considerations for Hazard Management

Recommendations are provided in the Summary Report (BGC, March 31, 2020a) as they pertain to all studied RDCK creeks. This section notes Procter 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 Procter 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:

- Stopping organic and mineral debris near the fan apex to avoid downstream aggradation and concordant avulsions. This strategy, while being effective, is expensive and requires regular maintenance to remove debris from the basin area and thus maintain storage capacity. Stream downcutting downstream of the structure which follows when the creek is depleted from its sediment source upstream, can be avoided by allowing grains of a specific size to pass through the structure. This will also be beneficial for downstream fish habitat.
- Most creeks on fans and fan-deltas tend to be wide and laterally unstable, though Procter Creek has been remarkably stable in its current channel, some of which may be due to efforts by residents to keep in in place. Forcing the creek in between berms flanking the creek narrowly on either side is undesirable. Deepening the channel through excavation in the absence of upstream sediment retention will invariably be followed by infill causing a cycle of expensive and potentially disruptive gravel excavations. This is being done at the Resort Municipality of Whistler on Fitzsimmons Creek to avoid long-term sediment accumulation and thus loss of freeboard between flanking dikes. It occurs 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 are preferred. However, setback berms, for example paralleling the creek at the 50th percentile bank erosion line would include several 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 fan apex to Kootenay Lake (~ 600 m) such setback berms would be expensive and would still require occasional sediment removal and maintenance works.

With reference to Figure 7-1, the following specific mitigation measures could be considered to reduce hazards and risks on Procter Creek:

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

Option	Description	Effect on Flood Hazard Reduction
(a)	Debris basin downstream of the fan apex with single outlet structure	Reduction in debris load from debris-flow scenarios, reduced chance of downstream avulsions. Major debris flow attenuation.
(b)	Various channel works to assure channel capacity including channel widening and armouring as well as bridge replacements of private bridges.	Will reduce avulsion risk and damage to bridges and culverts. Only effective for debris flows in combination with option (a).
(c)	Culvert replacement of Harrop-Procter Road.	Will reduce avulsion risk. Only effective for debris flows in combination with option (a) and only fully effective for debris floods in combination with option (b).
(d)	Railway Bridge replacement	Avoidance of culvert blockage and upstream avulsions. Only effective for debris flows in combination with option (a)

This table demonstrates that, to prevent debris flows from impacting the existing development, debris must be stopped before reaching development. Unfortunately, there is no space for a deflection berm as most of the fan is densely developed. Enlarging the channel to pass a debris flow down to Kootenay Lake is also not possible as there is no space for a channel with sufficient dimensions and the channel is not steep enough to convey debris flows in their entirety to the lake. Narrow flanking berms would need to be too high and there is no room for their footprint between existing properties.

Procter Creek fan-delta hosts assets with an estimated $16M in total improvement value. Of the steep creek fan-deltas studied in detail (Table 1-1), Procter Creek has a relatively average improvement value but the highest number of parcels (BGC, March 31, 2019. Hence, while likely expensive, Option (a) may be viable at Procter Creek if it can be shown that first, the costs are commensurate with potentially saving one or more statistical lives and second, the ratio of the construction and maintenance costs to the asset-to-be-protected cost is reasonable.

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. In BGC's opinion, and in absence of any comprehensive debris-flow mitigation works, existing and any proposed development within composite hazard rating areas on Procter Creek fan should be carefully scrutinized against RDCK's level of risk tolerance. If RDCK chooses to adopt quantitative life safety risk tolerance criteria, BGC recommends a quantitative risk assessment be completed for Procter Creek for evaluation against these criteria.
- Removal of any bridges across Procter Creek that are no longer of use.
- Construction of a low (< 1 m high) deflection berm upstream of the concrete weir to avoid avulsions on the east side of the Procter Creek fan-delta.
- In case of a wildfire in the Procter Creek watershed, pending the immediate post-wildfire assessment which will likely be conducted by FLNORD professionals. The RDCK should develop evacuation criteria for Procter Creek with consideration of the hazard areas defined on the composite hazard rating map, especially for those residents located in the red and orange areas. BGC also notes that residents outside of direct impact areas may also need to be considered in evacuation plans, based on factors such as access/egress and the availability of medical services. Details of when such evacuations were to occur would need to be established in collaboration with the RDCK, FLNORD and BGC.

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.

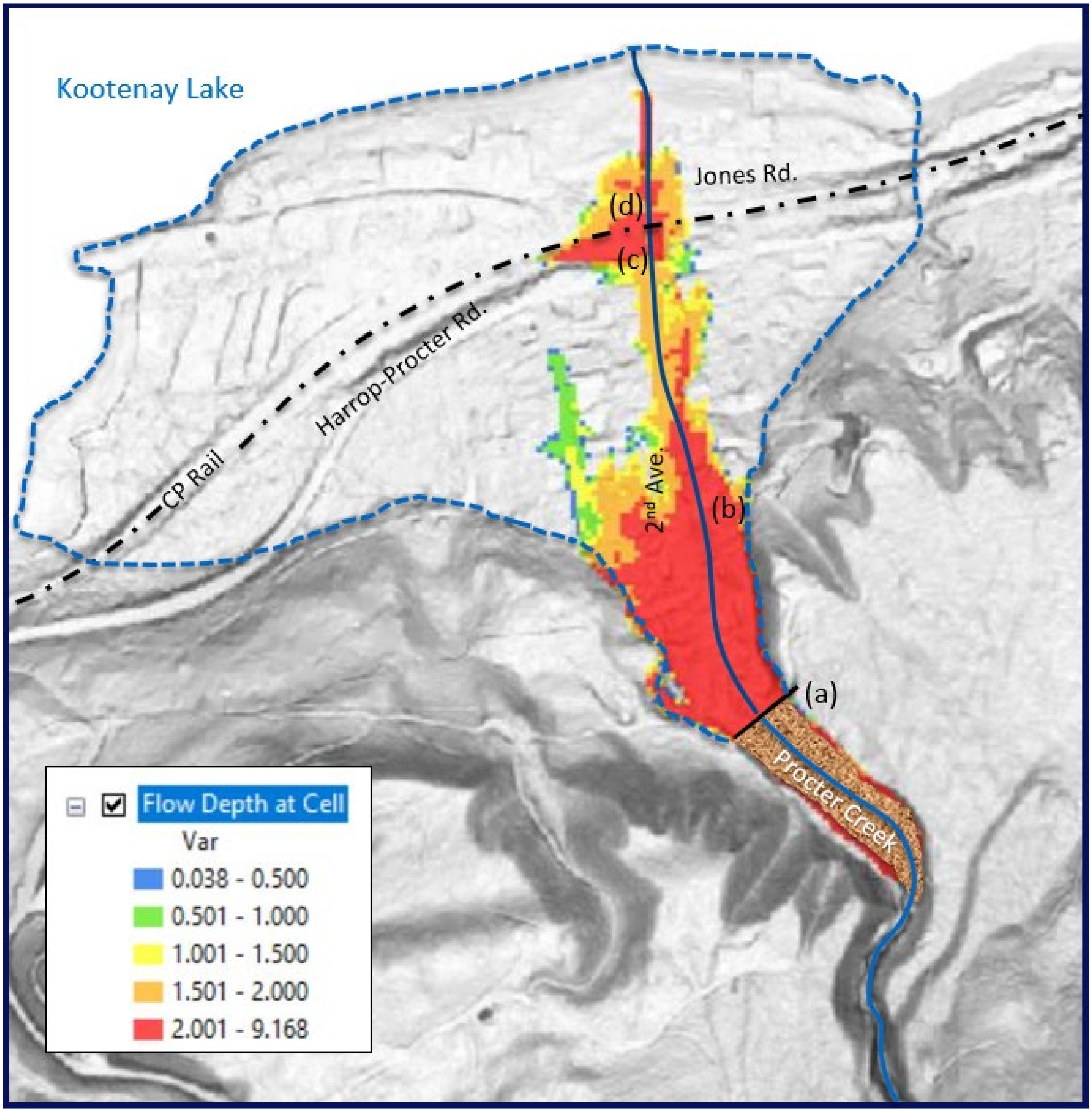

Figure 7-1. Debris-flow inundation map showing flow depths for a 500-year return period debris flow (Q_{MAX} = 250 m^3/s) on Procter Creek from FLO-2D modelling. The figure shows conceptual-level mitigation options for Procter Creek fan-delta. Note that these mitigation options have not been tested by numerical modelling and only serve as an impetus for further discussion. Other options will likely be developed at the conceptual design level.

