RDCK FLOODPLAIN AND STEEP CREEK STUDY

Harrop Creek

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TABLE OF REVISIONS

ISSUE	DATE	REV	REMARKS
DRAFT	February 18, 2020		Interim draft. Drawings 07, 08 excluded and model results included for discussion purposes.
FINAL	March 31, 2020		Final issue

LIMITATIONS

BGC Engineering Inc. (BGC) prepared this document for the account of Regional District of Central Kootenay . The material in it reflects the judgment of BGC staff in light of the information available to BGC at the time of document preparation. Any use which a third party makes of this document or any reliance on decisions to be based on it is the responsibility of such third parties. BGC accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions based on this document.

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EXECUTIVE SUMMARY

This report and its appendices provide a detailed hydrogeomorphic hazard assessment of Harrop Creek. This 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 consequences from debris flooding. 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 Harrop Creek fan-delta. This work is the foundation for possible future quantitative risk assessments or conceptualization and eventual design and construction of mitigation measures.

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

Multiple hazard scenarios were developed for specific event return periods. This included bulking of flow to allow for higher organic and mineral sediment concentrations and bridge blockage scenarios.

Two numerical models were employed to simulate the chosen hazard scenarios on the fan-delta. The reason for using two models was to simulate a range of results as both models have their distinct advantages and shortfalls. In addition, BGC applied a bank erosion model that allows estimation of bank erosion for different probabilities. This is especially important for debris floods, which are known to result in sudden and intensive bank recession in a single runoff event. Table E-1 provides key observations derived from the numerical modelling.

The multiple process numerical modelling ensemble approach demonstrates the key hazards and associated risks stem from (a) the potential of the Erindale Road bridge blockage and subsequent avulsions and (b) avulsions near the fan apex which tend to favour the eastern portion of the fan. Flooding of roads and possible road embankment breaches would sever the access to affected fan-delta segments and to nearby fan-deltas which is important for emergency preparedness.

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

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

Process	Key Observations
Clearwater inundation (HEC-RAS results for all return periods)	• Harrop Creek avulses for all modelled flows near the fan-delta apex. • Avulsions are shallow and follow existing avulsion channels • As flow avulsions reach Harrop Proctor Road and the railway embankments, the flows will pond and, depending on flood duration, eventually overtop the embankments assuming that culverts are rendered dysfunctional (potentially leading to a breach of the road or rail embankments). • Downstream of the railway crossing of Harrop Creek, flows will become unconfined due to the expected Erindale Road bridge blockage (low capacity) and flow through developments east and west of Harrop Beach Road. • While the overall composite hazard rating is comparatively low, flooding of basements and first floors with low entry elevations could still result in substantial economic damage.
Sedimentation	• Sedimentation associated with debris floods will be focused in the active channel and avulsion channels. The lower active channel downstream of the railway crossing could, in extreme events, aggrade to bank full. • The average deposition depth across the affected fan-delta portion will likely be around 10 cm.
Bank Erosion	• Bank erosion ranges between 4 m (20-year) and 30 m (500-year) while maximum erosion can reach to almost 50 m (500-year debris flood). Bank erosion potential generally decreases downstream. • Properties within the 50th percentile bank erosion corridor are likely subject to being affected by erosion if unprotected.
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 Harrop Creek will build up sediment and avulse particularly east of Harrop Beach Road and west of the active channel. • The location and width of CP Railway embankment breaches are very difficult to predict. Such breaches could lead to sudden and rapid and deep water flows immediately downstream of the breach. This process is not reflected in BGC's hazard maps.

The composite hazard rating map combines all hazard scenarios into one map and incorporates the respective debris flood frequencies. It provides a sense of the areas that could possibly be impacted by future debris floods up to the highest modelled return period. The composite hazard rating map can serve to guide subdivision and other development permit approvals. It requires discussions and regulatory decisions on which hazard zone is attributed to specific land use prescriptions, covenants, bylaws or other limiting clauses for both existing and proposed development.

The categories range from very low to very high hazard. Very low hazard is defined as areas likely to not be affected by any of the modeled scenarios up to the 500-year return period debris floods, but which are not free of hazard. Very low hazard zones could be impacted by flows of higher return periods, or if, over time, the channel bed of Harrop Creek aggrades, or is artificially altered. All other hazard categories are classified via the impact force intensity. The composite hazard rating map shows that most of the Harrop Creek fan-delta is subject to very low and low hazards. Moderate and high hazards are generally confined to the channel of Harrop Creek as well as in localized avulsion channels.

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

While not comprehensive or quantitative, BGC provides several considerations for creek hazard management. These include (from the top of the fan delta to the bottom): A debris basin downstream of the fan apex to reduce sedimentation on the fan; a deflection berm on east side of channel downstream of fan apex to prevent some avulsions to the eastern fan section; various constructed channels that follow avulsion channels across the fan to reduce flow in the main channel and avulsion potentials downstream; and increase the capacity of bridges and culverts along the main channel. In addition to physical mitigation, other measures should be considered such as development restrictions.

Some uncertainties persist in this study. As with all hazard assessments and corresponding maps, they constitute a snapshot in time. Re-assessment and/or re-modelling may be warranted due to significant alterations of the surface topography or scenario assumptions, such as future fan-delta developments, debris floods, formation or reactivation of existing large landslides in the watershed that could impound Harrop Creek, or bridge re-design. 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.

Not all hazards can be adequately modelled as each process displays some chaotic behaviour. For example, unforeseen log or ice 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 also alter the morphodynamics of the fan-delta and the upstream channel.

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

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1. INTRODUCTION

1.1. Summary

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

Table 1-1. List of study areas.

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

This report details the approach used by BGC to conduct a detailed steep creek geohazards assessment for Harrop Creek, located approximately 21 km northeast of Nelson, BC, in Electoral Area E. The site lies on the south side of Kootenay Lake West Arm and flows along the east side of the community of Harrop, BC into the lake.

The community of Harrop has undergone a number of name changes in history as described by Nesteroff in the Nelson Star newspaper (January 25, 2015). For the purposes of this report, the name Harrop Creek is applied acknowledging that the creek is also known as Mill Creek. This is consistent with the official spelling by the BC Geographical Names Office (2019).

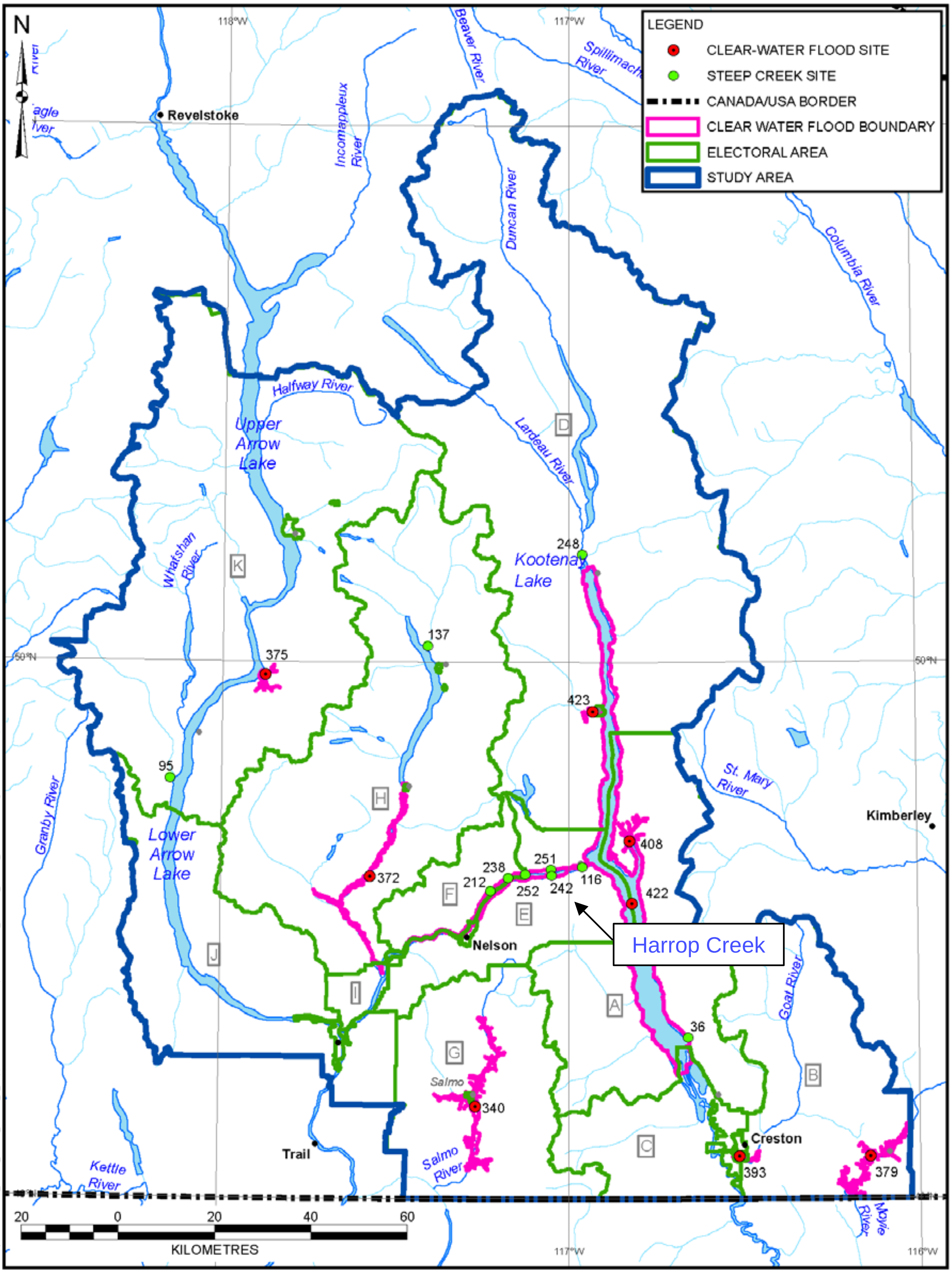

Figure 1-1. **Hazard areas prioritized for detailed flood and steep creek mapping. Site labels correspond to hazard identification numbers in Cambio Communities. Harrop Creek (No. 242) is labelled on the figure.**

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 Harrop 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 (BGC, March 31, 2020a) 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 Harrop 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-delta, and creek characteristics.
- Development of a comprehensive site history of floods and mitigation activity.
- Development of frequency-magnitude (F-M) relationships (flow (discharge) and sediment volume).
- Consideration of climate change impacts on the frequency and magnitude of steep creek flood hazard processes.
- Identification of active and inactive[1] portions of the alluvial fan-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.
- Consideration of processes specific to fan-deltas (backwater effect during times of high lake levels and high peak discharges).
- Recommendations for hazard management on the alluvial fan-delta.

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

For clarity, BGC notes that the current study is a hazard assessment. No estimation of geohazard consequences or risk were completed as part of the Stream 2 scope of work.

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

Table 1-2. Return period classes.

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

1.3. Deliverables

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

This report is best read with access to a BGC web application, Cambio^{TM}. Cambio displays the results of both the Stream 1 and Stream 2 studies. The application can be accessed at *www.cambiocommunities.ca,* using either Chrome or Firefox web browsers. A Cambio user guide is provided in the Summary Report (BGC, March 31, 2020a). As outlined in Section 1.1, the report is best read with the Summary Report (BGC, March 31, 2020a) and Methodology Report (BGC, March 31, 2020b).

1.4. Study Team

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

- Kris Holm, M.Sc., P.Geo., Principal Geoscientist
- Sarah Kimball, M.A.Sc., P.Eng., P.Geo., Senior Geological Engineer
- Matthias Jakob, Ph.D., P.Geo., Principal Geoscientist
- Hamish Weatherly, M.Sc., P.Geo., Principal Hydrologist
- Lauren Hutchinson, M.Sc., P.Eng., Intermediate Geotechnical Engineer
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- Matthias Busslinger, M.A.Sc., P.Eng., Senior Geotechnical Engineer
- Carie-Ann Lau, M.Sc., P.Geo., Intermediate Geoscientist

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

- Jack Park, B.A.Sc., EIT, GIT, Junior Geological Engineer
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Table 1-3. Study team.

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6.4	Matthias Jakob	Lauren Hutchinson
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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.

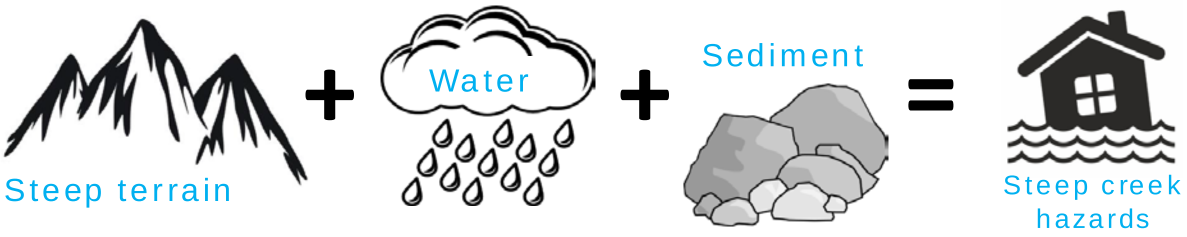


Figure 2-1. Illustration of steep creek hazards.

Steep creek hazards span a continuum of processes from cleat-water flood to debris flows (Figure 2-2). Debris flow is by definition a landslide process. This section introduces these hazards; more details are provided in Section 1 of the Methodology Report (BGC, March 31, 2020b). Definitions of specific hazard terminology used in this report are provided in Appendix A.

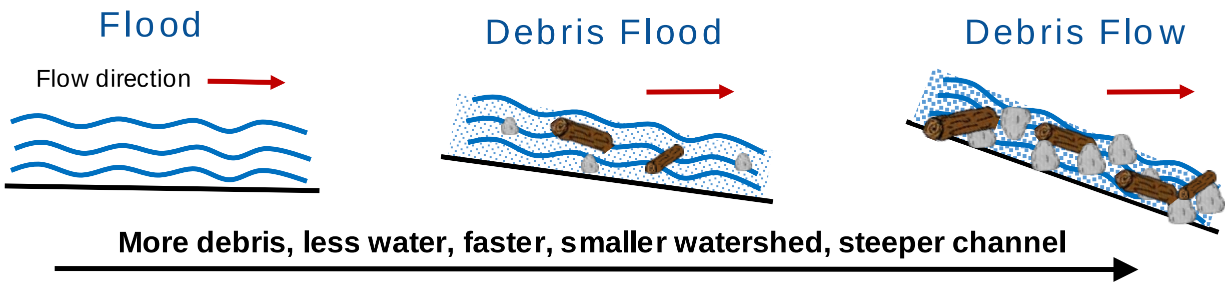


Figure 2-2. Continuum of steep creek hazards.

2.2. Clearwater Floods and Debris Floods

Clearwater floods occur due to rainfall, or when snow melts. Recent major clearwater 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 Jakob and Church (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 of water filled with water. Then it is spilled down a children's slide. That's a clearwater flood. Refilling the bucket to 10 litres and taking a shovel of sand and perhaps some twigs and put it into the bucket. Now the water-sediment mixture occupies 12 litres worth of volume. It has bulked by a factor of 1.2. If one mixes it a bit and then spill it down the slide, one has a bulked debris flood with some 20% sediment concentration by volume. The experiment can be repeated with increasing volumes of sediment until it becomes a debris flow (see Section 2.3).

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

Within the RDCK, recent debris floods occurred on Fletcher Creek and Hamill Creek in June 2013 (Figure 2-3). The June 2013 events were damaging at both creeks, with multiple homes being flooded and 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.

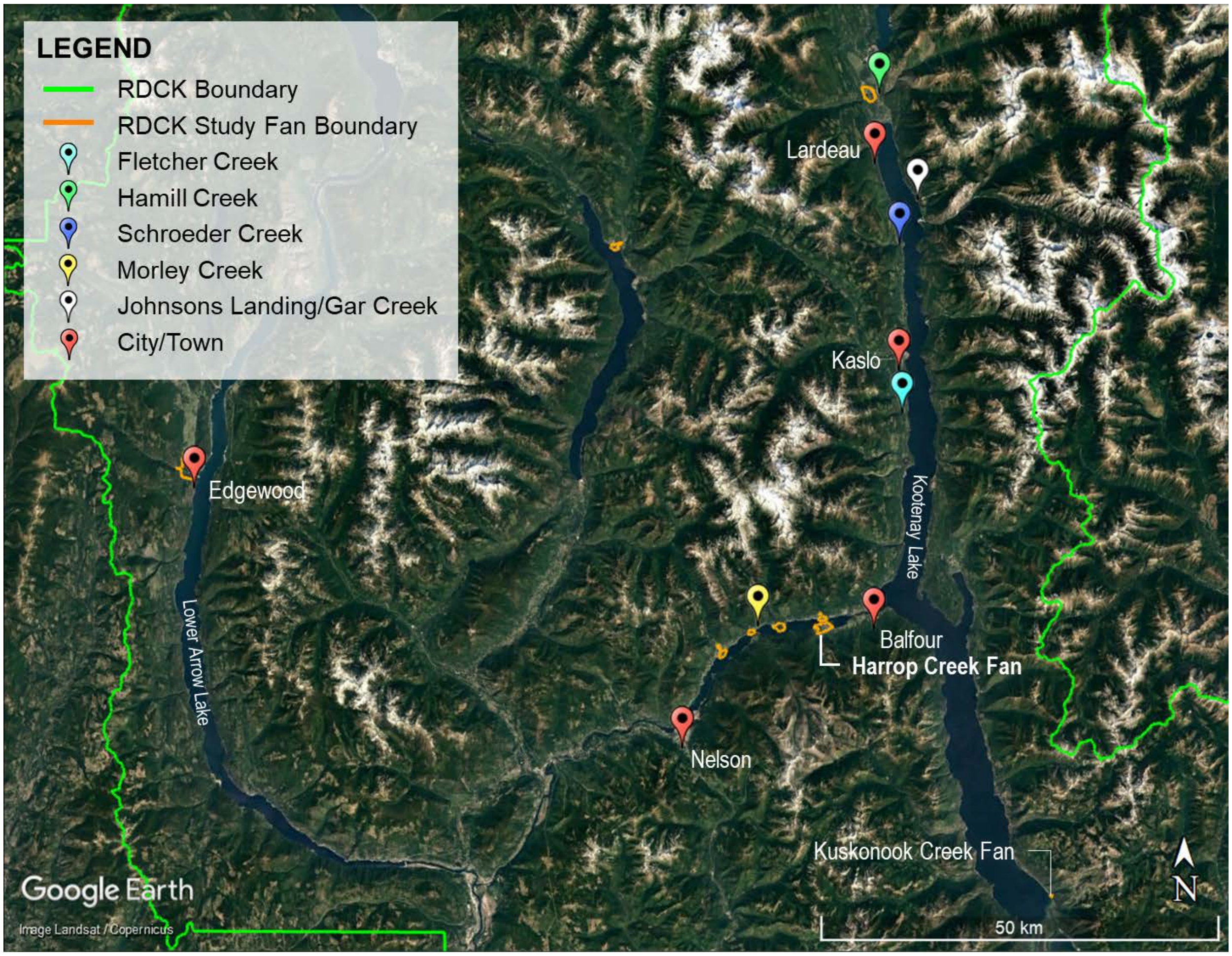


Figure 2-3. Locations of RDCK fan-deltas and recent clearwater floods, debris flows, and debris floods (Google Earth Pro, 2016).

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-delta apex. If the creek is subject to debris flows, the peak discharge may be 1 to 2 orders of magnitude higher than a 200-year flood (Jakob, 2005). Figure 2-4 demonstrates this concept with an example cross-section of a steep creek, including representative flood depths for the peak discharge of the following processes:

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

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

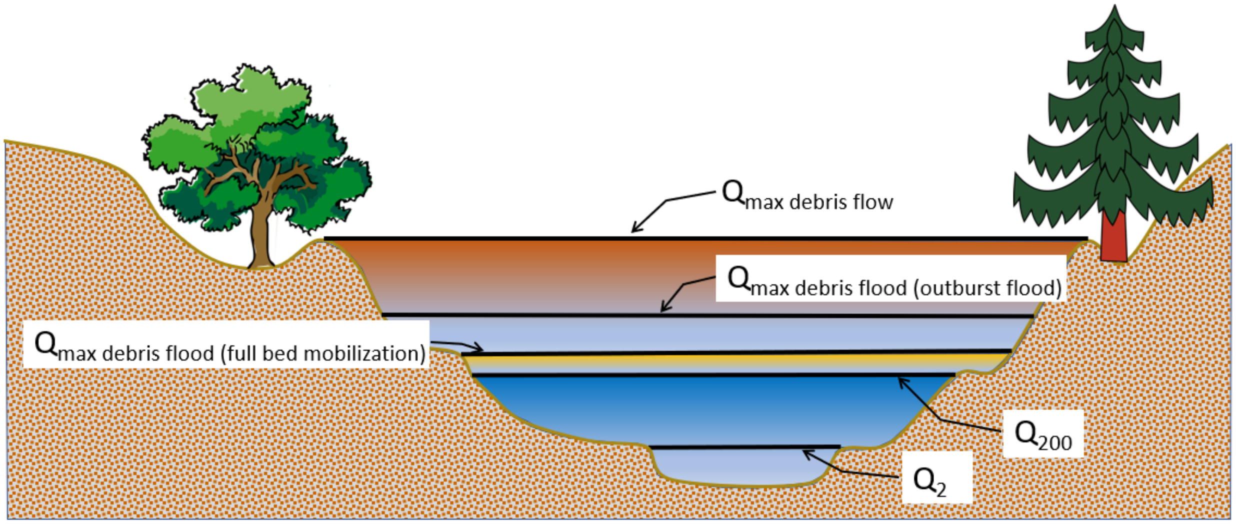


Figure 2-4. **Conceptual steep creek channel cross-section showing peak discharge levels for different events. Note that for some outburst floods or debris flows the discharge may well exceed what is shown here.**

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 clearwater floods, a longer duration is more likely to saturate protective dikes, increasing the likelihood for piping and dike failure prior to, or instead of, the structure being overtopped. For debris floods, the duration of the event will also affect the total volume of sediment transported and the amount of bank erosion occurring.

2.5. Avulsions

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

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

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

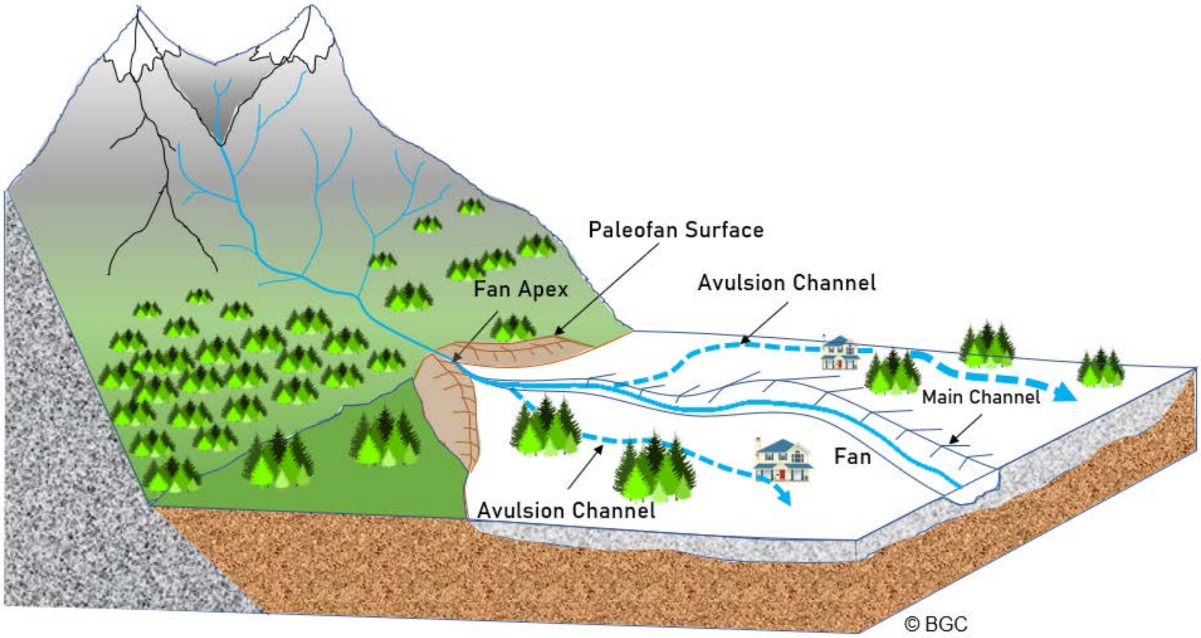


Figure 2-5. Schematic of a steep creek channel with avulsions downstream of the fan apex. Artwork by BGC.

2.6. Steep Creek Process

BGC assessed the potential steep creek process types and hazards on Harrop 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, Harrop Creek plots in the zone of floods to debris floods (Figure 3-3). The points shown on the plot are subject to some error and watersheds can be subject to multiple processes at different timescales; for this reason, it is important to consider additional evidence to supplement the assessment of process type.

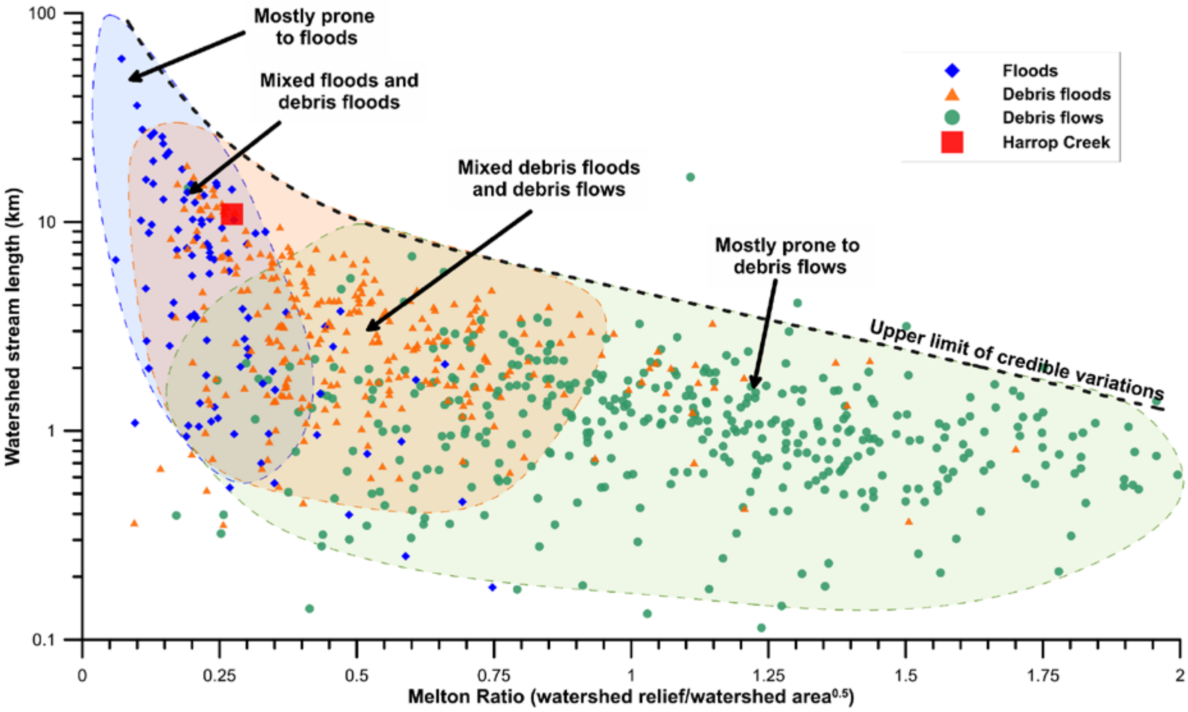


Figure 3-6. Tendency of creeks to produce floods, debris floods and debris flows, as a function of Melton Ratio and stream length (data from Holm et al., 2016 and Lau, 2017). See Section 3.2 for Harrop Creek watershed data.

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

BGC interprets Type 1 debris floods to be the dominant hydrogeomorphic process at Harrop Creek for lower return periods, while Type 2 debris floods dominate in the higher return periods that were studied. This rationalization is discussed further in Section 6.1.

3. STUDY AREA CHARACTERIZATION

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

3.1. Site Visit

Field work on Harrop Creek was conducted from July 5 to 9, 2019 and on November 20, 2019 by the following BGC personnel: Carie-Ann Lau, M.Sc., P.Geo., Kris Holm, M.Sc., P.Geo., Matthias Busslinger, M.A.Sc., P.Eng., Matthias Jakob, Ph.D., P.Geo., Beatrice Collier-Pandya, B.A.Sc., EIT, and Hilary Shirra, B.A.Sc., EIT. Field work included channel hikes to look for evidence of high-water marks, measurement of grain size diameters (Wolman sampling) at the fan-delta apex and the channel mouth, measurement of cross-sections at bridge and other infrastructure crossing locations, collection of tree core samples for dendrogeomorphic analysis, and excavation of test pits (Drawings 02A, 02B) to develop stratigraphic profiles supplemented by radiocarbon dating of samples. The watershed was also flown by helicopter and numerous photographs were taken for later analysis of major sediment sources to the channel.

3.2. Physiography

Harrop Creek is located approximately 21 km northeast of Nelson, BC on the West Arm of Kootenay Lake and flows north through the unincorporated community of Harrop into the lake. 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 03 shows a profile along the creek mainstem and tributaries. Representative photographs of the watershed and fan-delta are provided in Appendix B.

The site lies within 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, which 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 is high in the Selkirk Mountains as moisture from coastal areas arrives from the west, resulting in a strong rain shadow effect at the eastern boundary of the range. Typical vegetation includes Engelmann Spruce and Subalpine Fir trees at lower elevations (from 500 m elevation), 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 elevation and are sparsely vegetated.

3.3. Geology

3.3.1. Bedrock Geology

The Harrop Creek watershed is underlain by granodioritic intrusive rocks of the Nelson Batholith, which formed in the Mid-Jurassic Period. The watershed is situated on the east side of the southern tail of the Nelson Batholith, which is characterized by moderately steep to vertically-dipping (45-90°) foliations that strike approximately north-south (Vogl & Simony, 1992). 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.

