RDCK FLOODPLAIN AND STEEP CREEK STUDY

Cooper Creek

Final
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TABLE OF REVISIONS

ISSUE	DATE	REV	REMARKS
DRAFT	March 26, 2020		Interim draft. Drawing 07 excluded and model results included for discussion purposes.
FINAL	March 31, 2020		Final issue.

LIMITATIONS

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ACKNOWLEDGEMENTS

BGC acknowledges the contributions of RDCK residents Harvey and Marlene Rempel to the present study.

EXECUTIVE SUMMARY

This report and its appendices provide a detailed hydrogeomorphic hazard assessment of Cooper Creek. This creek was chosen as a high priority creek amongst hundreds in the Regional District of Central Kootenays from a risk perspective because of its comparatively high hazards and perceived consequences from hydrogeomorphic events (debris flows and debris floods). This report provides a comprehensive geomorphological and hydrological background and details the analytical techniques applied to create scenario and composite hazard rating maps for the Cooper Creek fan. This work is the foundation for possible future quantitative risk assessments or conceptualization and eventual design and construction of mitigation measures.

Cooper 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. Landslide dam and bridge blockage scenarios were also considered.

A numerical hydro-dynamic model was employed to simulate debris flood hazard scenarios on the fan. BGC also estimated bank erosion from a physically-based model for different debris flood probabilities. Table E-1 provides key observations derived from the numerical modelling.

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

Process	Key Observations
Clear-water inundation (HEC-RAS model results for all return periods)	• Along the right (south) bank upstream of Highway 31, avulsions would result in ponding against the highway embankment and flow heading south along the highway ditch. For return periods greater than 20 years, flow overtops the highway in multiple locations. • Two avulsions also occur over the left (north) bank near the top of the fan. Flow from these avulsions is contained on the upstream side of the highway for return periods of 50 years and less, and flow north, impacting several residential homes. For the 200-year event and larger, flood water overtops the highway and flows towards the Duncan River, likely impacting more residential homes. • Downstream of the highway bridge, avulsions follow new and existing channels, largely in wooded areas. A few residential properties on the left (south) bank would be impacted. This impact occurs during all return periods; however, the extent and intensity varies. • For the scenarios where the Highway 31 bridge has been blocked, flooding upstream of the bridge increases and flooding over the highway occurs north and south of the creek. Overland flooding south of the creek continues toward the Duncan River and overtops Duncan Lake Road from Highway 31 to the Duncan Lake Road Bridge.

Process	Key Observations
	• While the overall hazard intensity of overbank flows is comparatively low for the return periods investigated, flooding of basements and first floors with low entry elevations could still result in substantial economic damage.
Sedimentation	• Sedimentation associated with debris floods is expected to occur in all avulsion paths and areas of ponding. • Average sediment deposition depths across affected fan portions are likely to range between 20 and 40 cm with deposition depths likely approaching water depths in areas subject to ponding. • Deposition upstream of the Highway 31 crossing due to possible bridge blockages could lead to the opening of additional avulsion paths not reflected in the modeling results.
Bank Erosion	• Average bank erosion ranges between 3 m (20-year) and 22 m (500-year) with maxima ranging between 4 m (20-year) and 32 m (500-year). Bank erosion potential generally increases downstream. • The Highway 31 bridge and properties within the 50th percentile bank erosion corridor are likely subject to being affected by erosion if unprotected. • Bank erosion could outflank the Highway 31 bridge though the likelihood of this occurrence has not been assessed.
Auxiliary Hazards	• An unquantified hazard exists on the Cooper Creek fan from impacts on Hamill Creek which discharges into Duncan River across from Cooper Creek. Hamill Creek appears to be a very active debris-flood (Type 1 and 3) creek (Drawing 04). Major debris floods and the associated sediment load could push Duncan River into the opposing (west) bank, leading to potentially high bank erosion rates and damage to the former Meadow Creek Cedar sawmill at the eastern end of McLauchlin Road. • Under all modeled scenarios, water will likely pond on the upstream (western) side of Highway 31. Highway overtopping may lead to highway erosion severing the highway. • Portions of the Cooper Creek fan are likely subject to inundation should there be a breach in Duncan Dam. This was not investigated by BGC and the return period of a dam breach is assumed to be higher than 500 years; the highest return period considered in this study.

The numerical modelling demonstrates the key hazards and associated risks stem from avulsions on both banks upstream of the Highway 31 crossing and may be attributable to exceeding channel capacity and channel aggradation. This could result in widespread flooding particularly on the central and southern lower fan.

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

The composite hazard rating map combines all hazard scenarios into one map and incorporates the respective debris flood and debris flow frequencies. It provides a sense of the areas that could possibly be impacted by future events up to the highest modelled return period. The composite hazard rating map can serve to guide subdivision and other development permit approvals. It requires discussions and regulatory decisions on which hazard zone is attributed to specific land use prescriptions, covenants, bylaws or other limiting clauses for both existing and proposed development. The categories range from very low to very high hazard. Very low hazard is defined as areas likely to not be affected by any of the modeled scenarios up to the 500-year return period debris floods, but which are not free of hazard. Very low hazard zones could be impacted by flows of higher return periods, or if, over time, the channel bed of Cooper Creek aggrades, or the channel or fan surface is artificially altered. All other hazard categories are classified via the impact force intensity. The composite hazard rating map demonstrates that significant hazards exist outside the active channel sections both upstream and downstream of the Highway 31 crossing. Given the large watershed area (240 km^2), Cooper Creek behaves more like a river than a creek and is characterized by moderate flow depth (up to 2 m upstream of the Highway 31 crossing) and flow velocities (up to 4 m/s or some 14 km/hr in narrow channel sections). These factors also result in substantial bank erosion potential on both sides of Cooper Creek. The “moderate” to “high” areas are generally confined to the active floodplain and adjacent low areas, while shallow flows spread both north and south from the main channel and specifically along Highway 31 ditches.

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): Deflection berms on the left bank in several locations upstream of the highway bridge to prevent avulsions to the northern section of the fan; installing bank protection upstream of Highway 31 bridge abutments to prevent outflanking; relief culverts in multiple locations north and south of the main channel under Highway 31 to prevent upstream ponding, overtopping and erosion; and bank erosion protection for properties adjacent to Duncan River.

Some uncertainties persist in this study. As with all hazard assessments and corresponding maps, they constitute a snapshot in time. Re-assessment and/or re-modelling may be warranted due to significant alterations of the surface topography or scenario assumptions, such as future fan developments, debris floods, or the formation or reactivation of existing large landslides in the watershed that could impound Cooper Creek. Breaches of the Highway 31 road embankment due to retrogressive erosion associated with overtopping could result in inundation and rapid sedimentation not reflected on BGC’s individual hazard scenarios or composite hazard rating map. 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 jams may alter flow directions and create avulsions into areas not specifically considered in the individual hazard scenarios.

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	Clear-water 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 Cooper Creek, located approximately 22 km northeast of Nelson, BC in Electoral Area D. The site lies on the north side of Kootenay Lake where Duncan River connects Duncan Lake to the north with Kootenay Lake to the south. The creek flows through Lardeau Provincial Park on the south side of the fan and into Duncan River.

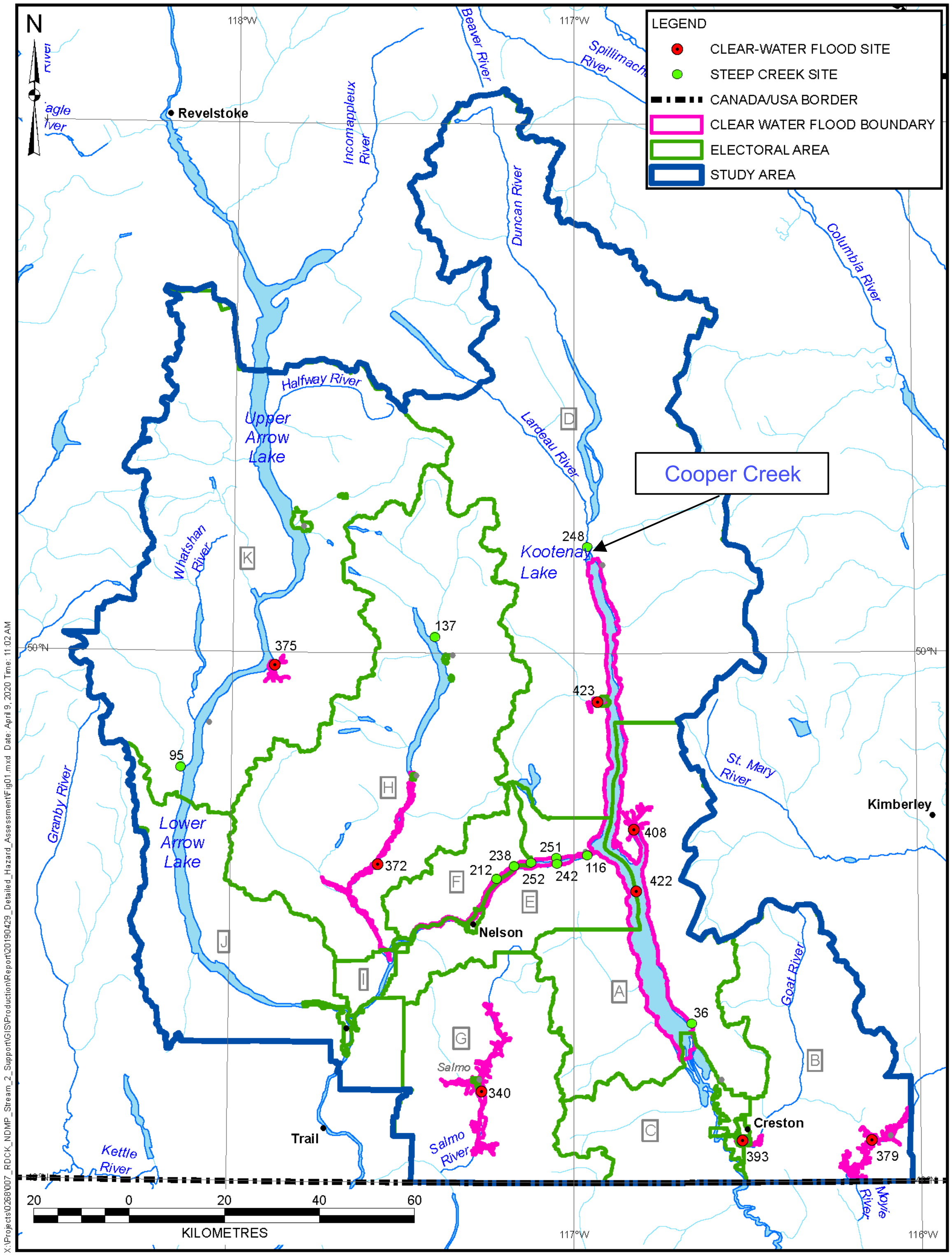

Figure 1-1. Hazard areas prioritized for detailed flood and steep creek mapping. Site labels correspond to hazard identification numbers in Cambio Communities. Cooper Creek (No. 248) is labelled on the figure.

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 Cooper Creek. This assessment also provides inputs to possible future work such as:

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

In addition to this report, BGC is providing a summary report for the entire assessment across different sites, *RDCK Floodplain and Steep Creek Study Summary* Report (BGC, March 31, 2020a) (referred to herein as the "Summary Report"). Readers are encouraged to read the Summary Report to obtain context about the objectives, scope of work, deliverables, and recommendations of the larger study. BGC is also providing a *RDCK Floodplain and Steep Creek Study Steep Creek Assessment Methodology Report* (BGC, March 31, 2020b) (referred to herein as the "Methodology Report") which describes the assessment methods applied for this study.

1.2. Scope of Work

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

At Cooper Creek, the scope of work included:

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

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

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

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

Table 1-2. Return period classes.

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

1.3. Deliverables

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

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

1.4. Study Team

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

- Kris Holm, M.Sc., P.Geo., Principal Geoscientist
- Sarah Kimball, M.A.Sc., P.Eng., P.Geo., Senior Geological Engineer
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- Jack Park, B.A.Sc., EIT, GIT, Junior Geological Engineer

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

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5.6	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.

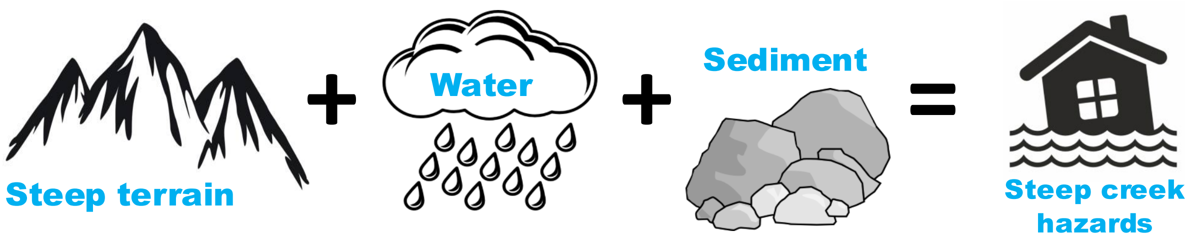


Figure 2-1. Illustration of steep creek hazards.

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

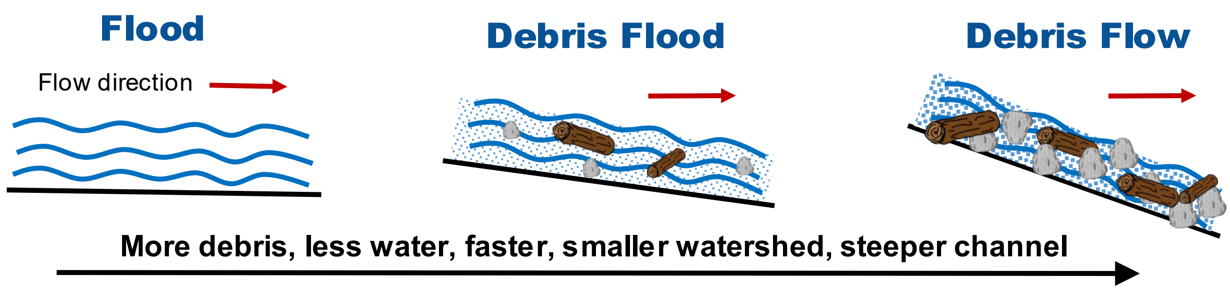


Figure 2-2. Continuum of steep creek hazards.

2.2. Clear-water Floods and Debris Floods

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

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

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

- Type 3 – Debris floods that are generated from natural (e.g., landslide dam) or artificial dam breaches.

The process of sediment and woody debris getting entrained in the water of a flood leads to an increase in the volume of organic and mineral debris flowing down a channel with a commensurate increase in peak discharge. This is referred to as flow bulking. Imagine a bucket 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.

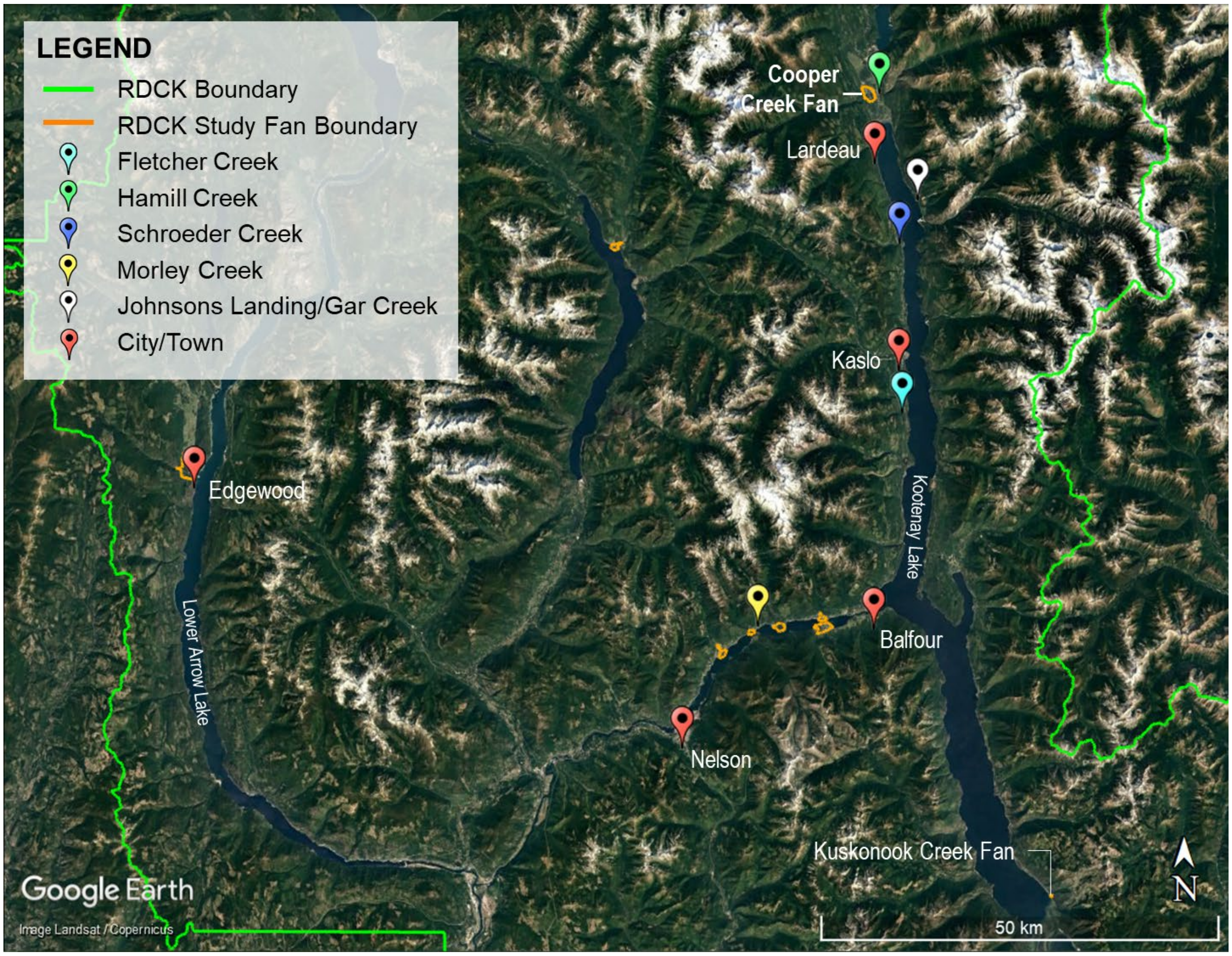


Figure 2-3. Locations of RDCK fans and recent floods, debris flows, and debris floods (Google Earth Pro, 2016).

2.4. Contextualizing Steep Creek Processes

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

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

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

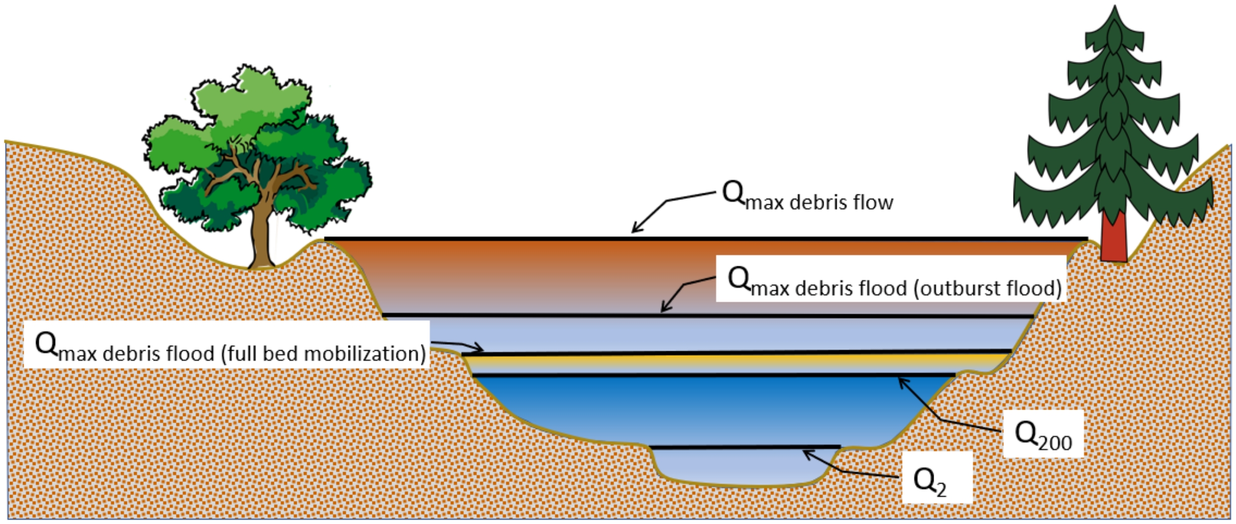


Figure 2-4. Conceptual steep creek channel cross-section showing peak discharge levels for different events. Note that for some outburst floods or debris flows the discharge may well exceed what is shown here.