8. CLOSURE

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

Yours sincerely,

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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 west at Procter Creek fan and the west arm of Kootenay Lake. Photo: BGC, July 6, 2019.

Photo 2.

Overview photo taken during helicopter overflight looking east at Procter Creek fan (right) in the distance, and Kootenay Lake. Photo: BGC, July 6, 2019.

Photo 3.

Overview photo taken during helicopter overflight looking down at the east Procter Creek outlet to the West Arm of Kootenay Lake. Photo: BGC, July 6, 2019.

Photo 4.

Overview photo taken during helicopter overflight looking north at Procter Creek fan and the West Arm of Kootenay Lake. Photo: BGC, July 6, 2019.

Photo 5.

Overview photo taken during helicopter overflight looking west at a scar from a former debris avalanche leading into Procter Creek, approximately 5 km upstream of the fan apex. Photo: BGC, July 6, 2019.

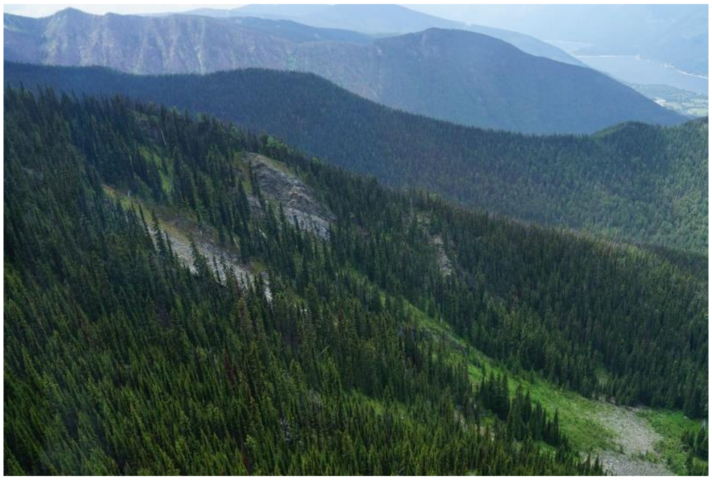


Photo 6.

Overview photo taken during helicopter overflight looking north at a scar from a debris avalanche in the Procter Creek watershed, approximately 5 km upstream of the fan apex. Photo: BGC, July 6, 2019.

Photo 7.

Tree with scar approximately 200 m downstream of the fan apex. Photo: BGC, July 6, 2019.

Photo 8.

Powerhouse approximately 6 m east of channel, approximately 200 m downstream of the fan apex. Photo: BGC, July 6, 2019.

Photo 9.

Looking upstream (south) at the water intake on Procter Creek. Photo: BGC, July 6, 2019.

Photo 10.

Looking downstream (north) at the water intake weir on Procter Creek. Photo: BGC, July 6, 2019.

Photo 11.

Looking south at the east Procter Creek outlet to Kootenay Lake. Photo: BGC, July 7, 2019.

Photo 12.

Looking upstream (south) at a trash rack made from cantilevered rails protecting the railway culverts. Photo: BGC, July 7, 2019.

Photo 13.

Standing on the right bank of Procter Creek looking downstream (north) approximately 60 m upstream from the east outlet to Kootenay Lake. Bank erosion and failure visible on left bank. Photo: BGC, July 5, 2019.

Photo 14.

Looking upstream at Procter Creek. A potential avulsion point is visible on the right bank, approximately 50 m upstream of the fan apex. Photo: BGC, July 7, 2019.

Photo 15.

Standing on the right bank of Procter Creek at the west outlet to Kootenay Lake looking downstream (west). Photo: BGC, July 7, 2019.

APPENDIX C
SEDIMENT SIZE SAMPLING

C.1. SAMPLING LOCATIONS

At Procter Creek, one Wolman Sample was taken, upstream of the fan apex. The sampling location (referred to as Procter 1) is shown in Figure C-1 and in Table C-1. Bed material conditions at the site are shown on Figure C-2.

Table C-1. Wolman sampling location.

Site Name	Procter 1
Location	Upstream of fan apex
Longitude	116°57'33.36"W
Latitude	49°36'53.00"N
Number of stones measured	100

Figure C-1. Wolman sampling location along Procter Creek. Google Earth image of May 1, 2016.

Figure C-2. Photograph taken of Wolman sampling location Procter 1. BGC photograph of November 20, 2019.

At the Procter 1 sampling location, the measuring tape was 21 m long and samples were randomly selected at intervals of 20 cm.

C.2. RESULTS

Results of the Wolman counts are shown in Table C-2 and on Figure C-3.

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

Grain Size	Procter 1
D_{95} (mm)	199
D_{84} (mm)	104
D_{50} (mm)	42
D_{15} (mm)	16
D_{5} (mm)	7

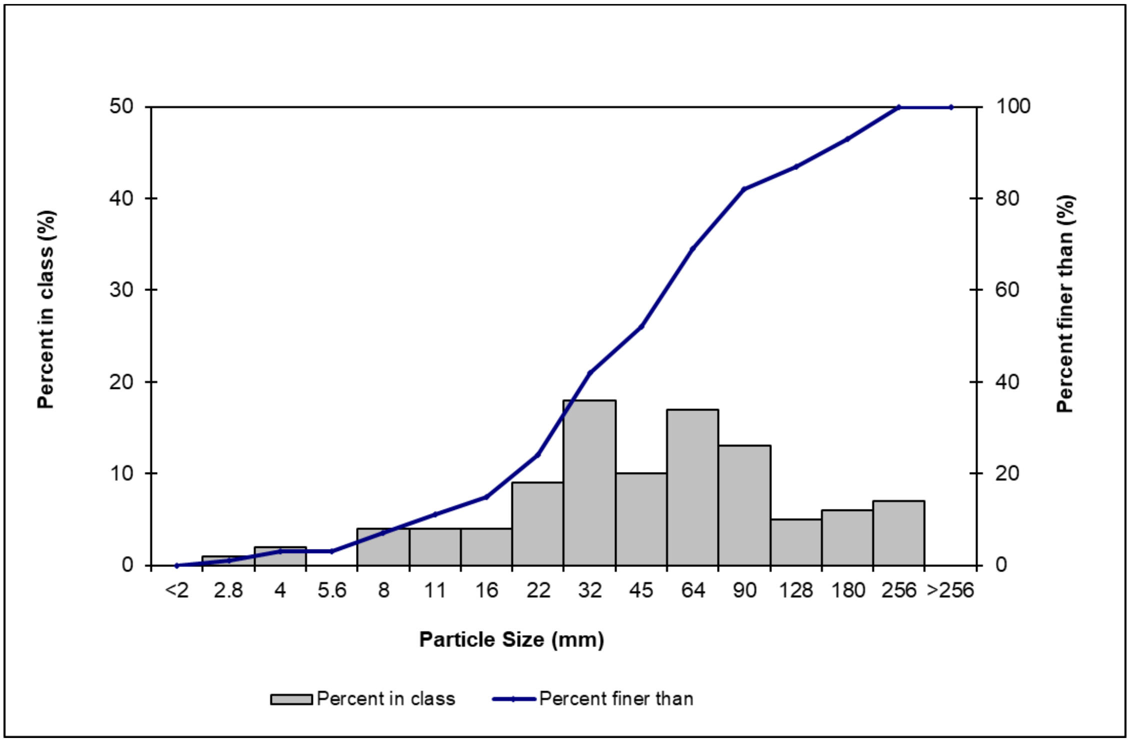


Figure C-3. Procter Creek grain size distribution at Procter 1 (upstream of fan apex) from Wolman count.

APPENDIX D
AIR PHOTO RECORDS

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

Year	Date	Roll Number	Photo Number	Scale
2006	9/1/2006	BCC06135	209-210	20,000
2000	9/17/2000	BCB00038	167-168	15,000
1993	6/20/1993	BCB93011	111-112	15,000
1988	7/22/1988	BC88090	100-102	15,000
1979	8/2/1979	BC79134	23-26	10,000
1974	6/17/1974	BC7568	165-169	8,000
1968	8/8/1968	BC7111	30-32	16,000
1958	7/25/1958	BC2478	14-16	15,840
1952	6/14/1952	BC1447	74-76	31,680
1939	7/24/1939	BC146	76-77	31,680
1929	4/18/1929	A1015	29-30	10,000

APPENDIX E
MODELLING SCENARIOS

E.1. MODELLING SCENARIOS

The scenarios analyzed for Procter 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 Procter Creek.