3.3.2. Surficial Geology

The surficial geology of the Harrop Creek watershed is dominantly glaciofluvial in the valley bottom, with till along valley walls and mixed colluvium and bedrock outcrops at upper elevations (Figure 3-1, Jungen, 1980). The abundant colluvium in the watershed, as well as the rockfall-prone bedrock outcrops, indicate 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. Debris flows sourced within till deposits are expected to contain a higher proportion of fine-grained sediment (fine sands, silts, and clays). All other factors being equal, these types of debris flows can flow further than those sourced from coarser-grained colluvial, fluvial, and glaciofluvial materials.

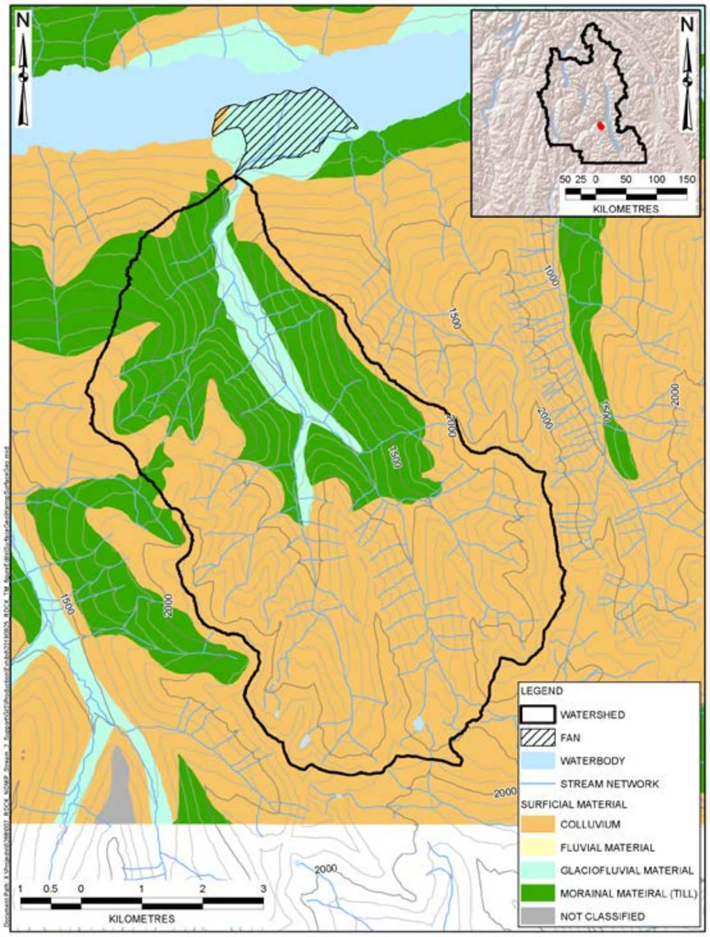


Figure 3-1. Surficial geology of the Harrop Creek watershed (from Province of BC, 2016).

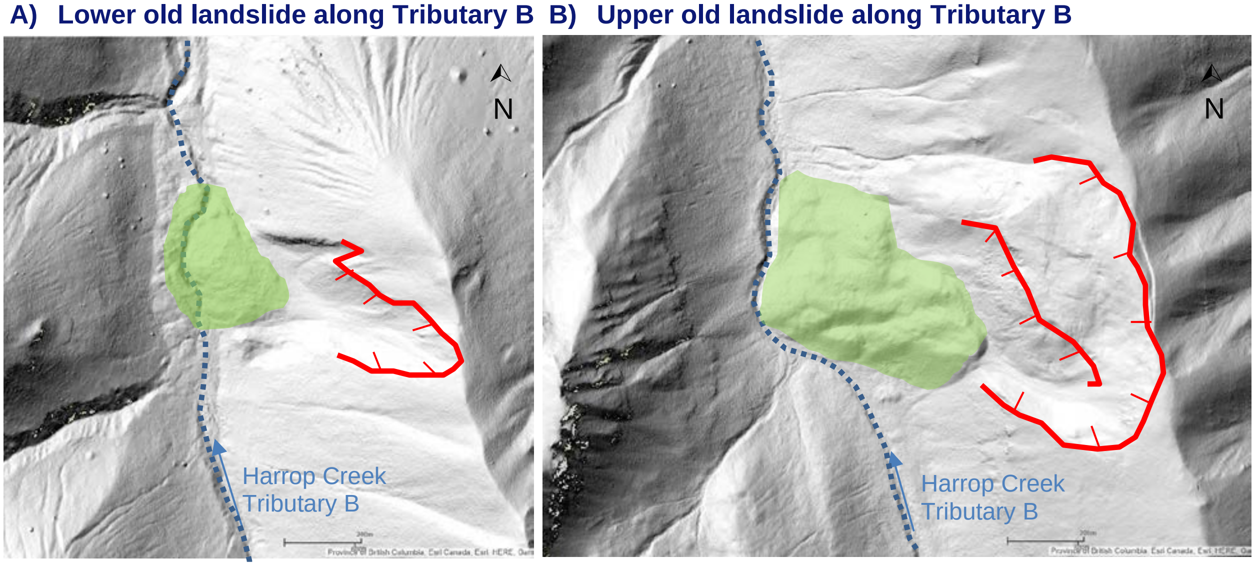
3.4. Geomorphology

3.4.1. Watershed

Geomorphological analysis of Harrop Creek included characterization of the watershed and fan-delta 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 Harrop Creek are the mountainous slopes of Mount Lesca (approximate elevation of 2372 m) at the southern edge of the watershed (Drawing 01). There are several small lakes present in the upper portion of the watershed (e.g., Mill Lake). Tributary C joins Harrop Creek 8.6 km upstream of the lake outlet (see location A in Drawing 03). Tributary B is the largest tributary and joins Harrop Creek 6.3 km upstream of the lake outlet (location B). Tributary A is the steepest tributary and joins Harrop Creek 3.9 km upstream of the lake outlet (location A). The fan-delta apex is located 1.9 km upstream of the lake outlet.

The creek channel throughout the watershed is deeply incised into thick glacial deposits at the valley bottom forming prominent edges of till terrace incision that are visible in the lidar imagery (Drawing 05). Along Tributary B, two large landslides are evident in the lidar (Figure 3-2). BGC estimates the landslide deposit areas are in the order of 70,000 m^2 for the lower landslide and 180,000 m^2 for the upper landslide. The upper landslide has pushed the channel to a new configuration while the lower landslide may have temporarily blocked the channel and was subsequently dissected by the creek. BGC visually assessed both landslides from a helicopter. Photo 4 in Appendix B shows the lower landslide and Photo 5 is looking down, along the upper landslide. The landslides are covered with mature forest suggesting that they are at least hundreds of years old. As these were the only deep-seated landslides identified by BGC in the watershed, the occurrence of two landslides during the Holocene implies an approximate frequency of 5,000 years.



A) Lower old landslide along Tributary B

B) Upper old landslide along Tributary B

Figure 3-2. Bare-earth lidar image of old landslides along Harrop Creek Tributary B (see Drawing 05 for location). Landslide headscarps are shown in red and the tributary is shown in blue dashed line.

Debris-flow activity in the watershed include three debris flow channels in the upper watershed that flow into Tributary B (Drawing 05). These channels have hummocky terrain at the top of their respective reaches that could provide sediment to the channel during high return period events. A prominent debris-flow channel (Tributary A, Drawing 03) is also located on the west side of Harrop Creek approximately 2.0 km upstream of the fan-delta apex.

A fault (Photo 7 and 8) that cuts through a west-facing slope meets Tributary C approximately 600 m upstream of location A (Drawings 02A, 02B, and 05). Slope movement to the north of the fault is evidenced by the scarps and lineaments oriented perpendicular to it. No association with existing landslides was apparent with this fault.

The hillslopes are forested with some recent forestry activity in the lower watershed on the west-facing valley side. Approximately 4% of the total watershed area has been logged since 1900 and 45% of the watershed area has burned since 1919 although the record is incomplete. The largest wildfire was recorded in 2017 and covered an area of approximately 30 km^2 (FLNRORD, 2019a; 2019b). Residents have noted increased sediment deposition since the 2017 forest fire especially during the 2019 freshet.

Table 3-1 summarizes relevant geomorphic characteristics of the Harrop 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-delta apex provides an indication of whether transportation of sediment is likely, and the fan-delta gradient approximates the angle where sediment deposition of larger flows from the watershed generally ensues.

Table 3-1. Watershed characteristics of Harrop Creek.

Characteristic	Value
Watershed area (km^2)	40
Fan-delta area (km^2)	2.1
Active Fan-delta area (km^2)[1]	2.0
Maximum watershed elevation (m)	2,334
Minimum watershed elevation (m)	610
Watershed relief (m)	1,724
Melton Ratio (km/km)[2]	0.3
Average channel gradient of mainstem above fan-delta apex (%)	15
Average channel gradient on fan-delta (%)	8
Average fan-delta gradient (%)	8

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. Harrop Creek Fan-Delta

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

Harrop Creek flows north across the fan-delta that extends into the West Arm of Kootenay Lake. The western most side of the fan-delta is slightly raised and appears to be recently inactive (Drawing 05). In lidar, avulsion channels from the fan-delta apex are present but become more muted as they proceed toward the distal end. Deposits on the fan-delta range from boulders at the fan-delta apex to sand on the distal portions of the fan-delta. Downstream of the fan-delta apex, the Harrop Creek channel passes through depositional areas from past events.

BGC suspects that the channel downstream of the railway crossing has been straightened but any channel works were completed before the beginning of the air photo record in 1929 (Drawing 04). The reach just upstream of the outlet into the lake has changed course numerous times over the air photo record. The active channel is 4 to 17 m wide on the fan-delta. The average channel gradient decreases from approximately 5% at the fan-delta apex to 3% near the channel outlet (Drawing 03).

The Harrop Creek fan-delta has adjusted due to the raise of lake levels when Corra Linn Dam, located southwest of Nelson, was activated in 1938. The dam raised lake levels by approximately 2 m (Touchstone Nelson, 2007) and BGC understands that this level will be maintained in the future. The distal portions of the fan-delta, visible in historical air photos (Section 6.2.1), were flooded by the lake level raise. The contemporary Harrop Creek channel is 5 m wide at the outlet to Kootenay Lake. Avulsion channels are visible on the lower fan-delta over an area of waterfront approximately 75 m long.

3.5. Existing Development

Development on the Harrop Creek fan-delta comprises the community of Harrop and the Sunshine Bay Regional Park (Drawings 02A, 02B). Canadian Pacific (CP) railway, petroleum infrastructure and communications infrastructure transect the mid-fan-delta. The Harrop Cable Ferry launches from the northwest side of the creek from the lower distal fan-delta.

In the 2016 census, Harrop is identified as an unincorporated place 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 people (Statistics Canada, 2016). The estimated total improvement value of parcels intersecting the Harrop Creek fan-delta based on the 2018 BC Assessment Data is $17,833,600 (BGC, March 31, 2019).

3.5.1. Bridges

Bridge locations are shown on Drawings 02A, 02B. Harrop Creek passes under five bridge structures on the fan-delta (Table 3-2, Figure 3-3). The Betty Boop Ave bridge is approximately 300 m upstream of Harrop-Procter Rd. It is a wooden bridge supported by steel I beams and a concrete abutment on both the left and right banks (Figure 3-3A). 200 m downstream of Betty Boop Ave, there is a much smaller pedestrian footbridge that sits on the natural banks of the channel (Figure 3-3B). The pedestrian footbridge and Booty Boot Ave bridge were not included in public datasets. Harrop-Procter Road Bridge is wide enough for two lanes of traffic and sits on steel pilings as well as concrete abutments approximately 1.5 vertical m above the channel center (Figure 3-3C-D). The CP Railway bridge is approximately 40 m upstream of Erindale Rd and is supported by piles at the left and right bank, as well as the midspan. A log crib structure on both left and right banks acts as a form of flood protection from the railway to an unknown distance downstream (Figure 3-3E). Erindale Rd is also a two-lane road and is supported by double I beams on both the left and right bank with some armouring along the channel bank (Figure 3-3F). An additional footbridge near the delta was recently washed out[3] (Photo 11, Appendix B) and is therefore not included in the table.

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[3] During BGC's site visit in July 2019, residents indicated that the watershed burned in 2017, and that large volumes of sand came down the channel in 2018. As a result, the fan-delta prograded approximately 20 to 30 m in 2018, mostly sand and fine gravel (2.5% new delta gradient). Wood pieces also came down during this flood. A footbridge near the outlet (not observed) was blocked by debris and the channel partially avulsed to the east into a property.

Table 3-2. Estimated dimensions of bridge crossings on Harrop Creek fan-delta.

Bridge	Height Above Channel Center (m)	Span (m)	Notes
Betty Boop Ave.	1.95 m	5.2	Single lane
Footbridge	1.3 m	Not measured	1.3 m clearance, deteriorating
Harrop-Proctor Road Bridge	4.2	12	Two-lane road
CP Railway Bridge	2.0	9	Single track
Erindale Rd. Bridge	2.5	9.4	Two-lane road

Note: The bridge dimensions were estimated from site photographs and typical dimensions for the size of road or track (as direct measurements were not collected in the field.

A) Betty Boop Bridge crossing Harrop Creek. Standing on left bank looking at abutment.

B) Wooden footbridge approximately 1.0 km upstream of Kootenay Lake. Condition is deteriorating.

C) Looking upstream (south) at Harrop-Procter Bridge.

D) Standing on Harrop-Procter Road Bridge looking downstream (north).

E) Standing on right bank looking west at railway bridge crossing Harrop Creek and log crib structure.

F) Standing on right bank looking at Erindale Rd bridge crossing Harrop Creek.

Figure 3-3. Bridge structures encountered on Harrop Creek fan-delta during BGC's field work in July 2019. Refer to Drawings 02A, 02B for locations.

3.5.2. Flood Protection Structures

BGC queried the Government of British Columbia's (2020) list of dikes by river/watercourse as well as the iMapBC Flood Protection Structural Works layer; however, the search revealed no official flood protection structures on Harrop Creek. Figure 3-4 summarizes makeshift flood protection measures installed on Harrop Creek fan-delta and encountered by BGC during their site visits. Flood protection structure locations are shown on Drawings 02A, 02B and 06. Note the extents of the structures were not delineated.

HRP-FP-01 – Rip rap protection on left bank above water intake house (tin roof is visible at end of berm).

HRP-FP-03 – Water intake with wooden deflection wall (4.10 m x 1.02 m x 0.07 m thick) across avulsion channel.

HRP-FP-04 – Bank erosion on outer (left) bank approximately 2 m tall. Note; house in the background, makeshift erosion protection with cemented stone wall on top deformed, green wire-mesh baskets, and logs placed further downstream.

HRP-FP-05 – Non-engineered dike on right bank made from rounded river rock.

HRP-FP-06 – Logs piled up on right bank to avoid avulsion.

Figure 3-4. Makeshift flood protection measures encountered on Harrop Creek fan-delta during BGC's field work in July 2019. Refer to Drawings 02A, 02B for locations. No photo taken for HRP02 – 1m high sandbag dike on left bank at potential avulsion point just next to water intake house on left bank.

3.6. Hydroclimatic Conditions

3.6.1. Existing Conditions

Climate normal data were obtained from Environment and Climate Change Canada's Kaslo station (Elevation 600 m), located approximately 35 km north of the Harrop Creek outlet (Environment and Climate Change Canada, n.d.). Daily precipitation and temperature data are available from 1894 to 2015. Figure 3-6 shows the average monthly temperature and precipitation for this station from the 1981 to 2010 climate normals. Precipitation (rain and snow) peaks in November. Average rainfall peaks in June with a slightly lower value. Total annual precipitation is 856 mm at the Kaslo weather station. The annual proportion of rain and snow is shown 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 Harrop Creek watershed, where the mountaintops reach up to about 2300 m in elevation. 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, the water vapour condenses forming clouds resulting in precipitation.

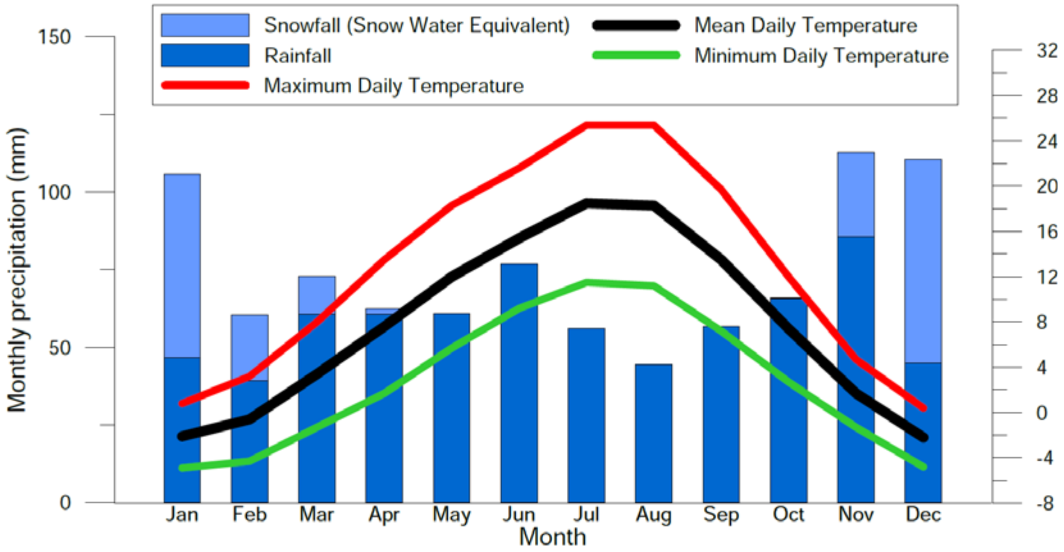

Figure 3-5. Climate normal data for Kaslo station from 1981 to 2010.

Table 3-3. Annual total of climate normal data for Kaslo 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 1418 mm, varying as a function of elevation. The same trend is evident in the historical mean annual precipitation as snow (PAS) over the watershed where the average PAS is 837 mm. Precipitation as snow increases with elevation; therefore, the watershed accumulates greater precipitation falling as snow compared to the Kaslo station.

3.6.2. Climate Change Impacts

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

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

The Climate NA model provides downscaled climate projections for future conditions (Wang et al., 2016). The projections based on the Representative Carbon Pathway (RCP) 8.5 indicate that the mean annual temperature in the Harrop Creek watershed is projected to increase from 2.1ºC (average between 1961 to 1990) to 5.7ºC by 2050 (average between 2041 to 2070). The mean annual precipitation is projected to increase from 1418 mm to 1499 mm while precipitation as snow is projected to decrease from 837 mm to 565 mm by 2050 in the Harrop Creek watershed. Projected change in climate variables from historical conditions for the Harrop Creek watershed 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.

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

Climate Variable	Projected Change
Mean Annual Temperature (MAT)	+3.6 ºC
Mean Annual Precipitation (MAP)	+81 mm
Precipitation as Snow (PAS)	-272 mm

4. SITE HISTORY

4.1. Introduction

Harrop Creek flows through the community of Harrop and into Kootenay Lake at Harrop Narrows. Residents have lived on the alluvial fan-delta since the late 1800s, and the area has served as an important ferry connection for the community of Redfish Creek on the opposite shore of Kootenay Lake. BGC notes that the community has had several names including Sawmill Point, West's Landing, McCoy's Siding/Point, and 13 Mile Point. Harrop Creek has also been referred to as Mill Creek.

4.2. Document Review

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

- Archival records from the BC Archives and Nelson Touchstone Museum.
- Reports provided to BGC by RDCK (Table 4-1), including:
    - Precondition applications (building permit, subdivision, and site-specific exemptions, etc.)
    - Hazard assessments (flooding, post-fire, etc.)
- Reports provided to BGC by Ministry of Forests, Lands, Natural Resource Operations and Rural Development (MFLNRORD) (Table 4-1)
- Research articles (Table 4-1)
- Historical flood and landslide events from the following sources:
    - Social media and online media reports
    - Septer (2007)
    - DriveBC historical events (2009 to 2017) (MoTI, 2019)
    - Canadian Disaster Database (Public Safety Canada, n.d.)
    - MFLNRORD.
    - Accounts from Harrop Creek residents
- Historical wildfire perimeters (MFLNRORD, n.d.)
- Cutblock perimeters (MFLNRORD, n.d.).

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

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

Year	Month/Day	Source	Purpose
1972	June	Water Resources Branch (BC Government)	Flood survey report
1989	January	Ministry of Environment	Hazard Assessment
1990	April	Northwest Hydraulic Consultants Ltd. and Thurber Consultants Ltd.	Hazard Assessment
1998	February 23	Klohn Crippen Consultants Ltd.	Alluvial and debris torrent fan-delta inventory
1995	August 15	Intermountain Engineering and Surveying Ltd.	Precondition for Building Permit
2002	March 7	Intermountain Engineering and Surveying Ltd.	Precondition for Building Permit
2003	May 23	Intermountain Engineering and Surveying Ltd.	Precondition for Building Permit
2004	December 16	Intermountain Engineering and Surveying Ltd.	Precondition for Building Permit
2005	May 4	Integrated Hydropedology Ltd.	Precondition for Building Permit
2006	June 30	Aqua Environmental Associates	Watershed assessment
2006	April 4	Intermountain Engineering and Surveying Ltd.	Precondition for Building Permit
2011	May 10	Deverney Engineering Services Ltd.	Precondition for Site-specific Exemption
2014	November 16	Lasca Group Technical Services Ltd.	Precondition for Building Permit
2015	September 4	Perdue Geotechnical Services Ltd.	Precondition for Building Permit
2015	December 27	Lasca Group Technical Services Ltd.	Precondition for Building Permit
2017	October 2	Ministry of Forests, Lands, Natural Resource Operations	Post-wildfire natural hazards risk analysis

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 assessment included Duhamel, Sitkum, Kokanee, Redfish, Harrop, Procter, Laird, and Narrows creeks. Except for the latter two (Laird and Narrows), those same creeks were prioritized for detailed study by BGC. A detailed comparison of the NHC/Thurber study with the present work is included in Section 6.7.1.

4.2.2. Aqua Environmental Associates (2006)

Aqua Environmental Associates (Aqua) completed a watershed assessment for Harrop Creek to review proposed forestry activities (cut blocks and roads) in 2006. The report outlines the sediment source assessment and riparian assessment which considered channel hazards associated with ‘channel wood’ (absence of wood, abundant small wood, dysfunctional wood) and channel stability (avulsion channels, bank erosion, bars). As part of the assessment, detailed descriptions of Harrop Creek reaches were provided.

4.2.3. Perdue Geotechnical Services (2015)

In 2015, Perdue Geotechnical Services (Perdue) conducted a geotechnical assessment as a precondition for a building permit at a property that borders Harrop-Procter Rd. Perdue described evidence of previous mass wasting processes in the form of debris lobes and levees near the fan apex. The colluvial deposits contain cobbles and boulders up to 1.0 m diameter. Perdue inferred the event date to be over 100 years based on the ages of the stand of trees. These debris levees were described as providing confinement to the channel for approximately 500 m downstream of the fan apex. The channel was described as being well armoured with native cobbles and boulders. Perdue estimated that the Harrop Creek could accommodate the instantaneous 200-year peak discharge in the upper reaches of the fan.

4.2.4. Ministry of Forests, Lands, Natural Resource Operations (2017)

Following the 2017 wildfire, the Ministry of Forests, Lands, and Natural Resources Operations (MFLNRO) completed a post-wildfire natural hazards risk analysis. The wildfire burned approximately 1172 ha (28% of watershed area) in the headwaters of Harrop Creek watershed. MFLNRO indicated elevated debris flow hazard in the headwaters of Harrop Creek Trib C (Drawings 03, 05). They assessed that a debris flow on this tributary could have water quality impacts downstream but is unlikely to be transported to the Harrop Creek fan-delta due to the low channel gradient of Harrop Creek. Further, the U-shape of the valley and patchiness of the burn severity were interpreted to reduce slope-channel connectivity such that the overall post-wildfire debris flow hazard was assessed to be low.

On the Harrop Creek fan, MFLNRO, assessed the likelihood of a debris flow fan affecting properties to be low and the likelihood of a flood event impacting infrastructure or properties to be moderate. The subjective ratings of low, moderate and high were based on accepted definitions in British Columbia and used a simple qualitative risk matrix (MFLNRO, 2017).

4.3. Historic Timeline

Figure 4-1 provides a timeline summary of floods and mitigation history for Harrop Creek. For location references, refer to Drawings 01, 02A, and 02B. The historical event inventory is assumed to be incomplete, but the information contained within it can be used to identify the location of past geohazards events and associated consequences of these events. From this information, the following can be concluded:

- At least five notable hydrogeomorphic events (1913, 1948, 1972, 1974 and 2018) have occurred in recorded history during freshet (snowmelt) conditions.
    - BGC interprets that at least the 1972 and 1974 events can be classified as damaging debris floods, given the record of extensive erosion and avulsion. Other flood events may also have been debris floods.
    - An NHC and Thurber report (NHC & Thurber, 1990) provides hydrographs for 1968, when discharge peaked on the fan-delta on the north side of Kootenay Lake opposite Harrop, and 1974 when discharge spiked on both creeks.
    - There are resident accounts of bank erosion, sediment deposition, fan-delta progradation, and blockage of a footbridge with sediment and debris leading to an avulsion and the footbridge washing out following the 2017 wildfire. The resident accounts refer to both the 2018 and 2019 freshets. Based on field evidence from the site visit in July 2019, BGC interprets that reported bank erosion and blockage of the footbridge occurred in 2018; however, attribution of other effects to an individual year could be not completed based on the available evidence and BGC acknowledges that elevated sediment transport and deposition may have occurred in both 2018 and 2019.
- Historical flood and debris-flood events have caused significant bank erosion, channel aggradation, and destroyed several bridges.
- Previous reports (NHC and Thurber, 1990) have noted the presence of large boulders and levees near the fan-delta apex, as well as historical channels on the western margin of the fan-delta, suggesting a debris flow event at an unknown date prior to development on the fan-delta.
- The channel has been significantly modified to constrain the channel under the highway and railway bridges. BGC suspects that the channel was straightened below the highway prior to the earliest air photo in 1929.
- The channel has been dredged (i.e., cleared with equipment) several times, typically following debris flood events or freshet floods.
- A forest fire burned a large portion of the upper watershed in 2017. Since the fire, residents have noted increased sediment deposition at the mouth of the channel.
- Water levels at the toe of the fan-delta are influenced by the reservoir levels on Kootenay Lake.

Geohazard History

2018 - Residents reported increased sediment deposition at mouth of channel during freshet

July-August 2017 - Lightning-caused Harrop Creek wildfire burned approximately 3,000 ha in the upper watershed; evacuation alerts issued for Harrop and other local communities

September 2004 - Blowdown event pushed creek westward at channel outlet and locally formed two channels

August 2003 - Lightning-caused Kutetl Fire in West Arm Provincial Park burned over 7,800 ha, including a portion of the upper watershed of Harrop Creek

1988 - Minor log jam in creek

June 1974 - Flooding reported with channel erosion on left bank downstream of highway. Highway bridge, railway bridge, and railway tracks damaged

June 3, 1972 - Flooding reported with channel erosion at fan apex, Harrop-Procter Road, and left bank downstream of highway. Highway bridge piers damaged and road closed; railway bridge damaged; channel outlet filled with sediment

Early 1950s - Debris flow on the west bank of Harrop Creek mainstem

1948 - Flooding reported on creek

1940s - Fresh event deposit visible in the air photo

Pre-1939 - Fresh event deposit visible in the air photo

June 1913 - Flooding on creek damaged property and CP Rail line, washed out road and bridge

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

View downstream from Mill Lake in upper watershed, 2017 (Copyright Province of British Columbia. All rights reserved. Reproduced with permission from the Province of British Columbia)

Harrop Creek, 2015 (Courtesy of Harrop-Procter Community Cooperative)

Outdoor winter scene of land clearing at Harrop looking towards delta of Redfish Creek, ca 1900-1910 (Courtesy of Touchstones Nelson: Museum of Art and History, 2002.001.07.008)

- 🟧 Wildfire
- 🟦 Flood
- 🟫 Landslide
- 🟨 Debris flow or debris flood
- ⬜ Channel location
- 🟨 Mitigation
- 🟪 Development event

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

Mitigation

August 2019 - Kokanee habitat restoration project undertaken at the mouth of Harrop Creek

October 1985 - Riprap bank protection installed upstream from confluence with lake

August 1980 - Log jams removed from creek

June 24, 1975 - Log jams removed from creek after freshet

1974 - Two new bridges constructed to replace those washed out during the flood; channel excavated between highway and railway

1972 - Channel excavated between highway and railway, and at channel mouth after flood

1956 - Harrop-Procter Road Bridge over Harrop Creek constructed

1930s - Channel excavation

1928 - Riverbank protection and opening of creek channel carried out on Harrop Creek

Development

Late 2000s to 2010s - Logging in watershed

1999 - Harrop-Procter Community Forest established

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

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

1930 - Identified as "Harrop Creek (not Mill Creek)" in the 1930 BC Gazetteer; named in association with the settlement of Harrop after Ernest Harrop, a local businessman

1925 - Approval granted for the development of the Harrop-Procter ferry with dock on creek fan

Early 1920s - Sawmill located on the flats near the West Arm of the creek

1900 - CPR spur built along south shore of Kootenay Lake, crossing over Harrop Creek

1894 - Photo-topographical survey of area undertaken by William Drewry, Topographical Survey of Canada

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

5. METHODS

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

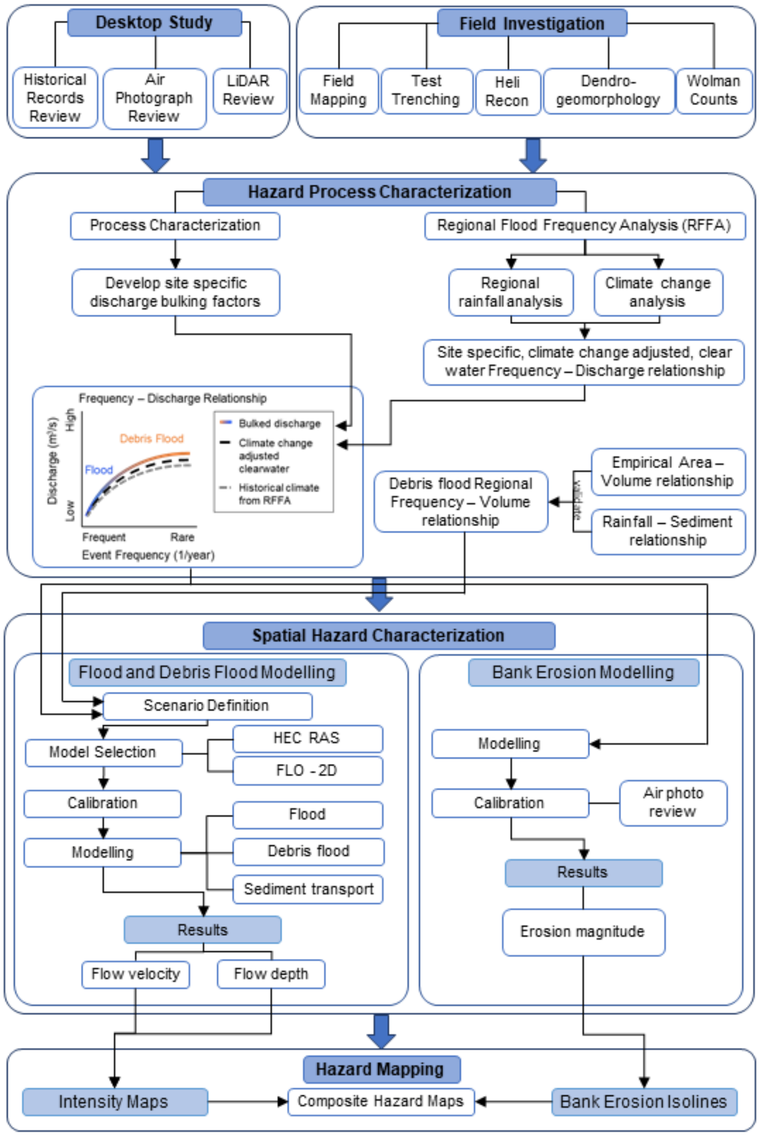

Figure 5-1. Flood and debris flood prone steep creeks workflow used for developing frequency-magnitude relationships, modelling, and preparing hazard maps.