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

2.5. Avulsions

An avulsion occurs when a watercourse jumps out of its main channel into a new course across its fan or floodplain (Appendix A). This can happen because the main channel cannot convey the flood discharge and simply overflows, or it occurs because the momentum of a flow allows overtopping on the outside of a channel bend. Finally, an avulsion can occur because a log jam or collapsed/blocked bridge redirects flow away from the present channel. The channel an avulsion flow travels down is referred to as an avulsion channel. An avulsion channel can be a new flow path that forms during a flooding event or a channel that was previously occupied 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 clear-water floods as they are well above the maximum flow depths achieved by such modern-day processes. For this reason, they are often suitable for development from a geohazard point of view.

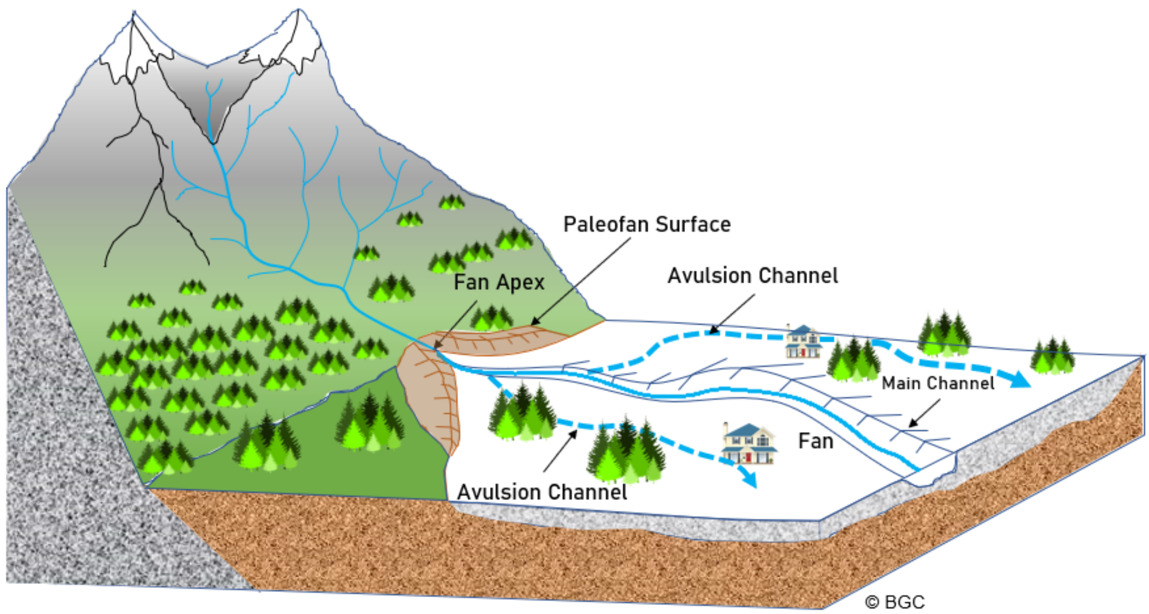


Figure 2-5. Schematic of a steep creek channel with avulsions downstream of the fan apex. Artwork by BGC.

3. STUDY AREA CHARACTERIZATION

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

3.1. Site Visit

Fieldwork on Cooper Creek was conducted on July 25, 2019 by BGC personnel Marc Oliver-Trottier and Anna Akkerman. Field work included channel hikes to observe bank conditions, look for evidence of erosion and protection; locate previous creek alignments; measure grain size diameters (Wolman sampling) near the fan apex and the mouth (Appendix C); and, measure cross-sections at the bridge and other infrastructure crossing locations. The upper watershed was flown by helicopter on July 6, 2019 and numerous photographs were taken for later analysis of major sediment sources to the channel (Appendix B).

3.2. Physiography

Cooper Creek is located approximately 22 km northeast of Nelson, BC at the north end of Kootenay Lake. The creek flows southeast across the fan through Lardeau Provincial Park into Duncan River. Drawings 01 and 02A show the watershed and fan boundaries of Cooper Creek on a shaded, bare earth digital elevation model (DEM) created from lidar data. Drawing 02B shows the fan on an orthophoto. Drawing 03 shows a profile along the creek mainstem and tributaries. Representative photographs of the watershed and fan are provided in Appendix B

The site lies on the eastern flank of the Selkirk Mountains, which are a subgroup of the Columbia Mountains. The watershed falls within the Central Columbia Mountain ecosection of the Northern Columbia Mountains ecoregion. The ecoregion is bounded by large hydroelectric reservoirs (Kootenay Lake, Slocan River, and Arrow Lake), into which numerous mountainous streams drain (Demarchi, 2011). The ecosection is characterized by long, uniformly steep slopes that terminate at sharp ridges and mountain peaks sculpted by cirque glaciers in narrow valleys (Holland, 1976). Precipitation is high in the Central Columbia ecosection, as moisture from coastal areas travels from the south and west, bringing high humidity and rain in summer, and deep snow in winter (Demarchi, 2011). Typical vegetation includes Western Red Cedar and Western Hemlock trees at lower elevations (from 500 m elevation) and Engelmann Spruce and Subalpine Fir trees along the mid-mountain slopes.

3.3. Geology

3.3.1. Bedrock Geology

The Cooper Creek watershed lies along the Kootenay Arc, which is a curving belt of highly deformed sedimentary, volcanic, and metamorphic rocks that extend along the western shore of Kootenay Lake (Fyles, 1964). The watershed area includes rocks from the Lardeau, Millford, Slocan, Badshot, and Hamill Groups and vary from sedimentary limestone, slate, siltstone, quartzite, and argillite, to basaltic volcanic rocks. Near the outlet of Cooper Creek, most of the sedimentary structures dip to the southwest, forming the western limb of the Meadow Creek anticline (Fyles, 1964). A northwest trending fault cuts across the watershed approximately 13 km upstream of the outlet of Cooper Creek (Drawing 05) (Cui, Miller, Schiarizza, and Diakow, 2017). Bedrock lineaments such as these often provide preferential surface flow paths and represent locations of structural weakness in the bedrock.

3.3.2. Surficial Geology

The surficial geology of the Cooper Creek watershed is dominantly colluvium overlying bedrock, with some glaciofluvial and till deposits as shown in Figure 3-1 (Wittneben, 1980). The valley walls are characterized by colluvium overlying bedrock as well as some steep slopes overlain by till. The highest ridges are mostly composed of bedrock, with some overlying colluvium and till. There are several small (<1.5 km^2) cirque glaciers that are located on north-facing slopes above 2100 m. The abundant colluvium in the watershed, as well as the rockfall-prone bedrock outcrops and recent glaciation, indicate that the watershed is supply unlimited, which implies a quasi-unlimited amount of sediment available in the watershed to be mobilized during extreme hydroclimatic events.

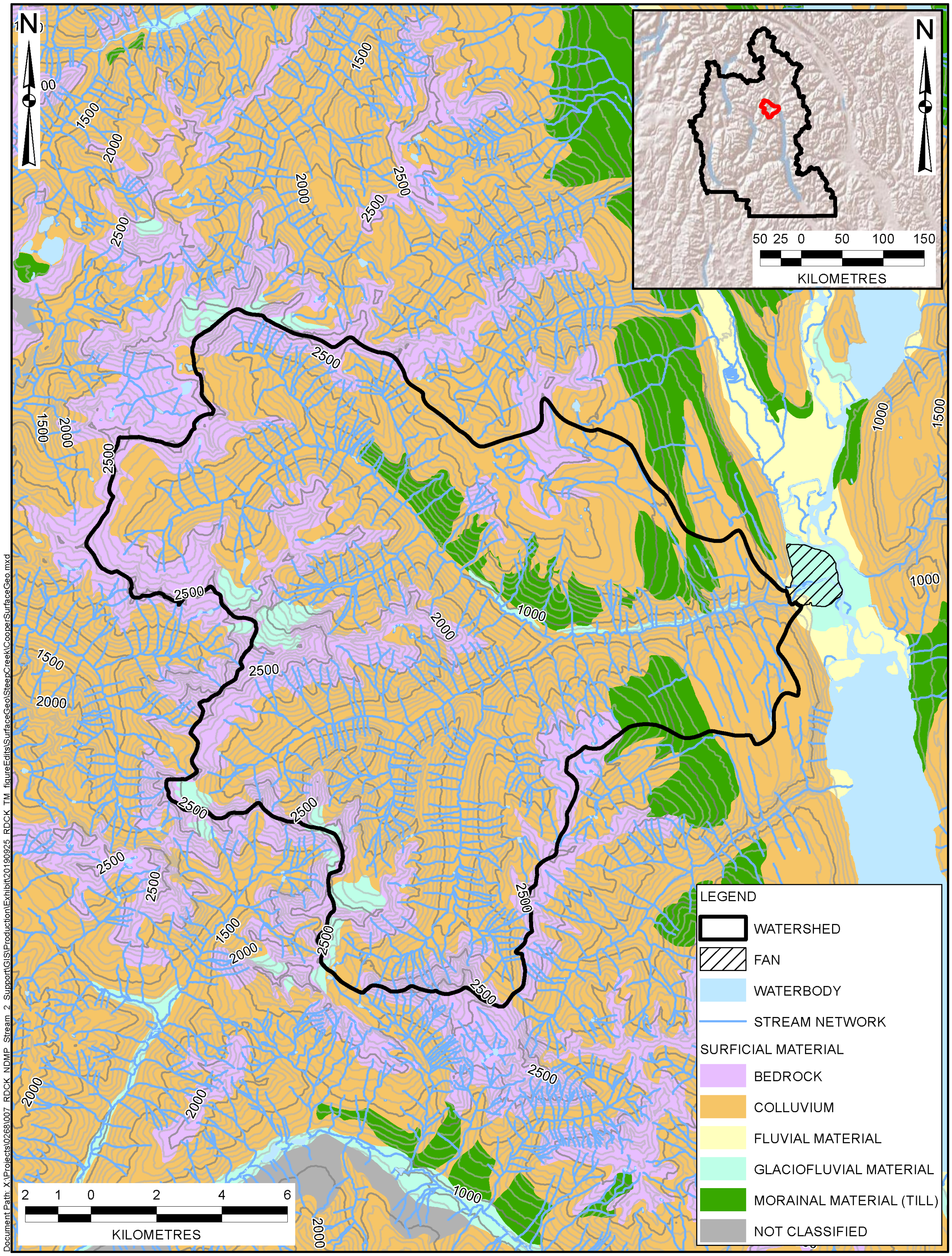


Figure 3-1. Surficial geology of the Cooper Creek watershed (from Province of BC, 2016).

3.4. Geomorphology

3.4.1. Watershed

Geomorphological analysis of Cooper Creek includes watershed and fan characterization using historical air photos (Drawings 04A and 04B) and lidar supplemented by literature on the regional geology, geologic history and physiography, and a field visit. Drawing 05 shows the geomorphic features of the watershed, including specific landforms and sediment sources in the watershed. Drawing 03 shows a channel profile for the watershed with annotations of reaches and representative channel gradients.

The headwaters of Cooper Creek are located on the mountainous slopes of the Goat Range. Mount Marion (approximate elevation 2,970 m) is on the north side of the watershed, Mount Cooper (3,090 m) is on the mid-west side. South of Mount Cooper, Mount McHardy (2,770 m) and Mount Dryden (2,800 m) form the western headwaters of the Cooper Creek watershed. The southern headwaters of the watershed are located on the mountainous slopes of Mount Brennan (2,900 m). The upper portions of the watershed are characterized by an alpine environment with retreating glaciers, permafrost and pro-talus ramparts. The alpine upper tributary valleys transition to confined, V-shaped valleys as Spokane Creek joins McKian Creek (A on Drawing 03 and 05), and on the mainstem of Cooper Creek approximately 13 km upstream of the fan apex (B on Drawings 03 and 05). The lower 7 km of Cooper Creek is in an incised bedrock canyon (Photo 6 and Photo 7, Appendix B). Active sediment sources, in the form of talus slopes, glacial moraines, and steep tributary creeks through colluvium deposits and raveling slopes, are present throughout the watershed.

The hillslopes in the Cooper Creek watershed are forested and logging is abundant in the lower watershed. Approximately 6% of the total watershed area has been logged since 1900 and 19% of the watershed area has burned since 1919, with the largest forest fire recorded in 1930 (FLNRORD, 2019a; 2019b). There is evidence of logging road failures along the incised reach of the main channel (Drawing 05).

Table 3-1 summarizes relevant geomorphic characteristics of the Cooper 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 clear-water flood, debris flood, or debris-flow processes (Section 3.4.3). The channel gradient above the fan apex provides an indication of whether transportation of sediment is likely, and the fan gradient approximates the angle where sediment deposition of larger flows from the watershed generally ensues.

On the lidar image at approximately 470 m downstream of the fan apex, a stream joins Cooper Creek from the north. However, no notable channel was observed during BGC's field visit on July 25, 2019. This stream is likely dry most of the year and its watershed area is relatively insignificant compared to the size of the Cooper Creek watershed (i.e. less than 5% of Cooper Creek watershed), therefore, its contribution was not considered in our modelling scenarios.

Table 3-1. Watershed characteristics of Cooper Creek.

Characteristic	Value
Watershed area (km^2)	244
Fan area (km^2)	2.5
Active fan area (km^2)	2.2
Maximum watershed elevation (m)	3,090
Minimum watershed elevation (m)	560
Watershed relief (m)	2,539
Melton Ratio (km/km)[2]	0.1
Average channel gradient of mainstem above fan apex (%)	6.5
Average channel gradient on fan (%)	6
Average fan gradient (%)	2

Note:
1. Melton ratio is an indicator of the relative susceptibility of a watershed to debris flows, debris floods or floods.

3.4.2. Cooper Creek Fan

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

Cooper Creek flows easterly across the fan that extends into the Duncan River floodplain. Cooper Creek has down cut through paleofan surfaces to reach the current level that is evidenced by terraces near the fan apex at various historical fan elevations (delineated in Drawing 06). Avulsion channels are present both north and south of the current channel along the channel on the fan. These features become more muted and shallower with distance from the fan apex. The reach near the outlet into the Duncan River has had several avulsions and channel changes throughout the historical air photo record (Drawings 04A and 04B) as shown on Drawing 06. Historically, Cooper Creek has had a braided morphology, indicating a high sediment supply and lateral instability (Drawing 04A). Over the last century, the creek has become more stable on the fan, which can partially be attributed to straightening of the channel near Cooper Highway Bridge prior to 1968. However, the more stable channel may also reflect a lack of significant floods and/or reduced sediment supply since the earliest air photo in 1929, or possibly a downcutting of Duncan River. The average channel gradient on the fan is 2% (Table 3-1).

Cooper Creek flows into Duncan River which is controlled upstream by Duncan Dam which holds back the Duncan Lake reservoir. Historical records (Section 4) suggest that the Duncan Dam has not affected flood levels of Duncan River and as such the Cooper Creek fan has not been significantly altered by the Duncan Dam construction and operation since activation of the dam in 1967. The Cooper Creek channel is approximately 50 m wide where it enters the Duncan River

3.4.3. Steep Creek Process

BGC assessed the potential steep creek process types and hazards on Cooper 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, Cooper Creek plots in the data cluster prone to debris floods to floods (Figure 3-2). The points shown on the plot are subject to some error and watersheds can be subject to multiple processes at different timescales. For example, it is not possible from this plot to determine if a small tributary near the fan apex could produce a debris flow that reaches the fan apex or travels beyond. For this reason, it is important to consider additional evidence to supplement the assessment of process type.

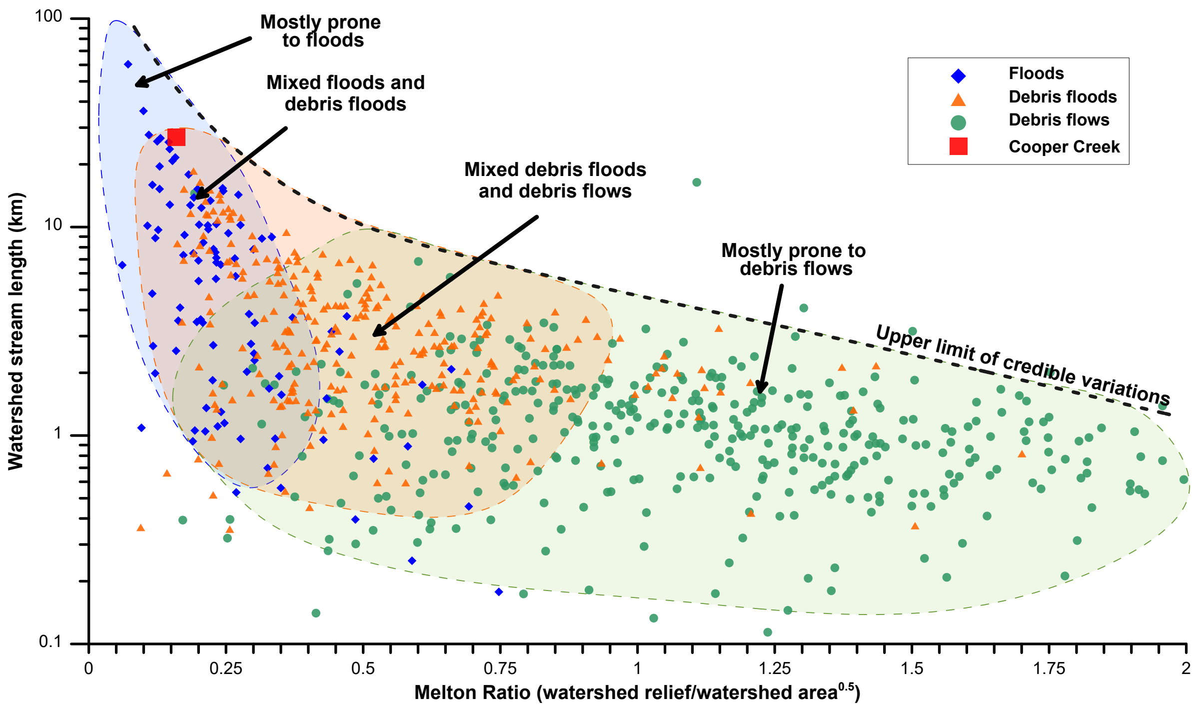


Figure 3-2. Tendency of creeks to produce floods, debris floods and debris flows, as a function of Melton Ratio and stream length (data from Holm et al., 2016 and Lau, 2017). See Section 3.4.1 for Cooper Creek watershed data.

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. See Section 6.1 for further details on the hydrogeomorphic processes considered by BGC to potentially impact the Cooper Creek fan.