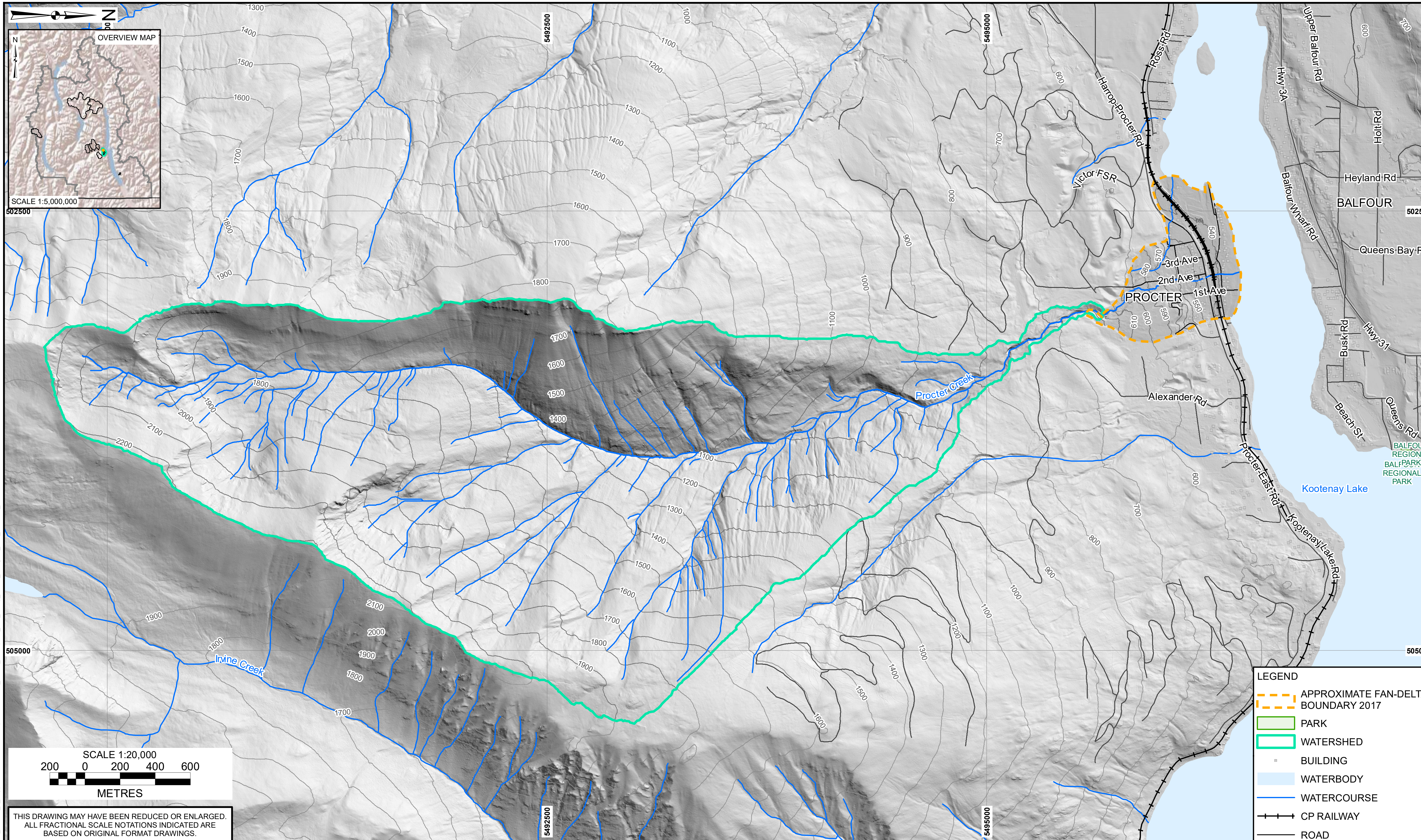
Scenario Name	Return Period (years)	Process Type	Bulking Factor	Bulked Peak Discharge (m^3/s)	Conveyance Structures			Flood Protection Structures				
					Name	Estimated Capacity (m^3/s)	Assumption	Name	Type	Bank Erosion Encroaching	$\tau/\tau c \geq 2$	Assumption
PRC-1	20	Debris Flood (Type 1)	1.02	4	Wooden Footbridge 1	8	Functioning as intended	N/A	N/A	N/A	N/A	All flood protection structures observed in the field are assumed to have minor impact on model results. See report for details on structures.
					Wooden Footbridge 2	6	Functioning as intended					
					Wooden Footbridge 3	2	Lightweight bridge, assumed to be washed away when at capacity					
					Second Ave Culvert	3	Over capacity, blocked					
					Footbridge with Iron Railing	4	Lightweight bridge, assumed to be washed away when at capacity					
					Harrop Procter Road Culvert	2	Functioning as intended					
					Railway Culvert	3	Functioning as intended					
					Jones Road Culvert	4	Functioning as intended					
PRC-2	50	Debris Flood (Type 2)	1.05	6	Wooden Footbridge 1	8	Functioning as intended	N/A	N/A	N/A	N/A	All flood protection structures observed in the field are assumed to have minor impact on model results. See report for details on structures.
					Wooden Footbridge 2	6	Functioning as intended					
					Wooden Footbridge 3	2	Lightweight bridge, assumed to be washed away when at capacity					
					Second Ave Culvert	3	Over capacity, blocked					

Scenario Name	Return Period (years)	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
					Footbridge with Iron Railing	4	Lightweight bridge, assumed to be washed away when at capacity					
					Harrop Procter Road Culvert	2	Functioning as intended					
					Railway Culvert	3	Functioning as intended					
					Jones Road Culvert	4	Functioning as intended					
PRC-3	200	Debris Flow	N/A	160 to 670	Wooden Footbridge 1	8	Lightweight bridge, assumed to be washed away when at capacity	N/A	N/A	N/A	N/A	All flood protection structures observed in the field are assumed to have minor impact on model results. See report for details on structures.
					Wooden Footbridge 2	6	Lightweight bridge, assumed to be washed away when at capacity					
					Wooden Footbridge 3	2	Lightweight bridge, assumed to be washed away when at capacity					
					Second Ave Culvert	3	Over capacity, blocked					
					Footbridge with Iron Railing	4	Lightweight bridge, assumed to be washed away when at capacity					
					Harrop Procter Road Culvert	2	Over capacity, blocked					
					Railway Culvert	3	Over capacity, blocked					
					Jones Road Culvert	4	Over capacity, blocked					

Scenario Name	Return Period (years)	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
PRC-4	500	Debris Flow	N/A	250 to 980	Wooden Footbridge 1	8	Lightweight bridge, assumed to be washed away when at capacity	N/A	N/A	N/A	N/A	All flood protection structures observed in the field are assumed to have minor impact on model results. See report for details on structures.
					Wooden Footbridge 2	6	Lightweight bridge, assumed to be washed away when at capacity					
					Wooden Footbridge 3	2	Lightweight bridge, assumed to be washed away when at capacity					
					Second Ave Culvert	3	Over capacity, blocked					
					Footbridge with Iron Railing	4	Lightweight bridge, assumed to be washed away when at capacity					
					Harrop Procter Road Culvert	2	Over capacity, blocked					
					Railway Culvert	3	Over capacity, blocked					
					Jones Road Culvert	4	Over capacity, blocked					

Notes:
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.
2. A railway embankment failure was considered for the 20- and 50-year return period scenarios.