5.1. Debris Flood Frequency Assessment

This section combines the methods established to estimate debris flood frequencies from remote sensing and field methods on Harrop Creek. They entail air photo interpretation, dendrogeomorphological assessment and test pitting.

5.1.1. Air Photo Interpretation

Air photos dated between 1929 and 2006 were examined for evidence of past sediment transport events on Harrop Creek. A complete list of the air photos reviewed is included in Appendix D. Events were identified from the appearance of bright areas and disturbed vegetation relative to previous air photos. Smaller events that did not deposit sediment outside the channel or significantly change the course of the channel are not captured in this analysis. Similarly, events that occurred during large gaps between air photos or successive events that overlap may not captured. Air photo interpretation was supplemented by historical records of past events (Figure 4-1).

5.1.2. Test Pitting

Test pits are dug to examine the stratigraphy of previous events to identify process type (flood or debris floods) and to date (where possible) organic materials. This provides a sense of when the last events occurred in a specific fan-delta sector and an estimate of long-term fan-delta aggradation rates.

Five test pits were excavated on the Harrop Creek fan-delta (Drawings 02A, 02B). TP-BGC-19-HRP-04 is located east of the active Harrop Creek channel, while the remaining four test pits are west of the active channel of Harrop Creek, south of McConnell Road. Two of these test pits (TP-BGC-19-HRP-04 and -01) are proximal to the fan-delta apex and the other two (TP-BGC-19-HRP-02 and 03) are on the mid to distal end of the fan-delta. Dendrogeomorphological (tree core) samples were collected from trees adjacent to (TP-BGC-19-HRP-02 and 03). Radiocarbon dating of samples collected from these test pits was completed to determine a minimum age of the deposits in the test pits. The last test pit is located east of the active channel and north of Erindale Road, on the distal end of the fan-delta.

Test pit logs and photographs are included in Appendix E.

5.2. Peak Discharge Estimates

5.2.1. Clearwater Peak Discharge Estimation

There are no hydrometric stations on Harrop 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 watershed 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., MoE, 1989; NHC, 1990; and Newton, 2015). Based on its watershed characteristics, the Harrop 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).

5.2.2. 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 Harrop 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).

5.2.3. Sediment Concentration Adjusted Peak Discharges

BGC accounted for expected flow bulking from organic and mineral sediment by multiplying the climate adjusted clearwater discharge with a bulking factor specific to each return period as outlined in Section 2 of the Methodology Report (BGC, March 31, 2020b).

5.3. Frequency-Magnitude Relationships

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

BGC assessed Harrop Creek for the 20-, 50-, 200-, and 500-year return periods. At these return periods, the hydrogeomorphic process was identified as debris flood based on climate adjusted peak discharges and stream morphometrics. Because the debris-flood events will carry sediment and woody debris, the climate adjusted clearwater discharge needs to be bulked accordingly. To

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

produce a bulked frequency-discharge relationship, a bulking factor was applied to the peak discharge for each return period, based on sediment availability and debris-flood process type. The bulked frequency-discharge relationship was then used in numerical modelling.

Another measure for magnitude is sediment volume. While sediment volume is less useful as input to numerical modelling, it is helpful to verify sediment deposition predicted by the model. Therefore, a regional frequency-volume relationship was created to compare to numerical modelling results. A detailed discussion of the methodology is provided in Section 2 of the Methodology Report (BGC, March 31, 2020b).

5.4. Numerical Debris Flood Modelling

BGC modelled the 20-, 50-, 200- and 500-year return periods debris floods. Details of the numerical modelling techniques are summarized in Section 2 of the Methodology Report (BGC, March 31, 2020b). Two hydraulic models were used, HEC-RAS 2D (Version 5.0.7) and FLO-2D (Version 19.07.21). HEC-RAS is a public domain hydraulic modelling program developed and supported by the United States Army Corps of Engineers (Brunner & CEIWR-HEC, 2016). It was used to model clearwater floods with climate-change adjusted and bulked flows.

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

Table 5-1 summarizes the key numerical modelling inputs selected for the HEC-RAS and FLO-2D models. Further details on modelling methods are presented in Section 2 of the Methodology Report (BGC, March 31, 2020b). Different Manning's n values were used between the HEC-RAS and FLO-2D models as during modelling execution each model treats roughness in a different way, further details are provided in Section 2 of the Methodology Report (BGC, March 31, 2020b). The impacts of Kootenay Lake level on the communities bordering the lake are investigated in the Kootenay Lake Flood Impact Analysis (BGC, January 15, 2020).

Table 5-1. Summary of numerical modelling inputs.

Variable	HEC-RAS	FLO-2D
Topographic Input	Lidar (2018)	Lidar (2018)
Grid cells	Variable (2- 20 m)	5 m
Manning's n	0.08 (channel), 0.02 (main roads), 0.1 (fan-delta)	0.06 (channel), 0.02 (main roads), 0.1 (fan-delta)
Upstream boundary condition	Steady Flow (Q_{20} and Q_{50})	Steady Flow (Q_{200} and Q_{500})
Downstream boundary condition	Steady stage at Kootenay Lake (534.6 m)	

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

A series of modelling scenarios were developed for Harrop Creek as presented in Appendix F. 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 and scenarios, while FLO-2D also provides approximate sediment deposition areas and depths that are compared to the regional frequency-volume relationship.

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.

5.5. 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-delta apex and the mouth of the creek. 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 Drawings 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 Harrop Creek: debris flood model result maps (i.e., model scenarios) and a composite hazard rating map. The model result maps support emergency planning and risk analyses, and the composite hazard rating map supports communication and policy implementation, as described further below.

5.6.1. Debris Flood Model Result Maps

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

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

FLO-2D and HEC-RAS 2D model outputs include grid cells showing the velocity, depth, and extent of debris flood inundation. These variables describe the intensity of an event. Hazard quantification needs to combine the intensity of potential events and their respective frequency. Sites with a low probability of being impacted and low intensities (for example, slow flowing ankle-deep muddy water) need to be designated very differently from sites that are impacted frequently and at high intensities (such as water and rocks flowing at running speed). For the latter, the resulting geohazard risk is substantially higher and development must be more restrictive than the former. The hazard maps are provided as a geospatial data package and displayed on Cambio Communities. A representative example of a hazard scenario for the 200-year return period is included as a static map (Drawing 07).

5.6.2. Composite Hazard Rating Map

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

Given their application in policy, the composite 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 map.

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

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

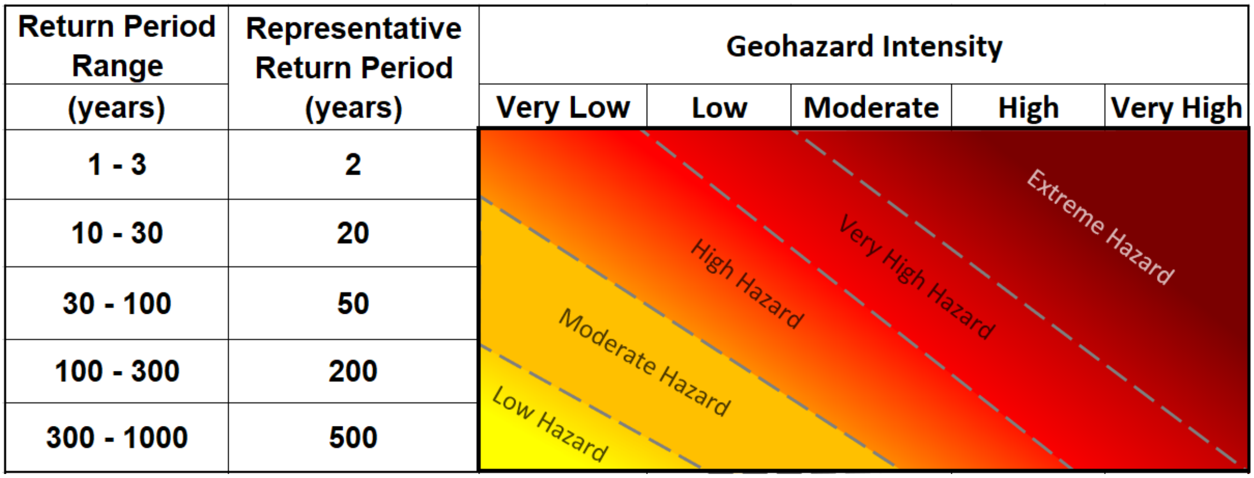
where v is flow velocity (m/s), d_f is the fluid's flow depth (m), ρ_f is the fluid density (kg/m3) to obtain a unit of force per metre flow width for the three left terms in Equation 5-1 and $P(H)$ is the annual probability of the geohazard. The unit of IIF is then Newton or kilo Newton per metre per year (kN/m per yr). Equation 5-1 and the concordant mapping is new in Canada.

Equation 5-1 can be translated into a matrix in which the impact force (IF) is on one axis and the return period (annual probability or P(H)) on the other. The matrix is then colour-coded to indicate the total hazard from yellow (low hazard) to dark red (extreme hazard) (Figure 5-2).

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

Paleosurfaces within the approximate fan area are interpreted as not being affected by contemporary hazardous geomorphic processes considered in this study (e.g., debris floods, debris flows, bank erosion) and have no hazard rating on the composite hazard rating map. 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 5-2 displays a wider range of return periods and intensities than are relevant to debris flood hazard on Harrop 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	Representative Return Period (years)	Geohazard Intensity				
(years)		Very Low	Low	Moderate	High	Very High
1 - 3	2					
10 - 30	20					
30 - 100	50					
100 - 300	200					
300 - 1000	500					

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

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

Interpreted hazard maps showing *IFF* values were developed for each return period class at all locations within the study area. For the individual hazard scenario maps, the raw (no interpretation nor zone homogenization) impact force modelling results are presented. For the composite hazard rating 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. Note that for debris floods, orange, red and dark red zones will be confined to the channel where the highest flow depths and flow velocities will be encountered. Overbank flows associated with debris floods will have much lower flow depths and velocities.

6. RESULTS

6.1. Hydrogeomorphic Process Characterization

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

- The average channel gradient above the fan-delta apex is 15% (Drawing 03), which is insufficient for sustained debris flow transport. Tributary A has an overall gradient of 30% before it meets Harrop Creek 2 km above the fan-delta apex, from where on the gradient is about 10% to the fan-delta.
- The average fan-delta gradient of 8% is typical of creeks prone to debris floods.
- A total of five test pits were excavated on the fan-delta. Soil logging of the test pits identified event thicknesses ranging from 0.1 to 1.6 m, with a median thickness of 0.4 m (Appendix E). These deposits are typical of debris floods as they are clast-supported, bedded and show signs of imbrication. None of the deposits encountered showed characteristics of being sourced from a debris flow or large landslide dam outbreak flood (LDOF) (e.g., matrix-supported and lack of bedding).
- The west side of the fan-delta is dissected by a number of small, shallow avulsion channels (Drawings 02A, 02B), which represent previous avulsions.
- The surficial expression of previous fan-delta deposits (sheets of gravel) are typical of debris floods.
- Accounts of previous flood events and analysis of historic air photos (see Section 6.2.1) are consistent with debris-flood activity due to associated erosion and observed movement of sediment in air photos.

Together, this evidence indicates that Harrop Creek is subject to supply-unlimited Type 1 debris floods for lower return periods (20- and 50-year). For higher return periods (200- and 500-year), Type 2 debris floods are believed to be the dominant process due to the presence of a debris flow tributary (Tributary A) approximately 2 km upstream of the fan-delta apex (Drawings 03, 05). The two deep-seated landslides in the upper watershed (Drawing 05) indicate that Type 3 debris floods are possible but at return periods greater than (>500-year) considered in this assessment.

Type 3 debris floods are also conceivable should there be a large stand-replacing moderate to high intensity fire in the watershed. Such an event could lead to a debris flow on one of the debris-flow prone tributaries on the west side of the creek (see Drawing 05). Debris-flow activity in these tributaries could form a temporary landslide dam and lead to an outbreak flood. This potential scenario ought to be considered in the context of a detailed post-fire hazard assessment which BGC has not attempted. A discussion of wildfire impacts on debris floods is included in Section 6.4.2.

6.2. Debris Flood Frequency Assessment

Debris flood frequency was assessed using historic air photos, test pits, and historical accounts.

6.2.1. Air Photo Interpretation

At least four notable hydrogeomorphic events have occurred since 1929 as identified from the air photo interpretation. Drawings 04A and 04B show air photos with events delineated. The interpreted deposition area and characteristics of the sediment transport events are described in Table 6-1. BGC interprets that all the noted events are likely Type 1 debris flood events due to the erosion and observed movement of sediment in air photos.

Table 6-1. Summary of Harrop Creek sediment transport events in air photo record (1939-2014).

Event Year[1]	Air Photo Year	Deposition Area (m^2)	Event Characteristics
1929 - 1939	1939	25,700	Fresh deposits in channel from the proximal fan-delta to the creek outlet.
1939 - 1945	1945	18,400	Fresh deposits in channel from the mid-fan-delta to the creek outlet
1952 - 1958	1958	9,300	Fresh deposits in channel at mid-fan-delta.
1972	1974	- [2]	Fresh deposits in channel at mid-fan-delta

Notes:

1. Event year interpreted from air photo dates and historical records. Where the exact date is unknown, the decade or time period between successive air photos is indicated.
2. Deposition area not delineated.

The deposition areas delineated from the air photos were combined with evidence from the test pits to estimate event volumes (Section 6.2.2).

6.2.2. Test Pitting

Radiocarbon sample dates and test pits logs were used to estimate minimum return periods and event deposit thicknesses (Table 6-2). The radiocarbon results showed a minimum event return period of 300 years for those areas in which test pits were dug. This number should be viewed as a minimum due to the limited number of test pits as well as the fact that organic materials suitable for radiocarbon dating to reconstruct event dates are not present in all deposits identified in the test pits. No events could be delineated from the radiocarbon sample results as dates did not agree between test pit locations. Detailed results of the radiocarbon dating are provided in Appendix G.

Table 6-2. Sediment volumes estimated from radiocarbon dates and test pit logging.

Event Date (years BP[1])	Sample	Depth (m)	# of units above	Minimum event return period (years)
2200	TP-HRP-05, GD	2.5	7	300
1500	TP-HRP-05, GB	1.6	3	500
4700	TP-HRP-01, G2	1.0	2	2400
5800	TP-HRP-04, G1	2.0	2	2900
4100	TP-HRP-02, G1	0.8	1	4200

Note:

1. Radiocarbon results are expressed in years before present (BP), where present is taken to be the year 1950.

Dendrogeomorphological samples were collected adjacent to TP-HRP-02 and TP-HRP-03 to obtain a minimum age of the uppermost stratigraphic layer at test pits. The results indicate a minimum establishment date (oldest tree ring identified in the sample) between 1936 and 1967.

Soil logging of the test pits identified event thicknesses ranging from 0.1 to 1.6 m, with a median thickness of 0.4 m (Appendix E). Given the size of Harrop Creek fan-delta, it was impractical to dig enough trenches to allow a seamless extrapolation of deposits across the fan-delta assuming that all deposits would have had organic samples suitable for radiocarbon dating. Instead, the median thickness of the deposits encountered in the test pits was used to compare numerical modelling results with magnitude estimates from the air photo interpretation and historical records (Table 6-3).

Table 6-3. Estimated deposition volume of Harrop Creek debris floods from the air photo record (1929-2006).

Event Year [1]	Air Photo Year	Deposition Area (m^2) [2]	Estimated Deposition Volume using median thickness (m^3)[1]
1929 - 1939	1939	25,700	10,000
1939 - 1945	1945	18,400	7,000
1952 - 1958	1958	9,300	4,000

Notes:

1. Where the event year is not known, it is reported as the date range between two air photos where evidence of the event is observed in the latter.
2. The deposition volume is estimated based on the median thickness (0.4 m) observed in test pits on the fan-delta.

These observations are not suitable to derive an F-M relationship because the air photo record does not entail all events that occurred, nor can deposition areas be attributed, without doubt, to a single event. Therefore, the results are used as an independent check of the overall fan-delta activity. Section 6.4 discusses the sediment volume F-M relationship further.

6.2.3. Summary

Notable Type 1 debris floods have occurred approximately every 15 years on Harrop Creek (Table 6-4). These events quickly avulse and deposit relatively thin (less than 0.5 m) layers of debris on the upper fan-delta surface and less than 0.2 m on the lower fan-delta. Fan-delta aggradation rates are relatively slow but spatially highly variable.

Table 6-4. Summary of past flood and debris flood events on Harrop Creek.

Event Year	Description
1913	Flooding damaged property and CP Rail line
1929 – 1939	Event deposit visible in 1939 air photo
1939 - 1945	Event deposit visible in 1945 air photo
1948	Flooding reported on creek
1952 - 1958	Event deposit visible on 1958 air photo
1972	Flooding with channel erosion at fan-delta apex, Harrop-Procter Road, and left bank downstream of highway. Damage to bridges and channel outlet filled with sediment
1974	Flooding with channel erosion on left bank downstream of highway and damage to bridges and railway tracks.
2019	Sediment deposition at channel mouth during freshet

6.3. Peak Discharge Estimates

Peak discharges for different return periods were estimated to serve as input to the numerical modelling. The workflow entailed an estimate of clearwater peak discharges, followed by a climate-change adjustment, and finally an adjustment for sediment bulking. Results of the analysis are presented in Table 6-5 and Figure 6-1. With respect to these results, the reader should note the following:

- Because there are no hydrometric stations on Harrop Creek, historical peak discharges (flood quantiles) were estimated using a Regional FFA. The provincial index-flood model was selected because it is slightly greater than the regional model.
- The historic peak discharge estimates based on the Regional FFA were adjusted by 20% to account for the impacts of climate change as per Section 4 of the Methodology Report (BGC, March 31, 2020b).
- The climate-adjusted, bulked peak discharges were used in the numerical modelling.

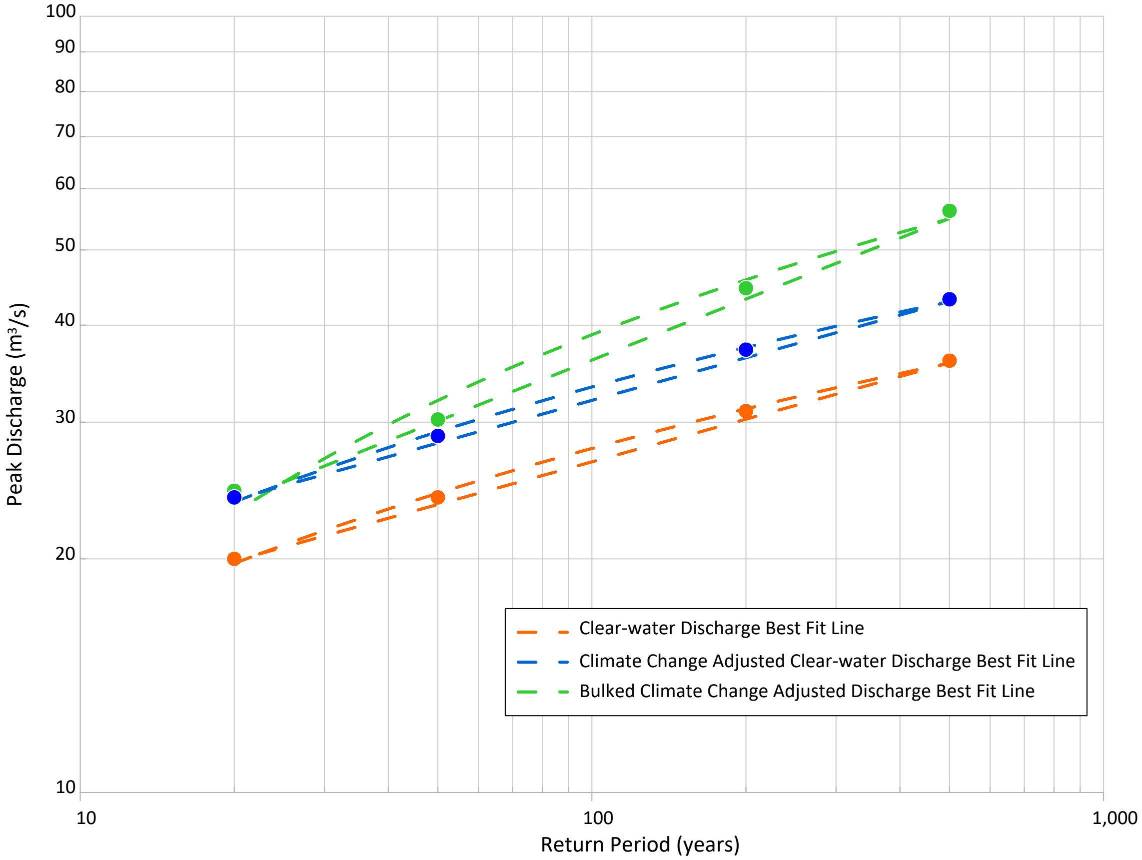


Figure 6-1. Frequency-discharge relationship for Harrop Creek.

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
2	0.5	10	10	1.0	10	n/a	Flood
20	0.05	20	25	1.02	25 [2]	1	Few active landslides in lower 20% watershed
50	0.02	25	30	1.05	30	1	Increased landslide activity from “few” to “several” in lower 20% of watershed, some woody debris.
200	0.005	30	35	1.2	45	2	Debris flow tributary exists approximately 2 km upstream of the fan-delta apex (Drawing 05)
500	0.002	35	45	1.3	60	2	Investigated the potential peak flows associated with a landslide dam outbreak flood (LDOF) on the debris flow tributary creek upstream. However, peak discharges estimated for the sediment bulked, climate-change adjusted peak flows were higher than the LDOF scenario, and, therefore the modelling considered the bulked, climate adjusted peak flows to be conservative.

Notes:

1. Refer to Section 2 of the Methodology Report (BGC, March 31, 2020b) for details on bulking method.
2. The bulking factor for the 20-year return period only resulted in a 0.4 m^3/s increase in peak discharge.

6.4. Frequency-Volume Relationship

6.4.1. General

BGC used several independent approaches to create a frequency-volume relationship for Harrop Creek. These included air photo analysis of sediment deposits, test pitting, dendrochronology, sediment transport equations, and application of regional relationships for fan-delta area – sediment volume and watershed area – sediment volume. The different methods were compared. Debris volume results from the air photo analysis and test pit volume results are shown in Table 6-3 and the results of the regional relationship and sediment transport equations are shown in Table 6-6. The volume estimates from the Rickenmann (2001) analysis are not credible given that events greater than 100,000 m^3 do not appear in the air photo record and are 5 to 6 times higher than those obtained from the regional frequency-magnitude analysis. This overestimate could be attributable to either BGC's (March 31, 2020b) hydrographs not being representative, or the critical discharge being underestimated. Therefore, for numerical modelling, the regional relationships were applied as they appear to provide more reasonable results. These sediment volumes for the 20- and 50- year return period events are associated with Type 1 debris floods, while the sediment volumes for the 200- and 500- year return period events are associated with Type 2 debris floods.

Table 6-6. Summary of event volumes for each return period based on the regional frequency-volume curve and the Rickenmann (2001) sediment transport equation.

Return Period (years)	Event Volume (m^3)	
	Regional Frequency Volume	Rickenmann (2001)
20	35,000	190,000
50	45,000	246,000
200	60,000	343,900
500	70,000	413,900

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

6.4.2. Wildfire Effects on Debris Flood Sediment Volumes

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

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

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

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

The results of this study should not be relied upon to predict post-wildfire behaviour in the Harrop Creek watershed, especially for large moderate to high burn severity wildfires. A large wildfire in 2017 consumed over 16.7 km^2 of 42.7 km^2 (40%) at moderate intensity (intensity ranges from low to high with the majority of the burnt area at moderate intensity) burnt extents are shown in Drawing 05. In the following years, elevated sediment transport and minor blockages were reported by residents; however, no significantly damaging debris-flow or debris-flood events occurred. This indicates that extreme events may require a substantial wildfire and a substantial runoff event within a few years after the fire. The debris flow tributaries on the west side of Harrop Creek Tributary B were not affected by the 2017 fire and thus, understanding the post-wildfire behaviour on these tributaries maintains the limitations outlined above.

6.5. Numerical Debris Flood Modelling

A summary of the key observations from the debris flood modelling is included in Table 6-7. The model results are shown on Drawing 07 as well as presented in Cambio Communities. (**Note Drawing 07 will be delivered with the Final Report, screen captures of HEC-RAS and FLO-2D model results are included with this interim draft for discussion purposes).**

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

Table 6-7. Summary of modelling results.

Process	Key Observations
Clearwater inundation (HEC-RAS results for all return periods)	• Harrop Creek avulses for all modelled flows near the fan-delta apex. • Avulsions are shallow and follow existing avulsion channels • As flow avulsions reach Harrop Proctor Road and the railway embankments, the flows will pond and, depending on flood duration, eventually overtop the embankments assuming that culverts are rendered dysfunctional (potentially leading to a breach of the road or rail embankments). • Downstream of the railway crossing of Harrop Creek, flows will become unconfined due to the expected Erindale Road bridge blockage (low capacity) and flow through developments east and west of Harrop Beach Road. • While the overall composite hazard rating is comparatively low, flooding of basements and first floors with low entry elevations could still result in substantial economic damage.
Sedimentation	• Sedimentation associated with debris floods will be focused in the active channel and avulsion channels. The lower active channel downstream of the railway crossing could, in extreme events, aggrade to bank full. • The average deposition depth across the affected fan-delta portion will likely be around 10 cm.
Bank Erosion	• Bank erosion ranges between 4 m (20-year) and 30 m (500-year) while maximum erosion can reach to almost 50 m (500-year debris flood). Bank erosion potential generally decreases downstream. • Properties within the 50th percentile bank erosion corridor are likely subject to being affected by erosion if unprotected.
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 Harrop Creek will build up sediment and avulse particularly east of Harrop Beach Road and west of the active channel. • The location and width of CP Railway embankment breaches are very difficult to predict. Such breaches could lead to sudden and rapid and deep water flows immediately downstream of the breach. This process is not reflected in BGC's hazard maps.

6.6. Bank Erosion Assessment

The air photo assessment compared available air photos from 1929 to 2006 to determine the historical changes in channel width at the seven cross-sections considered in the bank erosion assessment (see Drawings 02A, 02B for cross-section locations). At Harrop Creek, cross sections 1 to 3 did not have visible banks in the air photos, therefore these sections were excluded from the air photo assessment. Table 6-8 summarizes the maximum channel width change between successive pairs of air photos at the cross-section at which it was observed. The maximum observed change in channel width between two successive air photos on Harrop Creek was 7 m, between 1979 and 1988 at cross-section 4. To provide context for these values, the average current bankfull width is 4 m at the cross sections analyzed. Potential error or uncertainty in these measurements may be introduced by shadows from vegetation, poor image quality, or stretching during rectification. BGC estimates the total error associated with the above factors is less than 5 m.

Table 6-8. Summary of channel width change for each air photo.

Air Photo Interval	Maximum Channel Width Change Between Photos (m)	Cross-Section of Maximum Channel Width Change (Drawings 02A, 02B)
1929-1958	3	5
1958-1968	0	-
1968-1979	3	6
1979-1988	7	4
1988-1997	0	-
1997-2006	0	-

A summary of the bank erosion model results by return period is outlined in Table 6-9. 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 6-9. Summary of bank erosion model results by return period.