3.5. Existing Development

Development on the Cooper Creek fan comprises the community of Cooper Creek, Highway 31, and communications infrastructure transecting the northern mid-fan. Several houses are within the fan, and there is a gas station 300 m north of the creek at the Highway 31 bridge crossing.

On the north side of the fan, there is a former sawmill, the Meadow Creek Cedar sawmill (Drawing 02B). In 2014, the sawmill burned down (Nelson Daily Staff, 2014). The mill was idle for years following the 2014 fire, and has been repurposed as a medical marijuana growing site (Keating, 2019)

The south side of the fan is sparsely developed and has mostly rural residences east of Highway 31 (Drawing 02B). West of Highway 31 on the south side, there is a gravel pit and active logging in the watershed as well as a local hiking trail along the right bank of the creek to the fan apex. The north side of the fan is more developed with many residences above and below Highway 31 as well as the closed Meadow Creek Cedar sawmill on the bank of Duncan River The closest buildings are approximately 80 m south from the active channel downstream of Highway 31; however, the right bank is actively eroding towards these properties (Photo 20, Appendix B).

The 2016 census does not have a population estimate for Cooper Creek and instead groups the community into the RDCK electoral area (Statistics Canada, 2016). The estimated total improvement value of parcels intersecting the Cooper Creek fan based on the 2018 BC Assessment Data is $5,322,800 (BGC, March 31, 2019).

3.5.1. Bridges

Cooper Creek passes under Cooper Highway Bridge 600 m upstream of its entrance to Duncan River (Table 3-2, Figure 3-3). The bridge location is shown on Drawing 02A, 02B. The active channel is approximately 30 m wide at the bridge. The Duncan Lake Road bridge connects the Cooper Creek fan to the east side of the Duncan River (Drawings 02A, 02B, 06). This bridge was not considered in the numerical modelling completed by BGC (Section 6.5).

Table 3-2. Estimated dimensions of bridge crossings over Cooper Creek.

Bridge	Span (m)	Height Above Channel Center (m)	Notes
Cooper Highway Bridge	28	3	Highway 31, 2-lane road

Note: The bridge dimensions were either taken in the field and lidar using typical dimensions for the size of road, if required.

A) On Cooper Highway Bridge looking upstream.

B) On Cooper Highway Bridge looking downstream.

C) Looking at Cooper Highway Bridge from upstream left bank.

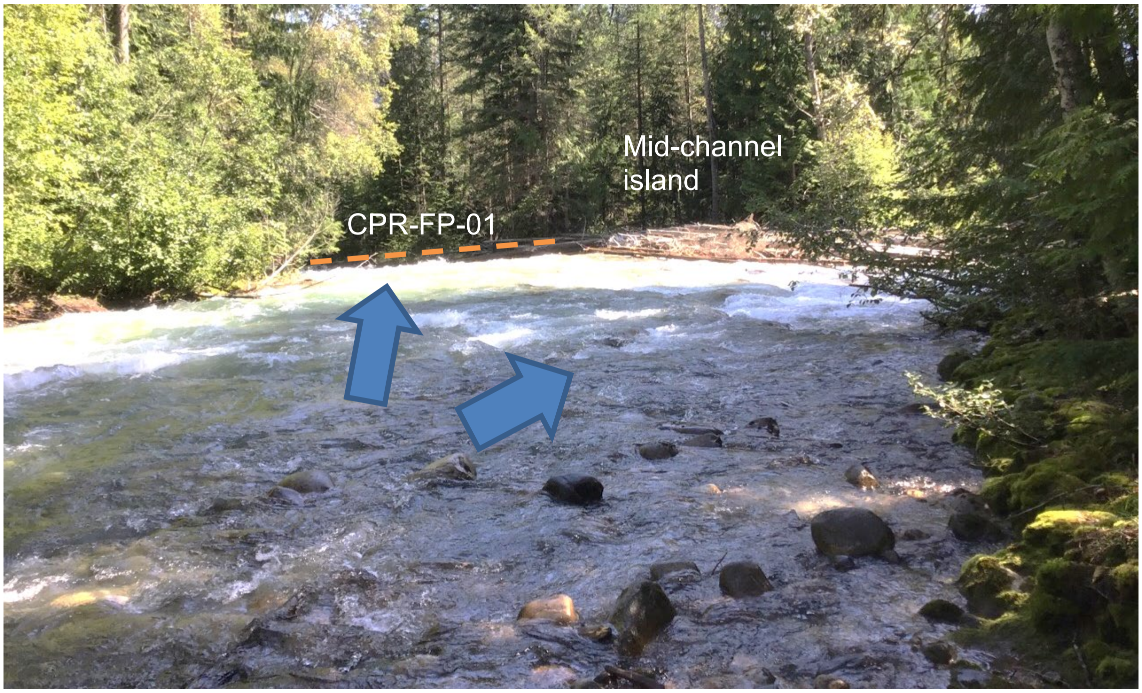
D) On upstream left bank looking across at riprap on right bank, upstream of Cooper Highway Bridge.

E) Looking at Cooper Highway Bridge from the left (north) bank on upstream side.

Figure 3-3. Cooper Highway Bridge on Cooper Creek fan observed during BGC's field work in July 2019. Refer to Drawing 02A, 02B for locations.

3.5.2. Flood Protection Structures

There are two flood protection structures on Cooper Creek as shown on Drawings 02A, 02B, and 06. The first structure (CPR-FP-01) is located approximately 600 m upstream of Highway 31 on the left (north) bank. This dike is registered under the iMapBC Flood Protection Structural Works layer. No signs of a dike were found at the location noted in iMapBC during July 2019 field visit by BGC; however, field staff could only view the location from the right bank due to site access constraints. The creek split around a large densely forested mid channel island and the left channel thread appears to pass through the stated dike location. (Figure 3-4A). The second structure (CPR-FP-02) is located approximately 300 m upstream of Highway 31 on the right bank. This berm was noted to be heavily vegetated during BGC's site visit (Figure 3-4B). The attributes of the flood protection structures are based on the iMapBC Flood Protection Structural Works layer, where available, and BGC's July 2019 field observations, and are outlined in Table 3-3.



A) Location of CPR-FP-01 dike, 600 m upstream of Highway 31 bridge crossing on the left bank of the creek.

B) Old berm, 300 m upstream of Highway 31 bridge crossing and 10 m from the right bank of the creek (CPR-FP-02).

Figure 3-4. Select flood protection structures along Cooper Creek. BGC photos taken July 25, 2019. Refer to Table 3-3 for attributes and Drawing 02A, 02B for locations.

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

Attribute	Flood Protection Structure	
BGC ID	CPR-FP-01	CPR-FP-02
Source[1,2]	iMapBC	BGC Field Observation
Type	Dike	Berm
Orphan (Y/N)[3]	Y	-
Comments	This structure was not found during the site visit by BGC.	Thick vegetation covered with moss and saplings.
Survey Year(s)	2003	-
Erosion Protection Side	Left	Right
Length (m)	15	~10

Notes:
1. iMapBC data downloaded from Flood Protection Structural Works layer on March 3, 2020.
2. BGC Field Observation made on July 25, 2019.
3. Only the structure within iMapBC data (CPR-FP-01) was classified as an orphan structure.

3.6. Hydroclimatic Conditions

3.6.1. Existing Conditions

Climate normal[3] data were obtained from Environment and Climate Change Canada's Duncan Lake Dam station (549 m), located approximately 5 km north of the Cooper Creek outlet (Environment and Climate Change Canada, n.d.). Daily precipitation and temperature data are available from 1963 to 2015. Figure 3-5 shows the average temperature and precipitation for this station based on 1981 to 2010 climate normals. Precipitation peaks in November, with about 25% falling as snow. The total annual precipitation is 807 mm: The distribution of these annual totals between rain and snow is shown in Table 3-4.

The measured precipitation at the Duncan Lake Dam weather station is lower than precipitation in the Cooper Creek watershed, where the mountaintops extend more than 2500 m above Duncan Lake. This is due to orographic effects, which occur when an air mass is forced up over rising terrain from lower elevations. As it gains altitude it quickly cools down, the water vapour condenses (forming clouds), ultimately resulting in precipitation.

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

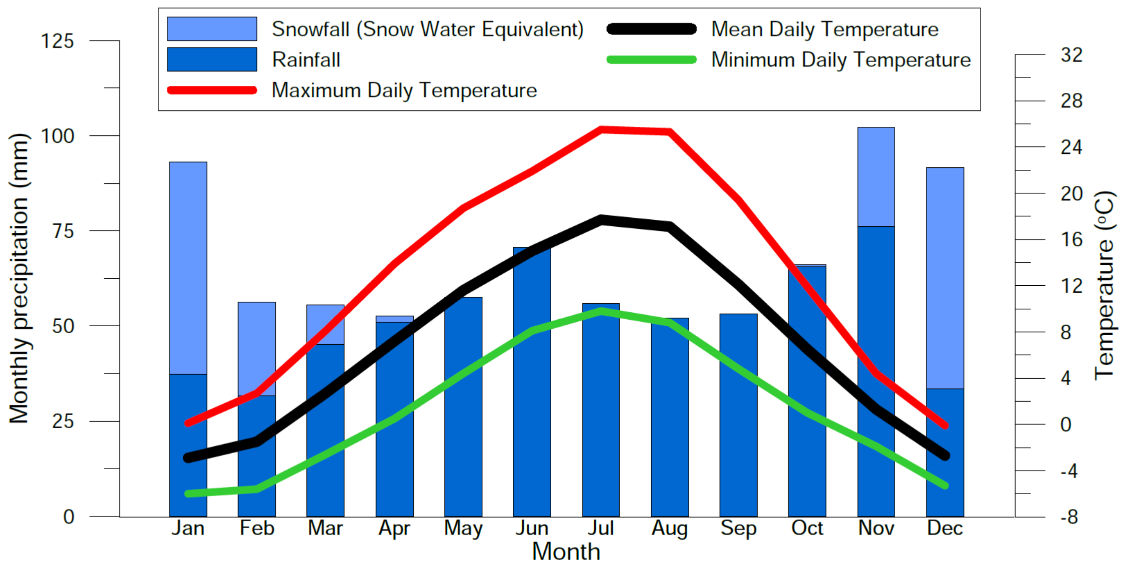


Figure 3-5. Climate normal data for Duncan Lake Dam station from 1981 to 2010.

Table 3-4. Annual total of climate normal data for Duncan Lake Dam weather station from 1981 to 2010.

Variable	Annual Total	Percent of total annual precipitation (%)
Rainfall (mm)	630	78
Snowfall (cm)	177	22
Precipitation (mm)	807	100

To understand the regional distribution of precipitation and snowfall patterns and supplement the data from the Duncan Lake Dam 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 1477 mm, varying as a function of elevation. The same trend is evident in the historical annual average Precipitation as Snow (PAS) over the watershed where the historical average PAS is 931 mm. PAS increases with elevation; therefore, the watershed accumulates greater precipitation falling as snow compared to the Duncan Lake Dam weather station.

3.6.2. Climate Change Impacts

The watershed lies within the Central 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 ClimateNA 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 MAT in the Cooper Creek watershed is projected to increase from 1.3ºC (historical period 1961 to 1990) to 4.9ºC by 2050 (average for projected period 2041 to 2070). The historical MAP is projected to increase from 1477 mm to 1571 mm by 2050 while historical PAS is projected to decrease from 931 mm to 686 mm by 2050 in the Cooper Creek watershed. Projected change in climate variables from historical conditions for the Cooper Creek watershed are presented in Table 3-5.

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

Climate Variable	Projected Change
Mean Annual Temperature (MAT)	+3.6 ºC
Mean Annual Precipitation (MAP)	+94 mm
Precipitation as Snow (PAS)	-245 mm

4. SITE HISTORY

4.1. Introduction

Cooper Creek flows through the community of Cooper Creek and into the Duncan River. Residents have lived on the fan since the late 1800s.

4.2. Document Review

In developing a flood, mitigation, and development history for Cooper 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).
- 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 residents.
- Historical wildfire perimeters (MFLNRORD, n.d.).
- Cut block perimeters (MFLNRORD, n.d.).

BGC's review of the above work is not aimed as a critique but rather a brief summary of the findings of each report. Each scientific or engineering/geoscientific study builds on the preceding one benefitting from the added knowledge. By summarizing aspects of the studies listed below, BGC is neither endorsing nor rejecting the findings of those studies, as this was not the scope of the present study.

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

Year	Month/Day	Source	Purpose
1972	June	Water Resources Branch (BC Government)	Flood survey report
1974	May	Water Resources Branch (BC Government)	Flood survey report
1991	March 22	Water Management Kootenay Region	Approval of Site-specific Exemption
1991	December 13	BC Ministry of Environment, Lands and Parks	Correspondence with property owner
1998		Klohn-Crippen Consultants Ltd.	Terrain Stability Inventory
2008	April 29	Deverney Engineering Services Ltd.	Precondition for Site-specific Exemption
2012	July 22	Regional District of Central Kootenay	Site Investigation
2013	September 21	Perdue Geotechnical Services Ltd.	Hazard Assessment

4.2.1. Deverney (2008)

In 2008, Deverney Engineering Services Ltd. (Deverney) completed a hazard assessment of Lot 2, Plan 8092, District Lot 1025 located north of Cooper Creek where it borders Cooper Ck Road on its northern side downstream of Highway 31. Deverney referred to channel straightening and dredging works prior to the 1966 air photo that were interpreted to be intended to confine the channel to a preferred path instead of meandering across the floodplain. The consequence of the straightening is a shorter channel with steeper gradient and higher flow velocities than the natural condition. Shallow avulsion channels were identified north of the creek where overland flow was assessed to be possible due to the shallow incision of Cooper Creek. Deverney identified the potential for Highway 31 to convey flows away from the channel in a flood event. Deverney assessed that debris torrents[4] and debris flows present a negligible hazard to the property but that shallow overland flow and avulsions are credible events (Deverney, 2008).

4.2.2. Perdue (2013)

Perdue Geotechnical Services (Perdue) completed a preliminary assessment of flood potential across Cooper Creek fan in 2013. Perdue assessed the channel reach immediately downstream of the fan apex to be the most stable on the fan due to the lateral confinement and higher flow velocities in this straightened section that limit aggradation and gravel bar development. Downstream, Perdue observed channel widening and accumulation of coarse bed load material and woody debris. Perdue indicated that the Highway 31 bridge acts as a channel constriction resulting in bank erosion along the left (north) bank of Cooper Creek. Downstream of the Highway 31 bridge, Perdue assessed that residential development occupies a potentially active floodplain area along the southern side of the channel. Perdue assessed that debris floods pose

[4] In the Deverney report, debris torrent appears to be used synonymously with debris flood in this report.

a credible risk to the Cooper Creek fan due to the active channel being of insufficient capacity to accommodate a 200-year return period peak discharge as well as the potential for landslide initiation in the watershed upstream of the fan (Perdue, 2013).

4.3. Historic Timeline

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

- At least seven notable hydrogeomorphic events have occurred in recorded history (pre-1929, 1938, 1972, 1974, 1997, 2007, 2012). Flood events have occurred during spring freshet (snowmelt) conditions. The most recent flood event (2012) caused concerns amongst residents regarding log accumulation and bank erosion. A notable debris flood in 1938 temporarily blocked the Duncan River.
- The watershed has been extensively logged and landslides have originated from logging roads that have deposited sediment into the channel.
- Channel straightening measures were undertaken in the late 1960s to address the sinuous nature of the channel on the alluvial fan. The natural channel width was much greater (approximately 250 m) prior to the channel straightening.
- The channel has been dredged (i.e., in channel material has been removed by equipment) several times since the channel straightening. Perdue Geotechnical Services (September 21, 2013) noted that these measures have been generally successful to reduce maintenance and channel hazards. However, the channel continues to accumulate sediment, causing the channel to widen and reduce the channel capacity.
- Water levels at the fan toe are influenced by the Duncan River, which is regulated by flows from the Duncan Dam upstream of Cooper Creek.

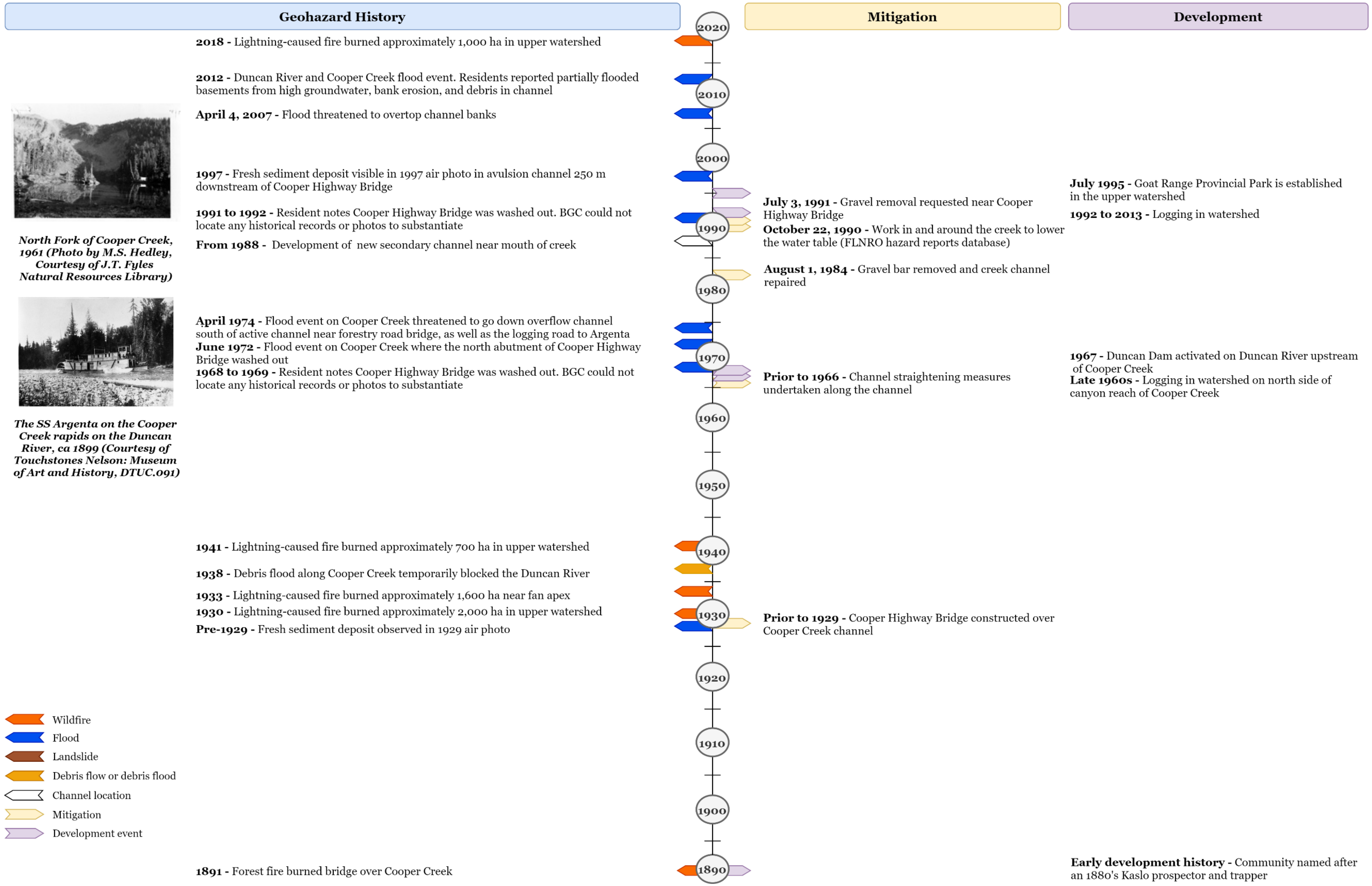


Figure 4-1. Summary of recorded geohazard, mitigation, and development history at Cooper Creek.