DRAWINGS



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3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY RDCK DATED 2017, AND GEOBASE CDED. 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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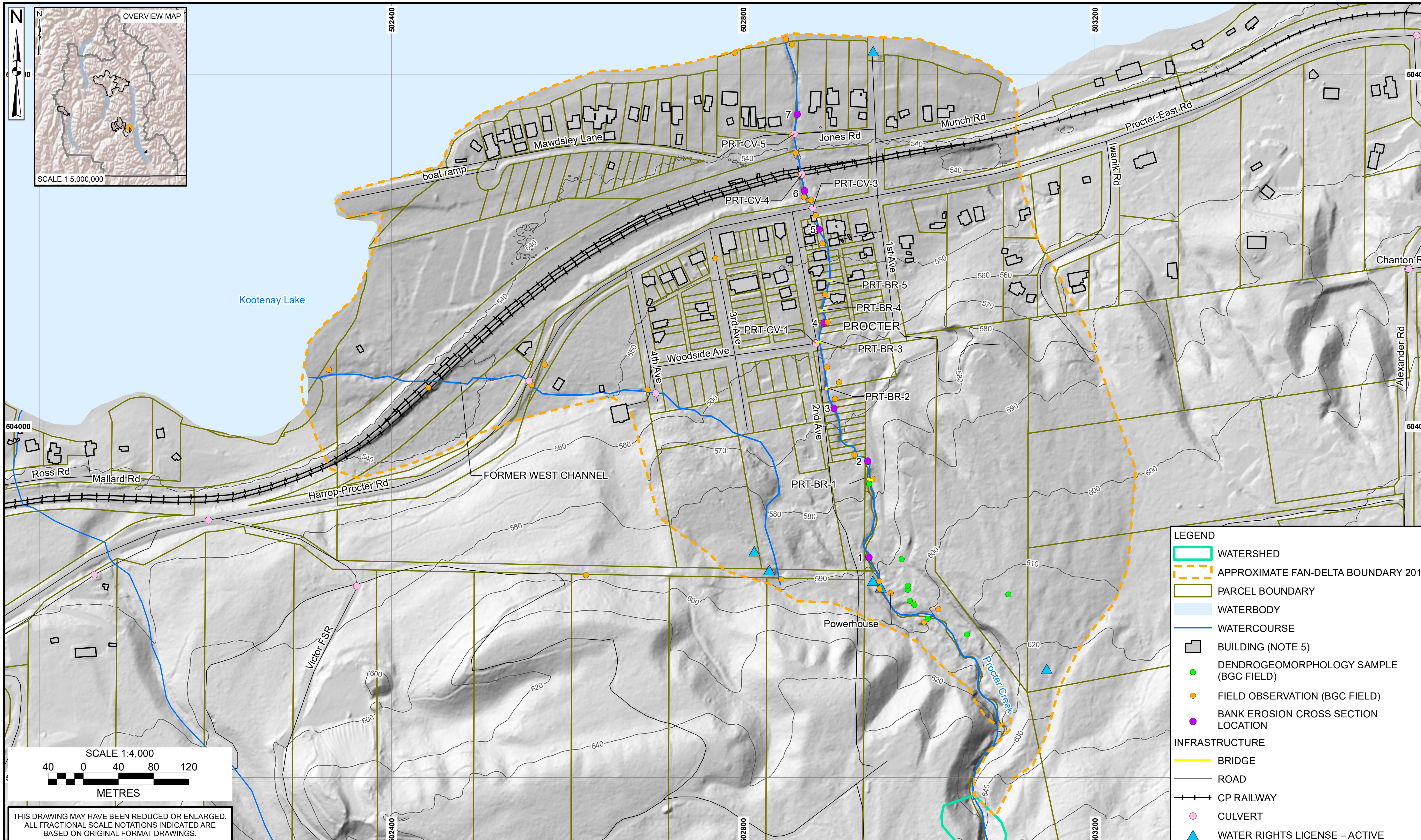
TITLE: PROCTER CREEK SITE LOCATION MAP

PROJECT No.: 0268007

DWG No: 01



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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. ROADS DATA FROM BC DIGITAL ROAD ATLAS. RAILWAY DATA FROM GEOBASE NATIONAL RAILWAY NETWORK. WATER RIGHTS LICENSE DATA FROM GEOBC. PARCELS FROM PARCELMAP BC.
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TITLE:
PROCTER CREEK
FAN-DELTA SITE MAP

PROJECT No.:	DWG No:
0268007	02A

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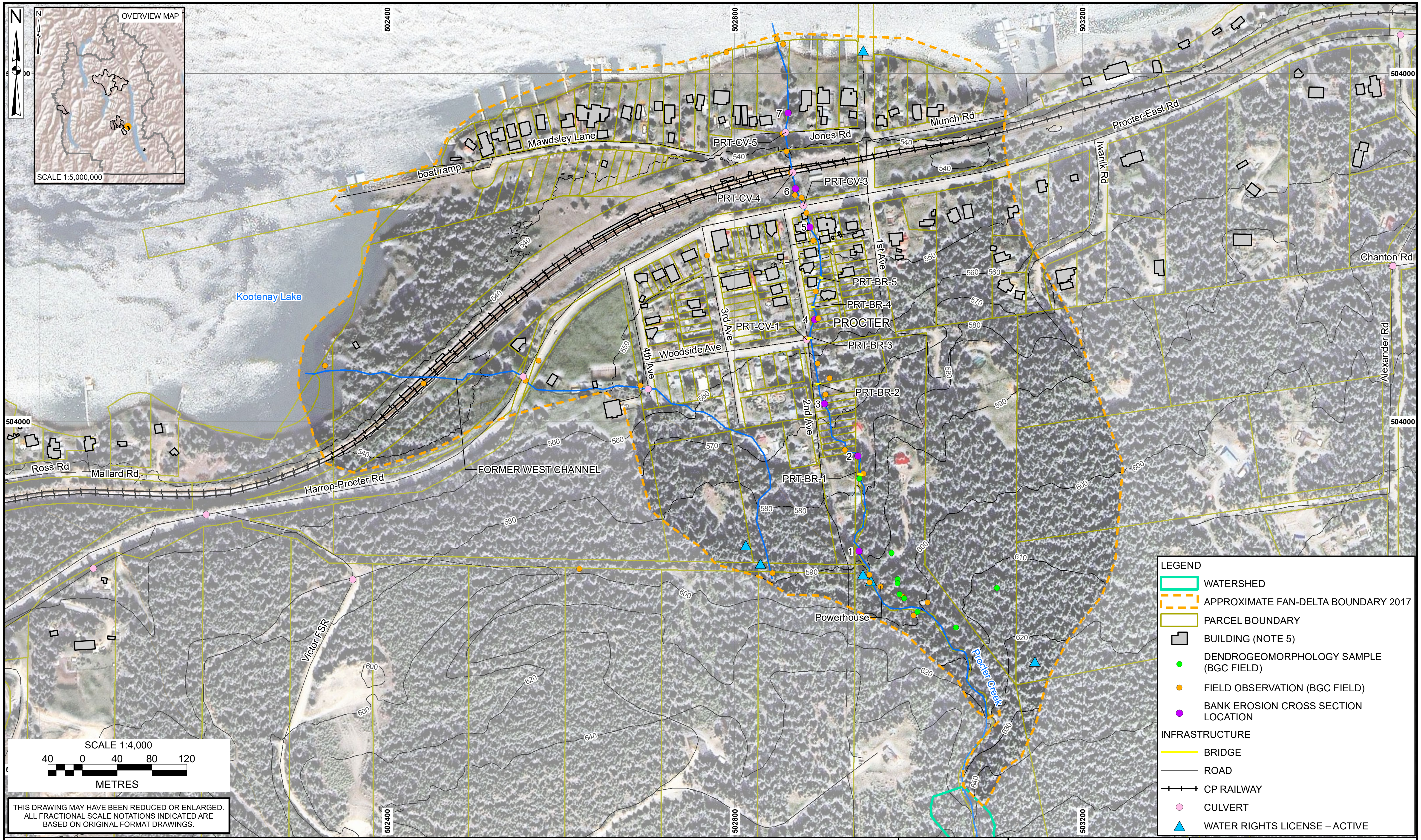