Return Period (years)	Minimum Erosion (m)	Average Erosion (m)	Maximum Erosion (m)
20	0	4	10
50	0	8	16
200	5	18	27
500	12	34	48

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

Figure 6-2 shows the 50% percentile modelled bank erosion at each cross-section. The predicted erosion differs between cross-sections based on the cross-section characteristics (e.g., channel geometry, channel slope, D_{84} grain size). Erosion peaks at cross-section 3 for the 20-year to 200-year return periods, and at cross-section 4 for the 500-year return period.

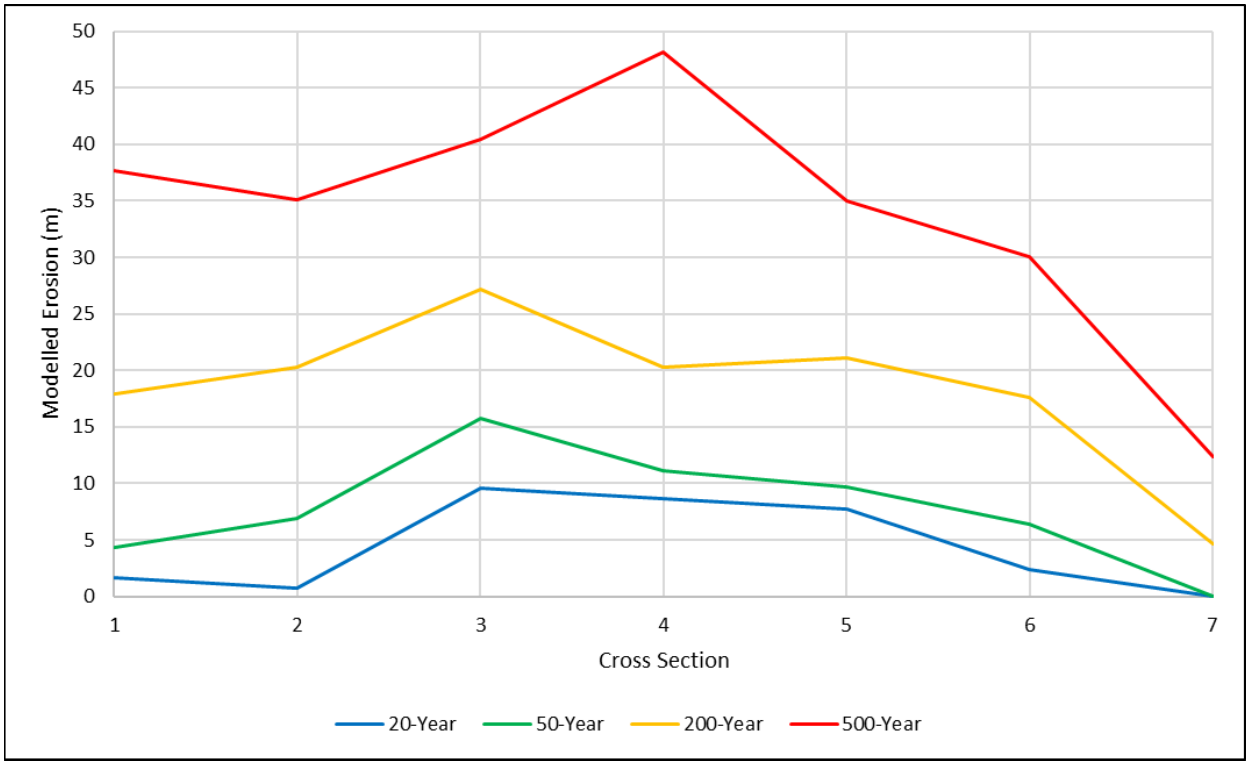


Figure 6-2. Harrop Creek 50th percentile bank erosion model results at each cross-section.

Buildings located on the property off of Mill Creek Road, adjacent to cross-section 2, fall within the improbable corridor for the 200-year return period event. Buildings close to the creek, north of Harrop Procter Road and south of Erindale Road, fall within the improbable corridor of the 500-year return period. Longer-term progressive erosion could impact buildings along the creek in these areas.

6.7. Hazard Mapping

Drawing 07 provides a representative hazard scenario map 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, hazard zones shown on the composite hazard rating map reflect categorization applicable to a wide range of hazard types, from clearwater floods to large landslides. The choice of categorization may affect interpretation by the map user and is subject to review and discussion with RDCK.

6.7.1. Comparison with NHC/Thurber (1990)

As outlined in Section 4.3, a detailed study of creeks on the Kootenay Lake west arm was completed in 1990 by NHC/Thurber. The NHC/Thurber (1990) study is highlighted and discussed separately as it is the key detailed study now being superseded by this report.

6.7.1.1. Methodological Differences

The NHC/Thurber (1990) assessment considered debris torrents[5], avulsions or channel shifts, and inundation. For each fan-delta 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 6-3 shows the NHC/Thurber risk map for Harrop Creek.

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

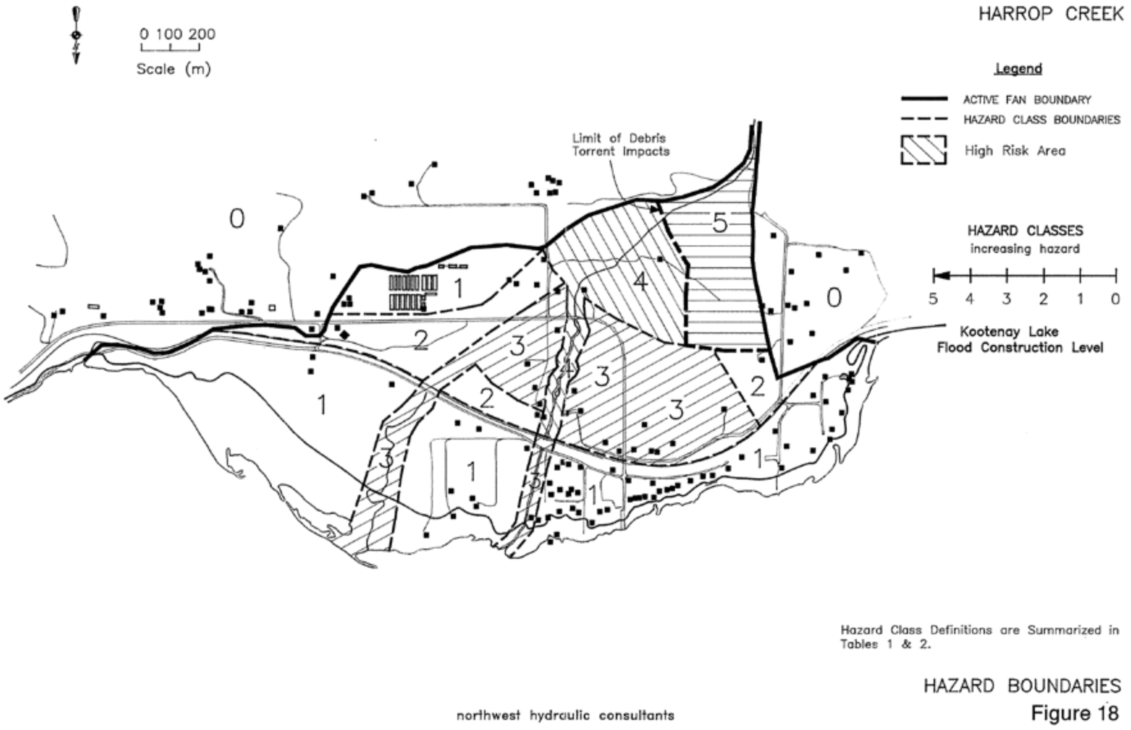

Figure 6-3. NHC/Thurber's (1990) Harrop Creek individual life risk map. Class 4 and 5 imply individual life loss risk values exceeding 1:10,000. Class 3 1:10,000 to 1:20,000. Class 0, 1 and 2 < 1:20,000.

This section compares BGC's and NHC/Thurber's approaches because the hazard maps of the two reports differ significantly with NHC/Thurber's hazard levels being generally much higher than those of BGC. The principal differences are highlighted in Table 6-10. For convenience, NHC/Thurber (1990) is abbreviated in Table 6-10 to N/T.

Table 6-10. 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 fan-deltas 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-delta 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 dendrochronology, test trenching and radiocarbon dating, 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 modeling of clearwater flows in main channels	Two types of sediment transport calculations, regional F-M sediment volume relationships, measurements of deposition depth in test trenches, empirical relationships between peak discharges and sediment volumes	Substantially greater effort by BGC (2020) compared to N/T, thus higher confidence in BGC (2020)
Probability of Avulsion	Method by Dawdy (1979) to determine probability of avulsion based on historical information and geomorphology	Numerical modeling-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 modeling 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 6-11

Table 6-11. 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.

6.7.1.2. Harrop Creek Specifics

NHC/Thurber (1990) interpreted boulder debris levees in the area proximal to the fan-delta apex to be evidence of past debris-flow events on Harrop Creek, but this hazard would quickly dissipate downstream due to reduced channel gradients and loss of confinement. For this reason, the hazard classification is highest near the fan-delta apex and decreases in the other areas of the fan-delta where channel change and avulsions were interpreted to constitute the dominant hazard type (NHC and Thurber, April 1990). In total 40% of the fan-delta is classified as hazard code 3, 4, or 5.

6.7.1.3. Summary

After careful review of the NHC/Thurber (1990) work, BGC concludes that the hazards and likely risks to loss of life are substantially lower than estimated by NHC/Thurber as determined through BGC's assessment. The main reason for this discrepancy is that NHC/Thurber did not benefit from lidar topography, subsurface investigation, detailed numerical modeling and an additional 30 years of data that have accrued since their study and the present. In absence of such detailed information and analysis it was likely justified to err on the conservative spectrum. BGC believes that the current work is a credible representation of hazards on Harrop Creek up to the 500-year return period scenarios considered.

7. SUMMARY AND RECOMMENDATIONS

7.1. Introduction

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

A variety of analytical desktop and field-based tools and techniques were combined to decipher Harrop 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, Harrop Creek is subject to supply-unlimited Type 1 debris floods for lower return periods (20- and 50-year). For higher return periods (200- and 500-year), Type 2 debris floods are believed to be the dominant process due to the presence of a debris flow tributary approximately 2 km upstream of the fan-delta apex (Drawing 03). The two deep-seated landslides in the upper watershed (Drawing 05) indicate that Type 3 debris floods are possible but at return periods (>500-year) greater than considered in this assessment.

7.2.2. Air Photo Interpretation, Dendrogeomorphology, and Test Pitting

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

- The largest debris flood occurred sometime between 1929 and 1939 as 1939 air photos show an area of freshly deposited debris of approximately 25,700 m^2.
- Dendrochronological investigations are not extensive enough to provide results usable for the development of the F-M curve.
- At least three notable hydrogeomorphic events have occurred since 1929. BGC interprets that all the noted events are likely Type 1 debris flood events due to their extensive erosion and observed movement of sediment in air photos.

7.2.3. Peak Discharge Estimates

In recognition of the impacts of climate change and potential bedload and suspended sediment loads, the clearwater flows estimated from 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 Harrop Creek range from 25 m^3/s (20-year flood) to 45 m^3/s (500-year flood).
- Sediment bulking factors of 1.02 (2% increase for the 20-year debris flood) to 1.3 (30% increase for the 500-year return period event) were adopted as input to numerical modelling.
- Consideration of climate change and sediment bulking increase the clearwater discharge estimate from 20 to 25 m^3/s for the 20-year debris flood, and from 35 to 60 m^3/s for the 500-year event.

7.2.4. Frequency-Magnitude Relationships

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

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

Return Period (years)	Adjusted Peak Discharge (m^3/s)
20	25
50	30
200	45
500	60

7.2.5. Numerical Flood and Debris Flood Modelling

Two numerical models were employed to simulate the chosen hazard scenarios on the Harrop 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 6-7 provided key observations derived from the numerical modelling.

The multiple process numerical modelling ensemble approach demonstrates that the key hazards and associated risks at Harrop Creek stem from the multiple avulsion paths as the main channel's capacity is exceeded at higher return periods.

7.2.6. 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 erosion predicted by modelling was calibrated with the air photo record, accounting for likelihood of a 50-year return period flood having occurred within the record span.

- Total bank erosion (both channel sides) is predicted to range between a maximum of 10 m for a 20-year debris flood event to approximately 50 m for a 500-year return period debris flood.
- Key locations where bank erosion could lead to greater risk include buildings located in close proximity to the creek between cross-section 2 (see Drawings 02A, 02B) and Erindale Road. Properties south of Harrop Procter Road could be at risk during events smaller than the 500-year event, while those north of Harrop Procter Road are at risk of progressive erosion for events greater than the 500-year event.

7.2.7. Hazard Mapping

Model results are cartographically expressed in two ways:

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

Both the individual scenario maps and the composite impact intensity frequency map serve as decision-making tools to guide subdivision and other development permit approvals.

7.3. Limitations and Uncertainties

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

- Future fan-delta development
- Substantial flood or debris flood events
- Development of large landslides in the watershed with the potential to impound Harrop Creek
- Bridge re-design
- Alteration to the existing dike near the creek outlet
- Substantial changes to Kootenay Lake levels.
- Significant wildfire events in the watershed.

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

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

7.4. Considerations for Hazard Management

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

Recommendations are provided in the Summary Report (BGC, March 31, 2020a) as they pertain to all studied RDCK creeks. This section notes Harrop 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 Harrop 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. 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 require access easements. Given the length of the fan-delta from the fan apex to Kootenay Lake (~1700 m) such setback berms would be very expensive and would still require occasional sediment removal and maintenance works.

Harrop Creek fan-delta hosts the second highest value of assets of the steep creek fan-deltas studied in detail (Table 1-1). Hence, while likely expensive, Option (a) may be viable at Harrop 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. As debris basins are usually not significant flow attenuators, avulsions on the upper fan and at stream crossings can still be expected due to channel or crossing undersizing. Hence, even with a debris basin in place, additional debris-flood mitigation measures would need to be considered.

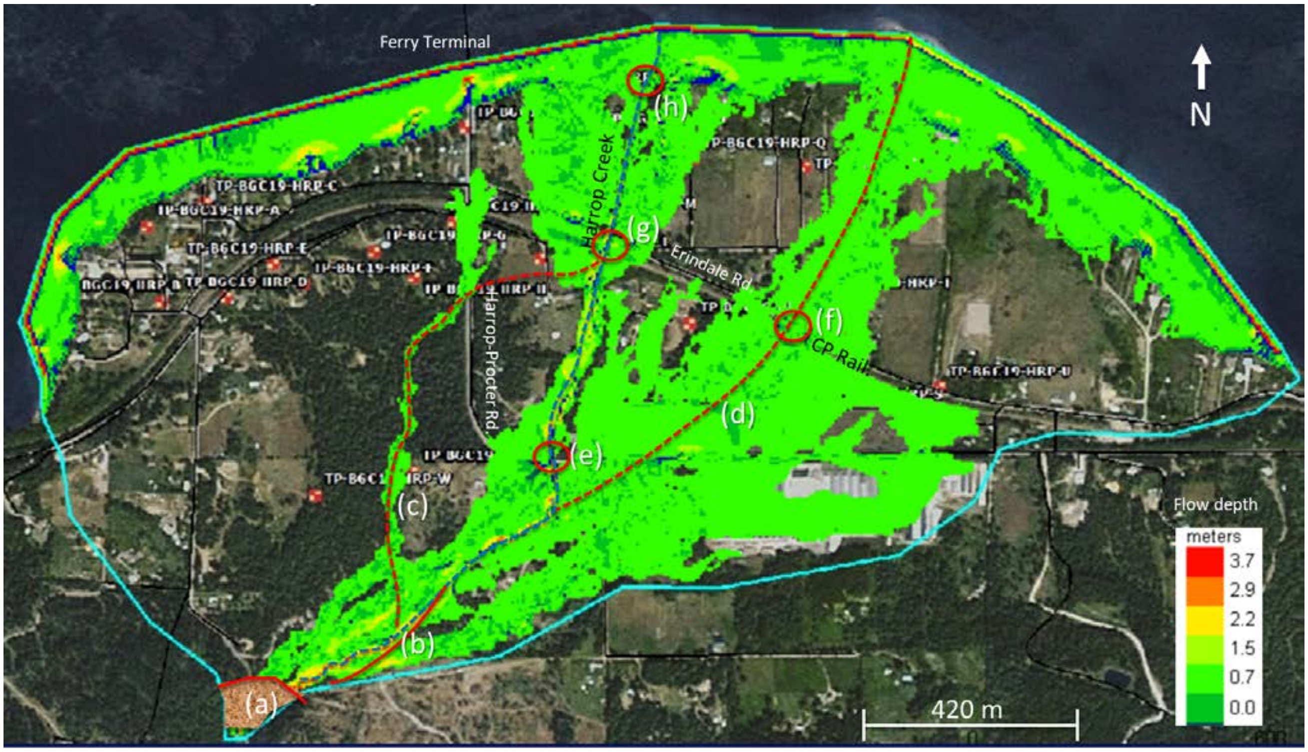

Figure 7-1. **Debris-flood inundation map showing flow depths for a 200-year return period debris flood on Harrop Creek from FLO 2D modeling. The figure shows conceptual-level mitigation options for Harrop Creek fan-delta. Note that these mitigation options have not been tested by numerical modelling and only serve as an impetus for further discussion. Other options will likely be developed at the conceptual design level.**

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

Table 7-2. Mitigation considerations for Harrop 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-flood scenarios, reduced chance of downstream avulsions.
(b)	Deflection berm on east side of channel downstream of fan apex	Reduction of avulsion potential to the eastern fan portions
(c)	Construction of engineered overflow sill into existing avulsion channel and construction of new channel section from Harrop-Procter Road eastward into Harrop Creek. Requires bridge or culvert at the Harrop-Procter Road crossing.	Reduction in flow down the existing Harrop Creek channel, hence reduction in avulsion potential
(d)	Long, constructed avulsion bypass channel requiring new bridge or culvert crossings at Harrop Procter Road, Erindale Road and CP Railway	Reduction in flow down the existing Harrop Creek channel, hence reduction in avulsion potential
(e) (f) (g) (h)	Enlargement or replacement of present bridge and culvert replacements at Harrop-Procter, Erindale roads and CP Rail	Reduction in avulsion potential at crossings

This table demonstrates that effective risk reduction can only be achieved through a combination of mitigation measures, all of which are associated with different costs. The construction of engineered avulsion channels would require property acquisitions or crossing agreements.

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.

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

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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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 south at the community of Harrop, the Harrop Creek delta, and Harrop Creek outlet into Kootenay Lake. The fan apex is indicated. Photo: BGC, July 6, 2019.

Photo 2.

Overview photo taken during helicopter overflight looking northwest at the Harrop Creek fan and the community of Harrop. Erindale Road (bottom to top) is running across the fan. Photo: BGC, July 6, 2019.

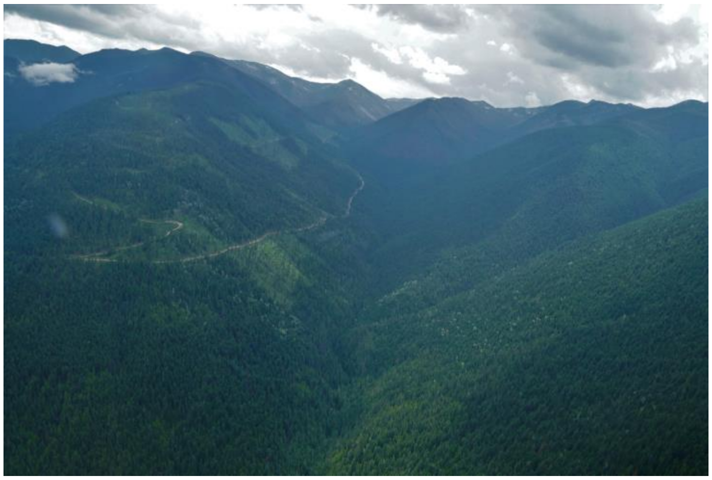

Photo 3.

Overview photo taken during helicopter overflight looking south along Harrop Creek. Tributary A joins Harrop Creek from the southeast (i.e., right side of photo). Photo: BGC, July 6, 2019.

Photo 4.

Overview photo taken during helicopter overflight looking southeast at old landslide scarp (orange dashed line) east of the Harrop Creek Tributary B, located approximately 7.5 km upstream of the outlet to Kootenay Lake (see Drawing 05 for location). Photo: BGC, July 6, 2019.

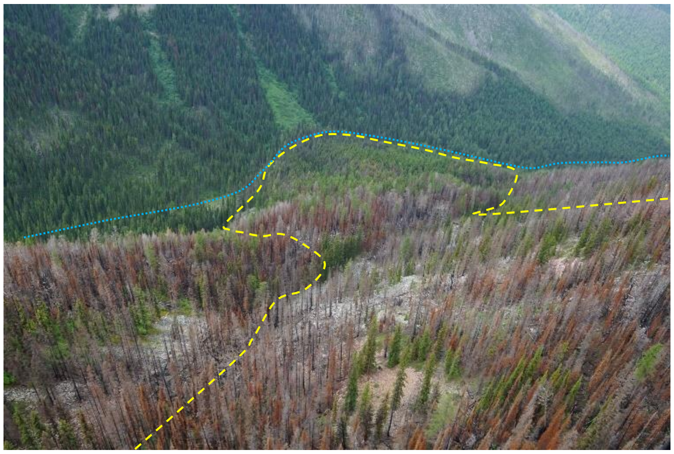

Photo 5.

Overview photo taken during helicopter overflight looking northeast at old landslide (yellow dashed line) which moved Harrop Creek Tributary B (blue dotted line) to the opposite valley side, located approximately 9.2 km upstream of the outlet to Kootenay Lake (see Drawing 05 for location). Photo: BGC, July 6, 2019.

Photo 6.

Overview photo taken during helicopter overflight looking north at Mill Lake and Harrop Creek main stem in the upper headwaters. Note the burn areas from the 2017 wildfire. Photo: BGC, July 6, 2019.

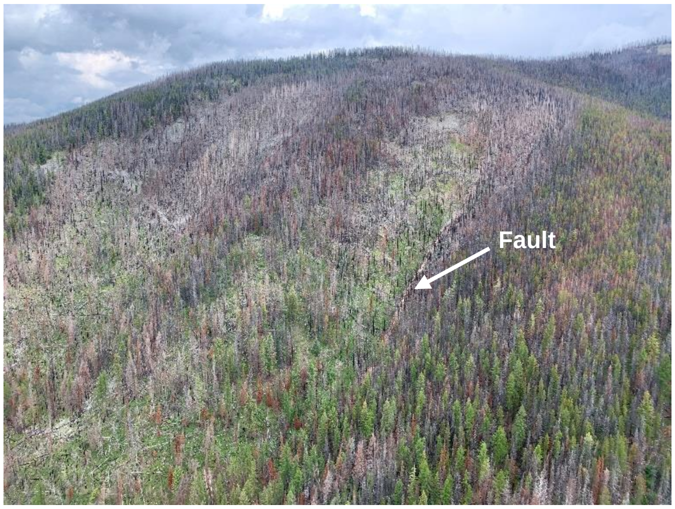

Photo 7.

Overview photo taken during helicopter overflight looking at northeast trending fault traced by a recent, post-wildfire debris flow path. The fault runs down a west facing slope and meets Harrop Creek Tributary C approximately 600 m upstream of location A (see Drawing 05 for location). Note the landslide features (including rock outcrops) to the north of the fault. Photo: BGC, July 8, 2019.

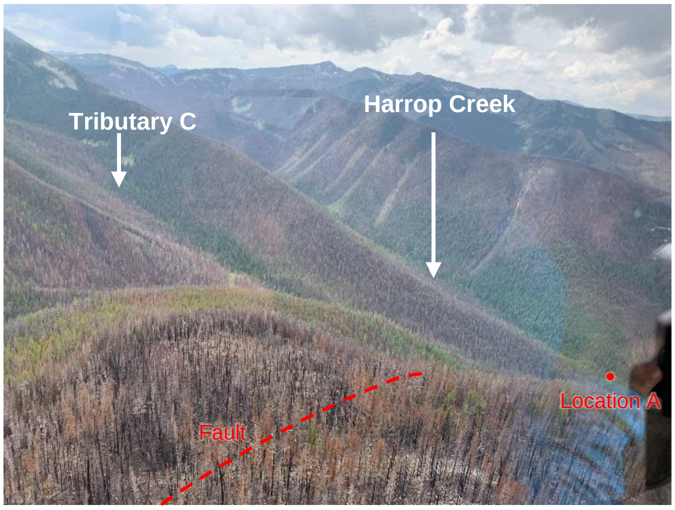

Photo 8.

Overview photo taken during helicopter overflight looking south at fault (Photo 7) in foreground, Location A is confluence of Harrop Creek and Tributary C. Note the extensive wildfire burn areas, as well as the snow avalanche/debris flow paths along Harrop Creek (see Drawing 05 for locations). Photo: BGC, July 8, 2019.

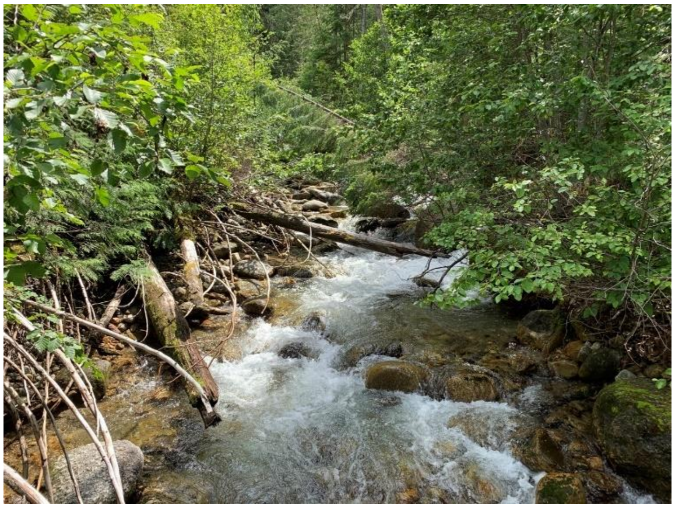

Photo 9.

Looking upstream (south) at Harrop Creek, approximately 2 km upstream of Kootenay Lake. Logs are lying across the creek. Photo: BGC, July 2019.

Photo 10.

Left bank erosion on outside channel bend of Harrop Creek, approximately 1.35 km upstream of the outlet to Kootenay Lake. Note trees fell across the creek. Estimated age of bank failure 2 years. Photo: BGC, July 2019.

Photo 11.

Looking upstream at aggraded Harrop Creek channel and remnants of recently washed out bridge (red arrow), approximately 50 m upstream of Kootenay Lake. Photo: BGC, July 2019.

Photo 12.

Harrop Creek fan at Harrop Creek outlet to Kootenay Lake. Photo: BGC, July 5, 2019.

APPENDIX C
SEDIMENT SIZE SAMPLING

C.1. SAMPLING LOCATIONS

At Harrop Creek, two Wolman Samples were taken, one downstream of the fan apex above the water intake, and the other upstream of Harrop Procter Road. The sampling locations (referred to as Harrop 1 and Harrop 2) are shown in Figure C-1 and in Table C-1. Bed material conditions at each site are shown on Figure C-2, and Figure C-3.

Table C-1. Wolman sampling locations.

Site Name	Harrop 1	Harrop 2
Location	Downstream of fan apex, upstream of water intake.	Upstream of Harrop Procter Road.
Longitude	117° 3'36.05"W	117° 3'11.41"W
Latitude	49°35'43.22"N	49°36'2.11"N
Number of stones measured	98	102

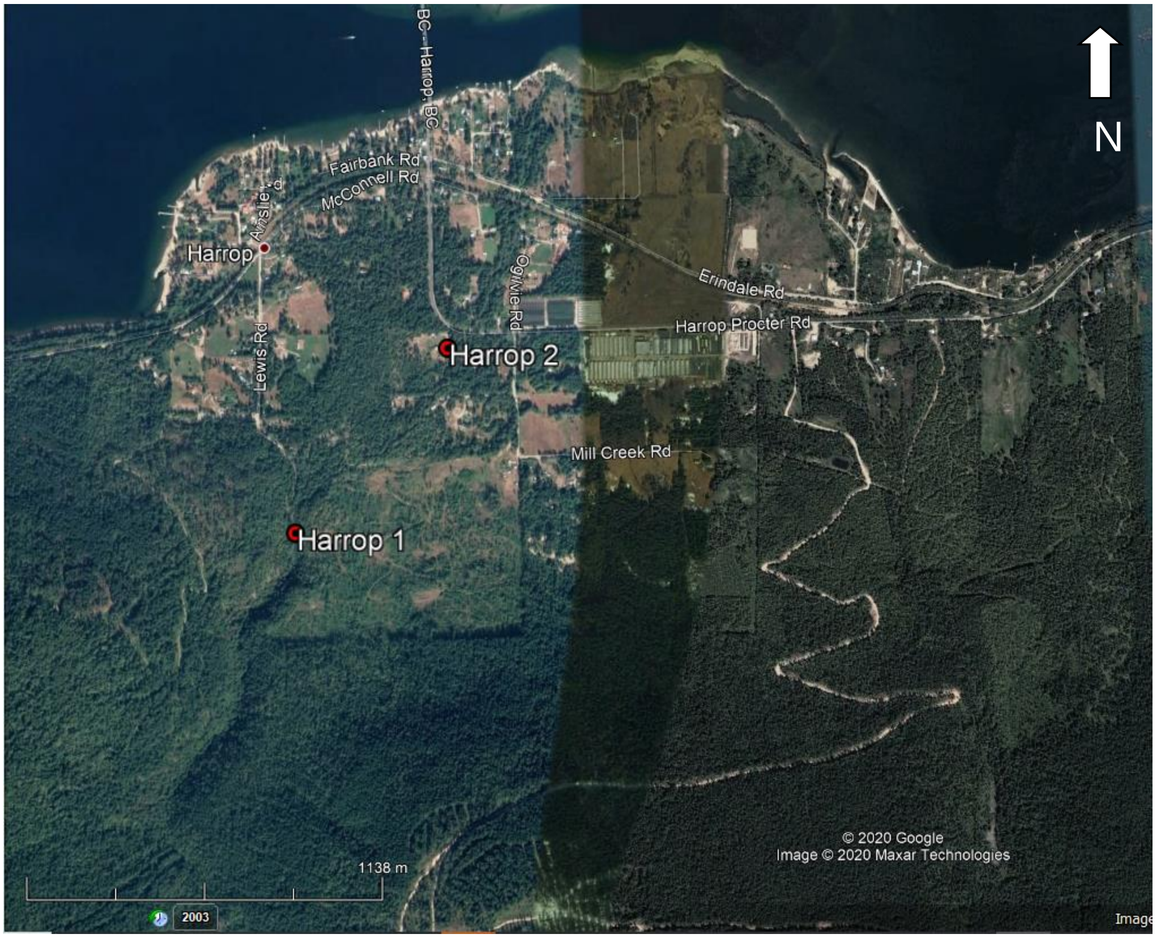

Figure C-1. Wolman sampling locations along Harrop Creek. Google Earth image of September 11, 2017.