5. METHODS

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

In comparison to Figure 5-1, the field investigation at Cooper Creek did not include test trenching or dendrogeomorphology.

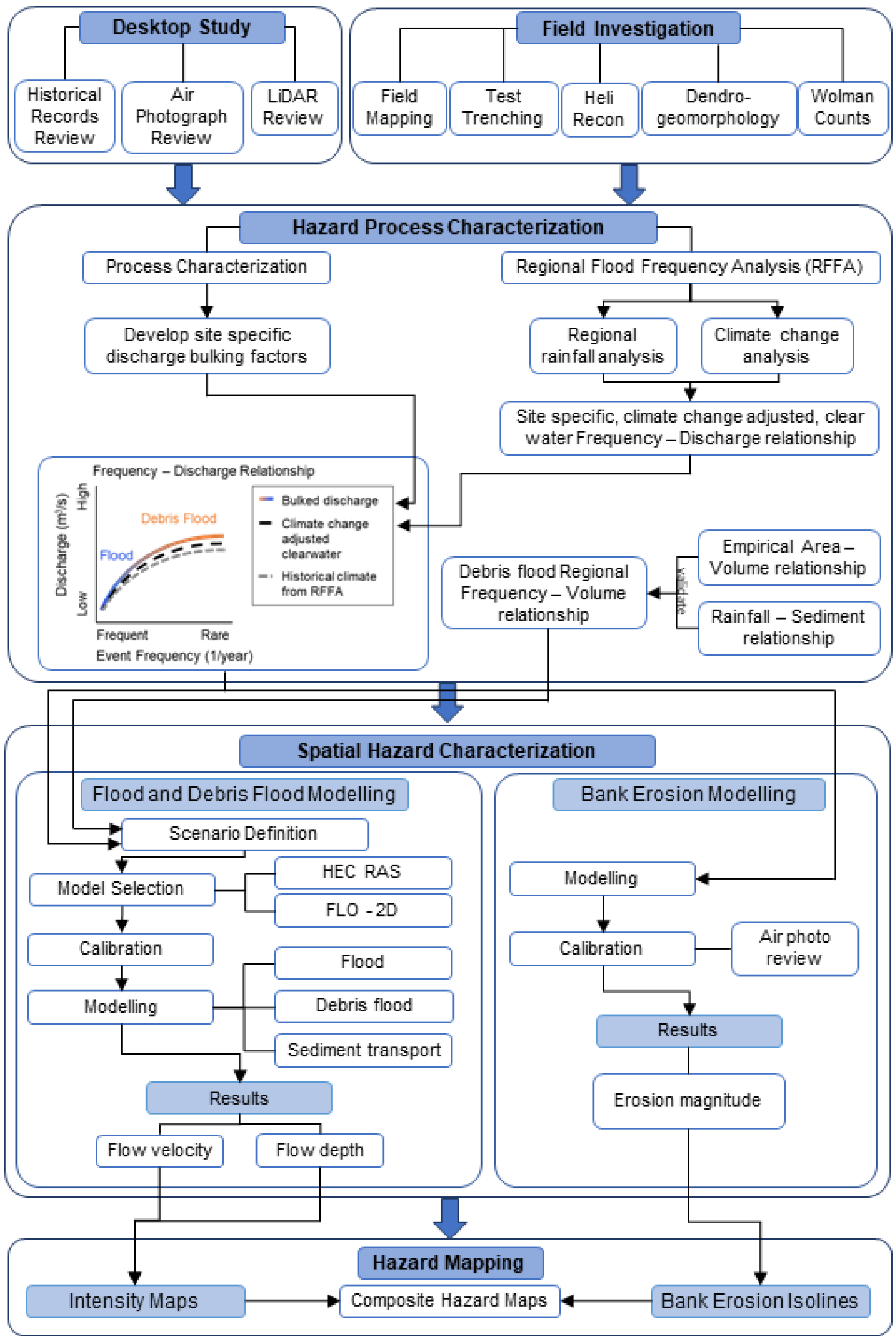


Figure 5-1. Flood and debris flood prone steep creeks workflow used for developing frequency-magnitude relationships, modelling, and preparing hazard maps.

5.1. Debris Flood Frequency Assessment – Air Photo Interpretation

At Cooper Creek, air photo interpretation was used to estimate debris-flood frequencies. Air photos dated between 1939 and 2017 were examined for evidence of past sediment transport events on Cooper 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 be captured. Air photo interpretation was supplemented by historical records of past events (Figure 4-1).

5.2. Peak Discharge Estimates

5.2.1. Clearwater Peak Discharge Estimation

There are no hydrometric stations on Cooper 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 Cooper 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., PGS, 2013). Based on its watershed characteristics, the Cooper Creek watershed was assigned to the '1 West 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 Cooper 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 (MAP, MAT, and PAS) to the Regional FFA model. The process-based methods included the trend analysis for climate-adjusted flood and precipitation data offered by the Pacific Climate Impacts Consortium (PCIC).

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

5.2.3. Sediment Concentration Adjusted Peak Discharges

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

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[5], 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 Cooper Creek for the 20-, 50-, 200-, and 500-year return periods. At these return periods, the dominant hydrogeomorphic process was identified as debris flood based on stream morphometrics and site observations (see Section 6.1). Because the debris-flood events will carry sediment and woody debris, the climate adjusted clear-water discharges need to be bulked accordingly. To produce a bulked frequency-discharge relationship, a bulking factor was applied to the peak discharge for each return period, based on sediment availability and debris-flood process type. The bulked frequency-discharge relationship was then used in numerical runout modelling.

Another measure for magnitude is sediment volume. While sediment volume is less useful as input to numerical modelling, it is helpful to verify sediment deposition predicted by the model. Therefore, a regional frequency-volume relationship was applied to compare to numerical modelling results and a well-known empirical sediment transport equation for steep creeks (Jakob et al., 2016; Jakob et al., submitted; Rickenmann, 2001). 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). Hydraulic modeling was done with HEC-RAS 2D (Version 5.0.7). 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 clear-water floods.

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

Table 5-1 summarizes the key numerical modelling inputs selected for the model. Further details on modelling methods are presented in Section 2 of the Methodology Report (BGC, March 31, 2020b).

Table 5-1. Summary of numerical modelling inputs.

Variable	HEC-RAS
Topographic Input	Lidar (2017)
Grid cells	Variable (5- 20 m)
Manning's n	0.06 (channel), 0.02 (main roads), 0.1 (fan)
Upstream boundary condition	Steady Flow (Q_{20} and Q_{50})
Downstream boundary condition	Flow rate to fill the lidar Duncan River channel

Note: The downstream boundary condition is the Duncan River at bankfull discharge. There is no return period associated with this discharge as Duncan River is a regulated watercourse.

The base topographic data used to develop a digital elevation model (DEM) for the HEC-RAS 2D model was lidar data acquired in October-November 2017. Initially, there were concerns that the lidar was collected during a period of high flow. As the lidar returns bounce off water surfaces and in the absence of a supplementary channel survey, the resultant DEM would have a reduced channel capacity. However, on review of the topographic data[6], streamflow in Cooper Creek appeared to have been low at the time of lidar acquisition.

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

Modelling results show inundation areas for various return periods and scenarios. As per the methods outlined in Section 2 of the Methodology Report (BGC, March 31, 2020b), sediment transport modelling in FLO-2D (Version 19.07.21) was applied where sediment concentrations were 10%. Sediment transport models for the 200- and 500-year events were completed; however, given the size of the watershed and peak discharges, the sediment volumes transported in the FLO-2D model were not realistic when compared with historical records for the area. For this reason, only the HEC-RAS results were relied upon for the 200- and 500-year return periods. These results assume the flood protection structures remain intact for all modelled return periods.

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

[6] This review involved drawing a number of cross-sections through the lidar DEM looking for evidence of a wide surface with a constant elevation. Such a surface would represent a wetted channel, as lidar returns bounce off rather than penetrate water. Because no significant constant elevation surface was observed on the cross-sections, it was concluded that streamflow was low at the time of lidar acquisition.

5.5. Bank Erosion Assessment

A bank erosion assessment was conducted using a physically based model calibrated to the erosion observed in historical air photos, as calculated at seven creek cross-sections between the fan apex and the mouth of the creek. 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 Drawing 02A, 02B. Refer to Appendix D for the full list of air photos consulted during the calibration process.

5.6. Hazard Mapping

BGC prepared hazard maps based on the combined results from the numerical debris flood modelling and bank erosion assessment. Specifically, BGC prepared two types of steep creek hazard maps for Cooper 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 HEC-RAS modelling.
2. Potential bank erosion extents.

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 (CPR-3a, Appendix E) 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 maps.

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

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

where v is flow velocity (m/s), ρ_f is the fluid density (kg/m^3) and d_f is the fluid's flow depth (m), to obtain a unit of force per metre flow width for the three left terms in Equation 5-1. $P(H)$ is the annual probability of the geohazard. The unit of IIF is then Newton or kilo Newton per metre per year (kN/m per yr). Equation 5-1 and the concordant mapping is new in Canada.

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

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

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

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

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

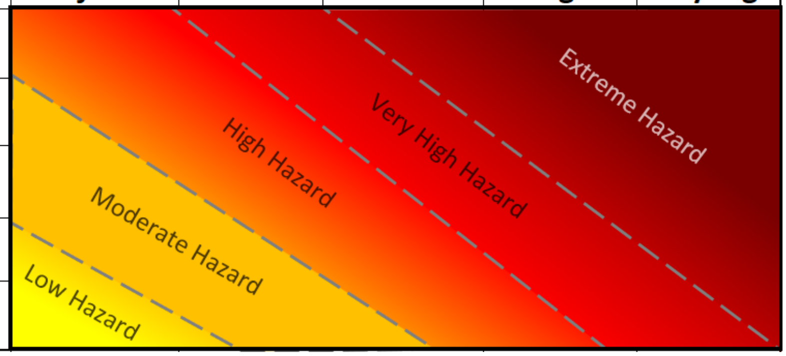


Figure 5-2. Simplified geohazard impact intensity frequency matrix.

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

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

6. RESULTS

6.1. Hydrogeomorphic Process Characterization

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

- The average channel gradient above the fan apex is 14% (Drawing 03), which is insufficient for sustained debris flow transport.
- The average fan gradient of 6% is typical of creeks prone to debris floods.
- There are multiple avulsion channels on the north and south sides of Cooper Creek (Drawings 04A, 04B, and 06).
- Accounts of previous flood events and analyses of historic air photos (see Sections 4 and 6.2) are consistent with debris-flood activity due to associated erosion and observed movement of sediment in air photos.

Together, this evidence indicates that Cooper Creek is subject to supply-unlimited Type 1 debris floods for the return periods investigated (20-, 50-, 200- and 500-year).

Using the methods outlined in Section 2 of the Methodology Report (BGC, March 31, 2020b), BGC did assess the likelihood and magnitude of Type 3 debris floods (outbreak flood to debris flood transition) that could be produced in the Cooper Creek watershed. BGC evaluated several landslide dam outbreak flood (LDOF) scenarios along the lower reaches of Cooper Creek, where it is confined by steep slopes. The findings signaled that tributary debris flows and debris avalanches at return periods considered by BGC (up to the 500-year return period) are unlikely to result in landslide dams whose failures would result in peak discharges higher than those of the same return period Type 1 debris floods. This is due to limitations in mobilizable sediment from tributary debris flows/debris avalanches and a relatively steep channel gradient, which limits the volume of water impounded by landslide dams. Large rock slides in the lower sections of Cooper Creek could result in outbreak floods in excess of the 500-year return period Type 1 debris flood, albeit at a higher return period (>500 years). This finding implies that if a development of greater than > 100 single family units or new subdivisions were proposed on the fan, the possibility of LDOFS would need to be considered (see Table D-2, p. 108, EGBC, 2018 stipulating a 1:2500-year event for the scenario).

Should there be a large stand-replacing moderate to high intensity fire in the watershed, debris floods of all types become more likely, as moderate and high severity wildfires increase the likelihood and magnitude of tributary debris flows. Due to their higher magnitude, debris flows that are a result of forest fires are substantially more likely to impound Cooper Creek or one if its tributaries and form a temporary landslide dam followed by an outbreak flood. Given the size of the Cooper Creek watershed, the debris flow would need to be sufficiently large and close to the Cooper Creek fan to result in high discharge. This potential scenario ought to be considered in the context of a detailed post-fire hazard assessment which BGC has not attempted

6.2. Debris Flood Frequency Assessment – Air Photo Interpretation

Results of the debris flood F-M assessment are presented in this section. As noted above, Cooper Creek is believed to be subject to supply-unlimited Type 1 debris floods for the 20-, 50-, 200- and 500-year return periods and Type 3 debris floods from tributary debris flows or landslides.

At least four notable hydrogeomorphic events have occurred since 1929 as identified from the air photo interpretation. Additional events in 1972 and 2012 are known from historical records (Figure 4-1) but were not delineated in the air photos. The impacts of the 1972 event are likely combined with the 1974 event in the 1976 air photo; however, since BGC cannot reliably attribute the observed channel shifting and sedimentation to one or the other event, it is catalogued as the 1974 event herein.

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 the noted events are likely Type 1 or Type 3 debris floods. Type 3 debris floods are considered possible due to the presence of logging road fill slope failures in the steep-sided valley walls upstream of the fan apex as well as natural tributary debris flows or rock falls, especially in the lower channel sections where Cooper Creek is confined. However, as noted in Section 6.1, tributary debris flows and debris avalanches are unlikely to result in landslide dams whose failures would result in peak discharges higher than those of the same return period Type 1 debris floods.

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

Event Year[1]	Air Photo Year	Deposition Area (m^2)	Estimated Event Volume (m^3)	Event Characteristics
Pre-1929	1929	101,000	76,000	Fresh deposits in channel from the fan apex to the creek outlet. Avulsions out of channel downstream of Highway 31.
1938	1939	74,100	48,000	Fresh deposits in channel from the fan apex to the creek outlet. Avulsion to the northeast downstream of highway bridge.
1974	1976	124,300	104,000	Fresh deposits in channel from fan apex to creek outlet. Channel shifting downstream of Highway 31. Channel continuing to shift since straightening.
1997	1997	-	-	Deposit in avulsion channel. Event volume too small to delineate accurately.
2007	2011	51,800	28,000	Fresh deposits in channel from the fan apex to the creek outlet. No obvious avulsions.

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

Notable flood or Type 1 or Type 3 debris floods have occurred approximately every 15 years on Cooper Creek (Table 6-2). These events have led to significant past avulsions evident in air photos from 1929 and 1974 (Drawing 04A). The channel location has remained relatively consistent since 1968. This is likely associated with channel straightening works (as noted on the 1968 air photo in Drawings 04A). The nature of the channel works and any adjacent structures built are unknown to BGC, although a berm (CPR-FP-02) was observed in the field (Section 3.5.2).

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

Event Year	Description
Pre-1929	Fresh sediment deposit visible in channel and avulsion channels in 1929 air photo.
1938	Fresh sediment deposit visible in 1939 air photo and corroborated with records of Cooper Creek blocking the Duncan River in 1938.
1972	Historical record of flooding in June 1972.
1974	Fresh sediment deposit visible in channel and avulsion channels in 1976 air photo as well as historical records of creek threatening to overflow banks.
1997	Fresh sediment visible in avulsion channel downstream of Highway 31.
2007	Fresh sediment deposit visible in channel and avulsion channels in 2011 air photo as well as reports of flooding in homes, bank erosion and debris in channel.
2012	Duncan River and Cooper Creek flood event. Residents reported partial flooding of basements, bank erosion and debris in channel.

6.3. Peak Discharge Estimates

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

- Because there are no hydrometric stations on Cooper 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).
- Type 3 debris floods that would have a peak discharge greater than a 500-year Type 1 debris flood are estimated to occur at return periods greater than that studied in this assessment.
- The climate-adjusted, sediment-bulked peak discharges were used in the numerical modelling.

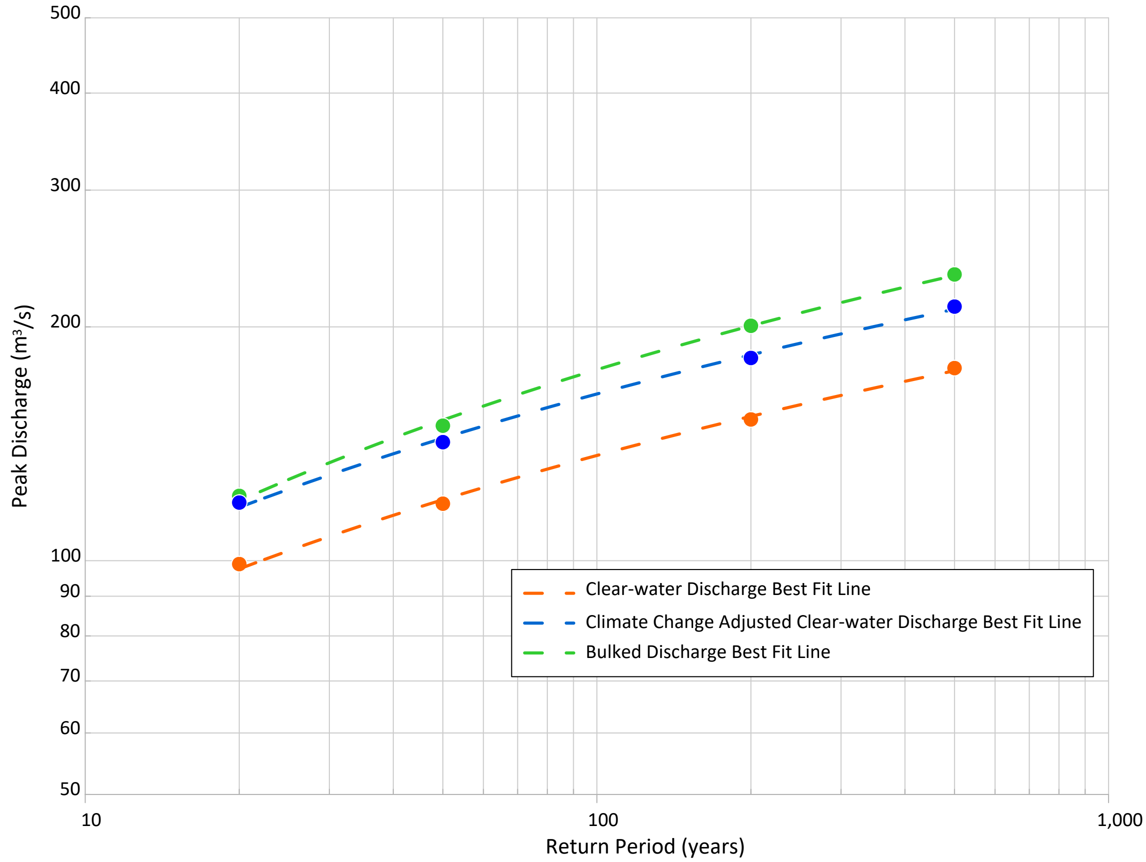


Figure 6-1. Frequency-discharge relationship for Cooper Creek.

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

Return Period (years)	AEP	Non-adjusted Peak Discharge (m^3/s)	Climate-adjusted Peak Discharge (m^3/s)	Bulking Factor	Bulked Peak Discharge (m^3/s)	Key Considerations	
						Debris Flood Type	Comments
20	0.05	99	119	1.02	120	Type 1	Few active landslide scarps and logging road failures into mainstem.
50	0.02	118	142	1.05	150	Type 1	Landslide activity increases to several, some woody debris.
200	0.005	152	182	1.1	200	Type 1	Several active landslides, ample woody debris.
500	0.002	177	212	1.1	230	Type 1	Landslide activity increases to many landslides into mainstem, extensive woody debris. Investigated the potential peak flows associated with a landslide dam outbreak flood (LDOF) on a debris flow tributary upstream and from side slope landslides. However, peak discharges estimated for the sediment bulked, climate-change adjusted peak flows were higher than the 500-year LDOF scenario, and, therefore the modelling considered the bulked, climate adjusted peak flows to be conservative.