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3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY RDCK, DATED 2017. CONTOUR INTERVAL IS 20 m AND 10 m ON FAN. IMAGERY FROM WORLD_IMAGERY_BASEMAP.
4. THE FAN BOUNDARY AS DRAWN IS APPROXIMATE AND DELINEATES THE LANDFORM BASED ON LIDAR DATED 2017. THE 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. ROADS DATA FROM BC DIGITAL ROAD ATLAS. RAILWAY DATA FROM GEOBASE NATIONAL RAILWAY NETWORK. WATER RIGHTS LICENSE DATA FROM GEOBC. PARCELS FROM PARCELMAP BC.
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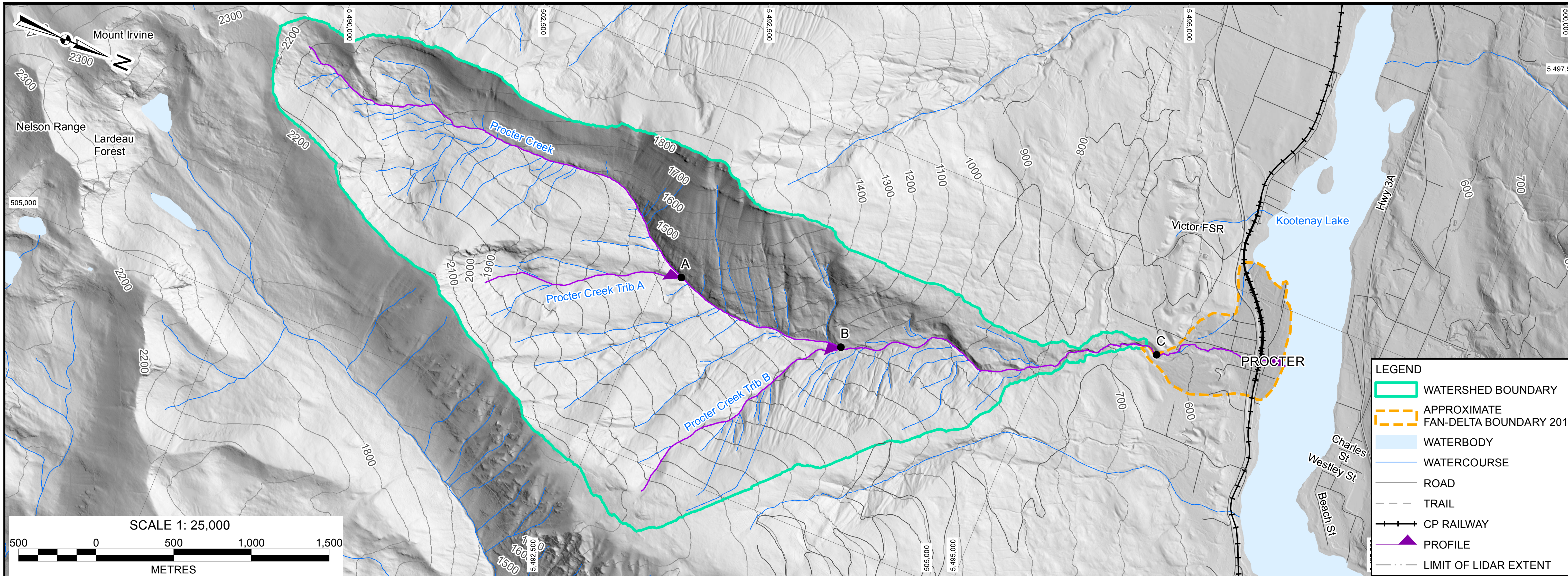

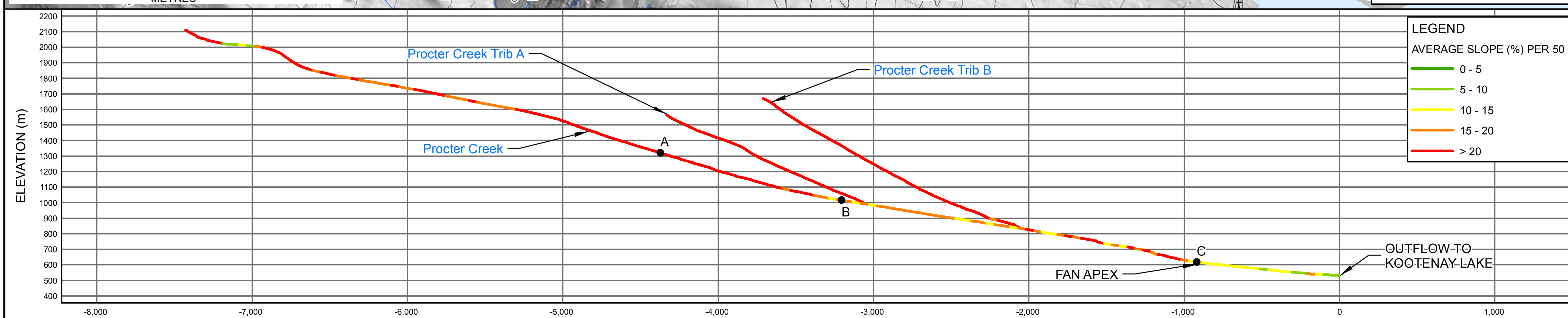

NO VERTICAL EXAGGERATION

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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
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TITLE: PROCTER CREEK PROFILE

PROJECT No.: 0268007

DWG No: 03

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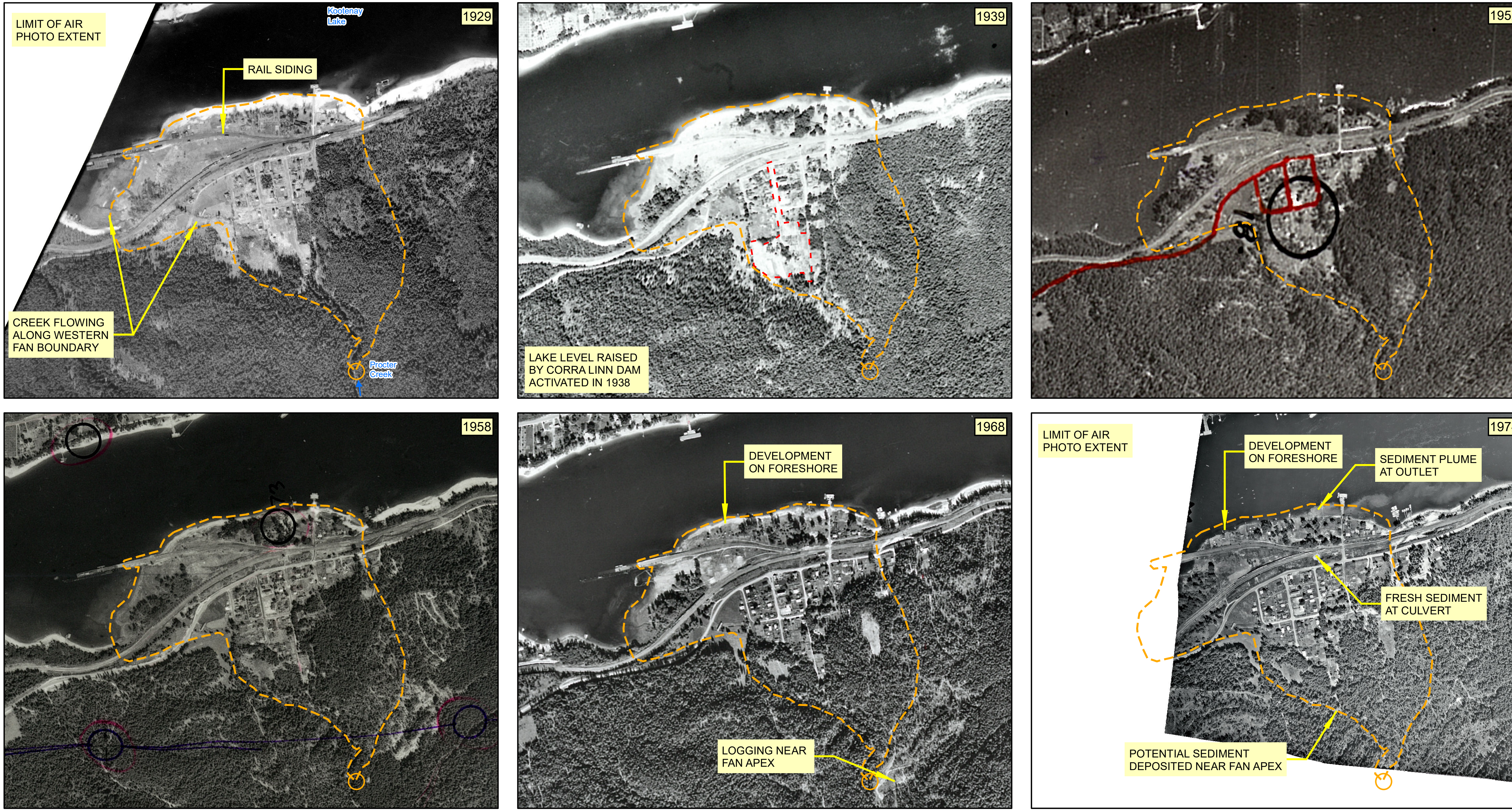

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METRES

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LEGEND

- APPROXIMATE FAN-DELTA BOUNDARY 2017
- FAN APEX
- APPROXIMATE EXTENT OF 1939 EVENT

NOTES:
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5. AIR PHOTO FROM YEARS 1952 AND 1958 WERE MARKED ON PHYSICAL COPIES PRIOR TO BGC'S AIR PHOTO INTERPRETATION.
6. AIR PHOTOS WITH NO LABELS INDICATE NO MAJOR DEVELOPMENT OR CHANGE IN CHANNEL FEATURES COMPARED TO PREVIOUS AIR PHOTO.
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TITLE: PROCTER CREEK AIR PHOTO COMPARISON