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

Figure C-3. Photograph taken of Wolman sampling location Harrop 2. BGC photograph of November 20, 2019.

At the Harrop 1 sampling location, the measuring tape was 21 m long and samples were randomly selected at intervals of 20 cm. At the Harrop 2 sampling location, the measuring tape was approximately 25 m long, and samples were taken every 20 cm.

C.2. RESULTS

Results of the Wolman counts are shown in Table C-2 and on Figure C-4 and Figure C-5.

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

Grain Size	Harrop 1	Harrop 2
D_{95} (mm)	215	173
D_{84} (mm)	126	112
D_{50} (mm)	49	51
D_{15} (mm)	18	22
D_5 (mm)	7	13

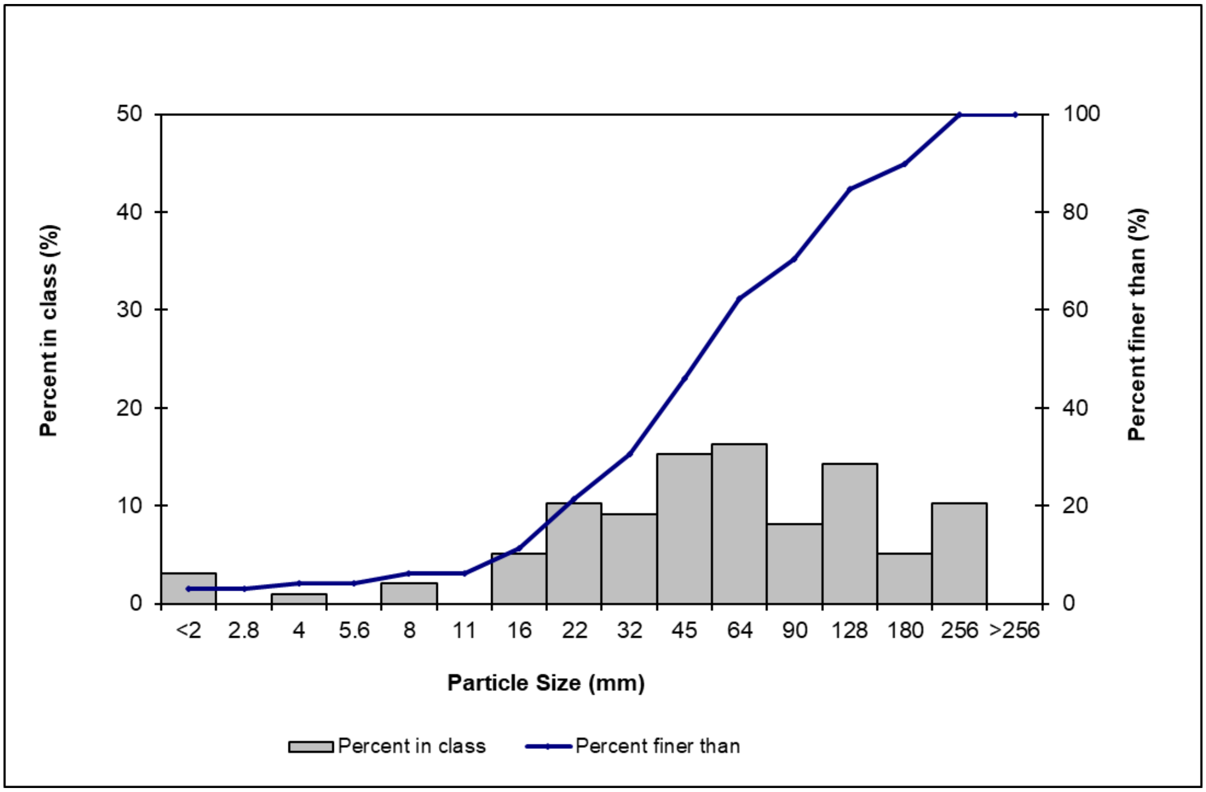

Figure C-4. Harrop Creek grain size distribution at Harrop 1 (downstream of fan apex, upstream of the water intake) from Wolman count.

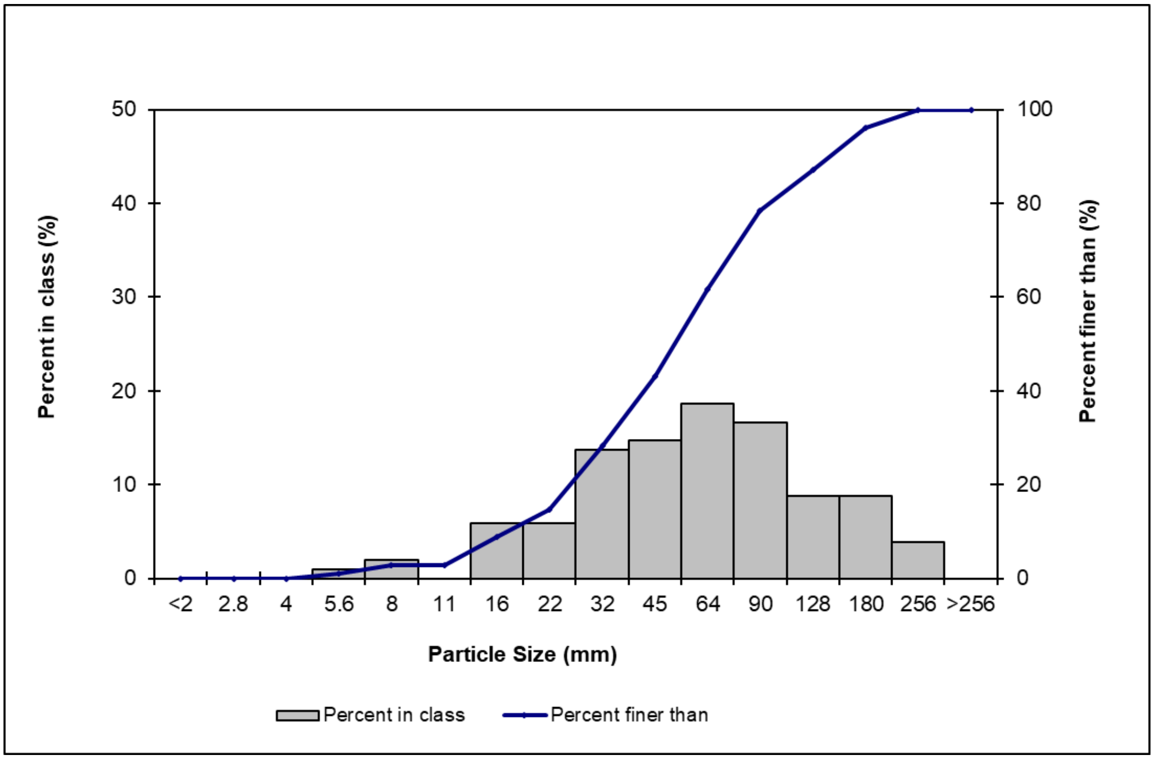

Figure C-5. Harrop Creek grain size distribution at Harrop 2 (upstream of Harrop Procter Road) from Wolman count.

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

APPENDIX D
AIR PHOTO RECORDS

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

Year	Date	Roll Number	Photo Number	Scale
2006	9/1/2006	BCC06135	36-37	20,000
	7/21/2006	BCC06061	205-207	20,000
2000	9/17/2000	BCB00038	121, 163-165	15,000
1997	8/22/1997	BCB97047	163-165, 262-264	15,000
1988	7/22/1988	BC88090	54-56, 105-107	15,000
1979	8/2/1979	BC79134	11-16, 32-36	10,000
1974	6/17/1974	BC7568	137-141, 148-154	8,000
1968	8/31/1968	BC7111	12-15	16,000
1988	8/8/1968	BC7109	25-27	16,000
1958	7/24/1958	BC2478	8-10, 50-52	15,840
1952	6/14/1952	BC1455	13-16	31,680
1945	6/5/1945	A7735	43528	25,000
1939	7/24/1939	BC146	71-73, 90-92	31,680
1929	4/18/1929	A1015	16-18	10,000

APPENDIX E
TEST PIT DETAILED LOGS AND PHOTOGRAPH LOGS

TP-BGC19-HRP-01

Page 1 **of** 1

Project: RDCK Floodplain and Steep Creek Study
Location : Harrop, BC
Project No. : 0268007

Survey Method : GPS
Coordinates : 496,069.E, 5,494,195.N
Ground Elevation (m) :569
Datum : NAD83

Start Date : 09 Jul 19
Finish Date: 09 Jul 19
Final Depth of Pit (m) : 2.5
Logged by : MJ
Reviewed by : N/A

Depth (m)	Symbol	Sample Material for Dating	Sample Age	Lithologic Description
0				Top soil removed.
				UNIT 1: FLUVIAL DEPOSIT Sand and gravel, matrix supported, subrounded to subangular, dry, Dmax = 6 cm, sloping with fan gradient to north (8% grade).
				SOIL 1 Silt, sandy, brown, modern rootlets, sloping to north.
				UNIT 2: DEBRIS FLOOD DEPOSIT Gravel and sand, matrix supported, subrounded to subangular, dry, no imbrication, mostly granitic source.
1		G-2 Charcoal (1 m)	4585 - 4831 cal BP	SOIL 2 Paleosol, sharp transition, brown brunisol.
2				UNIT 3: DEBRIS FLOW DEPOSIT Gravel, sandy, some cobbles, subrounded to subangular, massive, clast supported, no imbrication, no cross stratificaion, Dmax = 0.4 m.
		G-1 Rootlet (2.3 m)	Not tested	SOIL 3
				UNIT 4: DEBRIS FLOOD DEPOSIT Gravel and sand, matrix supported, subrounded to subangular, dry, no imbrication, mostly granitic source.
3				END OF TEST PIT 2.5 m.

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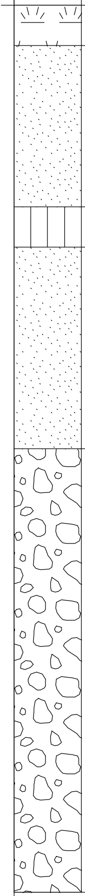
TP-BGC19-HRP-02

Page 1 **of** 1

Project: RDCK Floodplain and Steep Creek Study
Location : Harrop, BC
Project No. : 0268007

Survey Method : GPS
Coordinates : 496,063.E, 5,494,597.N
Ground Elevation (m) :551
Datum : NAD83

Start Date : 09 Jul 19
Finish Date: 09 Jul 19
Final Depth of Pit (m) : 2.2
Logged by : MJ
Reviewed by : N/A



Depth (m)	Symbol	Sample Material for Dating	Sample Age	Lithologic Description
0				Top soil, duff and B-horizon, removed.
				UNIT 1: OVERBANK FLOW Sand, fine to medium, light grey, some horizontal bedding.
		G-1 Paleosol (sand) (0.75 m)	4000 - 4239 cal BP	PALEOSOL Sand, fine, silty, dark brown, discontinuous across test pit, diffuse lower boundary.
1				UNIT 2: OVERBANK FLOW Sand, fine to medium, light grey, some horizontal bedding, modern rootlets throughout.
2				UNIT 3: DEBRIS FLOOD DEPOSIT Sand and gravel, trace cobbles and boulders, matrix supported, subrounded to subangular, loose, non-cohesive, dry, Dmax = 1 m.
3				END OF TEST PIT 2.2 m.

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Client: RDCK

TP-BGC19-HRP-03

Page 1 **of** 1

Project: RDCK Floodplain and Steep Creek Study
Location : Harrop, BC
Project No. : 0268007

Survey Method : GPS
Coordinates : 495,883.E, 5,494,745.N
Ground Elevation (m) :545
Datum : NAD83

Start Date : 09 Jul 19
Finish Date: 09 Jul 19
Final Depth of Pit (m) : 1.8
Logged by : MJ
Reviewed by : N/A

Depth (m)	Symbol	Sample Material for Dating	Sample Age	Lithologic Description
0				Top soil removed
1				UNIT 1: DEBRIS FLOOD DEPOSIT Gravel, and sand, fine, some cobbles, matrix supported, subrounded to subangular, dry, numerous rootlets in top 100 mm, no organics, D50 = 0.1 m, Dmax = 0.5 m.
				UNIT 2: FLUVIAL DEPOSIT Gravel, sandy, massive, apparent cohesion, dry.
2 3				END OF TEST PIT 1.8 m.

RDCK (STRAT_COL) RDCK.GDL BGC.GDT 9/27/19

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Client: RDCK

TP-BGC19-HRP-04

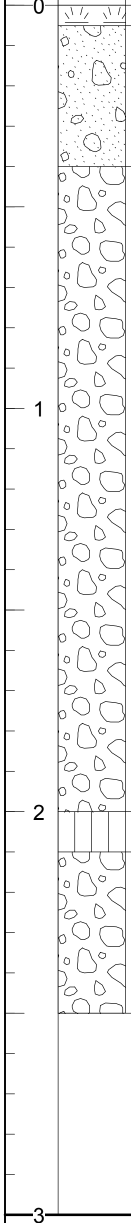
Page 1 **of** 1

Project: RDCK Floodplain and Steep Creek Study
Location : Harrop, BC
Project No. : 0268007

Survey Method : GPS
Coordinates : 495,914.E, 5,494,114.N
Ground Elevation (m) :580
Datum : NAD83

Start Date : 09 Jul 19
Finish Date: 09 Jul 19
Final Depth of Pit (m) : 2.5
Logged by : MJ
Reviewed by : N/A

Depth (m) | Symbol



Sample Material for Dating	Sample Age	Lithologic Description
		Top soil removed.
		UNIT 1: FLUVIAL DEPOSIT Sandy gravels, up to 2 cm thick, matrix supported, no stratification, no imbrication.
		UNIT 2: DEBRIS FLOOD DEPOSIT Massive, unstratified debris flow unit, subrounded to subangular, dry to slightly moist, no imbrication, D50 = 2 cm, Dmax = 45 cm. Sand lenses present from 1.2 to 1.45 m.
G-1 Charcoal (2 m)	5749 - 5917 cal BP	PALEOSOL Light brown soil, paleosol, fine sand.
		UNIT 3: DEBRIS FLOOD DEPOSIT Massive, unstratified debris flow unit, subrounded to subangular, dry to slightly moist, no imbrication, D50 = 2 cm, Dmax = 45 cm.
		END OF TEST PIT 2.5 m.

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Client: RDCK

TP-BGC19-HRP-05

Page 1 **of** 1

Project: RDCK Floodplain and Steep Creek Study
Location : Harrop, BC
Project No. : 0268007

Survey Method : GPS
Coordinates : 496,857.E, 5,494,559.N
Ground Elevation (m) :540
Datum : NAD83

Start Date : 09 Jul 19
Finish Date: 09 Jul 19
Final Depth of Pit (m) : 2.6
Logged by : MJ
Reviewed by : N/A

Depth (m)	Symbol	Sample Material for Dating	Sample Age	Lithologic Description
0				Top soil, brunisol, silty sand, light grey.
				UNIT 1: FLUVIAL DEPOSIT Sand, fine to coarse, thinly laminated, irregular, sharp contact to charcoal below.
		G-A Charcoal (0.6 m)	Not tested	PALEOSOL/CHARCOAL
1				UNIT 2: OVERBANK DEPOSITS Sand, fine, light brown, mottled, poorly stratified, faint bedding, overbank deposits.
				UNIT 3: FLUVIAL DEPOSIT Gravel, sandy.
		G-B Charcoal (1.6 m)	1411 - 1552 cal BP	PALEOSOL Charcoal, faint paleosol.
				UNIT 4: OVERBANK DEPOSITS Sand, fine, light brown, poorly stratified, faint bedding, overbank deposits.
				PALEOSOL Charcoal, faint paleosol
				UNIT 5: FLUVIAL DEPOSIT Fine to coarse sand, thinly laminated, irregular, sharp contact to charcoal below.
2		G-C Charcoal with paleosol (2 m)	Not tested	PALEOSOL/CHARCOAL
				UNIT 6: OVERBANK DEPOSITS Sand, fine, light brown, stratified.
				CHARCOAL
		G-D Charcoal (2.5 m)	2117 - 2310 cal BP	UNIT 7: OVERBANK DEPOSITS Sand, fine, light brown, poorly stratified, faint bedding, overbank deposits.
				CHARCOAL
				UNIT 8: FLUVIAL DEPOSIT Mostly gravel unit, Dmax = 8 cm.
				END OF TEST PIT 2.6 m.
3				

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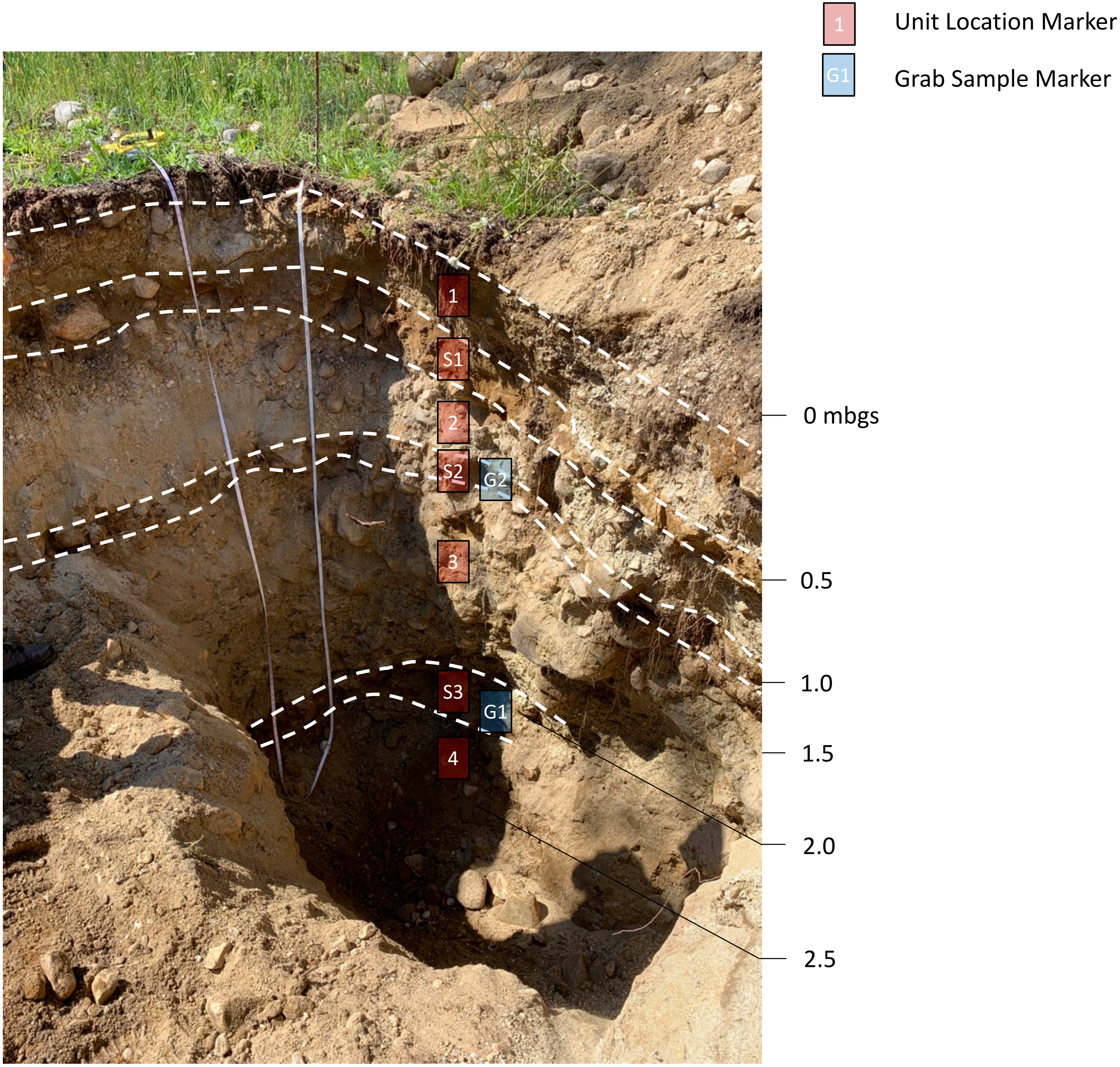
Client: RDCK



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SCALE:
DATE: 02-2020
PREPARED BY: BCP
CHECKED BY:
APPROVED BY:

REGIONAL DISTRICT CENTRAL KOOTENAY
BGC

REPORT TITLE:
RDCK FLOODPLAIN AND STEEP CREEK STUDY – MILL CREEK (HARROP)

FIGURE TITLE:
TP-BGC19-HRP-01

PROJECT NO: 0268-007
FIGURE NO: C-1

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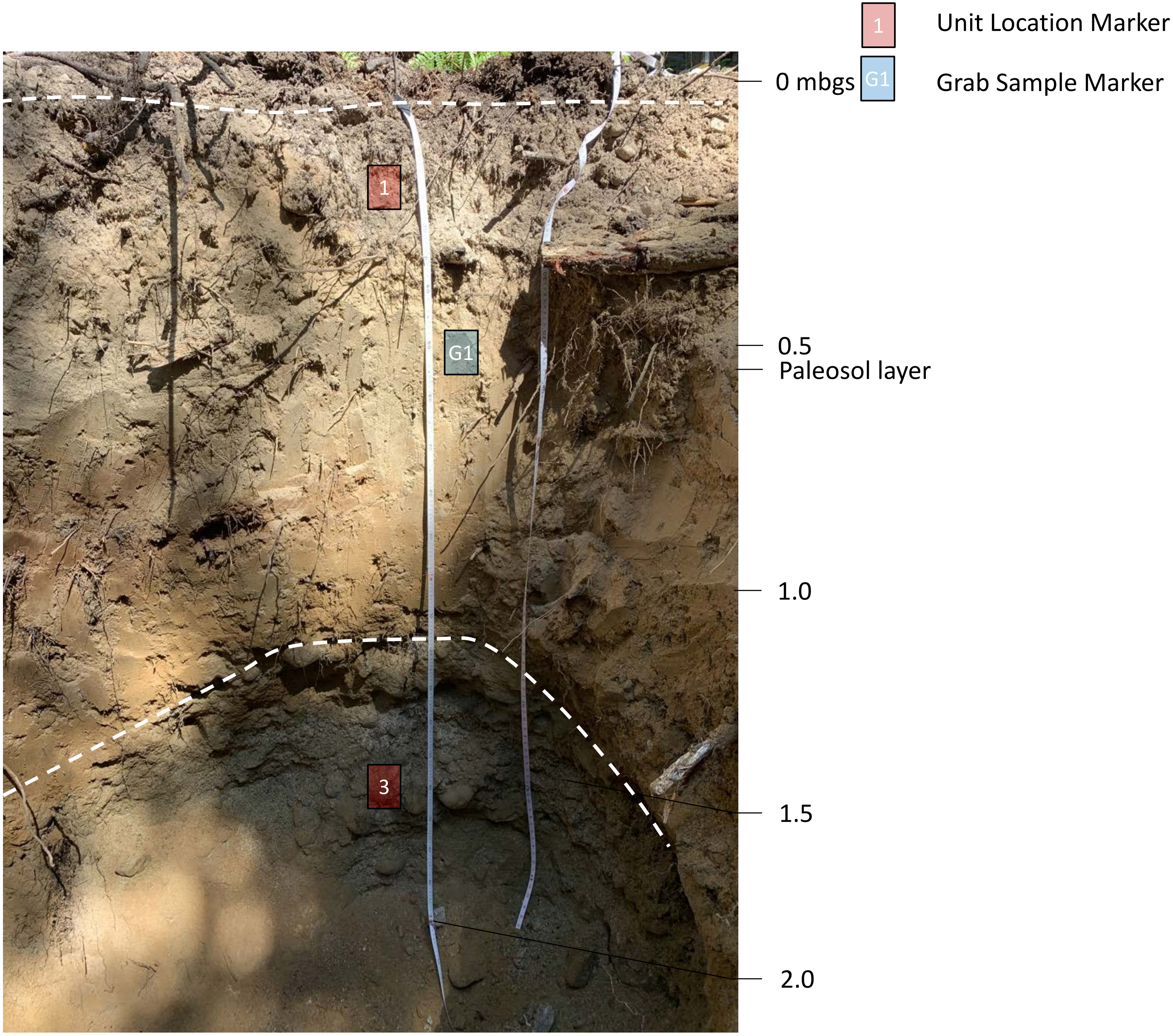

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REGIONAL DISTRICT CENTRAL KOOTENAY

BGC

REPORT TITLE:
RDCK FLOODPLAIN AND STEEP CREEK STUDY – MILL CREEK (HARROP)

FIGURE TITLE:
TP-BGC19-HRP-02

PROJECT NO:
0268-007

FIGURE NO:
C-2

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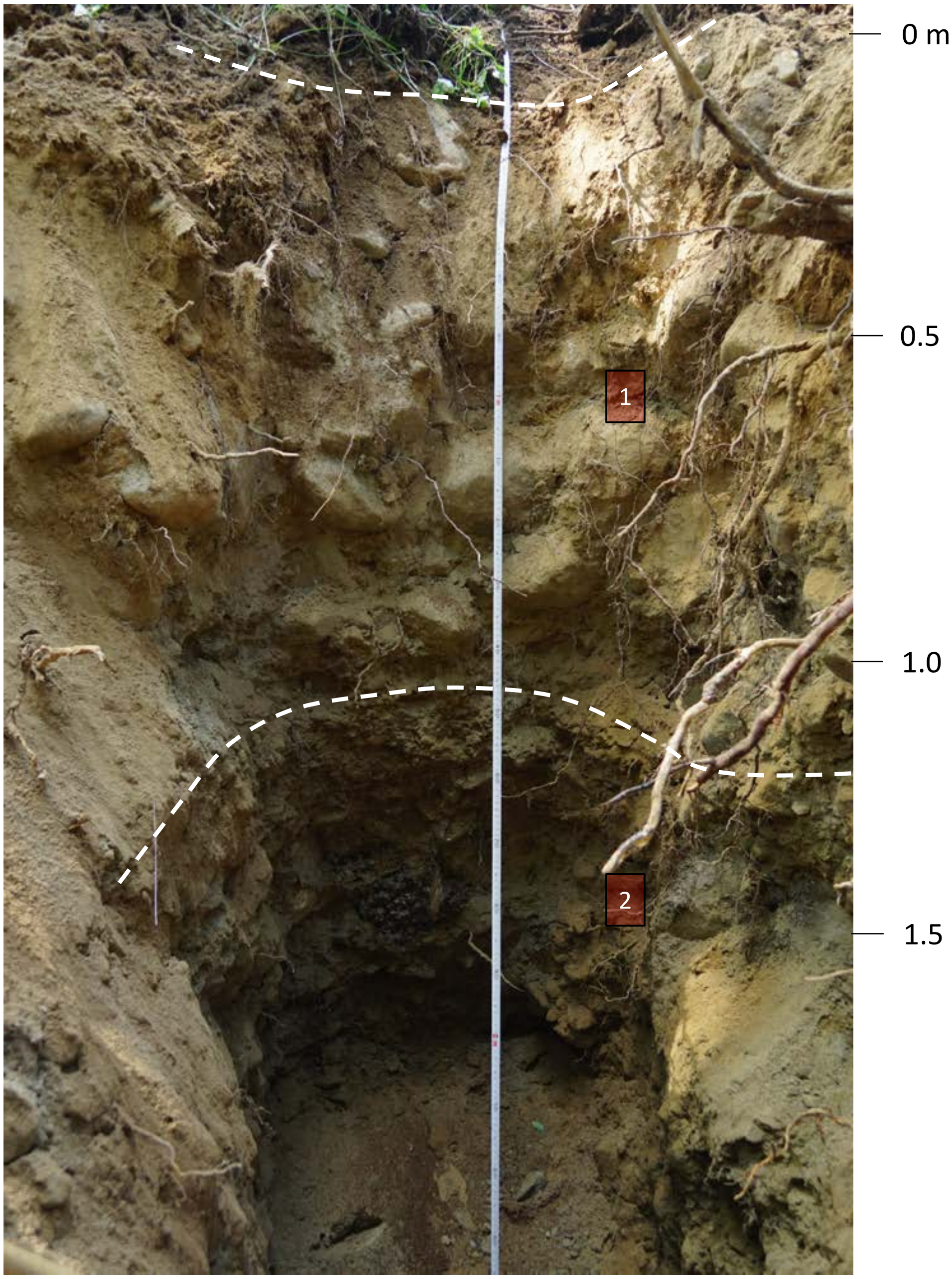
1 Unit Location Marker

G1 Grab Sample Marker



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SCALE:

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REPORT TITLE: RDCK FLOODPLAIN AND STEEP CREEK STUDY – MILL CREEK (HARROP)

FIGURE TITLE: TP-BGC19-HRP-03

PROJECT NO: 0268-007

FIGURE NO: C-3

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REGIONAL DISTRICT CENTRAL KOOTENAY

BGC

REPORT TITLE:
RDCK FLOODPLAIN AND STEEP CREEK STUDY – MILL CREEK (HARROP)

FIGURE TITLE:
TP-BGC19-HRP-04

PROJECT NO:
0268-007

FIGURE NO:
C-4

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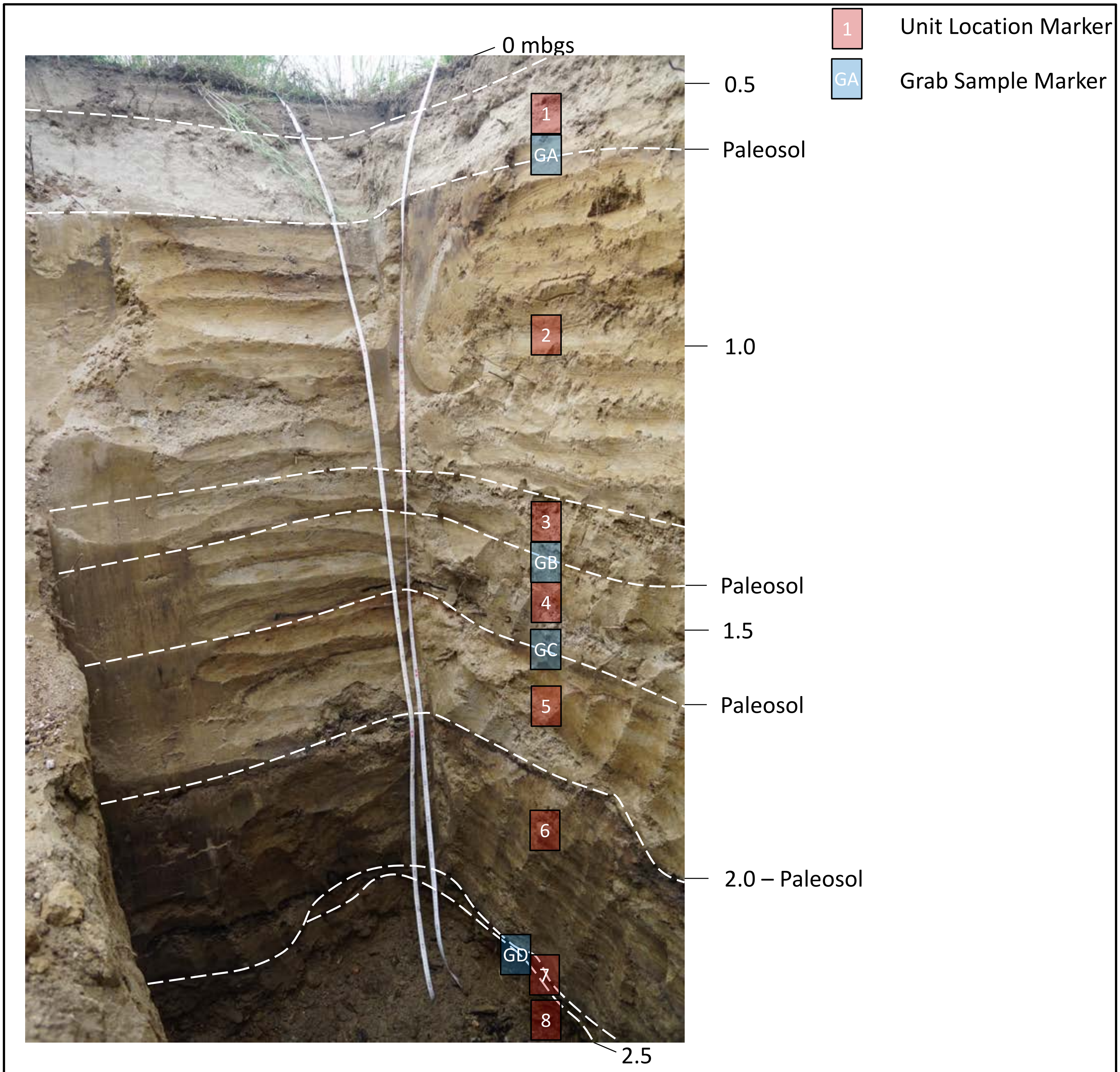

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SCALE:
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APPROVED BY:

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REPORT TITLE: RDCK FLOODPLAIN AND STEEP CREEK STUDY – MILL CREEK (HARROP)

FIGURE TITLE: TP-BGC19-HRP-05

PROJECT NO: 0268-007

FIGURE NO: C-5

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APPENDIX F
MODELLING SCENARIOS

F.1. MODELLING SCENARIOS

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

Table F-1. Modeling scenario summary for Harrop Creek.