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

6.4. Frequency-Volume Relationship

6.4.1. General

BGC used several independent approaches to create a frequency-volume relationship for Cooper Creek. These included air photo analysis of sediment deposits, an empirical sediment transport equation (Rickenmann, 2001), and application of regional relationships for fan area – sediment volume and watershed area – sediment volume (Jakob et al., 2016; Jakob et al., submitted). The different methods were compared, as described below.

Debris volume results from the air photo analysis are shown in Table 6-1 and the results of the regional relationship and empirical sediment transport equation are shown in Table 6-4. The volume estimates from the regional relationship are not credible given that they significantly overestimate event volumes that have not been replicated in the air photo record and are approximately double those obtained from the Rickenmann (2001) sediment transport analysis.

This overestimate could be attributable to the regional relationship being developed from creeks that have watershed sizes less than 100 km^2. The application of this relationship to Cooper Creek (watershed area of 244 km^2) could also be inappropriate due to the lack of data from creeks with a similar geomorphology.

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

Return Period (years)	Event Volume (m^3)	
	Regional Frequency Volume	Rickenmann (2001)
20	139,000	54,000
50	179,000	67,000
200	239,000	90,000
500	278,000	108,000

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

6.4.2. Wildfire Effects on Debris Flood Sediment Volumes

The effect of wildfires on debris flood hazards is extremely complex and cannot be solved deterministically. Regional climate change projections indicate that there will be an increase in the hourly intensity of extreme rainfall an increase in the 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. Factors to consider in assessing the impact of forest fires on hydrogeomorphic response include:

- 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 Cooper Creek watershed, especially for large moderate to high burn severity wildfires.

6.5. Numerical Debris Flood Modelling

A summary of the key observations from the debris flood modelling is included in Table 6-5. The model results are presented in Cambio Communities and a representative example is shown on Drawing 07 (CR-3a, Appendix E).

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

Table 6-5. Summary of modelling results.

Process	Key Observations
Clear-water inundation (HEC-RAS model results for all return periods)	• Along the right (south) bank upstream of Highway 31, there are avulsions which result in ponding against the highway embankment and flow heading south along the highway ditch. For return periods greater than the 20-year event, flow overtops the highway at multiple locations. • Two avulsions also occur over the left (north) bank near the top of the fan. Flow from these avulsions is contained on the upstream side of the highway for return periods of 50 years and less, and flow north, impacting several residential homes. For the 200-year event and larger, flooding overtops the highway and flows towards the Duncan River, impacting more residential homes.

Process	Key Observations
	• Downstream of the highway bridge, avulsions follow new and existing channels, largely in wooded areas, but a few residential properties on the left (south) bank would be impacted. This impact occurs during all return periods; however, the extent and intensity varies. • For the scenarios where the Highway 31 bridge has been blocked, flooding upstream of the bridge increases and flooding over the highway occurs north and south of the creek. Overland flooding south of the creek continues toward the Duncan River and overtops Duncan Lake Road from Highway 31 to the Duncan Lake Road Bridge. • While the overall hazard intensity of overbank flows is comparatively low for the return periods investigated, flooding of basements and first floors with low entry elevations could still result in substantial economic damage.
Sedimentation	• Sedimentation associated with debris floods is expected to occur in all avulsion paths and areas of ponding. • Average deposition depth across affected fan portions are likely to range between 20 and 40 cm with deposition depth approaching water depth in areas subject to ponding. • Deposition upstream of the Highway 31 crossing due to possible bridge blockages could lead to the opening of additional avulsion paths not reflected in the modeling results.
Auxiliary Hazards	• An unquantified hazard exists on the Cooper Creek fan from impacts on Hamill Creek which discharges into Duncan River across from Cooper Creek. Hamill Creek appears to be a very active debris-flood (Type 1 and 3) creek (Drawing 04). Major debris floods and the associated sediment load could push Duncan River into the opposing (west) bank, leading to potentially high bank erosion rates and damage to the former Meadow Creek Cedar sawmill at the eastern end of McLauchlin Road. • Under all modeled scenarios, water will likely pond on the upstream (western) side of Highway 31. Highway overtopping may lead to highway erosion severing the highway. • Portions of the Cooper Creek fan are likely subject to inundation should there be a breach in Duncan Dam. This was not investigated by BGC and the return period of a dam breach is assumed to be higher than 500 years; the highest return period considered in this study.

6.6. Bank Erosion Assessment

An air photo assessment was completed using air photos and satellite imagery from 1929 to 2015 to determine the historical changes in channel width at the seven cross-sections considered in the bank erosion assessment (see Drawing 02A, 02B for cross-section locations). Table 6-6 summarizes the maximum channel width change between successive pairs of air photos at the cross-section at which it was observed. Potential error or uncertainty in these measurements may be introduced by shadows from vegetation, poor image quality, or distortion during rectification. BGC estimates the total error associated with the above factors is less than 5 m.

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

Air Photo Interval	Maximum Channel Width Change Between Photos (m)	Cross-Section of Maximum Channel Width Change (Drawing 02A, 02B)
1929-1939	2	4
1939-1945	6	6
1945-1968	57	3
1968-1976	10	5
1976-1988	3	6
1988-1997	0	-
1997-2000	3	7
2000-2006	13	3
2006-2015	3	7

The maximum observed change in channel width between two successive air photos on Cooper Creek was 57 m, between 1945 and 1968 at cross-section 3. Channel widths decreased starting in the late-1960s at many cross sections due to straightening and channelization of the creek. For this reason, BGC used the period post-1960s for calibration as it is more representative of current conditions on the fan. Since 1968, the greatest observed change was 13 m at cross-section 3 between 2000 and 2006.

The air photo assessment was used to calibrate a physically based bank erosion model. BGC assumed that the maximum event magnitude during the post-channelization period (i.e., from 1968 to 2015) was a 50-year event and calibrated the model to produce erosion magnitudes similar to the observed erosion. Given that a shorter time period used for the analysis (47 years instead of the entire 86-year period of air photo record) the likelihood that a 50-year event occurred in this period is reduced, resulting in greater uncertainty in the actual event magnitude. A summary of the bank erosion model results by return period is outlined in Table 6-7. This table displays the minimum, maximum, and average erosion modelled across all cross-sections considered at each of the four return periods modelled.

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

Return Period (years)	Minimum Erosion (m)	Average Erosion (m)	Maximum Erosion (m)
20	0	3	4
50	4	8	17
200	13	17	20
500	15	22	32

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 all return periods, as the gradient is higher at cross-sections 3 and 4 (see Drawing 02A, 02B for locations) than at the remaining cross sections. The larger channel width at cross-section 4 limits the potential for erosion relative to cross-section 3. This pattern is consistent with the air photo assessment which has showed the greatest erosion at cross-section 3 in both in the pre- and post-channelization periods. The predicted erosion has the potential to impact the abutments of the Highway 31 bridge, but no properties are likely to be affected. Cross-section 7, which has a wide channel geometry and low gradient, has the lowest predicted erosion for all return periods except the 200-year event.

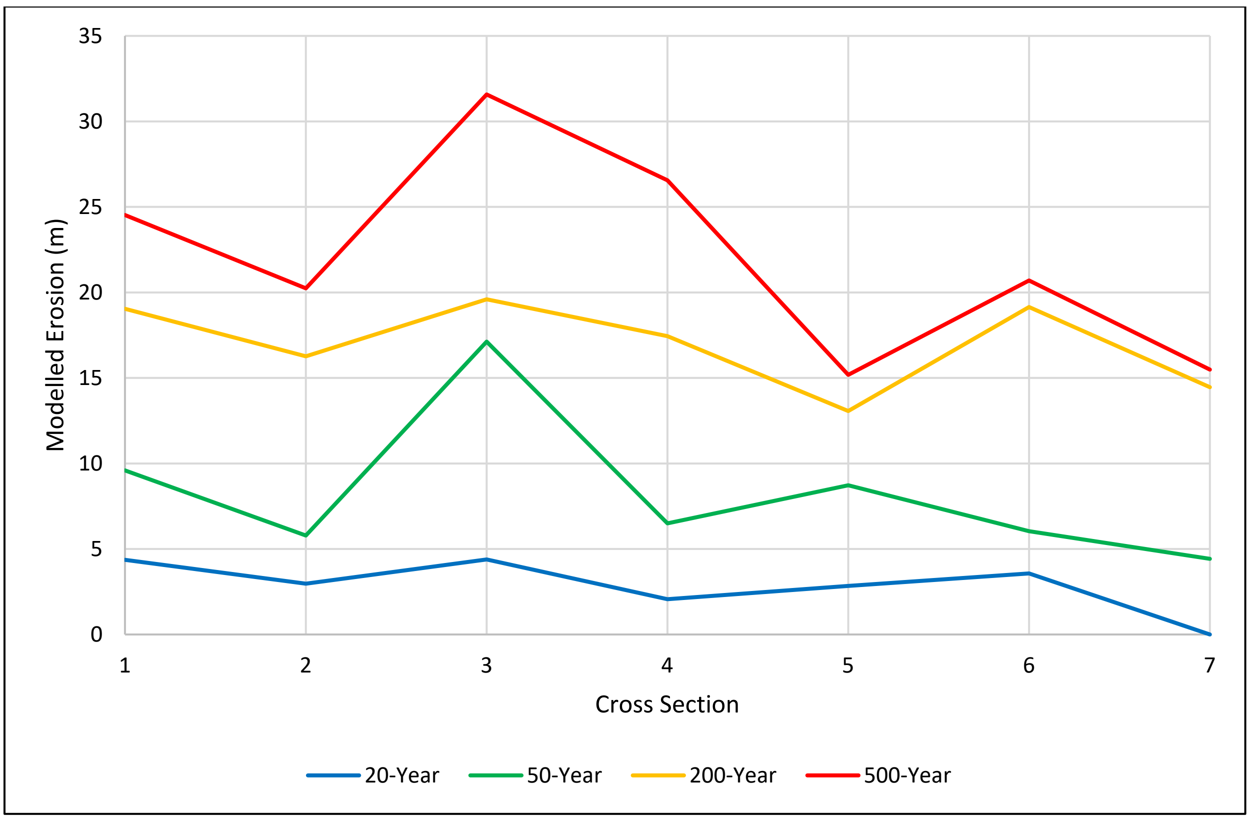


Figure 6-2. Cooper Creek 50th percentile bank erosion model results at each cross-section.

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.

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.

6.7. Hazard Mapping

Drawing 07 provides a representative model scenario map for the 200-year return period (CPR-3A, Appendix E). 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 clear-water floods to large landslides. The choice of categorization may affect interpretation by the map user and is subject to review and discussion with RDCK.

The composite hazard rating map demonstrates that significant hazards exist outside the active channel sections both upstream and downstream of the Highway 31 crossing. Given the large watershed area (240 km^2), Cooper Creek behaves more like a river than a creek and is characterized by moderate flow depth (up to 2 m upstream of the Highway 31 crossing) and flow velocities (up to 4 m/s or some 14 km/hr in narrow channel sections). These factors also result in substantial bank erosion potential on both sides of Cooper Creek. The “moderate” to “high” areas are generally confined to the active floodplain and adjacent low areas, while shallow flows spread both north and south from the main channel and specifically along Highway 31 ditches.

7. SUMMARY AND RECOMMENDATIONS

7.1. Introduction

This report provides a detailed hazard assessment of the Cooper Creek fan. Cooper 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 Cooper Creek.

A variety of analytical desktop and field-based tools and techniques were combined to decipher Cooper 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, Cooper Creek is subject to supply-unlimited Type 1 debris floods for all return periods investigated (20-, 50-, 200-, and 500-year). Type 3 debris floods are believed to be possible at the return periods investigated but at lower magnitudes than Type 1 debris floods.

7.2.2. Air Photo Interpretation

Air photo interpretation was completed to gain an understanding of watershed and channel changes on the fan and help with the construction of an F-M relationship. Highlights from this analysis include:

- Significant debris flood events occurred prior to 1929, 1938, 1972, 1974, 1997, and 2007. An additional flood event was recorded in 2012 in the historical records, but no evidence was observed in the 2017 air photo.
- The largest debris flood is interpreted to be the event in 1974, as the 1976 air photo shows an area of freshly deposited debris of approximately 124,300 m^2 corresponding with an estimated event volume of 104,000 m^3. Given that known events occurred in 1972 and 1974, this total event volume could include sediment from both the 1972 and 1974 floods.
- In the late 1960s, Cooper Creek was straightened upstream of the Highway 31 bridge. While not documented in detail, it is likely that recurring gravel removals occurred until the early 1990s.
- Past events led to avulsions as evident in air photos from 1939 and 1976 (Drawing 04A). The channel location has remained relatively consistent since 1976, which is likely associated with channel straightening in the late 1960s and dredging activities (Drawings 04A, 04B).

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 discharge was adopted as per Section 4 of the Methodology Report (BGC, March 31, 2020b).
- The climate-change adjusted peak discharges for Cooper Creek range from 119 m^3/s (20-year flood) to 213 m^3/s (500-year flood).
- Sediment bulking factors of 1.05 (5% increase for the 20-year debris flood) to 1.1 (10% increase for the 500-year debris flood) were adopted as input to numerical modelling.
- Consideration of climate change and sediment bulking increase the clearwater discharge estimate from 99 to 120 m^3/s for the 20-year debris flood, and from 177 to 230 m^3/s for the 500-year event.
- Higher peak discharges are possible for higher return period events through large landslide dam outburst floods.

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. Cooper Creek debris flood frequency-magnitude relationship.

Return Period (years)	Adjusted Peak Discharge (m^3/s)
20	120
50	150
200	200
500	230

7.2.5. Numerical Flood and Debris Flood Modelling

The hydraulic model HEC-RAS was employed to simulate the chosen hazard scenarios on the Cooper Creek fan. Table 6-5 provides key observations derived from the numerical modelling.

The numerical modelling results demonstrate that the key hazards and associated risks at Cooper 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 bank erosion model was calibrated based on the air photo analysis by comparing the predicted 50-year erosion to the maximum measured erosion in the reach from the period after channelization (1968 to 2015).
- The maximum modelled erosion ranges from 4 m in a 20-year event to 32 m in a 500-year event at cross-section 3. The maximum likely erosion also ranges from 4 m to 32 m during the 20-year to 500-year events at this location, as the floodplain is low relative to the channel and the full modeled erosion is therefore considered possible.
- Bank erosion is unlikely to affect infrastructure along Cooper Creek, except of the Highway 31 bridge (see Drawing 02A, 02B).

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 are provided on Cambio Communities and a representative example for the 200-year return period is presented on Drawing 07 (CPR-3A, Appendix E).
- 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 hazard rating 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 assessments and concordant maps, the hazard maps prepared at Cooper Creek represent a snapshot in time. Future changes to the Cooper Creek watershed or fan including the following may warrant re-assessment and/or re-modelling:

- Future fan development
- Substantial flood or debris flood events
- Development of large landslides in the watershed with the potential to impound Cooper Creek
- Bridge re-design
- Significant wildfire events in the watershed in sufficiently proximal locations to the Cooper Creek fan to affect hazards on the fan
- Major earthworks within the active portion of the fan.

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

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. This section notes Cooper Creek-specific issues that could be considered in the short term. 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 Cooper Creek fan.

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

1. Stopping organic and mineral debris near the fan apex to avoid downstream aggradation and concordant avulsions. Note that this strategy, while being effective, is very expensive and requires regular maintenance. In some cases, it may also lead to creek downcutting downstream which may or may not be a desirable consequence.
2. Most creeks on fans tend to be wide and laterally unstable. Forcing the creek in between berms flanking the creek is undesirable. Instead, setback berms that provide maximum room for the creek to shift and build up sediment is preferred.

The above options may not achieve a desirable cost-benefit ratio when compared to the asset values currently located on the fan. In the interim, the following specific mitigation measures could be considered:

- The southern and central portions (south of Cooper Creek Road) of Cooper Creek are largely undeveloped and characterized by woodlands. This portion of the fan is most prone to inundation and should not be further developed in absence of substantial mitigation works as it allows natural avulsion processes to occur in areas where it results in little harm.
- The Cooper Creek bridge on Highway 31 is a flow restriction. Modeled bank erosion lines are outside the bridge's abutments which implies that during an extreme flood, the abutments could be outflanked and the bridge isolated. BGC did not attempt to determine the bridge abutment stability.
- Enforcement of erosion-related construction setbacks from top of bank to avoid undercutting of building foundations during debris floods.

The following are site-specific mitigation considerations. These are not prioritized, and additional options may emerge during future mitigation option analyses. These considerations are conceptual only and their feasibility has not been assessed by BGC. They are coded by letters in Figure 7-1 and described in Table 7-2.

Table 7-2. Preliminary, conceptual-level, site specific mitigation options for Cooper Creek. Note that none of the options have been examined in detail.

Mitigation Option	Description
a, b, c	Deflection berms along the northern portion of upper Cooper Creek to avoid avulsions to the northern fan sector
d	Bank erosion protection for Hamill Creek-related erosion on the west side of Duncan River
e	Bank protection upstream of Highway 31 bridge abutment to avoid outflanking
f, g, h, i, j, k, l	Relief culverts beneath Highway 31 to avoid upstream ponding, overtopping and highway erosion.

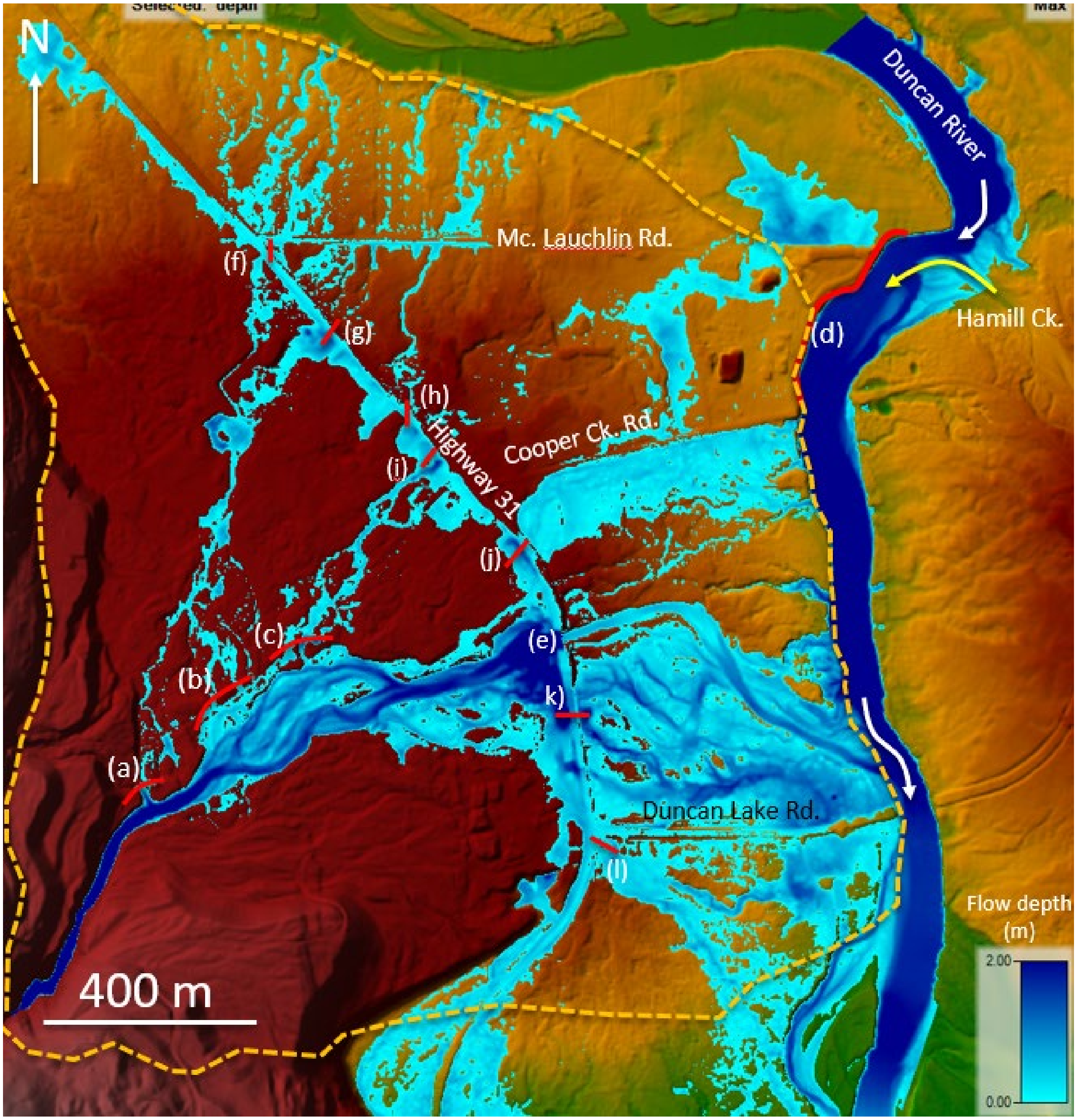


Figure 7-1. Flood inundation map showing flow depths for a 500-year return period clear-water flood on Cooper Creek and conceptual-level mitigation options for Cooper Creek fan. Note that these options have not been tested by numerical modelling and only serve as an impetus for further discussion. Other options will likely be developed at the conceptual design level.