PROJECT No.: 0268007

DWG No: 04A

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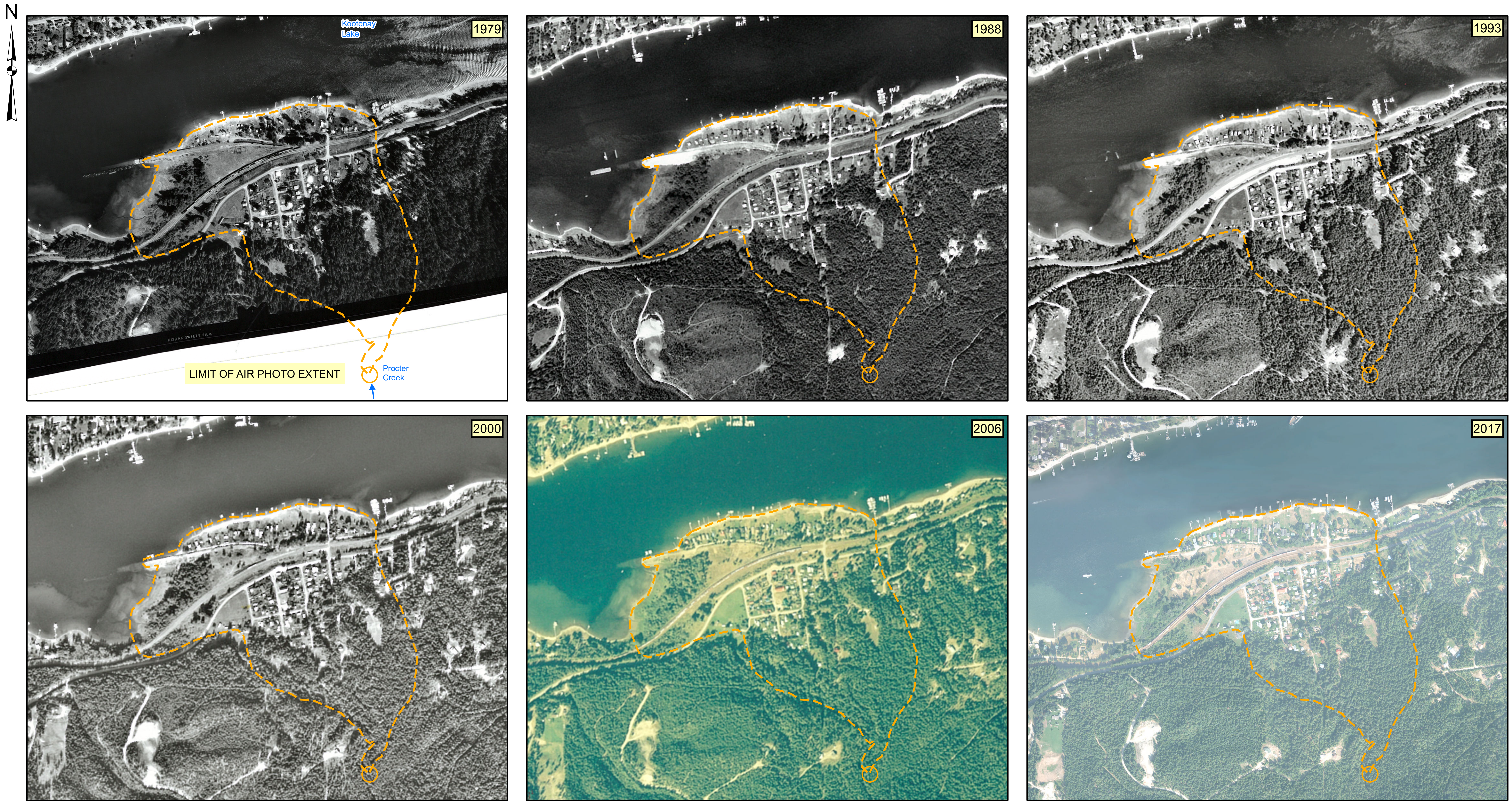

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METRES

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LEGEND

APPROXIMATE FAN-DELTA BOUNDARY 2017

FAN APEX

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5. AIR PHOTOS WITH NO LABELS INDICATE NO MAJOR DEVELOPMENT OR CHANGE IN CHANNEL FEATURES COMPARED TO PREVIOUS AIR PHOTO.
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PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: PROCTER CREEK AIR PHOTO COMPARISON

PROJECT No.: 0268007

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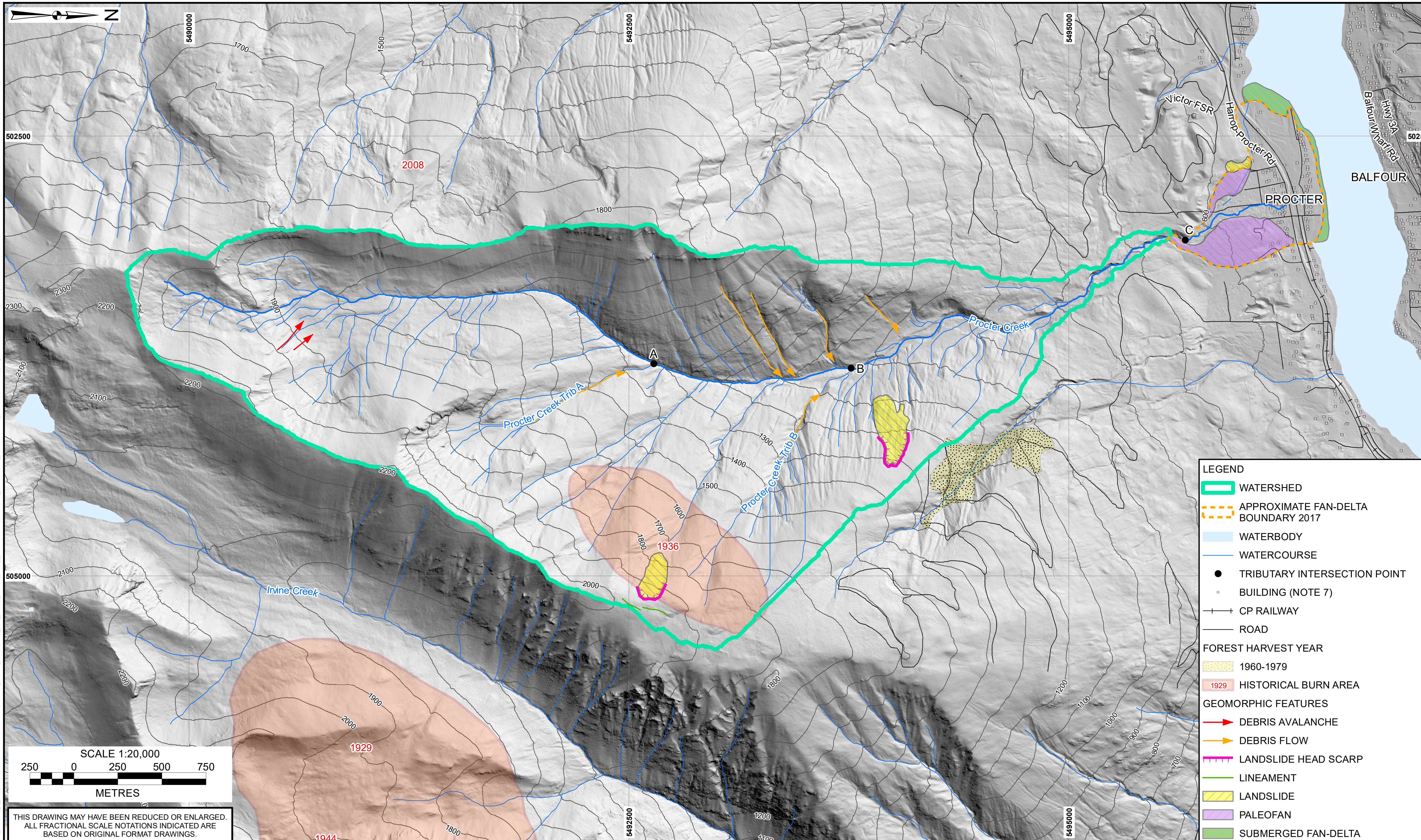