Scenario Name	Return Period (yrs)	Process Type	Bulking Factor	Bulked Peak Discharge (m^3/s)	Conveyance Structures			Flood Protection Structures				
					Name	Estimated Capacity[1] (m^3/s)	Assumption	Name	Type	Bank Erosion Encroaching	$\tau/\tau_c \geq 2$	Assumption
MLL-1	20	Debris Flood (Type 1)	1.02	24	Betty Boop Bridge	30	Functioning as intended	Mill_1	Bank erosion protection (rip rap), left bank	N	Y	Left in as is, negligible affect to model results
					Footbridge	N/A	Destroyed when over capacity due to condition	Mill_2	Wooden deflection wall, right bank	N	Y	Left in as is, negligible affect to model results
					Harrop-Procter Road Bridge	160	Functioning as intended	Mill_3	Bank erosion protection, river rock, left bank	N	Y	Left in as is, negligible affect to model results
					Railway Bridge	50	Functioning as intended	Mill_4	Bank erosion protection, river rock, right bank	N	Y	Left in as is, negligible affect to model results
					Erindale Road Bridge	50	Functioning as intended					
MLL-2	50	Debris Flood (Type 2)	1.05	30	Betty Boop Bridge	30	Functioning as intended	Mill_1	Bank erosion protection (rip rap), left bank	N	Y	Left in as is, negligible affect to model results
					Footbridge	N/A	Destroyed when over capacity due to condition	Mill_2	Wooden deflection wall, right bank	N	Y	Left in as is, negligible affect to model results
					Harrop-Procter Road Bridge	160	Functioning as intended	Mill_3	Bank erosion protection, river rock, left bank	N	Y	Left in as is, negligible affect to model results
					Railway Bridge	50	Functioning as intended	Mill_4	Bank erosion protection, river rock, right bank	N	Y	Left in as is, negligible affect to model results
					Erindale Road Bridge	50	Functioning as intended					
MLL-3	200	Debris Flood (Type 2)	1.2	45	Betty Boop Bridge[2]	30	Functioning as intended	Mill_1	Bank erosion protection (rip rap), left bank	N	Y	Left in as is, negligible affect to model results
					Footbridge	N/A	Destroyed when over capacity due to condition	Mill_2	Wooden deflection wall, right bank	N	Y	Left in as is, negligible affect to model results
					Harrop-Procter Road Bridge	160	Functioning as intended	Mill_3	Bank erosion protection, river rock, left bank	N	Y	Left in as is, negligible affect to model results

Scenario Name	Return Period (yrs)	Process Type	Bulking Factor	Bulked Peak Discharge (m^3/s)	Conveyance Structures			Flood Protection Structures				
					Name	Estimated Capacity[1] (m^3/s)	Assumption	Name	Type	Bank Erosion Encroaching	$\tau/\tau_c \geq 2$	Assumption
					Railway Bridge	50	Functioning as intended	Mill_4	Bank erosion protection, river rock, right bank	N	Y	Left in as is, negligible affect to model results
					Erindale Road Bridge	50	Functioning as intended					
MLL-4	500	Debris Flood (Type 2)	1.3	56	Betty Boop Bridge[2]	30	Functioning as intended	Mill_1	Bank erosion protection (rip rap), left bank	N	Y	Left in as is, negligible affect to model results
					Footbridge	N/A	Destroyed when over capacity due to condition	Mill_2	Wooden deflection wall, right bank	N	Y	Left in as is, negligible affect to model results
					Harrop-Procter Road Bridge	160	Functioning as intended	Mill_3	Bank erosion protection, river rock, left bank	N	Y	Left in as is, negligible affect to model results
					Railway Bridge	50	Over capacity, bridge blocked	Mill_4	Bank erosion protection, river rock, right bank	N	Y	Left in as is, negligible affect to model results
					Erindale Road Bridge	50	Over capacity, bridge 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. The Betty Boop Bridge appears to be an engineered structure that would require an assessment by a qualified professional to assess the impacts of flow overtopping the bridge. For the purposes of this study the bridge was left as is as flow is able to move around it.

APPENDIX G
LABORATORY TESTING RESULTS

Table G-1. Summary of samples sent for laboratory testing.

Field Sample ID	Laboratory	Beta ID	Analysis	Sample Type	Unit	Depth (mbgs)	Conventional Age (years BP)
TP-BGC19-HRP-01-G2	Beta Analytics	532754	Standard AMS	Charcoal	2	1.00	4690
TP-BGC19-HRP-02-G1	Beta Analytics	532755	Standard AMS	Paleosol (sand)	1	0.75	4160
TP-BGC19-HRP-04-G1	Beta Analytics	532756	Standard AMS	Charcoal	2	2.00	5790
TP-BGC19-HRP-05-GB	Beta Analytics	532757	Standard AMS	Charcoal	3	1.60	1482
TP-BGC19-HRP-05-GD	Beta Analytics	532758	Standard AMS	Charcoal	7	2.50	2214

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ISO/IEC 17025:2005-Accredited Testing Laboratory

August 16, 2019

Ms. Emily Moase
BGC Engineering
500-980 Howe Street
Vancouver, BC V6Z 0C8
Canada

RE: Radiocarbon Dating Results

Dear Ms. Moase,

Enclosed are the radiocarbon dating results for ten samples recently sent to us. As usual, the method of analysis is listed on the report with the results and calibration data is provided where applicable. The Conventional Radiocarbon Ages have all been corrected for total fractionation effects and where applicable, calibration was performed using 2013 calibration databases (cited on the graph pages).

The web directory containing the table of results and PDF download also contains pictures, a cvs spreadsheet download option and a quality assurance report containing expected vs. measured values for 3-5 working standards analyzed simultaneously with your samples.

Reported results are accredited to ISO/IEC 17025:2005 Testing Accreditation PJLA #59423 standards and all chemistry was performed here in our laboratory and counted in our own accelerators here. Since Beta is not a teaching laboratory, only graduates trained to strict protocols of the ISO/IEC 17025:2005 Testing Accreditation PJLA #59423 program participated in the analyses.

As always Conventional Radiocarbon Ages and sigmas are rounded to the nearest 10 years per the conventions of the 1977 International Radiocarbon Conference. When counting statistics produce sigmas lower than +/- 30 years, a conservative +/- 30 BP is cited for the result. The reported d13C values were measured separately in an IRMS (isotope ratio mass spectrometer). They are NOT the AMS d13C which would include fractionation effects from natural, chemistry and AMS induced sources.

When interpreting the results, please consider any communications you may have had with us regarding the samples.

Thank you for prepaying the analyses. As always, if you have any questions or would like to discuss the results, don't hesitate to contact us.

Sincerely,

Chris Patrick

Digital signature on file

Chris Patrick Director

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REPORT OF RADIOCARBON DATING ANALYSES

Emily Moase
BGC Engineering

Report Date: August 16, 2019
Material Received: August 01, 2019

Laboratory Number	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)	
Beta - 532754	**TP-BGC19-HRP-01-G2**	**4170 +/- 30 BP**	IRMS δ13C: -25.0 o/oo

(73.2%)	**2819 - 2662 cal BC**	**(4768 - 4611 cal BP)**
(20.0%)	**2882 - 2833 cal BC**	**(4831 - 4782 cal BP)**
(2.2%)	**2649 - 2636 cal BC**	**(4598 - 4585 cal BP)**

Submitter Material:	Organics
Pretreatment:	(charred material) acid/alkali/acid
Analyzed Material:	Charred material
Analysis Service:	AMS-Standard delivery
Percent Modern Carbon:	59.50 +/- 0.22 pMC
Fraction Modern Carbon:	0.5950 +/- 0.0022
D14C:	-404.95 +/- 2.22 o/oo
∆14C:	-409.90 +/- 2.22 o/oo(1950:2,019.00)
Measured Radiocarbon Age:	(without d13C correction): 4170 +/- 30 BP
Calibration:	BetaCal3.21: HPD method: INTCAL13

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), "present" = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

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REPORT OF RADIOCARBON DATING ANALYSES

Emily Moase
BGC Engineering

Report Date: August 16, 2019
Material Received: August 01, 2019

Laboratory Number	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)	
Beta - 532755	**TP-BGC19-HRP-02-G1**	**3770 +/- 30 BP**	IRMS δ13C: -23.0 o/oo

(89.3%)	**2290 - 2131 cal BC**	**(4239 - 4080 cal BP)**
(6.1%)	**2086 - 2051 cal BC**	**(4035 - 4000 cal BP)**

Submitter Material: Organics
Pretreatment: (charred material) acid/alkali/acid
Analyzed Material: Charred material
Analysis Service: AMS-Standard delivery
Percent Modern Carbon: 62.54 +/- 0.23 pMC
Fraction Modern Carbon: 0.6254 +/- 0.0023
D14C: -374.57 +/- 2.34 o/oo
∆14C: -379.77 +/- 2.34 o/oo(1950:2,019.00)
Measured Radiocarbon Age: (without d13C correction): 3740 +/- 30 BP
Calibration: BetaCal3.21: HPD method: INTCAL13

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), "present" = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

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REPORT OF RADIOCARBON DATING ANALYSES

Emily Moase	Report Date: August 16, 2019
BGC Engineering	Material Received: August 01, 2019

Laboratory Number	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)	
Beta - 532756	**TP-BGC19-HRP-04-G1**	**5100 +/- 30 BP**	IRMS δ13C: -23.1 o/oo

(58.2%)	**3881 - 3800 cal BC**	**(5830 - 5749 cal BP)**
(37.2%)	**3968 - 3896 cal BC**	**(5917 - 5845 cal BP)**

Submitter Material: Charcoal
Pretreatment: (charred material) acid/alkali/acid
Analyzed Material: Charred material
Analysis Service: AMS-Standard delivery
Percent Modern Carbon: 53.00 +/- 0.20 pMC
Fraction Modern Carbon: 0.5300 +/- 0.0020
D14C: -470.00 +/- 1.98 o/oo
∆14C: -474.41 +/- 1.98 o/oo(1950:2,019.00)
Measured Radiocarbon Age: (without d13C correction): 5070 +/- 30 BP
Calibration: BetaCal3.21: HPD method: INTCAL13

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), "present" = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

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REPORT OF RADIOCARBON DATING ANALYSES

Emily Moase

BGC Engineering

Report Date: August 16, 2019

Material Received: August 01, 2019

Laboratory Number	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)	
Beta - 532757	**TP-BGC19-HRP-05-GB**	**1600 +/- 30 BP**	IRMS δ13C: -22.4 o/oo

(95.4%) **398 - 539 cal AD** **(1552 - 1411 cal BP)**

Submitter Material: Charcoal
Pretreatment: (charred material) acid/alkali/acid
Analyzed Material: Charred material
Analysis Service: AMS-Standard delivery
Percent Modern Carbon: 81.94 +/- 0.31 pMC
Fraction Modern Carbon: 0.8194 +/- 0.0031
D14C: -180.60 +/- 3.06 o/oo
∆14C: -187.41 +/- 3.06 o/oo(1950:2,019.00)
Measured Radiocarbon Age: (without d13C correction): 1560 +/- 30 BP
Calibration: BetaCal3.21: HPD method: INTCAL13

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), "present" = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

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REPORT OF RADIOCARBON DATING ANALYSES

Emily Moase		Report Date:	August 16, 2019
BGC Engineering		Material Received:	August 01, 2019

Laboratory Number	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)	
Beta - 532758	**TP-BGC19-HRP-05-GD**	**2180 +/- 30 BP**	IRMS δ13C: -24.7 o/oo

(95.4%) **361 - 168 cal BC** **(2310 - 2117 cal BP)**

Submitter Material: Charcoal
Pretreatment: (charred material) acid/alkali/acid
Analyzed Material: Charred material
Analysis Service: AMS-Standard delivery
Percent Modern Carbon: 76.23 +/- 0.28 pMC
Fraction Modern Carbon: 0.7623 +/- 0.0028
D14C: -237.68 +/- 2.85 o/oo
Δ14C: -244.01 +/- 2.85 o/oo(1950:2,019.00)
Measured Radiocarbon Age: (without d13C correction): 2180 +/- 30 BP
Calibration: BetaCal3.21: HPD method: INTCAL13

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), “present” = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

BetaCal 3.21

Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -25.0 o/oo)

Laboratory number **Beta-532754**

Conventional radiocarbon age **4170 ± 30 BP**

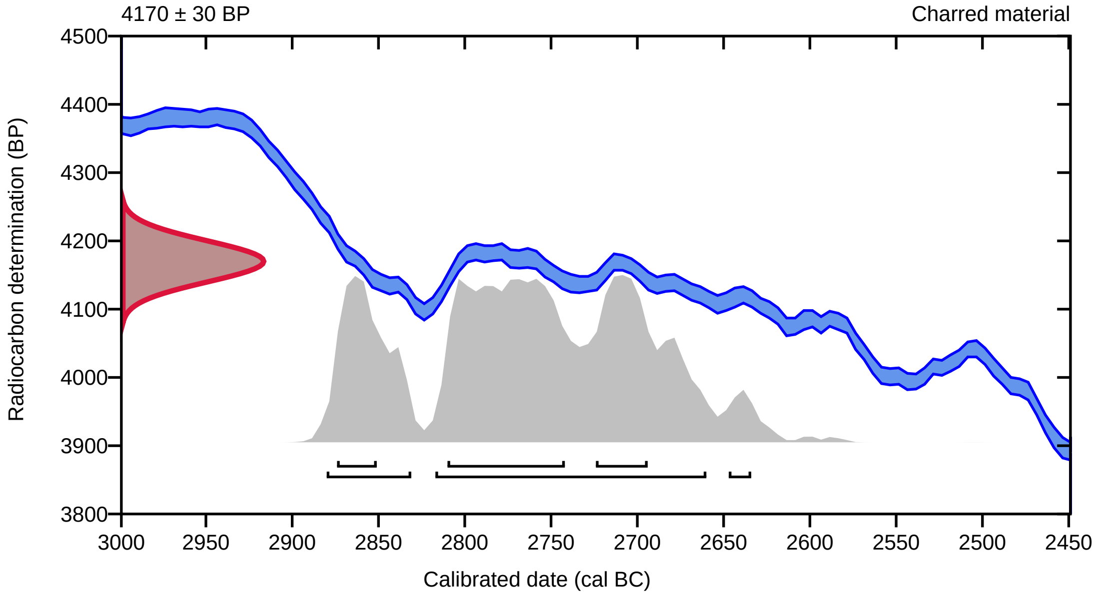
95.4% probability

(73.2%)	2819 - 2662 cal BC	(4768 - 4611 cal BP)
(20%)	2882 - 2833 cal BC	(4831 - 4782 cal BP)
(2.2%)	2649 - 2636 cal BC	(4598 - 4585 cal BP)

68.2% probability

(38.7%)	2812 - 2744 cal BC	(4761 - 4693 cal BP)
(16.8%)	2726 - 2696 cal BC	(4675 - 4645 cal BP)
(12.7%)	2876 - 2853 cal BC	(4825 - 4802 cal BP)

TP-BGC19-HRP-01-G2



Database used

INTCAL13

References

References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

BetaCal 3.21

Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -23.0 o/oo)

Laboratory number **Beta-532755**

Conventional radiocarbon age **3770 ± 30 BP**

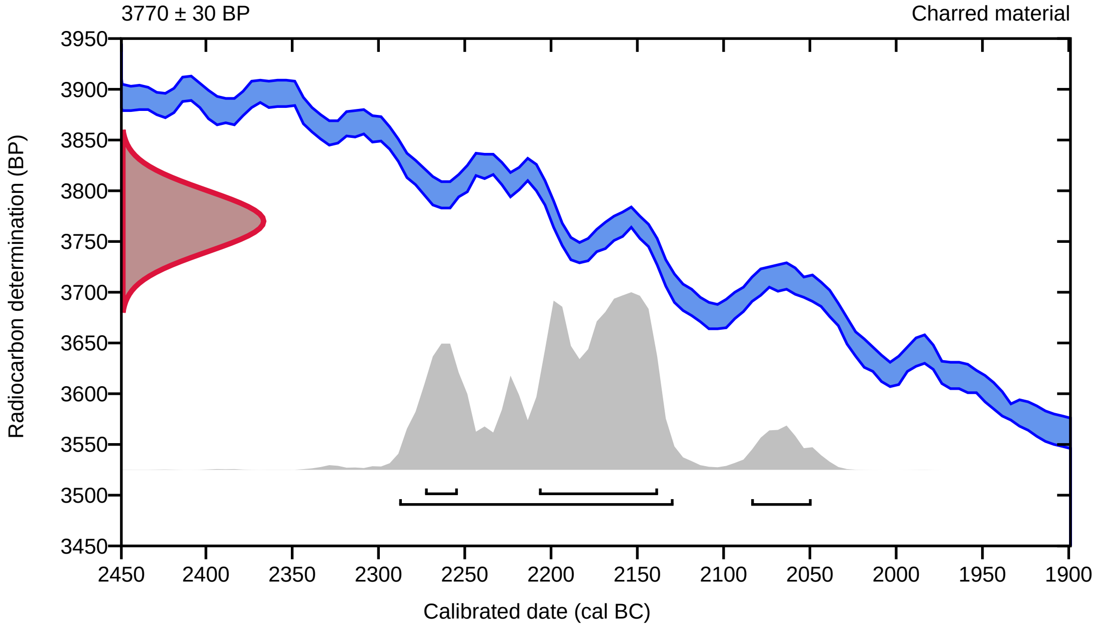
95.4% probability

(89.3%)	2290 - 2131 cal BC	(4239 - 4080 cal BP)
(6.1%)	2086 - 2051 cal BC	(4035 - 4000 cal BP)

68.2% probability

(56.2%)	2209 - 2140 cal BC	(4158 - 4089 cal BP)
(12%)	2275 - 2256 cal BC	(4224 - 4205 cal BP)

TP-BGC19-HRP-02-G1



Database used

INTCAL13

References

References to Probability Method

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References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

BetaCal 3.21

Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -23.1 o/oo)

Laboratory number **Beta-532756**

Conventional radiocarbon age **5100 ± 30 BP**

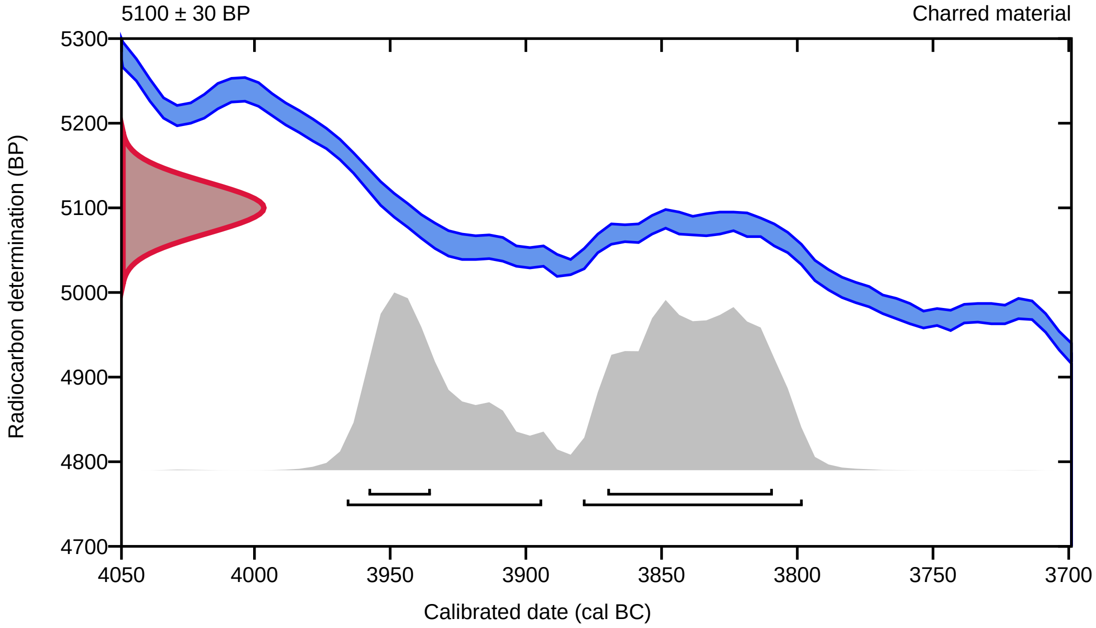
95.4% probability

(58.2%)	3881 - 3800 cal BC	(5830 - 5749 cal BP)
(37.2%)	3968 - 3896 cal BC	(5917 - 5845 cal BP)

68.2% probability

(48.3%)	3872 - 3811 cal BC	(5821 - 5760 cal BP)
(19.9%)	3960 - 3937 cal BC	(5909 - 5886 cal BP)

TP-BGC19-HRP-04-G1



Database used

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References

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References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

BetaCal 3.21

Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -22.4 o/oo)

Laboratory number **Beta-532757**

Conventional radiocarbon age **1600 ± 30 BP**

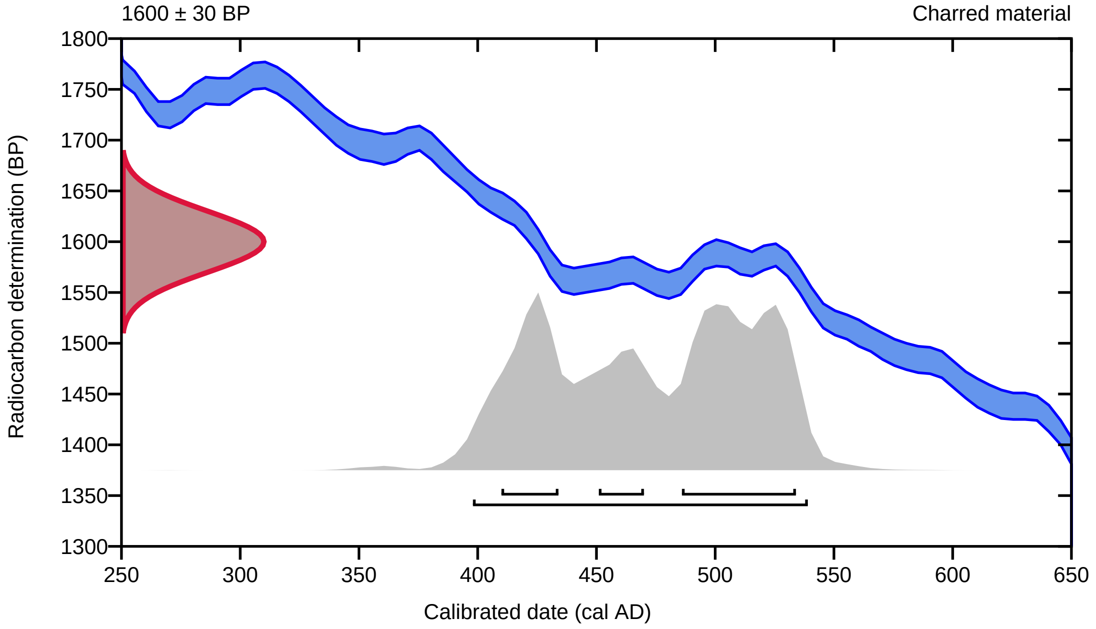
95.4% probability

(95.4%)	398 - 539 cal AD	(1552 - 1411 cal BP)

68.2% probability

(38.1%)	486 - 534 cal AD	(1464 - 1416 cal BP)
(18.3%)	410 - 434 cal AD	(1540 - 1516 cal BP)
(11.8%)	451 - 470 cal AD	(1499 - 1480 cal BP)

TP-BGC19-HRP-05-GB



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References

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Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

BetaCal 3.21

Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -24.7 o/oo)

Laboratory number **Beta-532758**

Conventional radiocarbon age **2180 ± 30 BP**

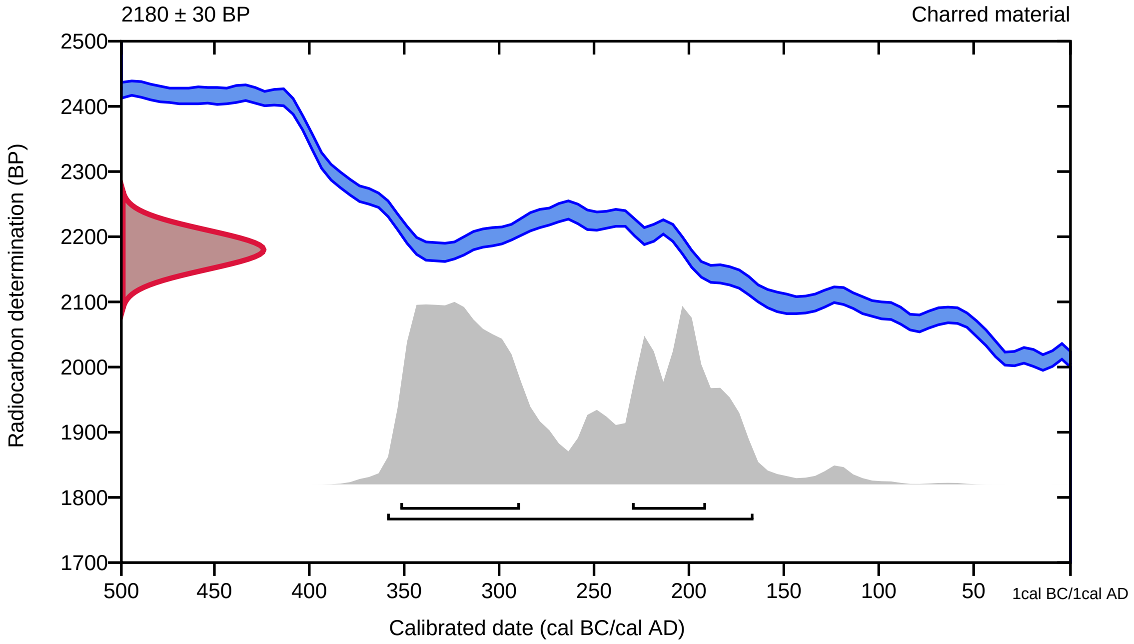
95.4% probability

(95.4%)	361 - 168 cal BC	(2310 - 2117 cal BP)

68.2% probability

(44.7%)	354 - 291 cal BC	(2303 - 2240 cal BP)
(23.5%)	232 - 193 cal BC	(2181 - 2142 cal BP)

TP-BGC19-HRP-05-GD



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References

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Reimer, et.al., 2013, Radiocarbon55(4).