8. CLOSURE

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

Yours sincerely,

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

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APPENDIX A
TERMINOLOGY

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

Table A-1. Geohazard terminology.

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

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

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

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

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

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

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

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

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APPENDIX B
SITE PHOTOGRAPHS

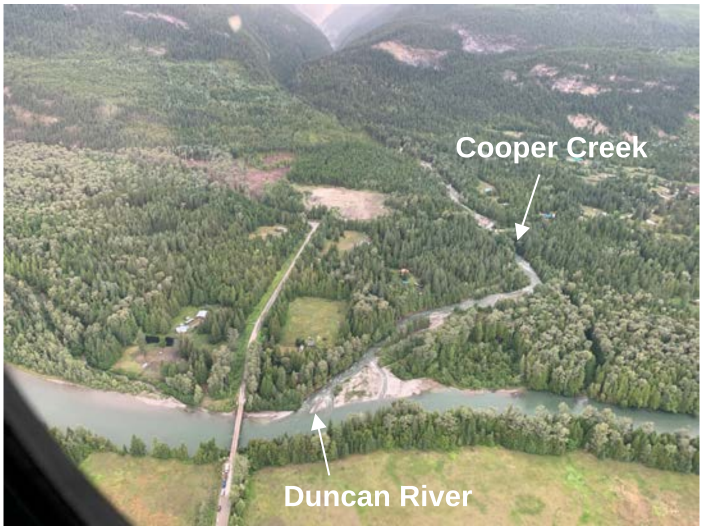


Photo 1.

Overview photo taken during helicopter overflight looking west at Cooper Creek discharging into Duncan River. Photo: BGC, July 6, 2019.

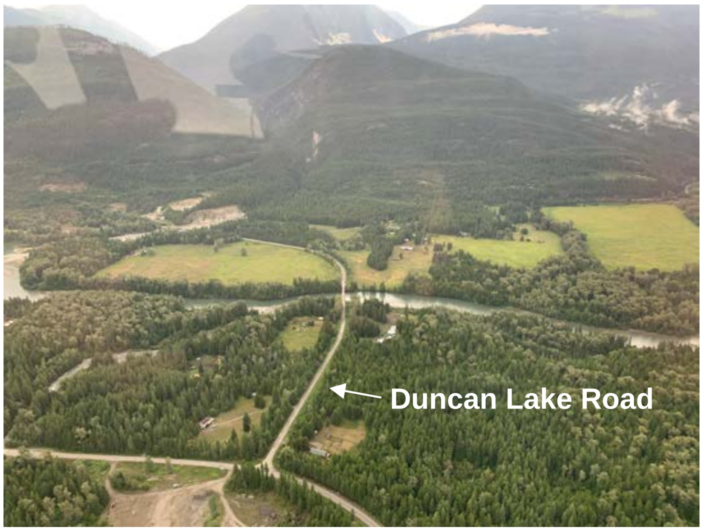


Photo 2.

Overview photo taken during helicopter overflight looking east at the Cooper Creek fan with Duncan Lake Road crossing Duncan River in mid photograph. Photo: BGC, July 6, 2019.

Photo 3.

Overview photo taken during helicopter overflight looking west at the Cooper Creek fan-delta with Highway 31 crossing Cooper Creek. Photo: BGC, July 6, 2019.

Photo 4.

Overview photo taken during helicopter overflight looking west at Cooper Creek passing the bridge at Highway 31 and discharging into Duncan River in the foreground. Photo: BGC, July 6, 2019.

Photo 5.

Overview photo taken during helicopter overflight looking down (north is up) at the lower Cooper Creek watershed, approximately 3.2 km upstream of the fan apex. Tributary channel (left) flowing into Cooper Creek (bottom right). Photo: BGC, July 6, 2019.

Photo 6.

Overview photo taken during helicopter overflight looking west at Cooper Creek incised in bedrock canyon, just upstream of fan apex. Photo: BGC, July 6, 2019.

Photo 7.

Standing on the right (south) bank bar looking upstream (flow is left to right) at Cooper Creek, approximately 150 m downstream of the fan apex. Note the bedrock exposure on the left bank across the creek. Photo: BGC, July 25, 2019.

Photo 8.

On the right (south) bank, looking upstream (west) at bank erosion along Cooper Creek approximately 250 m downstream of the fan apex. Photo: BGC, July 25, 2019.

Photo 9.

On the right (south) bank looking downstream (east) at Cooper Creek and Cooper Creek Highway bridge in the distance, approximately 300 m upstream of the bridge. Photo: BGC, July 25, 2019.

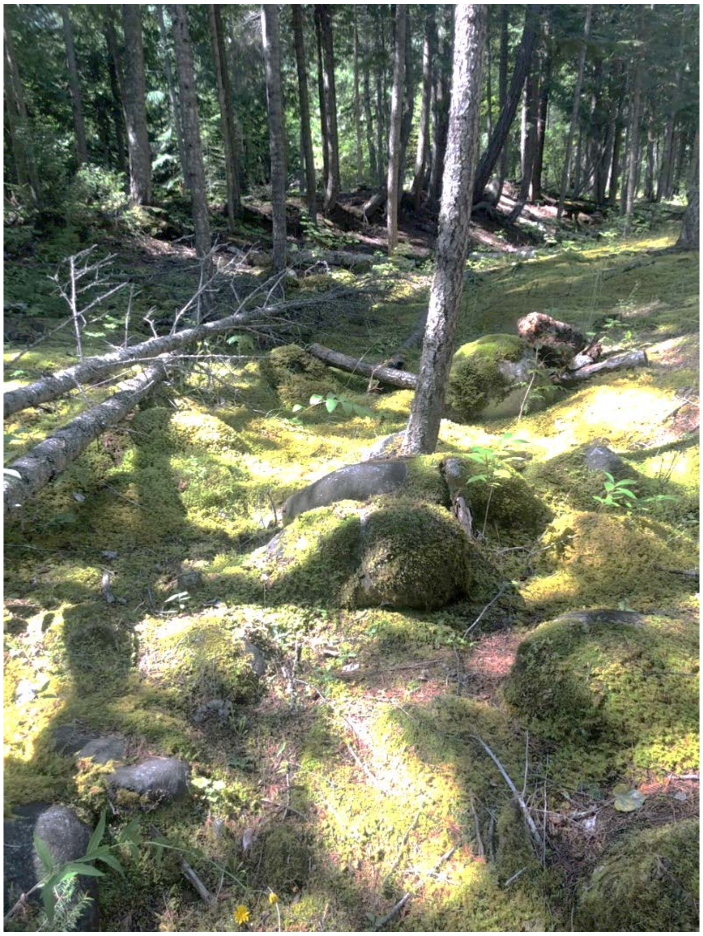


Photo 10.

South of Cooper Creek, looking at old creek avulsion channel, moss covered boulders and undercut trees on old bank, approximately 60 m south of creek, 150 m west of Highway 31. Photo: BGC, July 25, 2019.

Photo 11.

On the Highway 31 bridge looking upstream (west) at Cooper Creek. Photo: BGC, July 25, 2019.

Photo 12.

On the Highway 31 bridge looking downstream (east) at Cooper Creek. Photo: BGC, July 25, 2019.

Photo 13.

Standing on the left (north) bank of Cooper Creek looking downstream at the Highway 31 bridge. Photo: BGC, July 25, 2019.

Photo 14.

Standing immediately downstream of the Highway 31 bridge on the left (north) bank looking at the riprap. Photo: BGC, July 25, 2019.

Photo 15.

Standing on the left (north) bank of Cooper Creek looking at large woody debris blocking historical overflow channel. Sand is visible on channel bed, indicating recent flow; however, vegetation has re-established in channel. Location is approximately 150 m downstream of the Cooper Creek Highway bridge. Photo: BGC, July 25, 2019.

Photo 16.

Standing on the left (north) bank of Cooper Creek looking upstream at bank erosion, approximately 200 m downstream of the Cooper Creek Highway bridge. Photo: BGC, July 25, 2019.

Photo 17.

Standing on the left (north) bank of Cooper Creek looking upstream, approximately 250 m downstream of the Cooper Creek Highway bridge. Bridge is visible in the distance. Photo: BGC, July 25, 2019.

Photo 18.

Standing on the left (north) bank of Cooper Creek looking downstream, approximately 250 m downstream of the Cooper Creek Highway bridge. Large woody debris (LWD) pile on left (north) bank blocks deep creek path rending it currently inactive. Photo: BGC, July 25, 2019.

Photo 19.

Standing on the left (north) bank looking downstream at bank, approximately 300 m upstream of the mouth. Photo: BGC, July 25, 2019.

Photo 20.

Standing on the left bank bar looking across to right bank (flow is right to left) at bank erosion approaching fence line, approximately 300 m upstream of the mouth. Photo: BGC, July 25, 2019.

Photo 21.

Standing in dry previous creek channel to the north of Cooper Creek looking downstream, approximately 300 m upstream of the mouth. Photo: BGC, July 25, 2019.

Photo 22.

Standing on the left (north) bank of Cooper Creek looking downstream, approximately 150 m upstream of the mouth. Minor distributary channel has split around a mid channel bar. Duncan Lake Road bridge is visible in the distance. Photo: BGC, July 25, 2019.

Photo 23.

Standing on the left (north) bank of Cooper Creek looking across at the right (south) bank, at the creek mouth. Photo: BGC, July 25, 2019.

Photo 24.

Standing on the left (north) bank of Cooper Creek looking downstream at the confluence with Duncan River, at the creek mouth. Duncan Lake Road bridge is visible in the distance. Photo: BGC, July 25, 2019.

Photo 25.

Standing on the left bank of Duncan River, looking downstream at the confluence with Cooper Creek. Duncan Lake Road bridge is visible in the distance. Photo: BGC, July 25, 2019.

APPENDIX C
SEDIMENT SIZE SAMPLING

C.1. SAMPLING LOCATIONS

At Cooper Creek, two Wolman Samples were taken, one downstream of the fan apex, and one upstream of the confluence with Duncan River. The sampling locations (referred to as Cooper 1, and Cooper 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	Cooper 1	Cooper 2
Location	Downstream of fan apex	Near confluence with Duncan River
Longitude	116°58'19.14"W	116°57'12.59"W
Latitude	50°11'45.41"N	50°11'50.68"N
Number of stones measured	115	107

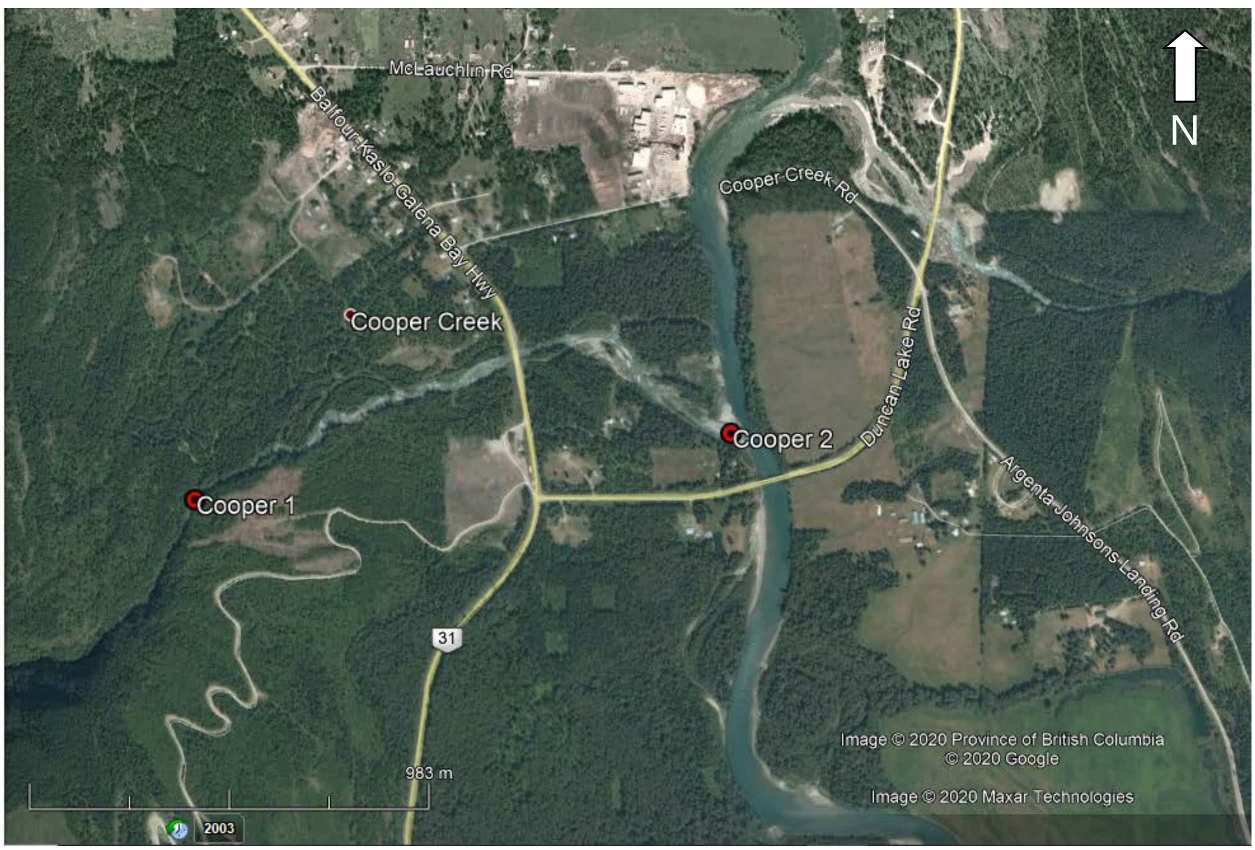


Figure C-1. Wolman sampling locations along Cooper Creek. Google Earth image of September 11, 2017.

Figure C-2. Photograph taken of Wolman sampling location Cooper 1. BGC photograph of July 25, 2019.

Figure C-3. Photograph taken of Wolman sampling location Cooper 2. BGC photograph of July 25, 2019.

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. Cooper Creek sediment distribution from Wolman Count Data.

Grain Size	Cooper 1	Cooper 2
D_{95} (mm)	178	173
D_{84} (mm)	140	126
D_{50} (mm)	47	67
D_{15} (mm)	12	26
D_5 (mm)	<2	10

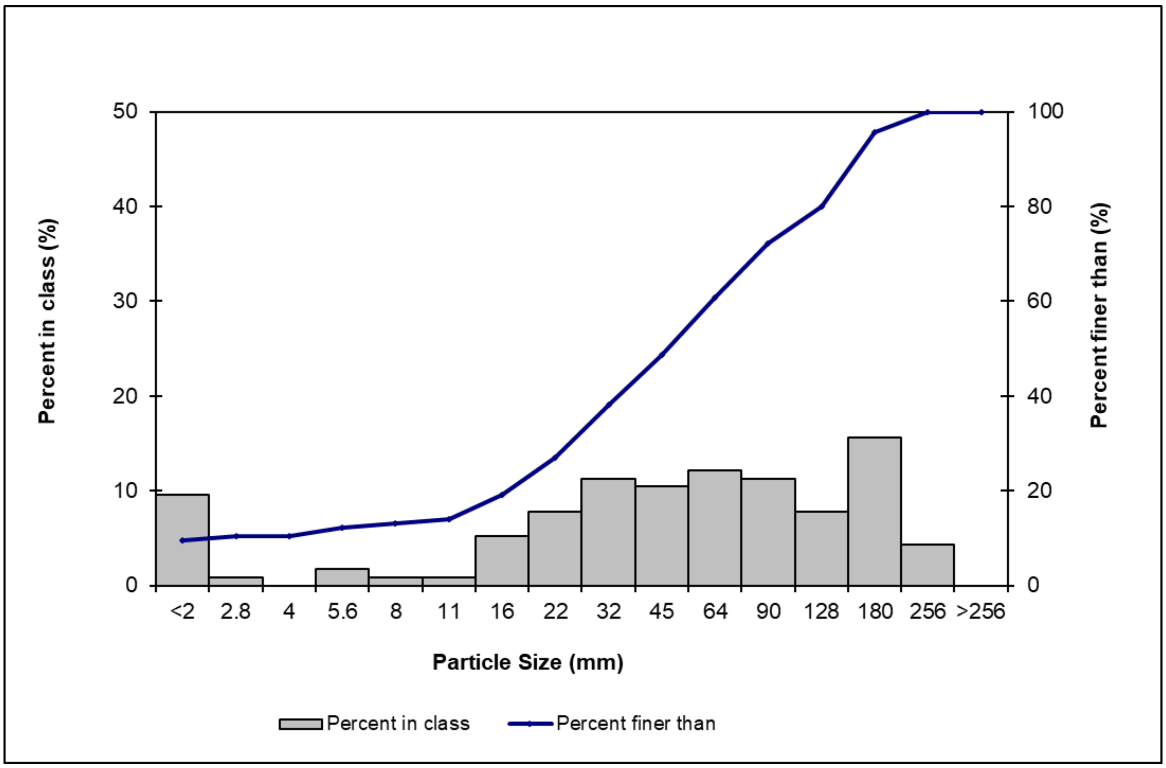


Figure C-4. Cooper Creek grain size distribution at Cooper 1 (near fan apex) from Wolman count.