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5. HISTORICAL CUT BLOCK DATA ONLY REPRESENTATIVE OF AREAS THAT INTERSECT WATERSHED BOUNDARY.
6. SUBMERGED FAN-DELTA DELINEATED BASED ON LAKE LEVEL FROM LIDAR DATED 2017.
7. BUILDING FOOTPRINTS DIGITIZED BY BGC BASED ON LIDAR AND REPRESENT ONLY A SUBSET 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.
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PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: PROCTER CREEK WATERSHED GEOMORPHOLOGY

PROJECT No.: 0268007

DWG No.: 05

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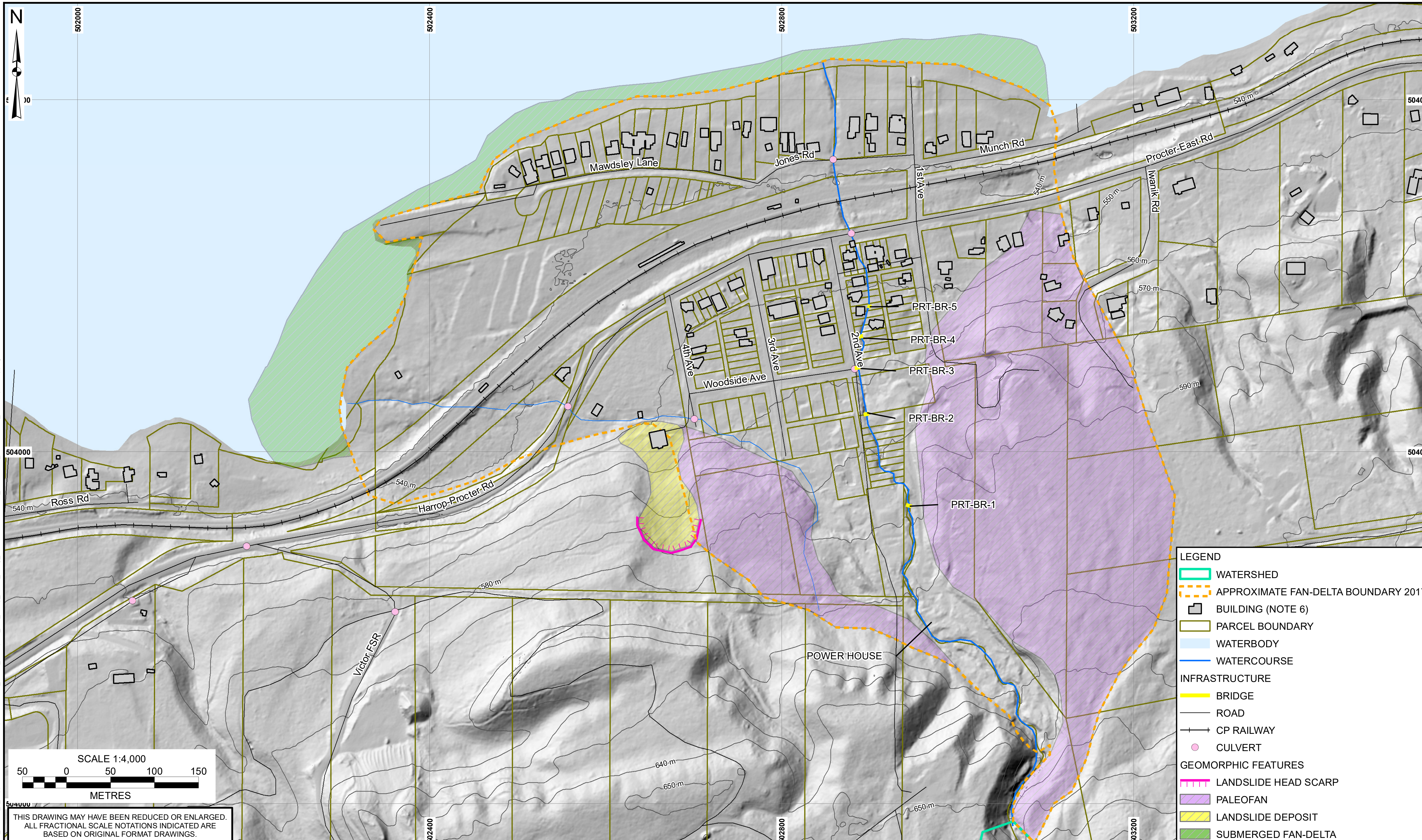

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3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY RDCK DATED 2017, AND GEOBASE CDED. CONTOUR INTERVAL IS 10m.
4. THE WATERSHED AND FAN-DELTA BOUNDARY AS DRAWN ARE APPROXIMATE AND DELINEATE THE LANDFORMS BASED ON LIDAR DATED 2017. THE BOUNDARIES SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DO THEY SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
5. SUBMERGED FAN-DELTA DELINEATED BASED ON LAKE LEVEL FROM LIDAR DATED 2017. WATER DATA FROM CANVEC, UPDATED BASED ON BGC FIELD OBSERVATIONS, WHERE APPLICABLE.
6. CULVERT LOCATIONS FROM BC MINISTRY OF TRANSPORTATION. ROADS DATA FROM BC DIGITAL ROAD ATLAS. RAILWAY DATA FROM GEOBASE NATIONAL RAILWAY NETWORK. 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.

SCALE:	1:4,000
DATE:	MAR 2020
DRAWN:	MW
CHECKED:	JJHP
APPROVED:	MJ

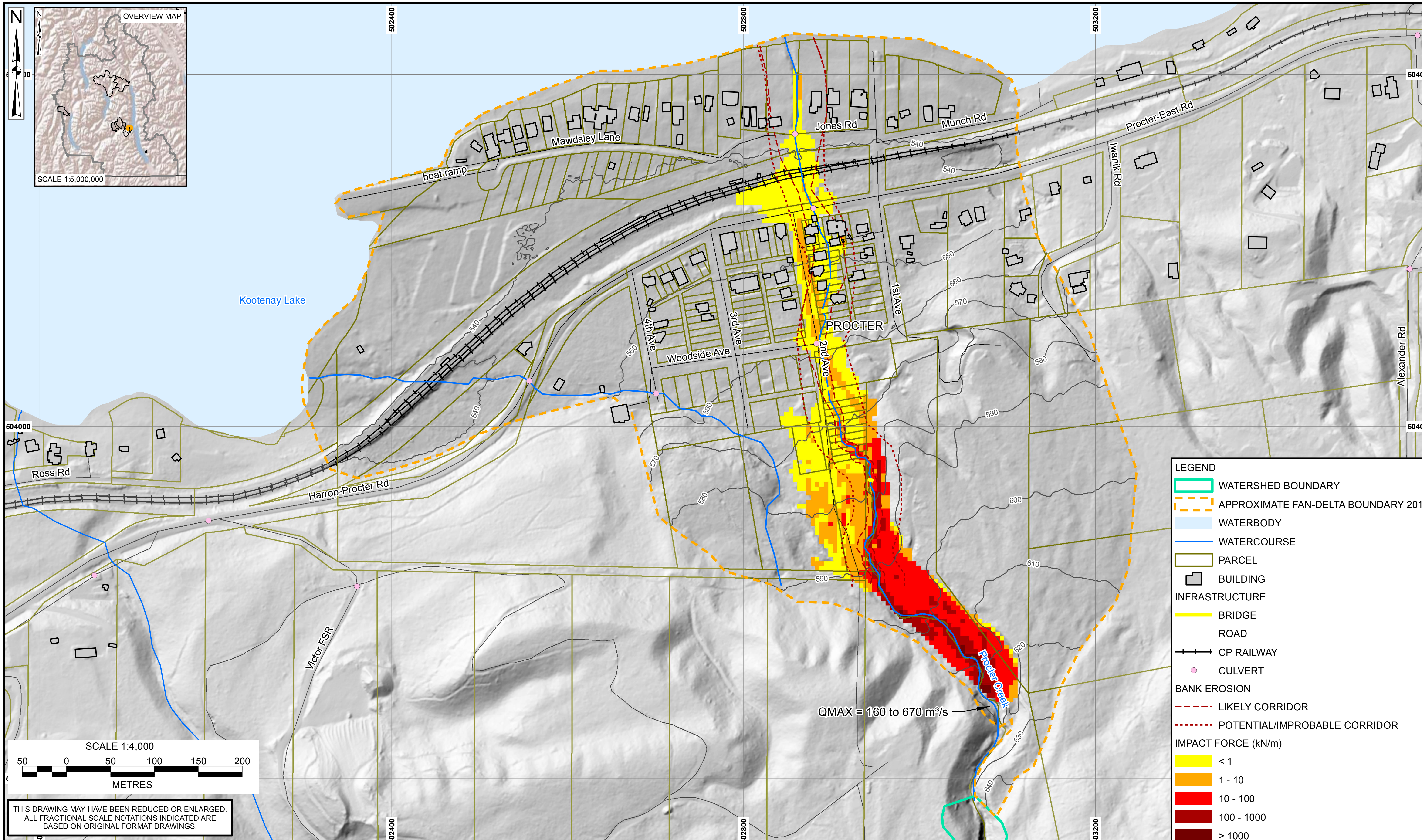
BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT: REGIONAL DISTRICT CENTRAL KOOTENAY