Beta Analytic
TESTING LABORATORY

Beta Analytic Inc
4985 SW 74 Court
Miami, Florida 33155
Tel: 305-667-5167
Fax: 305-663-0964
info@betalabservices.com

ISO/IEC 17025:2005-Accredited Testing Laboratory

Quality Assurance Report

This report provides the results of reference materials used to validate radiocarbon analyses prior to reporting. Known-value reference materials were analyzed quasi-simultaneously with the unknowns. Results are reported as expected values vs measured values. Reported values are calculated relative to NIST SRM-4990B and corrected for isotopic fractionation. Results are reported using the direct analytical measure percent modern carbon (pMC) with one relative standard deviation. Agreement between expected and measured values is taken as being within 2 sigma agreement (error x 2) to account for total laboratory error.

Report Date: August 19, 2019
Submitter: Ms. Emily Moase

QA MEASUREMENTS

Reference 1

Expected Value: 0.42 +/- 0.04

Measured Value: 0.42 +/- 0.03 pMC

Agreement: Accepted

Reference 2

Expected Value: 129.41 +/- 0.06 pMC

Measured Value: 129.39 +/- 0.40 pMC

Agreement: Accepted

Reference 3

Expected Value: 96.69 +/- 0.50 pMC

Measured Value: 96.98 +/- 0.29 pMC

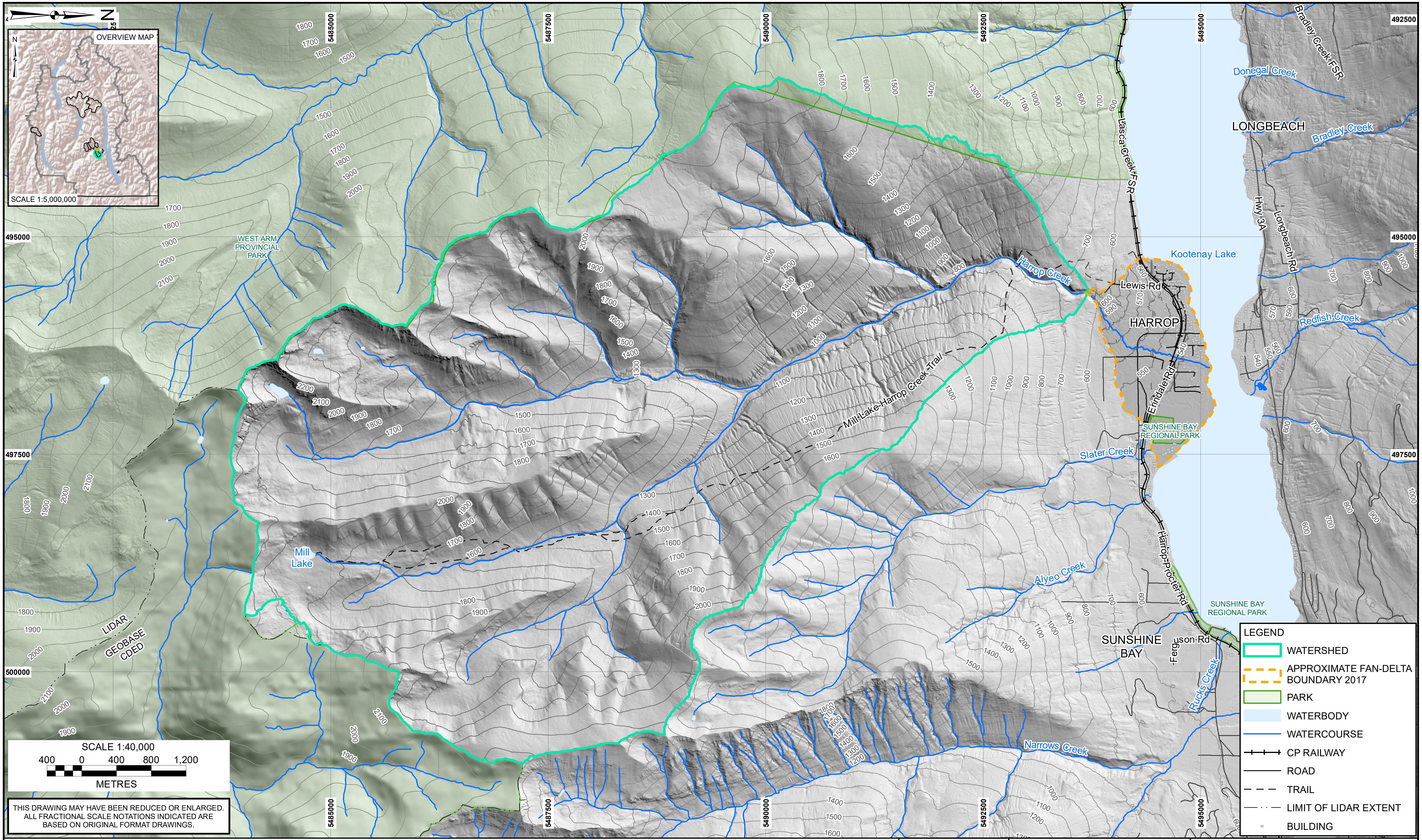
Agreement: Accepted

COMMENT: All measurements passed acceptance tests.

Validation: Digital signature on file

Date: August 19, 2019

DRAWINGS



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NOTES:
1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "RDCK FLOODPLAIN AND STEEP CREEK STUDY - HARROP CREEK", AND DATED MARCH 2020.
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.
6. PROJECTION IS NAD 1983 UTM ZONE 11N.
7. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED OR USED FOR ANY PURPOSE OTHER THAN THE PURPOSE FOR WHICH BGC GENERATED IT. BGC SHALL HAVE NO LIABILITY FOR ANY DAMAGES OR LOSS ARISING IN ANY WAY FROM ANY USE OR MODIFICATION OF THIS DOCUMENT NOT AUTHORIZED BY BGC. ANY USE OF OR RELIANCE UPON THIS DOCUMENT OR ITS CONTENT BY THIRD PARTIES SHALL BE AT SUCH THIRD PARTIES' SOLE RISK.

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DATE:	MAR 2020
DRAWN:	LL
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: HARROP CREEK
SITE LOCATION MAP

PROJECT No.: 0268007

DWG No: 01

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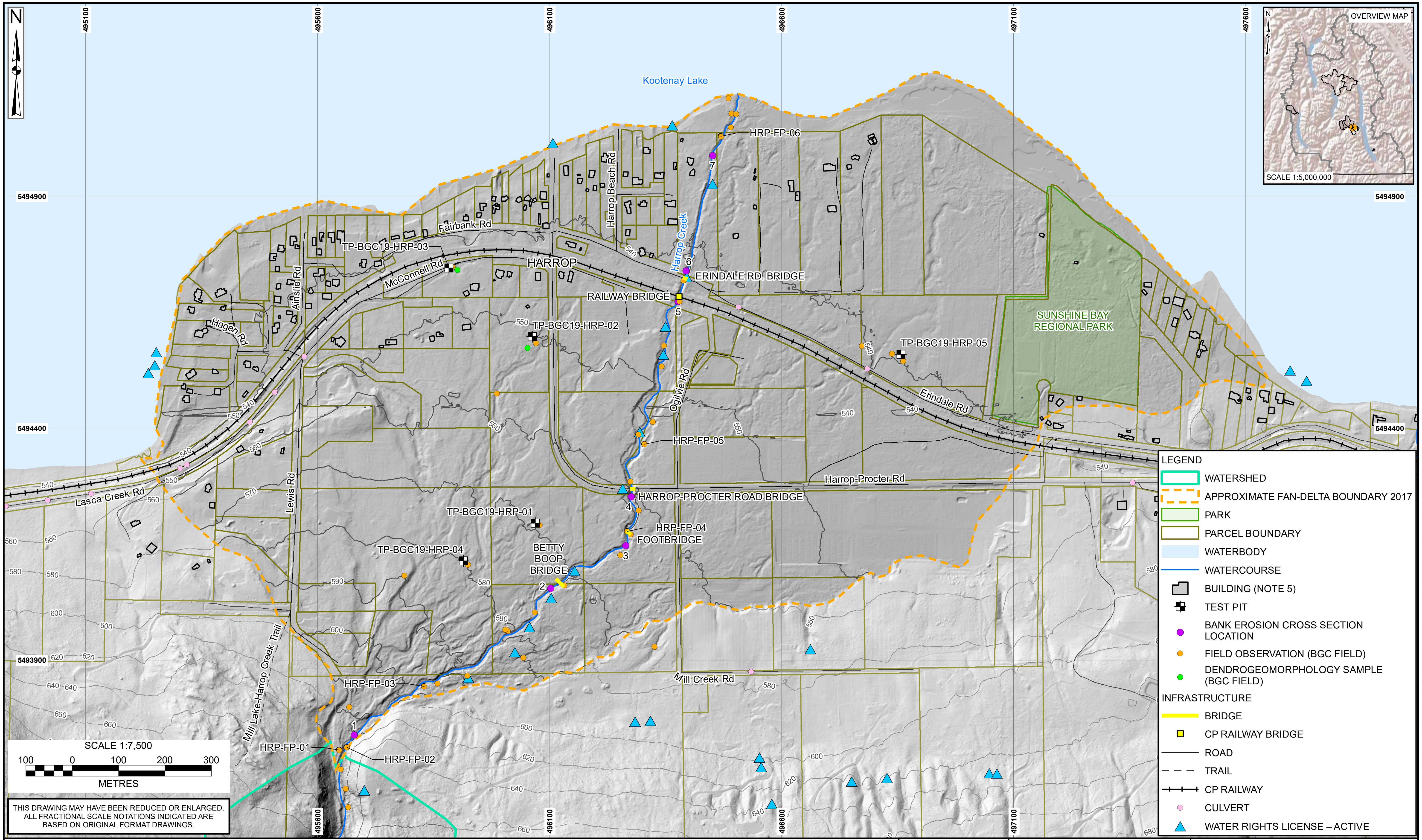

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LEGEND

▭	WATERSHED
▭	APPROXIMATE FAN-DELTA BOUNDARY 2017
🟩	PARK
▭	PARCEL BOUNDARY
▭	WATERBODY
—	WATERCOURSE
▭	BUILDING (NOTE 5)
▞	TEST PIT
●	BANK EROSION CROSS SECTION LOCATION
●	FIELD OBSERVATION (BGC FIELD)
●	DENDROGEOMORPHOLOGY SAMPLE (BGC FIELD)

INFRASTRUCTURE

—	BRIDGE
▢	CP RAILWAY BRIDGE
—	ROAD
– –	TRAIL
+++	CP RAILWAY
○	CULVERT
▲	WATER RIGHTS LICENSE – ACTIVE

NOTES:
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3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY RDCK, DATED 2017. CONTOUR INTERVAL IS 20 m AND 10 m ON FAN.
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. PARKS DATA FROM GOVERNMENT OF BC.
6. PROJECTION IS NAD 1983 UTM ZONE 11N.
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SCALE: 1:7,500
DATE: MAR 2020
DRAWN: LL
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: HARROP CREEK FAN-DELTA SITE MAP
PROJECT No.: 0268007
DWG No: 02A

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LEGEND

🟩	WATERSHED
▭	APPROXIMATE FAN-DELTA BOUNDARY 2017
🟩	PARK
▭	PARCEL BOUNDARY
—	WATERCOURSE
▭	BUILDING (NOTE 5)
▨	TEST PIT
●	BANK EROSION CROSS SECTION LOCATION
●	FIELD OBSERVATION (BGC FIELD)
●	DENDROGEOMORPHOLOGY SAMPLE (BGC FIELD)

INFRASTRUCTURE

—	BRIDGE
☐	CP RAILWAY BRIDGE
—	ROAD
– –	TRAIL
┼┼┼	CP RAILWAY
●	CULVERT
▲	WATER RIGHTS LICENSE – ACTIVE

NOTES:
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3. BASE TOPOGRAPHIC DATA AND ORTHOPHOTO BASED ON LIDAR PROVIDED BY RDCK, DATED 2017. CONTOUR INTERVAL IS 20 m AND 10 m ON FAN.
4. THE FAN BOUNDARY AS DRAWN IS APPROXIMATE AND DELINEATES THE LANDFORM BASED ON LIDAR DATED 2017. THE BOUNDARY SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DOES IT SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
5. WATER DATA FROM CANVEC, UPDATED BASED ON BGC FIELD OBSERVATIONS, WHERE APPLICABLE. BUILDING FOOTPRINTS DIGITIZED BY BGC BASED ON LIDAR AND REPRESENT ONLY A SUBSET OF TOTAL BUILDINGS ON THE FAN-DELTA. CULVERT LOCATIONS FROM BC MINISTRY OF TRANSPORTATION. ROADS DATA FROM BC DIGITAL ROAD ATLAS. RAILWAY DATA FROM GEOBASE NATIONAL RAILWAY NETWORK. WATER RIGHTS LICENSE DATA FROM GEOBC. PARCELS FROM PARCELMAP BC. PARKS DATA FROM GOVERNMENT OF BC.
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DATE:	MAR 2020
DRAWN:	LL
CHECKED:	JJHP
APPROVED:	MJ

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

PROJECT:
RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE:
HARROP CREEK
FAN-DELTA SITE MAP

PROJECT No.: 0268007
DWG No: 02B

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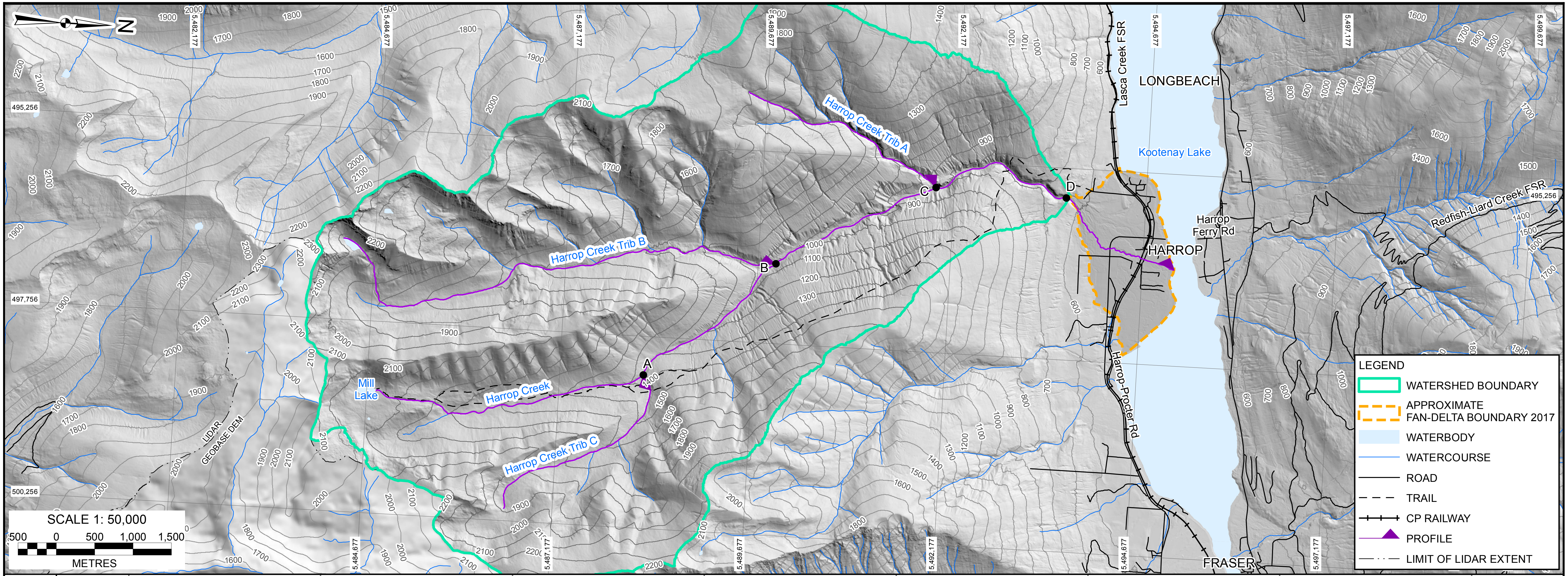

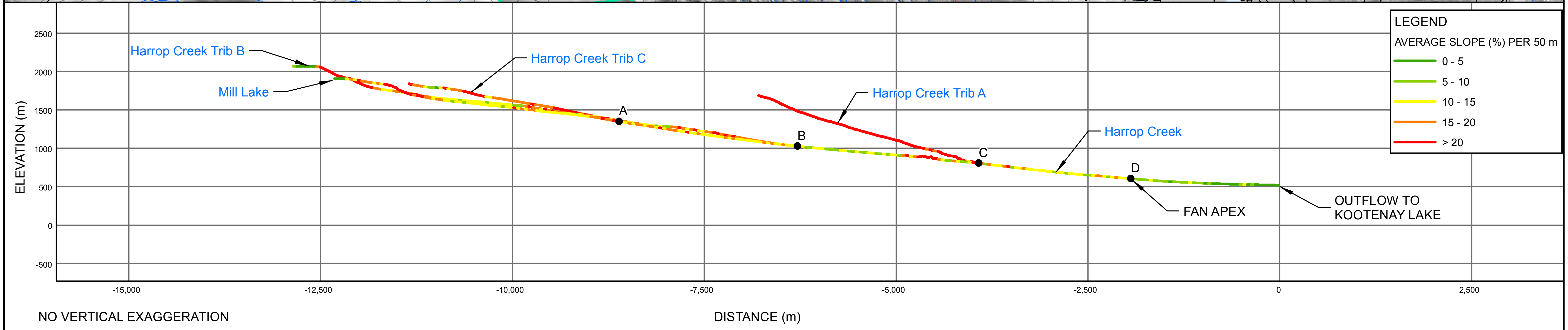

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2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "RDCK FLOODPLAIN AND STEEP CREEK STUDY – HARROP CREEK", AND DATED MARCH 2020.
3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY RDCK AND GEOBASE CDED, DATED 2017 AND 2013, RESPECTIVELY.
4. THE WATERSHED AND FAN BOUNDARIES AS DRAWN ARE APPROXIMATE AND DELINEATE THE LANDFORMS. THE BOUNDARIES SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DO THEY SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
5. WATERSHED BOUNDARIES DELINEATED FROM BGC'S RIVER NETWORK TOOLS, WATERBODIES SOURCED FROM CANVEC, WATERCOURSES SOURCED FROM BGC'S RIVER NETWORK TOOLS AND CANVEC, ROADS AND TRAILS SOURCED FROM GEOBC DIGITAL ROAD ATLAS. RAILWAY DATA FROM GEOBASE NATIONAL RAILWAY NETWORK.
6. ELEVATION PROFILE SHOWS DISTANCE RELATIVE TO THE CREEK OUTLET ON X-AXIS AND ELEVATION DERIVED FROM THE BASE TOPOGRAPHIC DATA ON Y-AXIS
7. PROJECTION IS NAD 1983 UTM ZONE 11N.
8. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED OR USED FOR ANY PURPOSE OTHER THAN THE PURPOSE FOR WHICH BGC GENERATED IT. BGC SHALL HAVE NO LIABILITY FOR ANY DAMAGES OR LOSS ARISING IN ANY WAY FROM ANY USE OF OR RELIANCE UPON THIS DOCUMENT NOT AUTHORIZED BY BGC. ANY USE OF OR RELIANCE UPON THIS DOCUMENT OR ITS CONTENT BY THIRD PARTIES SHALL BE AT SUCH THIRD PARTIES' SOLE RISK.

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CHECKED:	JJHP, LCH
APPROVED:	MJ

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AN APPLIED EARTH SCIENCES COMPANY

CLIENT:
REGIONAL DISTRICT CENTRAL KOOTENAY

PROJECT:
RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE:
HARROP CREEK PROFILE

PROJECT No.: 0268007
DWG No: 03

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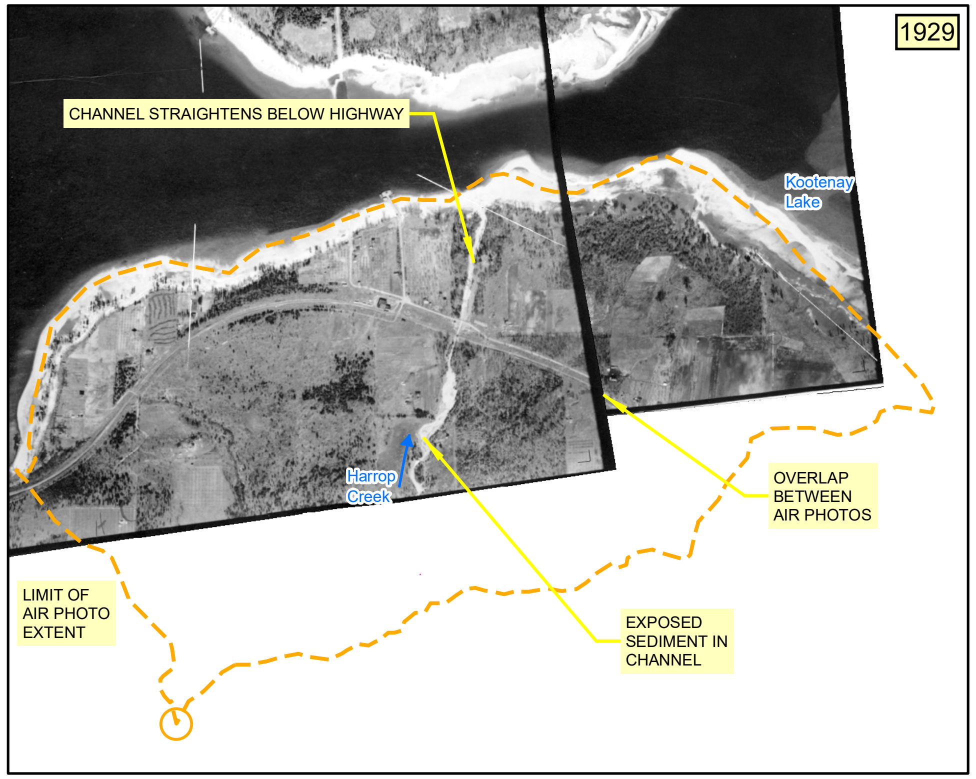