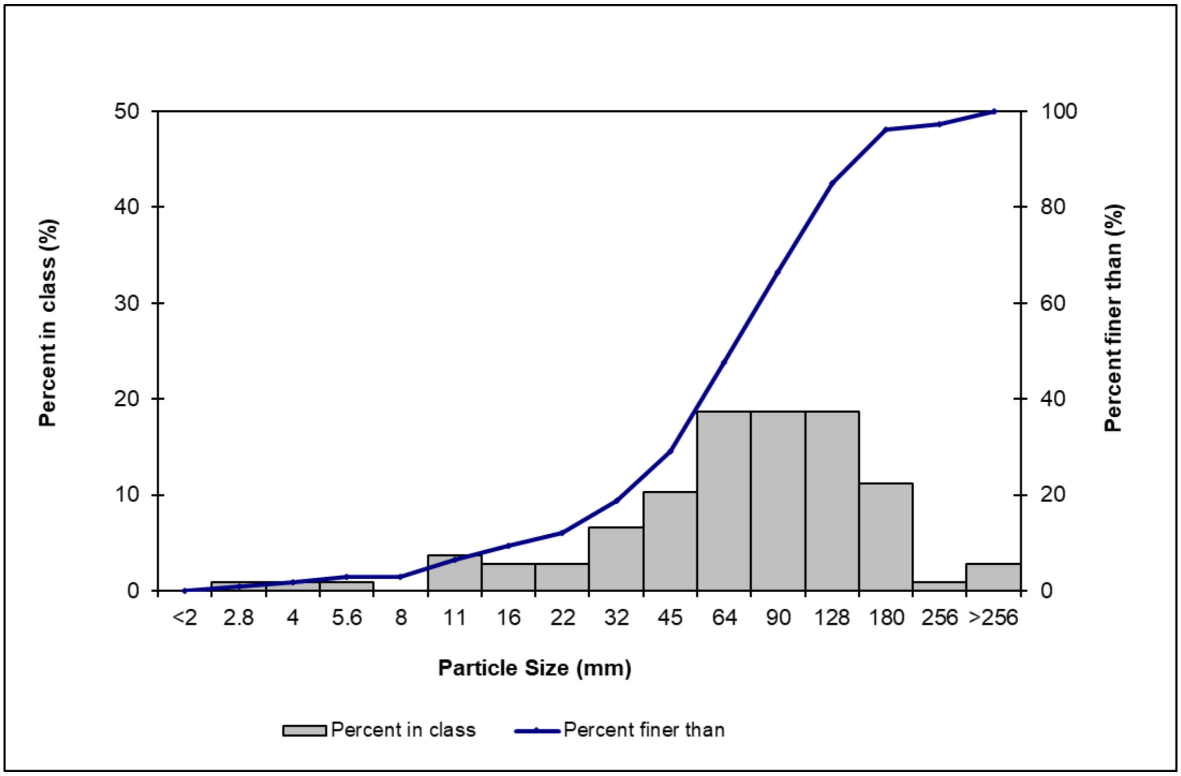


Figure C-5. Cooper Creek grain size distribution at Cooper 2 (near confluence with Duncan River) from Wolman count.

As demonstrated in Table C-2, the grain size distribution at the fan apex is similar to that at the mouth. This result is consistent with a relatively constant channel gradient across the fan.

APPENDIX D
AIR PHOTO RECORDS

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

Year	Date	Roll Number	Photo Number	Scale
2006	7/21/2006	BCC06066	218-221	20,000
1997	9/24/1997	BCB97105	115-118, 157-158, 160-161	15,000
	9/24/1997	BCB97100	231-234	15,000
1988	7/21/1988	BC88053	91-95, 129-133	15,000
1980	9/5/1980	BC80119	106-108	40,000
1976	7/16/1976	BC7856	73, 103-106	20,000
1968	9/9/1968	BC7101	18-23	16,000
	9/9/1968	BC7115	203-208	16,000
	8/31/1968	BC7117	56-59	16,000
1951	7/30/1951	BC1338	44-46, 77-79	31,680
1945	7/10/1945	A9523	75, 79	25,000
	7/10/1945	A9524	90, 93	25,000
1939	7/15/1976	BC174	55-58, 82-85	31,680
1929	4/18/1929	A1025	11-13	10,000
	4/18/1929	A1021	64-68	10,000

APPENDIX E
MODELLING SCENARIOS

E.1. MODELLING SCENARIOS

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

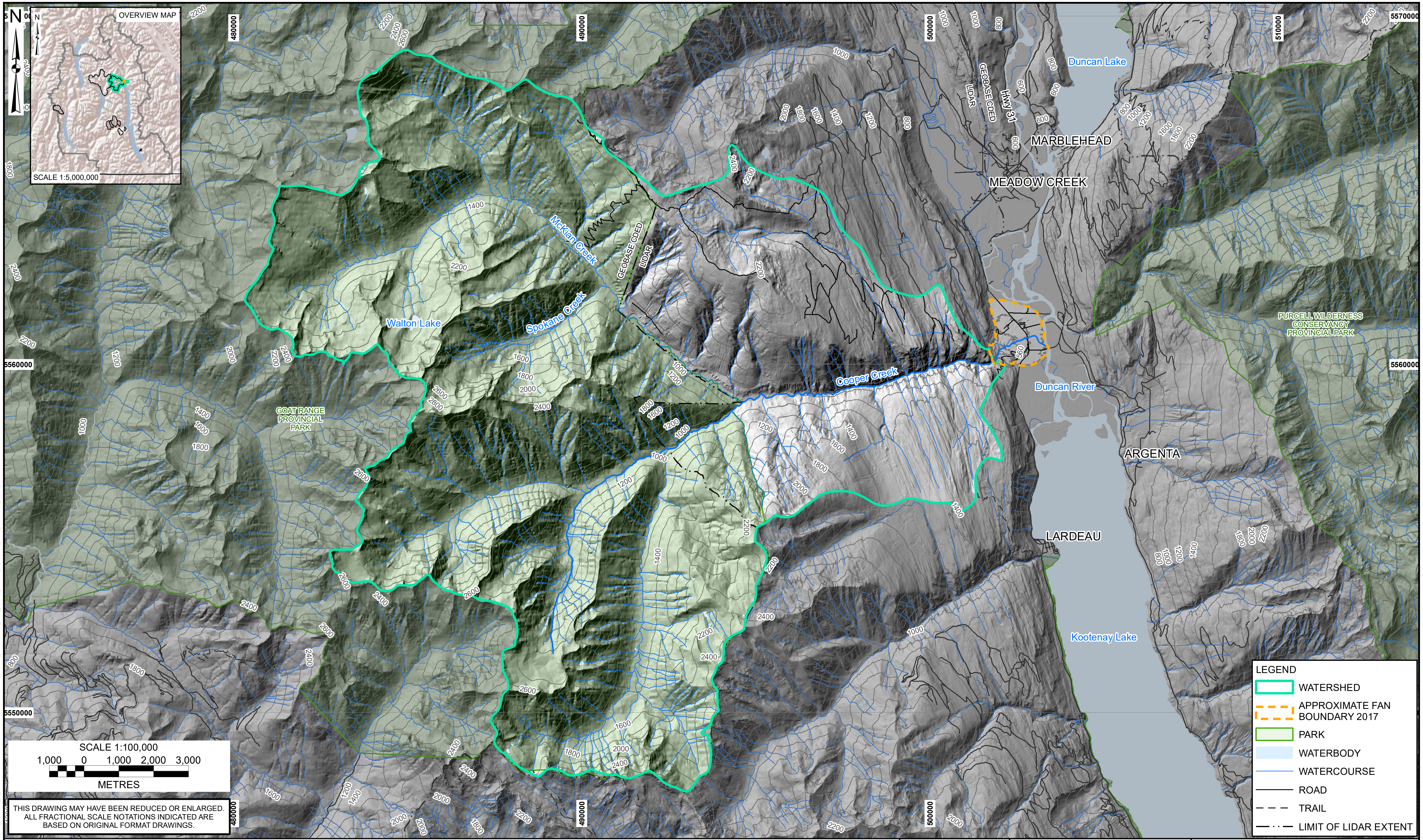
Table E-1. Modeling scenario summary for Cooper Creek.

Scenario Name	Return Period (years)	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	τ/τc ≥ 2	Assumption
CPR-1	20	Debris Flood (Type 1)	1.02	120	Cooper Highway Bridge	180	Functioning as intended	Cooper_1	Orphaned dike	N	Y	Functioning as intended
								Cooper_2	Riprap protecting left bank, downstream of bridge.	N	Y	Functioning as intended
CPR-2	50	Debris Flood (Type 1)	1.05	150	Cooper Highway Bridge	180	Functioning as intended	Cooper_1	Orphaned dike	N	Y	Functioning as intended
								Cooper_2	Riprap protecting left bank, downstream of bridge.	N	Y	Functioning as intended
CPR-3a	200	Debris Flood (Type 1)	1.1	200	Cooper Highway Bridge	180	Functioning as intended	Cooper_1	Orphaned dike	N	Y	Functioning as intended
								Cooper_2	Riprap protecting left bank, downstream of bridge.	N	Y	Functioning as intended
CPR-3b	200	Debris Flood (Type 1)	1.1	200	Cooper Highway Bridge	180	Blocked	Cooper_1	Orphaned dike	N	Y	Functioning as intended
								Cooper_2	Riprap protecting left bank, downstream of bridge.	N	Y	Functioning as intended
CPR-4	500	Debris Flood (Type 1)	1.1	230	Cooper Highway Bridge	180	Blocked	Cooper_1	Orphaned dike	N	Y	Functioning as intended
								Cooper_2	Riprap protecting left bank, downstream of bridge.	N	Y	Functioning as intended

Note:

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

DRAWINGS



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 REPORT TITLED "RDCK FLOODPLAIN AND STEEP CREEK STUDY - COOPER 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.
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. PARKS DATA FROM GOVERNMENT OF BC. ROADS DATA FROM BC DIGITAL ROAD ATLAS.
6. PROJECTION IS NAD 1983 UTM ZONE 11N.
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BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

PROJECT:
RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE:
COOPER CREEK
SITE LOCATION MAP

PROJECT No.:	DWG No:
0268007	01

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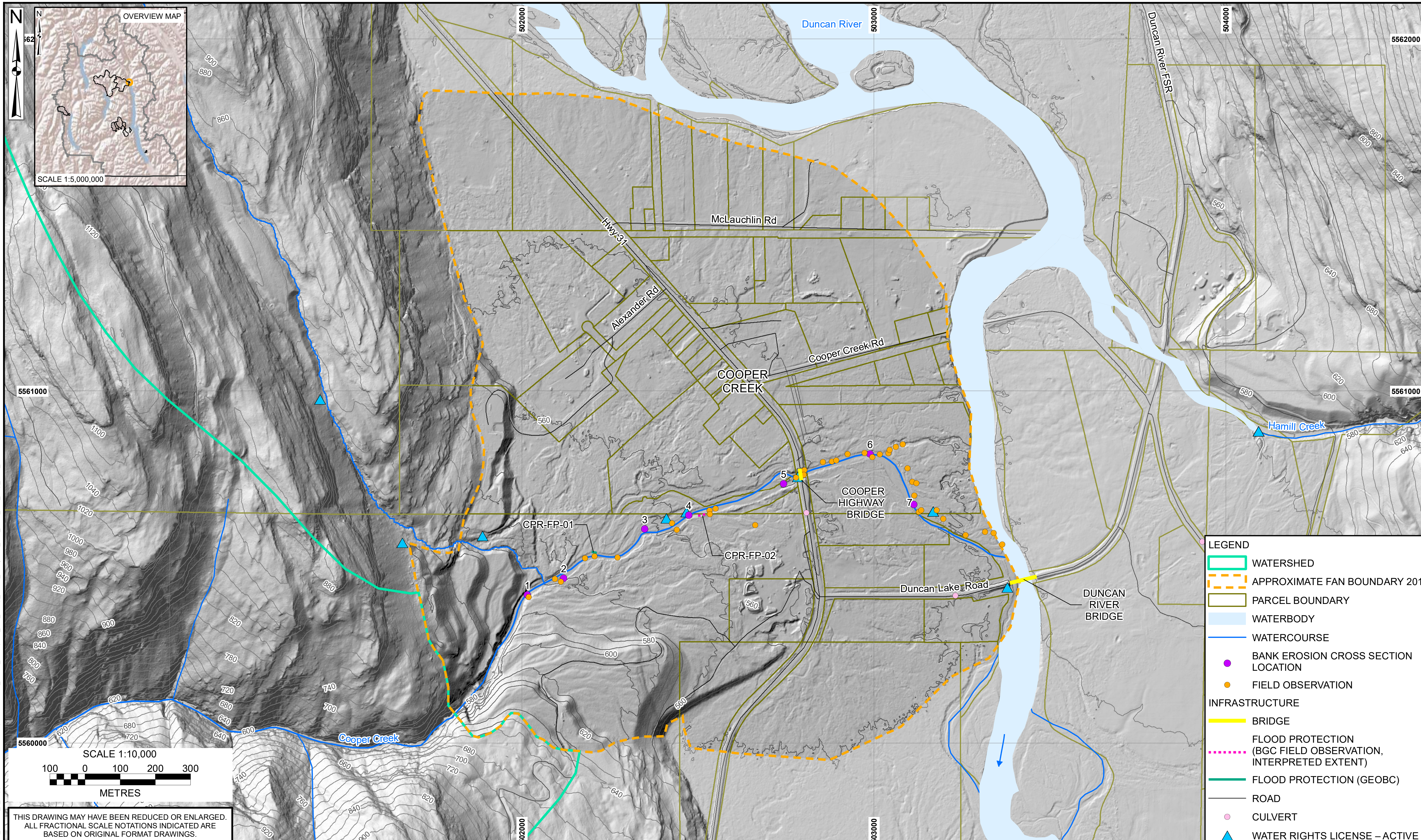

NOTES:
1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "RDCK FLOODPLAIN AND STEEP CREEK STUDY - COOPER CREEK", AND DATED MARCH 2020.
3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY RDCK, DATED 2017. CONTOUR INTERVAL IS 20 m AND 10 m ON FAN.
4. 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. BUILING FOOTPRINTS WERE NOT DIGITIZED FOR COOPER CREEK FAN. CULVERT LOCATIONS FROM BC MINISTRY OF TRANSPORTATION. ROADS DATA FROM BC DIGITAL ROAD ATLAS. FLOOD PROTECTION DATA FROM GEOBC AND BGC FIELD OBSERVATIONS (APPROXIMATE). PARCELS FROM PARCELMAP BC.
6. PROJECTION IS NAD 1983 UTM ZONE 11N.
7. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED OR USED FOR ANY PURPOSE OTHER THAN THE PURPOSE FOR WHICH BGC GENERATED IT. BGC SHALL HAVE NO LIABILITY FOR ANY DAMAGES OR LOSS ARISING IN ANY WAY FROM ANY USE OR MODIFICATION OF THIS DOCUMENT NOT AUTHORIZED BY BGC. ANY USE OF OR RELIANCE UPON THIS DOCUMENT OR ITS CONTENT BY THIRD PARTIES SHALL BE AT SUCH THIRD PARTIES' SOLE RISK.

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DATE:	MAR 2020
DRAWN:	LL
CHECKED:	JJHP
APPROVED:	MJ

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: COOPER CREEK FAN SITE MAP

PROJECT No.: 0268007

DWG No: 02A

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NOTES:
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2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "RDCK FLOODPLAIN AND STEEP CREEK STUDY - COOPER 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. IMAGERY FROM WORLD_IMAGERY_BASEMAP.
4. THE FAN BOUNDARY AS DRAWN IS APPROXIMATE AND DELINEATES THE LANDFORM BASED ON LIDAR DATED 2017. THE BOUNDARY SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DOES IT SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
5. WATER DATA FROM CANVEC, UPDATED BASED ON BGC FIELD OBSERVATIONS, WHERE APPLICABLE. BUILING FOOTPRINTS WERE NOT DIGITIZED FOR COOPER CREEK FAN. CULVERT LOCATIONS FROM BC MINISTRY OF TRANSPORTATION. ROADS DATA FROM BC DIGITAL ROAD ATLAS. FLOOD PROTECTION DATA FROM GEOBC AND BGC FIELD OBSERVATIONS (APPROXIMATE). PARCELS FROM PARCELMAP BC.
6. PROJECTION IS NAD 1983 UTM ZONE 11N.
7. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED OR USED FOR ANY PURPOSE OTHER THAN THE PURPOSE FOR WHICH BGC GENERATED IT. BGC SHALL HAVE NO LIABILITY FOR ANY DAMAGES OR LOSS ARISING IN ANY WAY FROM ANY USE OR MODIFICATION OF THIS DOCUMENT NOT AUTHORIZED BY BGC. ANY USE OF OR RELIANCE UPON THIS DOCUMENT OR ITS CONTENT BY THIRD PARTIES SHALL BE AT SUCH THIRD PARTIES' SOLE RISK.

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DATE:	MAR 2020
DRAWN:	LL
CHECKED:	JJHP
APPROVED:	MJ

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

PROJECT:	RDCK FLOODPLAIN AND STEEP CREEK STUDY
TITLE:	COOPER CREEK FAN SITE MAP
PROJECT No.: 0268007	DWG No: 02B

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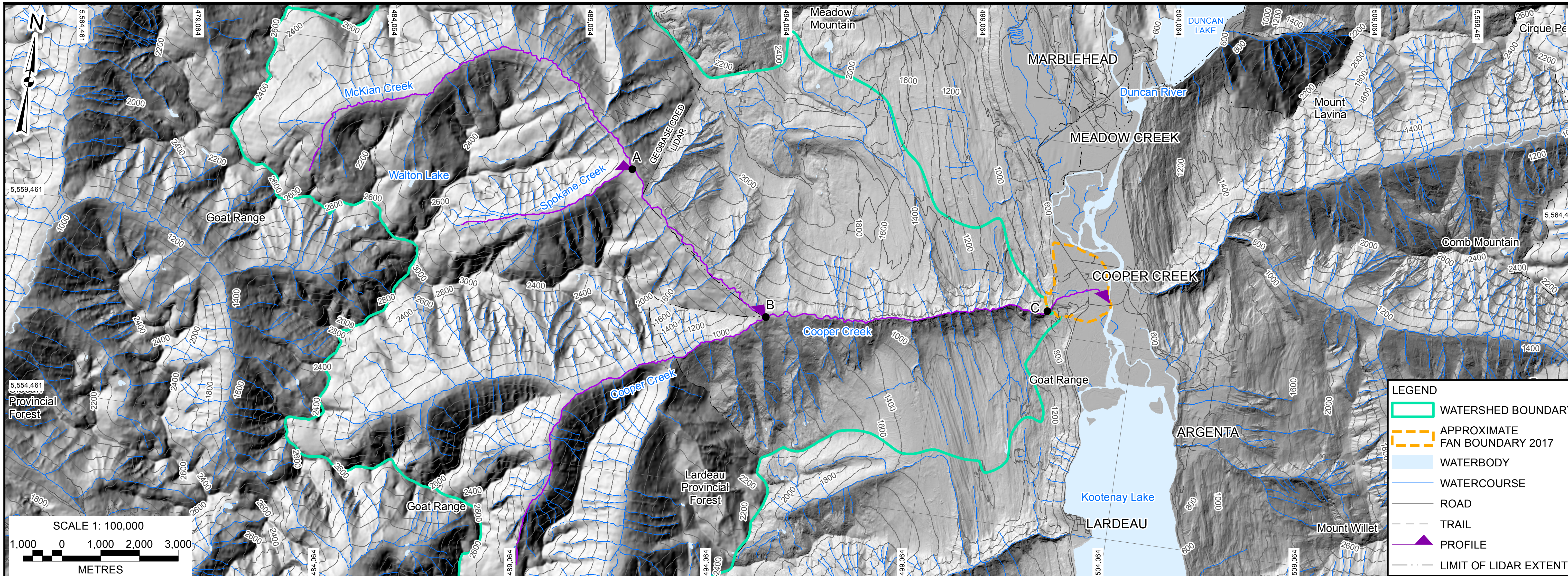