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: PROCTER CREEK FAN-DELTA GEOMORPHOLOGY

PROJECT No.:	DWG No:
0268007	06



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 - PROCTER CREEK", AND DATED MARCH 2020.
3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY RDCK, DATED 2017. CONTOUR INTERVAL IS 20 m AND 10 m ON FAN.
4. BUILDING FOOTPRINTS DIGITIZED BY BGC. ROADS DATA FROM BC DIGITAL ROAD ATLAS. BANK PROTECTION FROM GEOBC AND BGC FIELD OBSERVATIONS. PARCEL MAP FROM PARCELMAP BC.
5. SCENARIO MAP SHOWS CLEARWATER IMPACT FORCE BASED ON FLO-2D MODEL RESULTS FOR THE 200-YEAR RETURN PERIOD COMPLETED BY BGC. THIS IS A REPRESENTATIVE MAP AND DOES NOT SHOW THE FULL SUITE OF MODELLED SCENARIOS. SCENARIO DETAILS ARE OUTLINED IN BGC REPORT.
6. THIS MAP REPRESENTS A SNAPSHOT IN TIME. FUTURE CHANGES (DEVELOPMENT, DEBRIS FLOOD/FLOW MITIGATION, GEOHAZARD EVENTS) MAY WARRANT RE-DRAWING OF CERTAIN AREAS.
7. PROJECTION IS NAD 1983 UTM ZONE 11N. VERTICAL DATUM IS UNKNOWN.
8. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED OR USED FOR ANY PURPOSE OTHER THAN THE PURPOSE FOR WHICH BGC GENERATED IT. BGC SHALL HAVE NO LIABILITY FOR ANY DAMAGES OR LOSS ARISING IN ANY WAY FROM ANY USE OR MODIFICATION OF THIS DOCUMENT NOT AUTHORIZED BY BGC. ANY USE OF OR RELIANCE UPON THIS DOCUMENT OR ITS CONTENT BY THIRD PARTIES SHALL BE AT SUCH THIRD PARTIES' SOLE RISK.

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CHECKED:	LCH
APPROVED:	MJ

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT: REGIONAL DISTRICT CENTRAL KOOTENAY

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: PROCTER CREEK 200 YEAR MODEL SCENARIO PRC-3

PROJECT No.: 0268007

DWG No: 07

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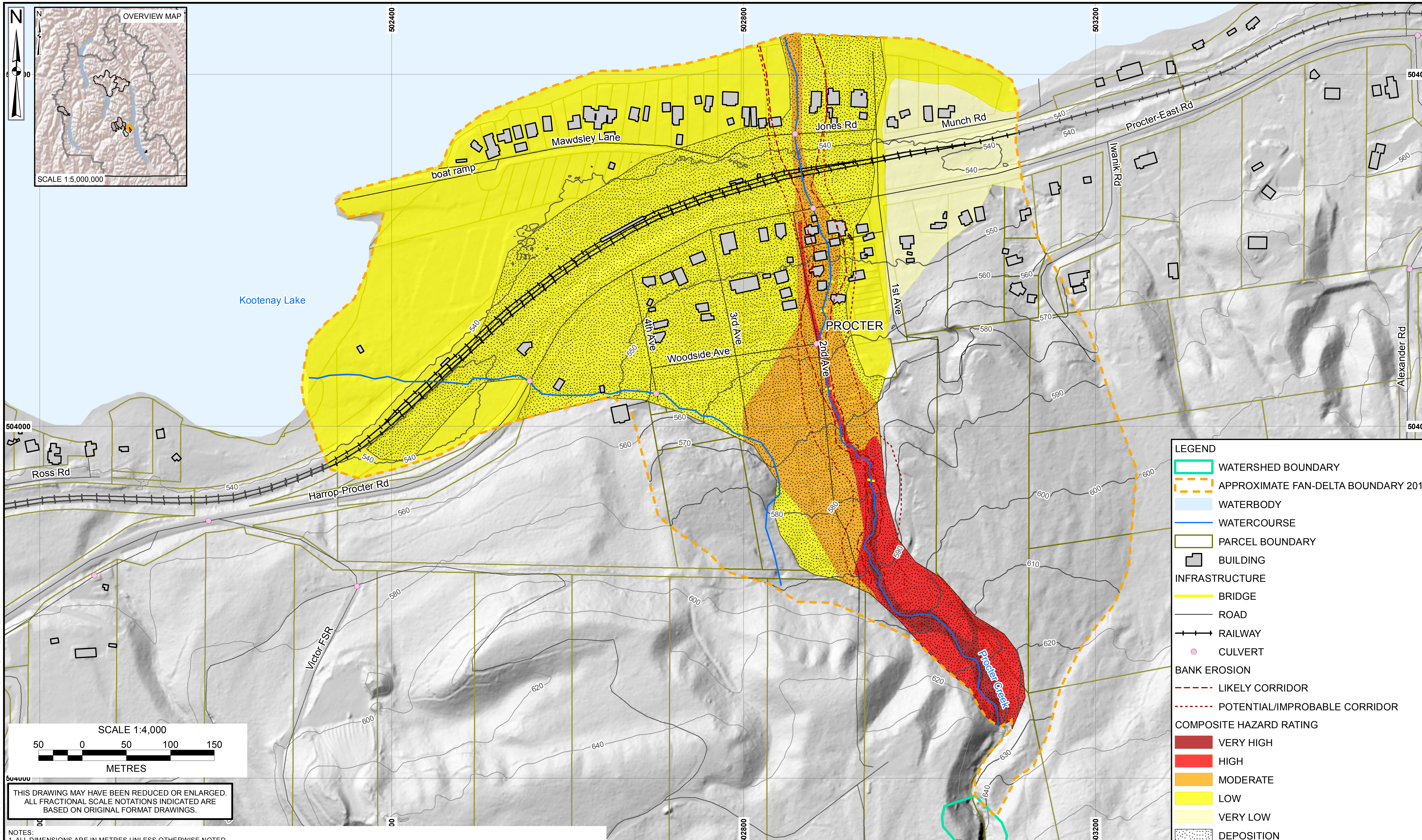

THIS DRAWING MAY HAVE BEEN REDUCED OR ENLARGED. ALL FRACTIONAL SCALE NOTATIONS INDICATED ARE BASED ON ORIGINAL FORMAT DRAWINGS.

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 - PROCTER CREEK", AND DATED MARCH 2020.
3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY RDCK, DATED 2017. CONTOUR INTERVAL IS 20 m AND 10 m ON FAN. THE FAN BOUNDARY AS DRAWN IS APPROXIMATE AND DELINEATES THE LANDFORM BASED ON LIDAR DATED 2017.
4. COMPOSITE HAZARD RATINGS PORTRAYED ON THIS DRAWING ONLY REPRESENT HAZARDS STUDIED WITHIN THE FAN-DELTA BOUNDARY.
5. 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 BASED ON LIDAR AND REPRESENT ONLY A SUBSET OF TOTAL BUILDINGS ON THE FAN-DELTA. CULVERT LOCATIONS FROM BC MINISTRY OF TRANSPORTATION. PARKS DATA FROM GOVERNMENT OF BC. ROADS DATA FROM BC DIGITAL ROAD ATLAS. RAILWAY DATA FROM GEOBASE NATIONAL RAILWAY NETWORK. ELECTRICAL, PETROLEUM, COMMUNICATION AND WATER INFRASTRUCTURE FROM INTEGRATED CADASTRAL INFORMATION SOCIETY. 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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BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:
REGIONAL DISTRICT OF CENTRAL KOOTENAY

PROJECT:
RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE:
PROCTER CREEK
COMPOSITE HAZARD RATING MAP

PROJECT No.: 0268007
DWG No: 08

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