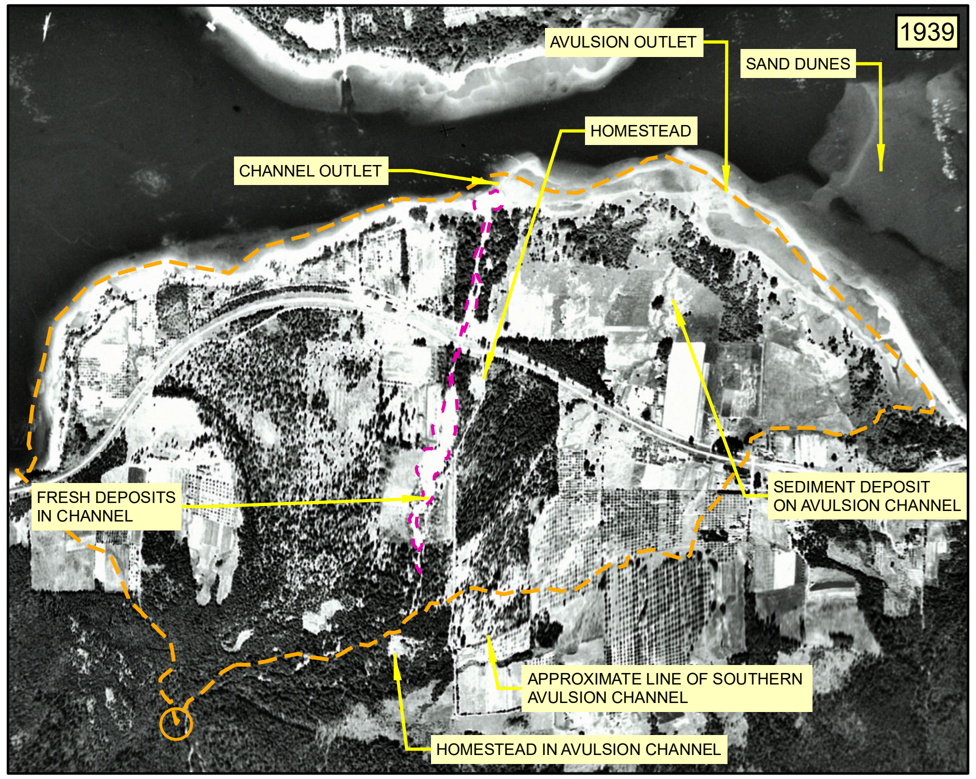

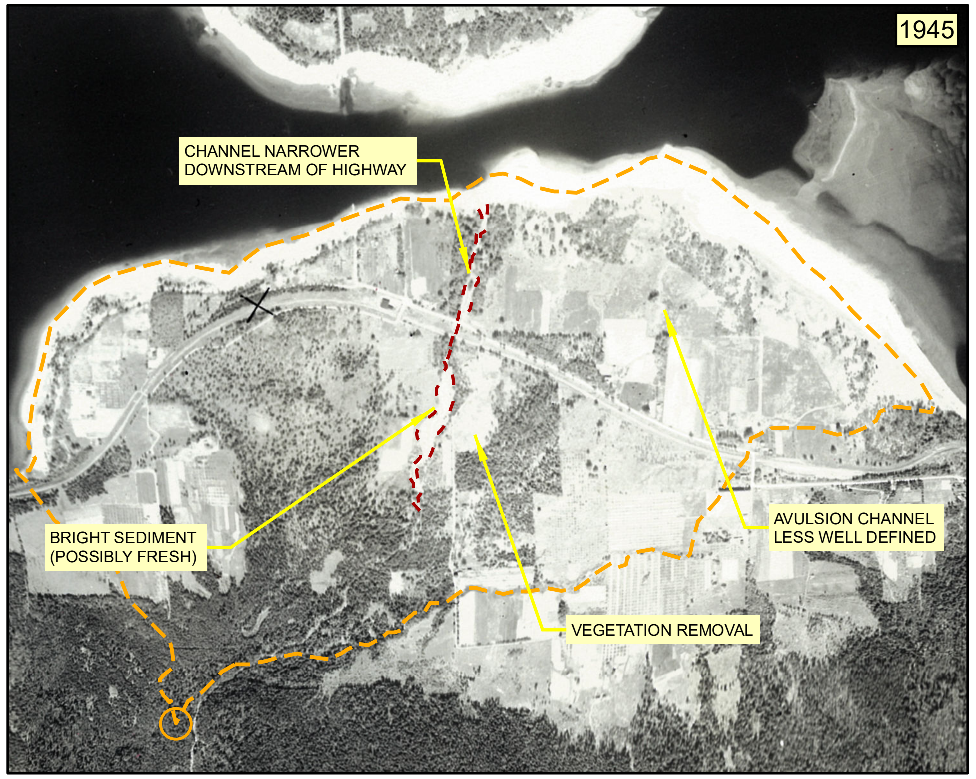

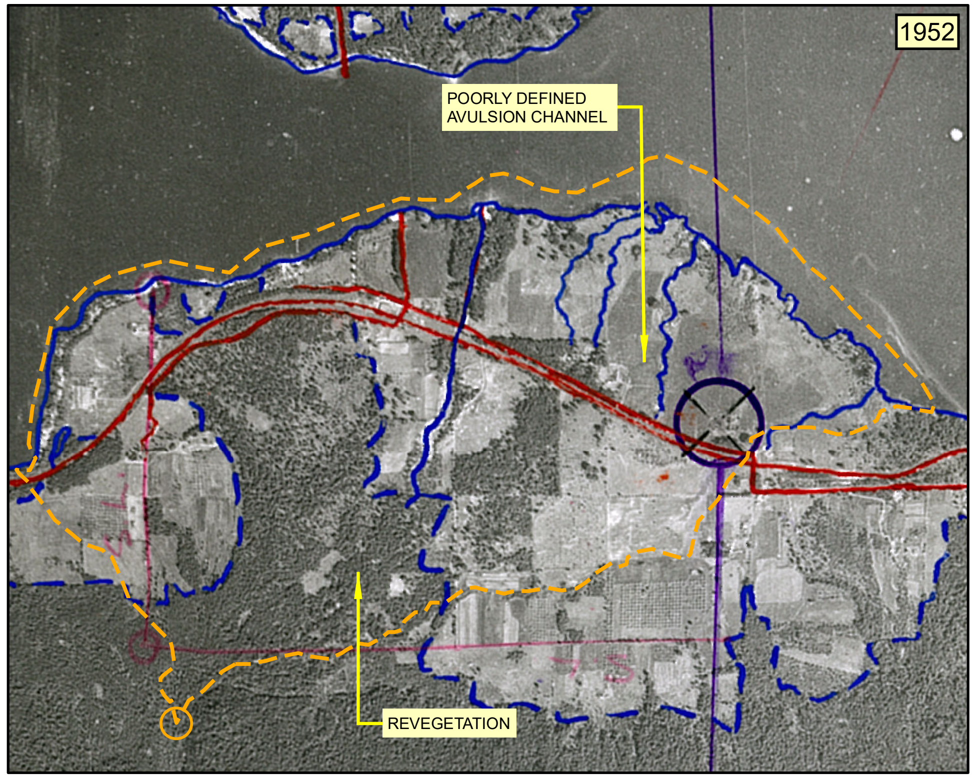

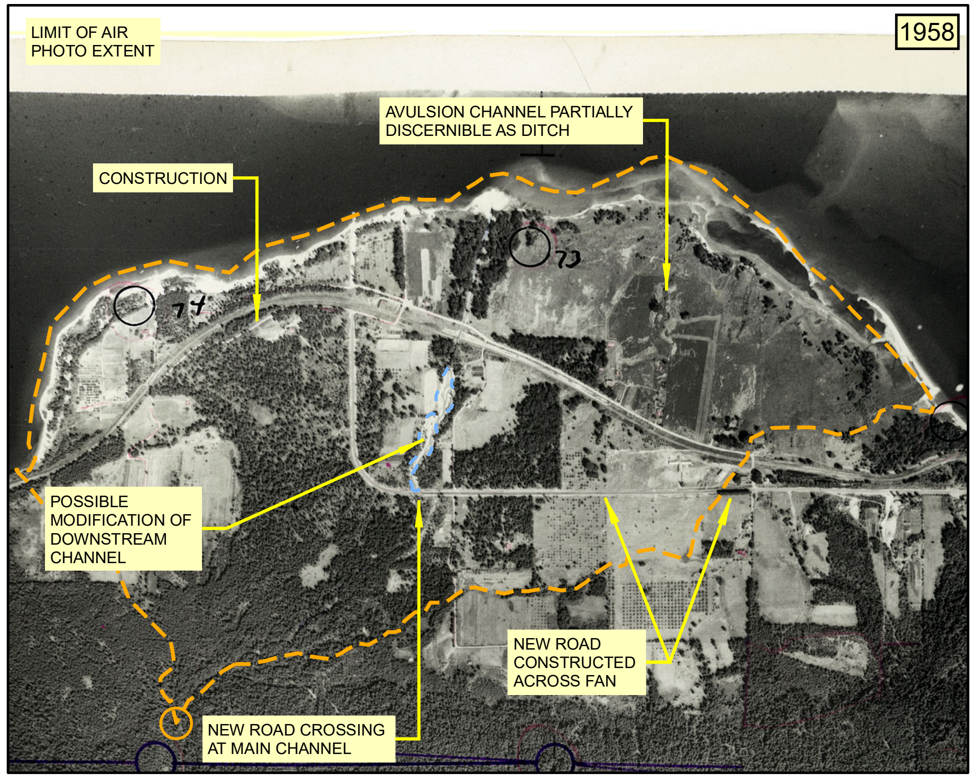

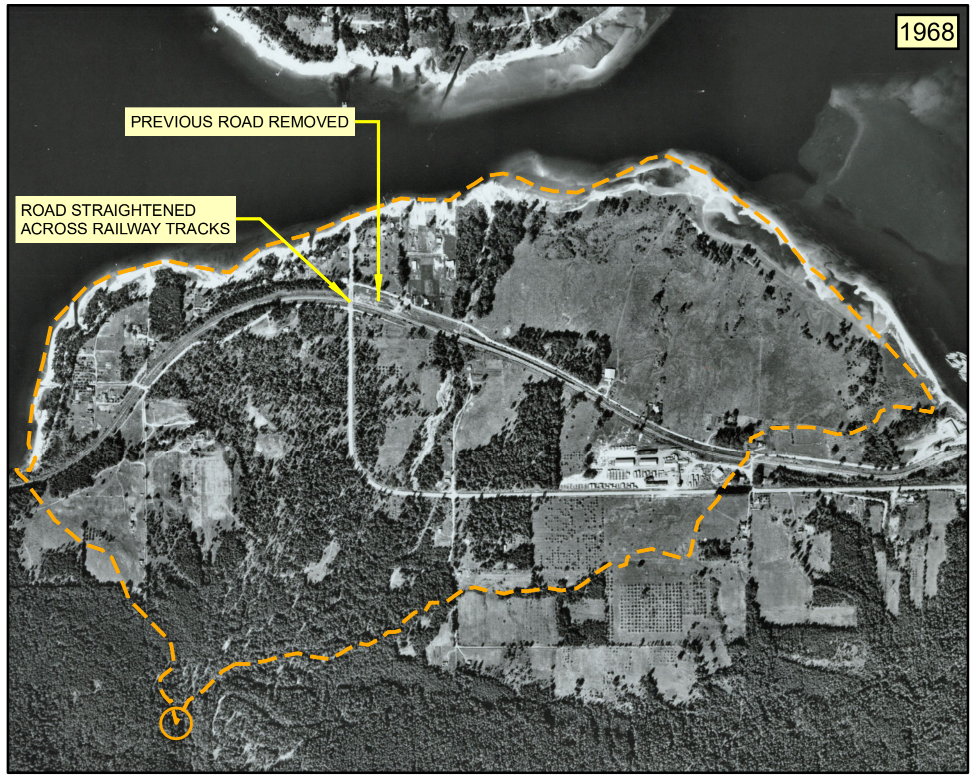

SCALE 1:20,000

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METRES

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LEGEND

▭	APPROXIMATE FAN-DELTA BOUNDARY 2017	- - -	APPROXIMATE EXTENT OF PRE-1939 EVENT
○	FAN APEX	- - -	APPROXIMATE EXTENT OF 1940's EVENT
		- - -	APPROXIMATE EXTENT OF 1950's EVENT

NOTES:

1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "STEEP CREEK HAZARD AND RISK ASSESSMENT - HARROP CREEK", AND DATED MARCH 2020.
3. BASE TOPOGRAPHIC DATA BASED ON AIR PHOTOS PROVIDED BY BC AIR PHOTO LIBRARY AND NATIONAL AIR PHOTO LIBRARY.
4. THE FAN BOUNDARY AS DRAWN IS APPROXIMATE AND DELINEATES THE LANDFORM BASED ON LIDAR DATED 2017. THE BOUNDARY SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DOES IT SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
5. LAKE LEVEL RAISED BY CORRA LINN DAM ACTIVATED IN 1938.
6. AIR PHOTO FROM YEAR 1952 WAS MARKED ON PHYSICAL COPIES PRIOR TO BGC'S AIR PHOTO INTERPRETATION.
7. COORDINATE SYSTEM IS UTM ZONE 11 NAD 1983. VERTICAL DATUM IS UNKNOWN.
8. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED OR USED FOR ANY PURPOSE OTHER THAN THE PURPOSE FOR WHICH BGC GENERATED IT. BGC SHALL HAVE NO LIABILITY FOR ANY DAMAGES OR LOSS ARISING IN ANY WAY FROM ANY USE OR MODIFICATION OF THIS DOCUMENT NOT AUTHORIZED BY BGC. ANY USE OF OR RELIANCE UPON THIS DOCUMENT OR ITS CONTENT BY THIRD PARTIES SHALL BE AT SUCH THIRD PARTIES' SOLE RISK.

SCALE: 1:20,000
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DRAWN: MIB, LL
CHECKED: JJHP, LCH
APPROVED: MJ

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:
REGIONAL DISTRICT CENTRAL KOOTENAY

PROJECT:
RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE:
HARROP CREEK
AIR PHOTO COMPARISON

PROJECT No.: 0268007
DWG No: 04A

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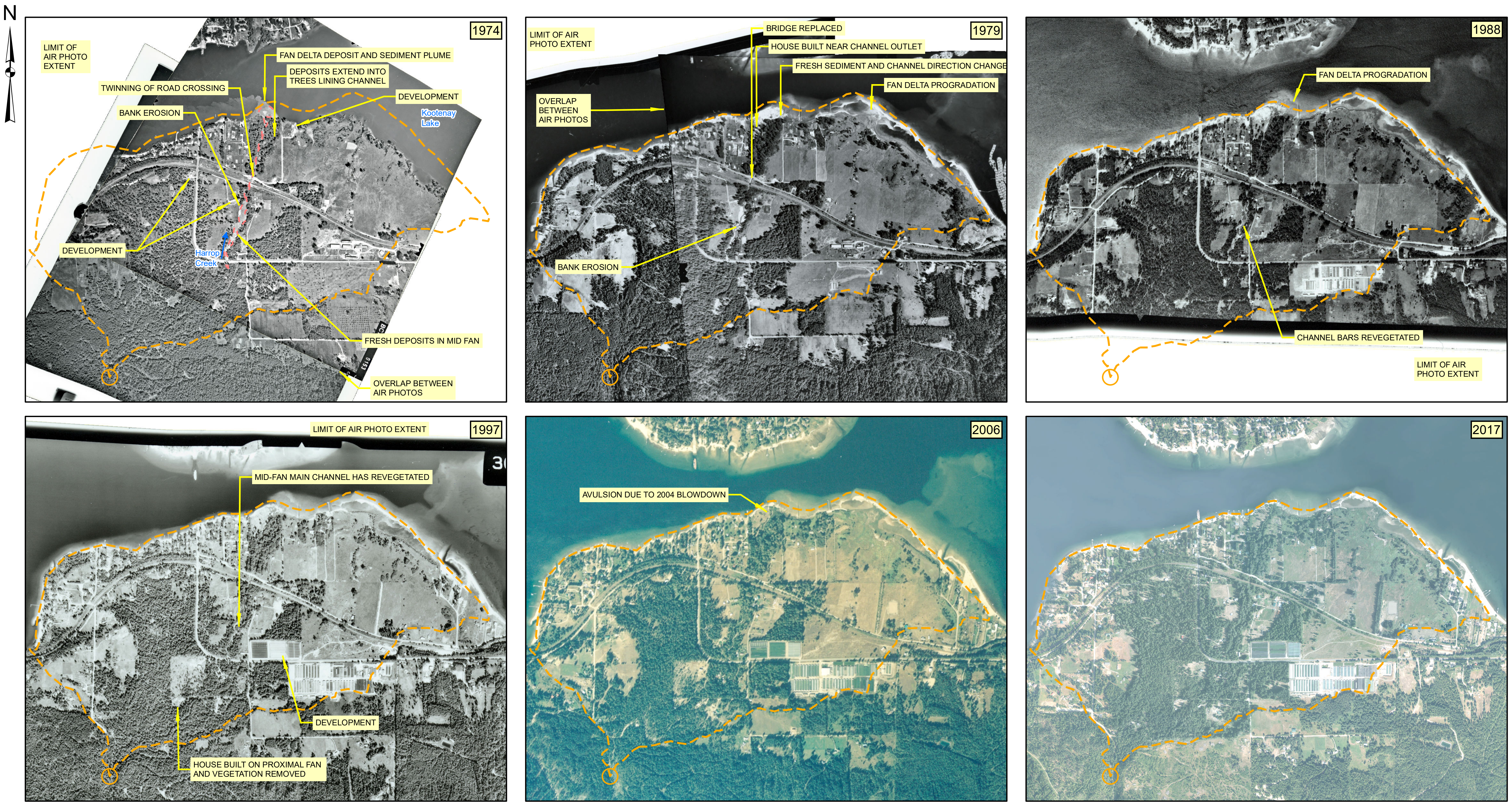

SCALE 1:20,000

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METRES

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LEGEND

▭	APPROXIMATE FAN-DELTA BOUNDARY 2017
- - -	APPROXIMATE EXTENT OF 1972 EVENT
○	FAN APEX

NOTES:
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3. BASE TOPOGRAPHIC DATA BASED ON AIR PHOTOS PROVIDED BY BC AIR PHOTO LIBRARY AND NATIONAL AIR PHOTO LIBRARY.
4. THE FAN BOUNDARY AS DRAWN IS APPROXIMATE AND DELINEATES THE LANDFORM BASED ON LIDAR DATED 2017. THE BOUNDARY SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DOES IT SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
5. AIR PHOTOS WITH NO LABELS INDICATE NO MAJOR DEVELOPMENT OR CHANGE IN CHANNEL FEATURES COMPARED TO PREVIOUS AIR PHOTO.
6. BANK EROSION INDICATES DISCERNIBLE EROSION FROM PREVIOUS IMAGE.
7. COORDINATE SYSTEM IS UTM ZONE 11 NAD 1983. VERTICAL DATUM IS UNKNOWN.
8. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED OR USED FOR ANY PURPOSE OTHER THAN THE PURPOSE FOR WHICH BGC GENERATED IT. BGC SHALL HAVE NO LIABILITY FOR ANY DAMAGES OR LOSS ARISING IN ANY WAY FROM ANY USE OR MODIFICATION OF THIS DOCUMENT NOT AUTHORIZED BY BGC. ANY USE OF OR RELIANCE UPON THIS DOCUMENT OR ITS CONTENT BY THIRD PARTIES SHALL BE AT SUCH THIRD PARTIES' SOLE RISK.

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DATE: MAR 2020
DRAWN: MIB, LL
CHECKED: JJHP, LCH
APPROVED: MJ

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:
REGIONAL DISTRICT CENTRAL KOOTENAY

PROJECT:
RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE:
HARROP CREEK
AIR PHOTO COMPARISON

PROJECT No.: 0268007
DWG No: 04B

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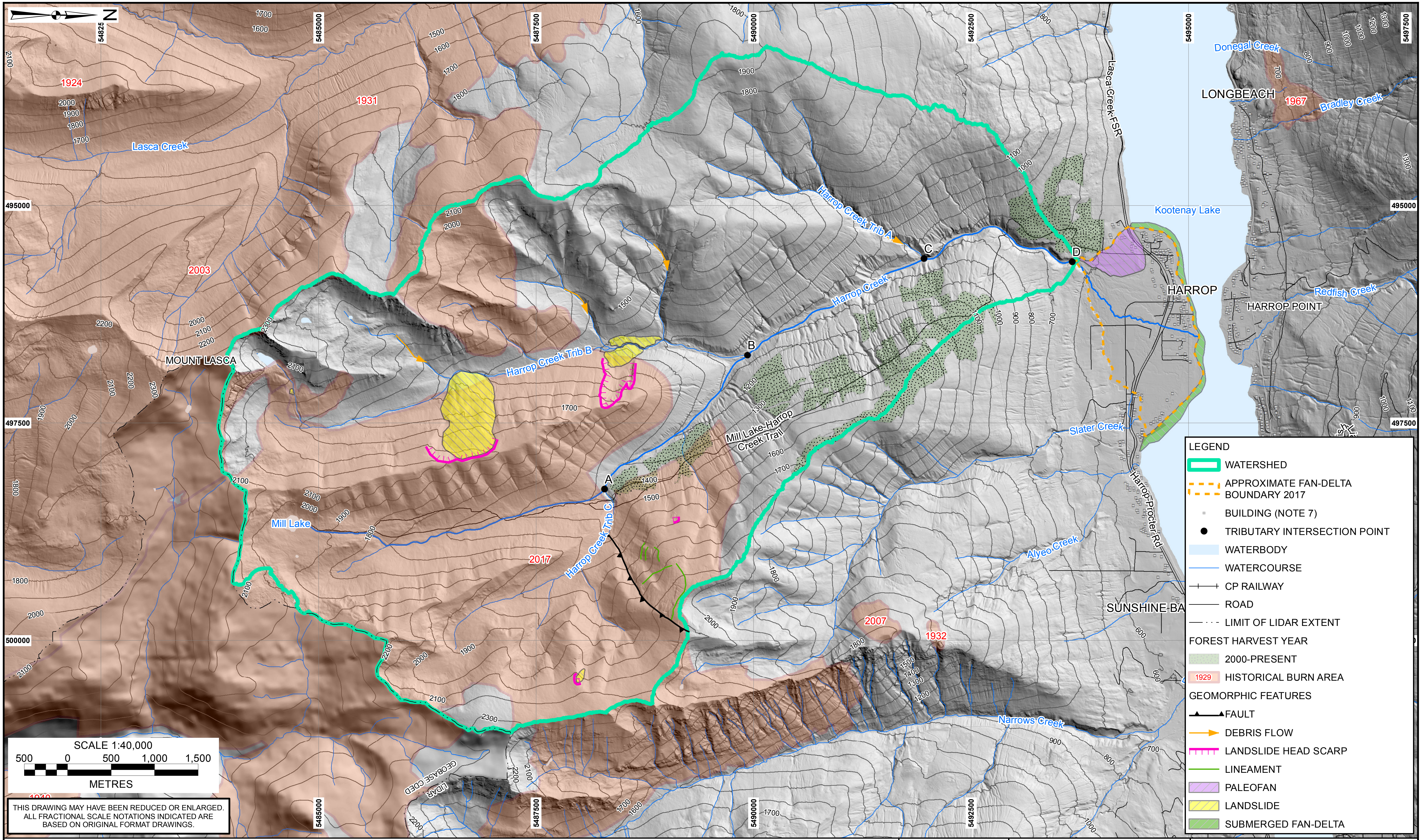

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3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY RDCK DATED 2017, AND GEOBASE CDED. CONTOUR INTERVAL IS 100m.
4. THE WATERSHED AND FAN-DELTA BOUNDARY AS DRAWN ARE APPROXIMATE AND DELINEATE THE LANDFORMS BASED ON LIDAR DATED 2017. THE BOUNDARIES SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DO THEY SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
5. HISTORICAL CUT BLOCK DATA FROM GEOBC DATASET DATED 2019 AND ONLY REPRESENTATIVE OF AREAS THAT INTERSECT WATERSHED BOUNDARY. HISTORICAL BURN AREA FROM GEOBC DATASET DATED 2019.
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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SCALE:	1:40,000
DATE:	MAR 2020
DRAWN:	MW
CHECKED:	JJHP
APPROVED:	MJ

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

PROJECT:
RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE:
HARROP CREEK
WATERSHED GEOMORPHOLOGY

PROJECT No.: 0268007

DWG No.: 05

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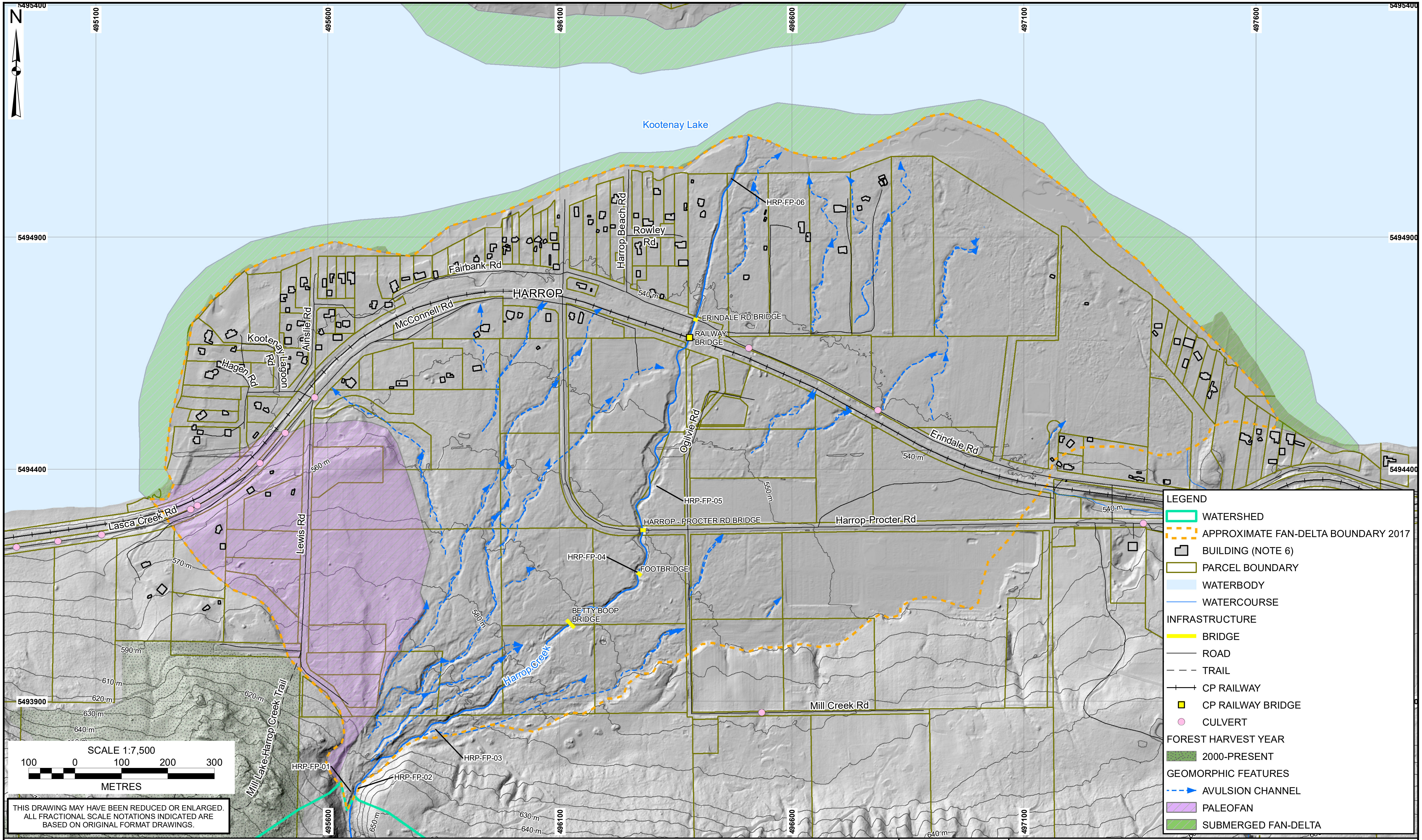

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4. THE WATERSHED AND FAN-DELTA BOUNDARY AS DRAWN ARE APPROXIMATE AND DELINEATE THE LANDFORMS BASED ON LIDAR DATED 2017. THE BOUNDARIES SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DO THEY SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
5. SUBMERGED FAN-DELTA DELINEATED BASED ON LAKE LEVEL FROM LIDAR DATED 2017.
6. CULVERT LOCATIONS FROM BC MINISTRY OF TRANSPORTATION. ROADS DATA FROM BC DIGITAL ROAD ATLAS. 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.
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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: HARROP CREEK
FAN-DELTA GEOMORPHOLOGY
PROJECT No.: 0268007
DWG No: 06

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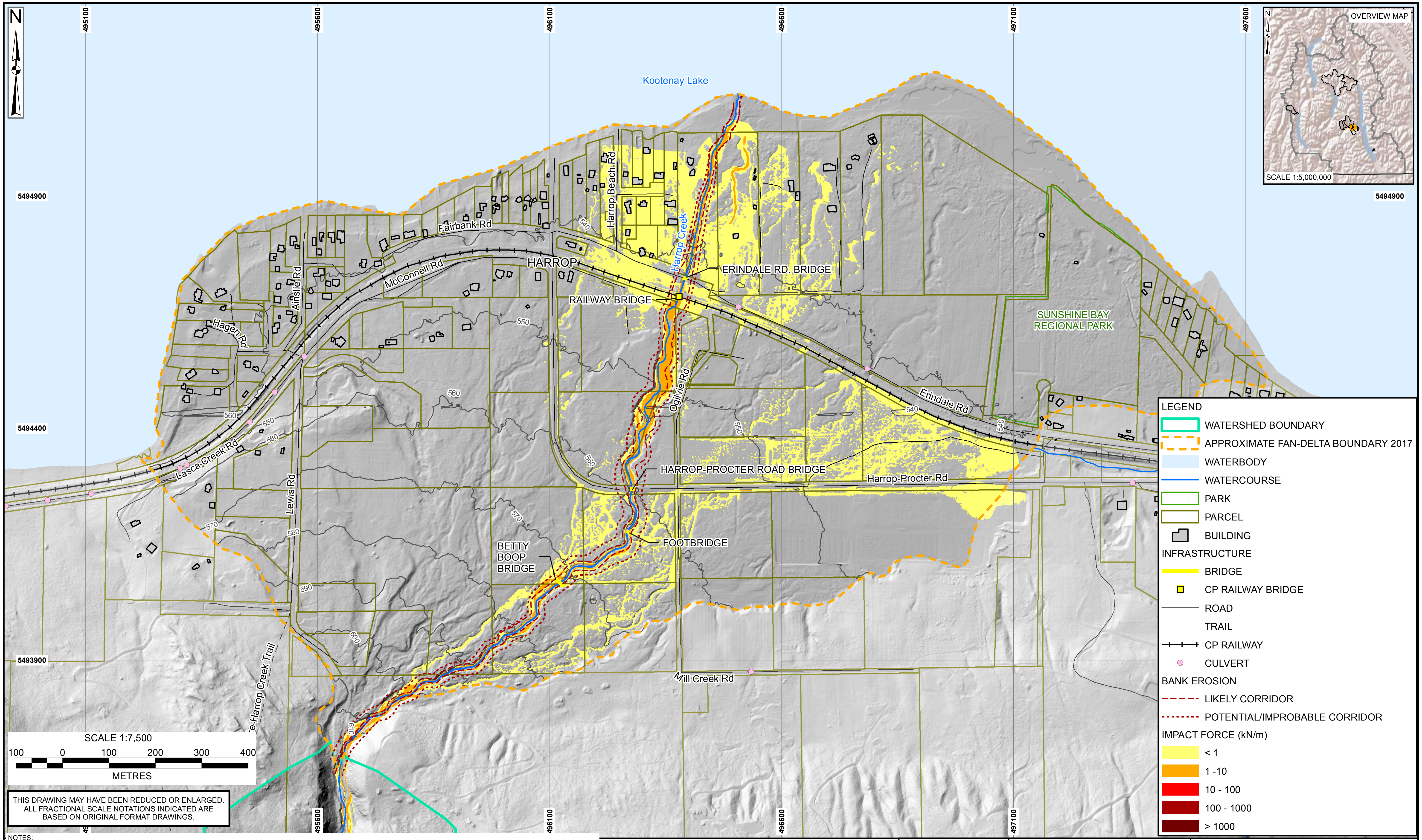

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BASED ON ORIGINAL FORMAT DRAWINGS.

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

SCALE:	1:7,500
DATE:	MAR 2020
DRAWN:	LL, MIB, STT
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:
HARROP CREEK 200 YEAR MODEL SCENARIO MLL-3

PROJECT No.:	DWG No:
0268007	07

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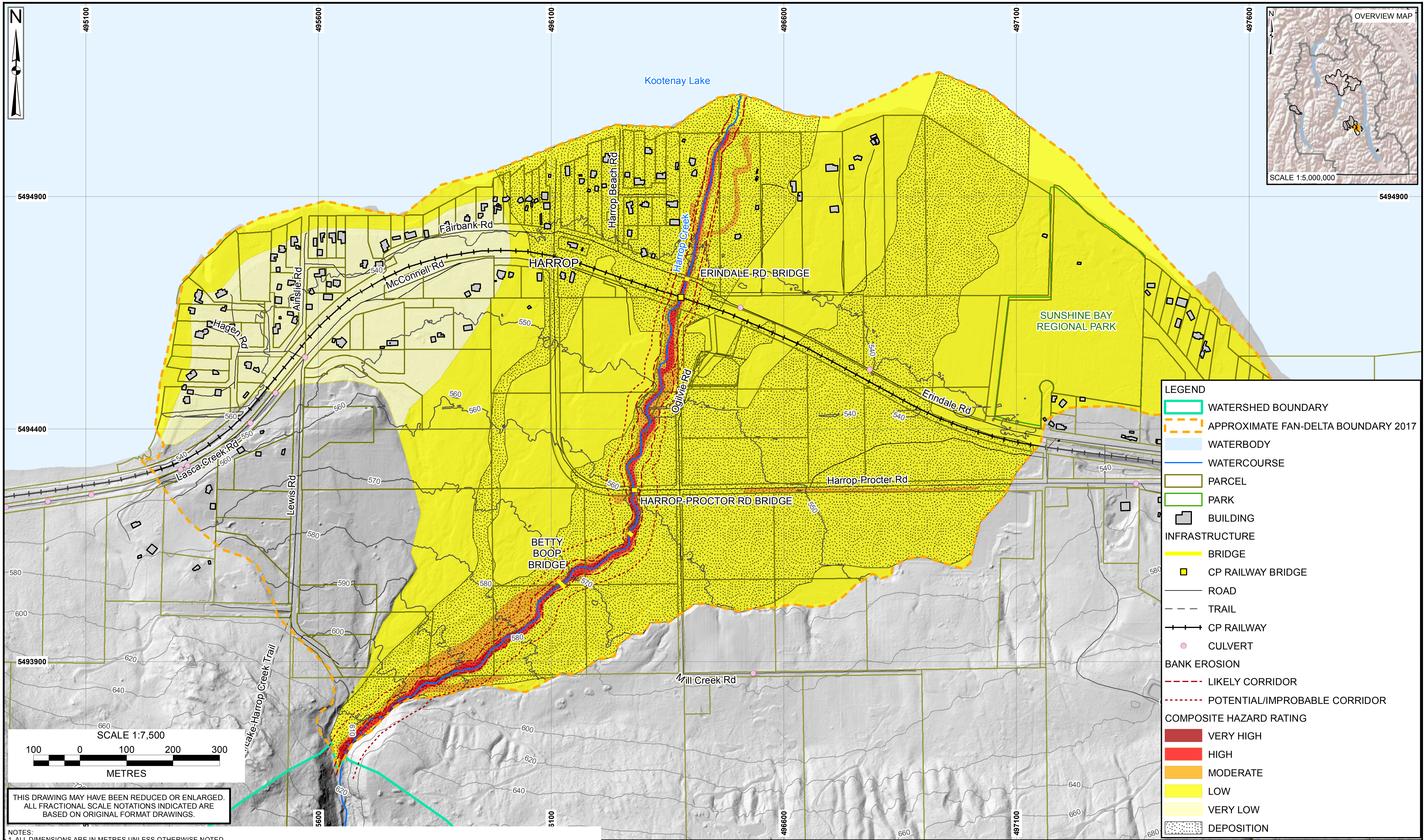

THIS DRAWING MAY HAVE BEEN REDUCED OR ENLARGED.
ALL FRACTIONAL SCALE NOTATIONS INDICATED ARE
BASED ON ORIGINAL FORMAT DRAWINGS.

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 - HARROP 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. 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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DRAWN: STT, LL, MIB
CHECKED: LCH
APPROVED: MJ

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

PROJECT:
RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE:
HARROP CREEK
COMPOSITE HAZARD RATING MAP

PROJECT No.: 0268007
DWG No: 08

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