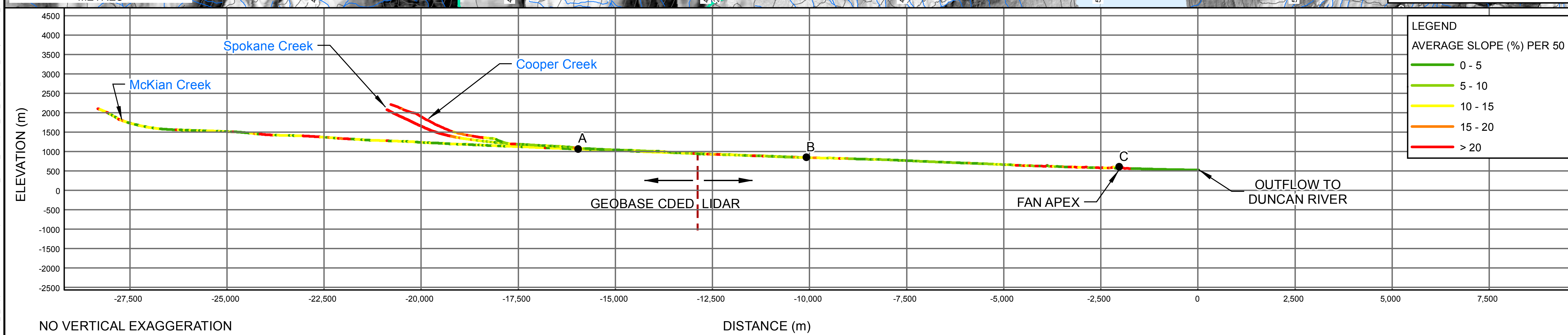

NO VERTICAL EXAGGERATION

NOTES:
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2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "RDCK FLOODPLAIN AND STEEP CREEK STUDY – COOPER CREEK", AND DATED MARCH 2020.
3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY RDCK DATED 2017. AND GEOBASE CDED. CONTOUR INTERVAL IS 100m.
4. THE WATERSHED AND FAN BOUNDARES AS DRAWN ARE APPROXIMATE AND DELINEATE THE LANDFORMS. THE BOUNDARIES SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DO THEY SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
5. WATERSHED BOUNDARIES DELINEATED FROM BGC'S RIVER NETWORK TOOLS, WATERBODIES SOURCED FROM CANVEC, WATERCOURSES SOURCED FROM BGC'S RIVER NETWORK TOOLS AND CANVEC, ROADS AND TRAILS SOURCED FROM GEOBC DIGITAL ROAD ATLAS.
6. ELEVATION PROFILE SHOWS DISTANCE RELATIVE TO THE CREEK OUTLET ON X-AXIS AND ELEVATION DERIVED FROM THE BASE TOPOGRAPHIC DATA ON Y-AXIS
7. PROJECTION IS NAD 1983 UTM ZONE 11N.
8. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED OR USED FOR ANY PURPOSE OTHER THAN THE PURPOSE FOR WHICH BGC GENERATED IT. BGC SHALL HAVE NO LIABILITY FOR ANY DAMAGES OR LOSS ARISING IN ANY WAY FROM ANY USE 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
CHECKED:	JJHP, LCH
APPROVED:	MJ

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: COOPER CREEK PROFILE

PROJECT No.: 0268007

DWG No: 03

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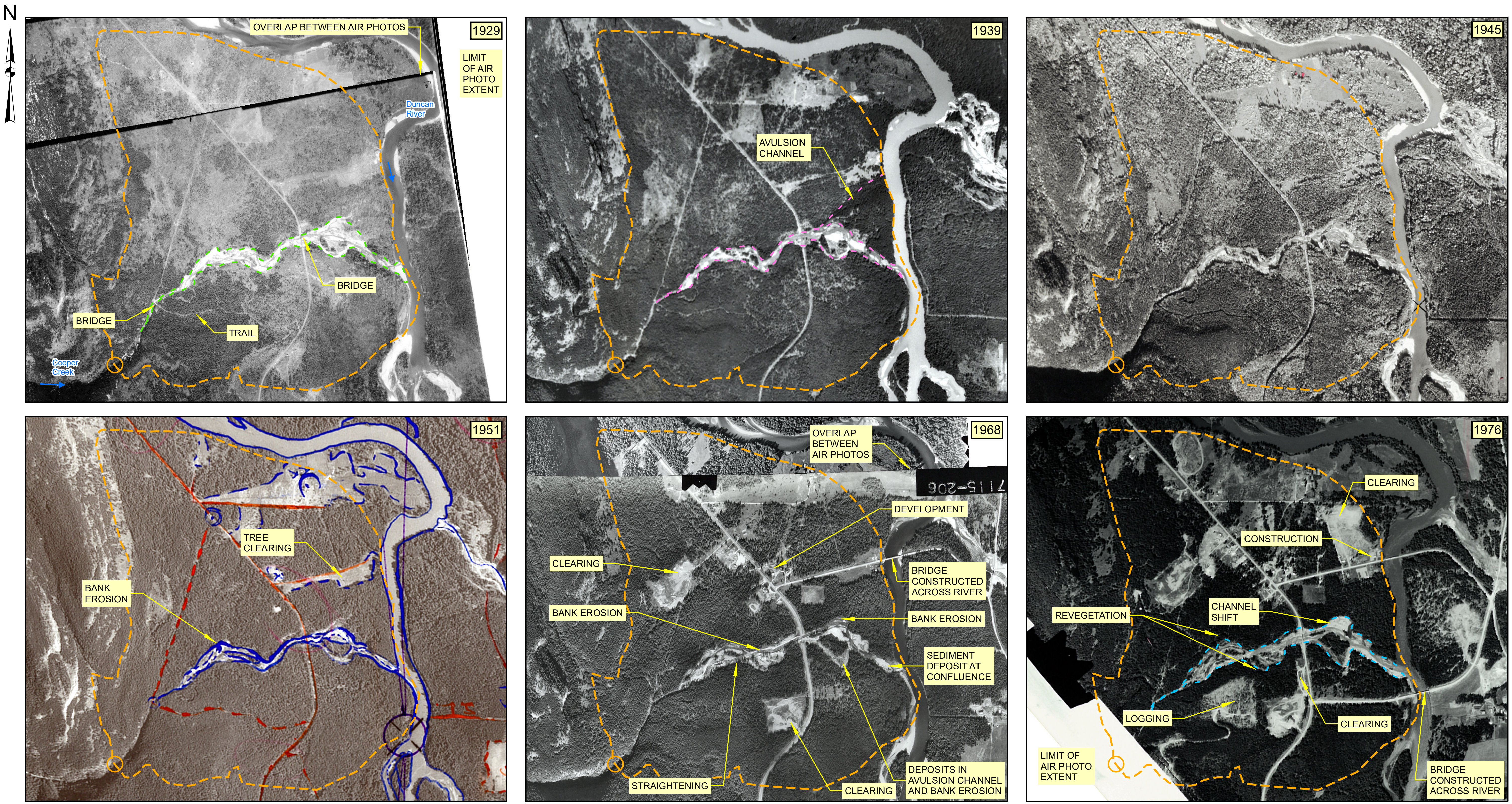

SCALE 1:20,000

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METRES

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

LEGEND

- APPROXIMATE FAN BOUNDARY 2017
- FAN APEX
- APPROXIMATE EXTENT OF PRE-1929 EVENT
- APPROXIMATE EXTENT OF 1938 EVENT
- APPROXIMATE EXTENT OF 1974 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 - COOPER CREEK", AND DATED MARCH 2020.
3. BASE TOPOGRAPHIC DATA BASED ON AIR PHOTOS PROVIDED BY BC AIR PHOTO LIBRARY AND NATIONAL AIR PHOTO LIBRARY.
4. THE FAN BOUNDARY AS DRAWN IS APPROXIMATE AND DELINEATES THE LANDFORM BASED ON LIDAR DATED 2017. THE BOUNDARY SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DOES IT SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
5. AIR PHOTO FROM YEAR 1951 WAS MARKED ON PHYSICAL COPIES PRIOR TO BGC'S AIR PHOTO INTERPRETATION.
6. BANK EROSION INDICATES DISCERNIBLE EROSION FROM PREVIOUS IMAGE. AIR PHOTOS WITH NO LABELS INDICATE NO MAJOR DEVELOPMENT OR CHANGE IN CHANNEL FEATURES COMPARED TO PREVIOUS AIR PHOTO.
7. COORDINATE SYSTEM IS UTM ZONE 11 NAD 1983. VERTICAL DATUM IS UNKNOWN.
8. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED OR USED FOR ANY PURPOSE OTHER THAN THE PURPOSE FOR WHICH BGC GENERATED IT. BGC SHALL HAVE NO LIABILITY FOR ANY DAMAGES OR LOSS ARISING IN ANY WAY FROM ANY USE OR MODIFICATION OF THIS DOCUMENT NOT AUTHORIZED BY BGC. ANY USE OF OR RELIANCE UPON THIS DOCUMENT OR ITS CONTENT BY THIRD PARTIES SHALL BE AT SUCH THIRD PARTIES' SOLE RISK.

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

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

PROJECT:	RDCK FLOODPLAIN AND STEEP CREEK STUDY
TITLE:	COOPER CREEK AIR PHOTO COMPARISON
PROJECT No.: 0268007	DWG No: 04A

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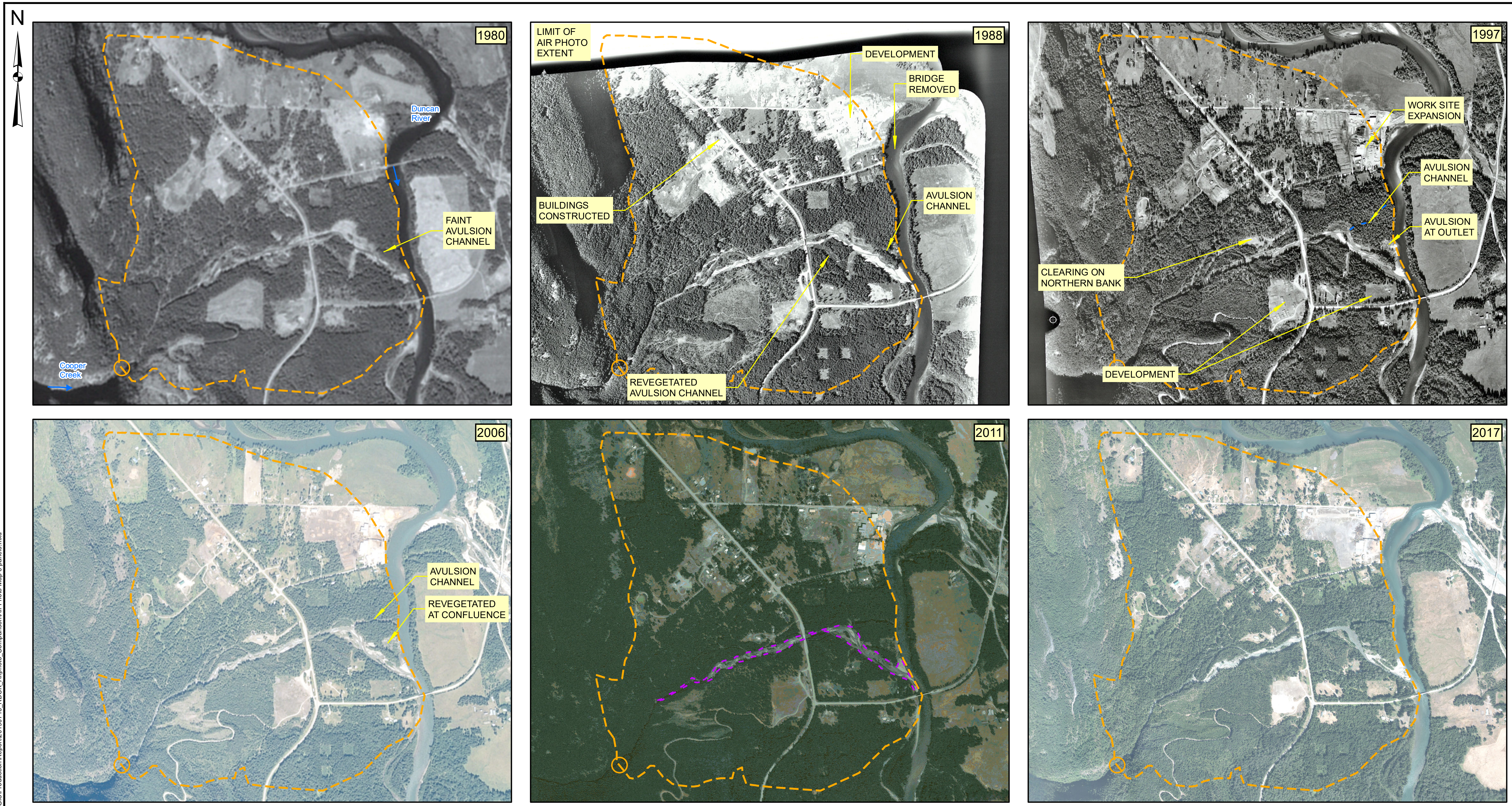

SCALE 1:20,000

200 0 200 400 600

METRES

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LEGEND

- APPROXIMATE FAN BOUNDARY 2017
- FAN APEX
- APPROXIMATE EXTENT OF 1997 EVENT
- APPROXIMATE EXTENT OF 2007 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 - COOPER CREEK", AND DATED MARCH 2020.
3. BASE TOPOGRAPHIC DATA BASED ON AIR PHOTOS PROVIDED BY BC AIR PHOTO LIBRARY AND NATIONAL AIR PHOTO LIBRARY.
4. THE FAN BOUNDARY AS DRAWN IS APPROXIMATE AND DELINEATES THE LANDFORM BASED ON LIDAR DATED 2017. THE BOUNDARY SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DOES IT SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
5. AIR PHOTOS WITH NO LABELS INDICATE NO MAJOR DEVELOPMENT OR CHANGE IN CHANNEL FEATURES COMPARED TO PREVIOUS AIR PHOTO.
6. COORDINATE SYSTEM IS UTM ZONE 11 NAD 1983. VERTICAL DATUM IS UNKNOWN.
7. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED OR USED FOR ANY PURPOSE OTHER THAN THE PURPOSE FOR WHICH BGC GENERATED IT. BGC SHALL HAVE NO LIABILITY FOR ANY DAMAGES OR LOSS ARISING IN ANY WAY FROM ANY USE OR MODIFICATION OF THIS DOCUMENT NOT AUTHORIZED BY BGC. ANY USE OF OR RELIANCE UPON THIS DOCUMENT OR ITS CONTENT BY THIRD PARTIES SHALL BE AT SUCH THIRD PARTIES' SOLE RISK.

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DRAWN:	MIB, LL
CHECKED:	JJHP, LCH
APPROVED:	MJ

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: COOPER CREEK AIR PHOTO COMPARISON

PROJECT No.: 0268007

DWG No: 04B

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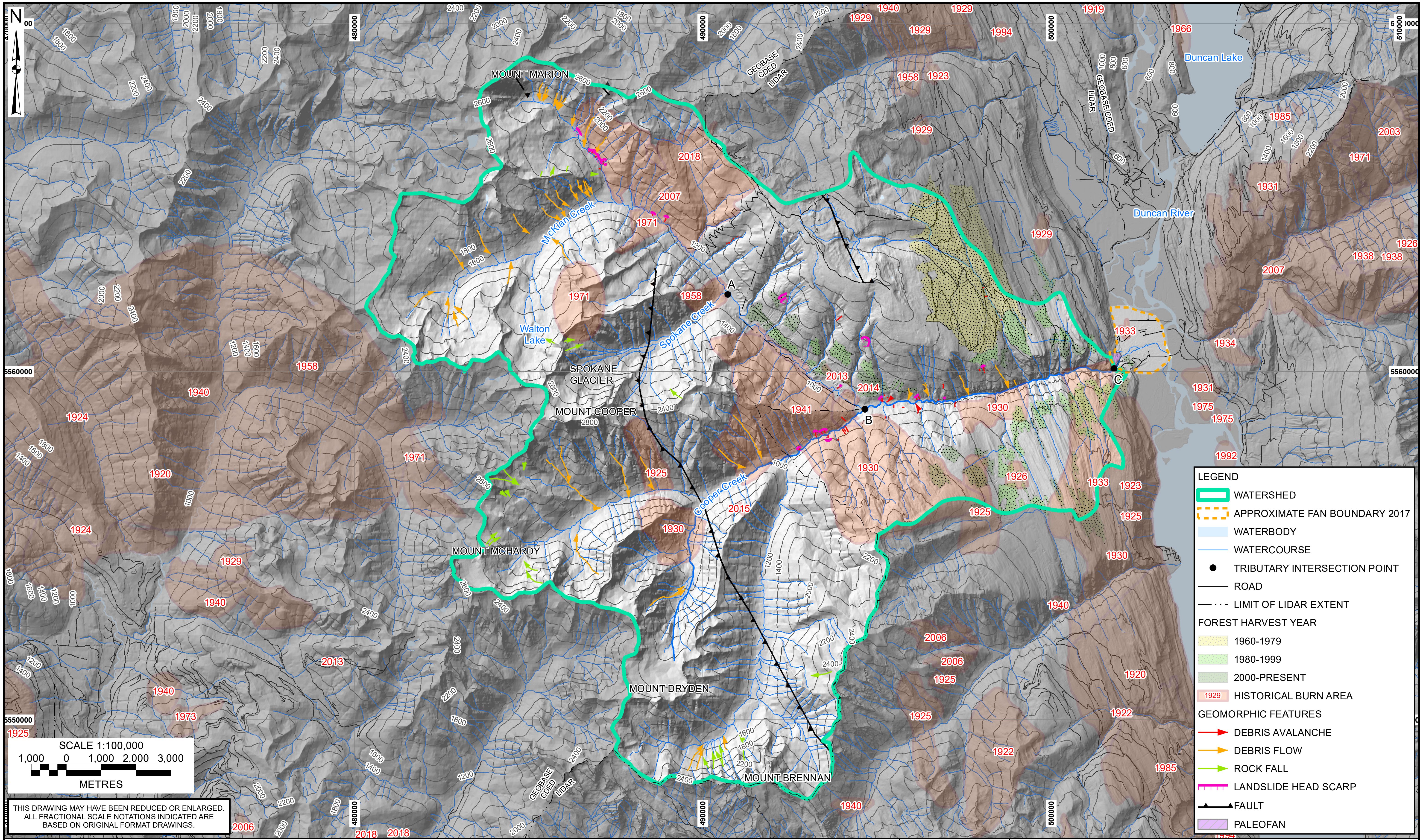

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3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY RDCK DATED 2017, AND GEOBASE CDED. CONTOUR INTERVAL IS 200m.
4. THE WATERSHED AND FAN BOUNDARY AS DRAWN ARE APPROXIMATE AND DELINEATE THE LANDFORMS BASED ON LIDAR DATED 2017. THE BOUNDARIES SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DO THEY SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
5. HISTORICAL CUT BLOCK DATA ONLY REPRESENTATIVE OF AREAS THAT INTERSECT WATERSHED BOUNDARY. FAULTS CLIPPED TO WATERSHED BOUNDARY, AND SOURCED FROM BC DIGITAL GEOLOGY.
6. ROADS DATA FROM BC DIGITAL ROADS ATLAS.
7. PROJECTION IS NAD 1983 UTM ZONE 11N.
8. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED OR USED FOR ANY PURPOSE OTHER THAN THE PURPOSE FOR WHICH BGC GENERATED IT. BGC SHALL HAVE NO LIABILITY FOR ANY DAMAGES OR LOSS ARISING IN ANY WAY FROM ANY USE OR MODIFICATION OF THIS DOCUMENT NOT AUTHORIZED BY BGC. ANY USE OF OR RELIANCE UPON THIS DOCUMENT OR ITS CONTENT BY THIRD PARTIES SHALL BE AT SUCH THIRD PARTIES' SOLE RISK.

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DATE:	MAR 2020
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APPROVED:	HW

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: COOPER CREEK WATERSHED GEOMORPHOLOGY

PROJECT No.: 0268007

DWG No.: 05

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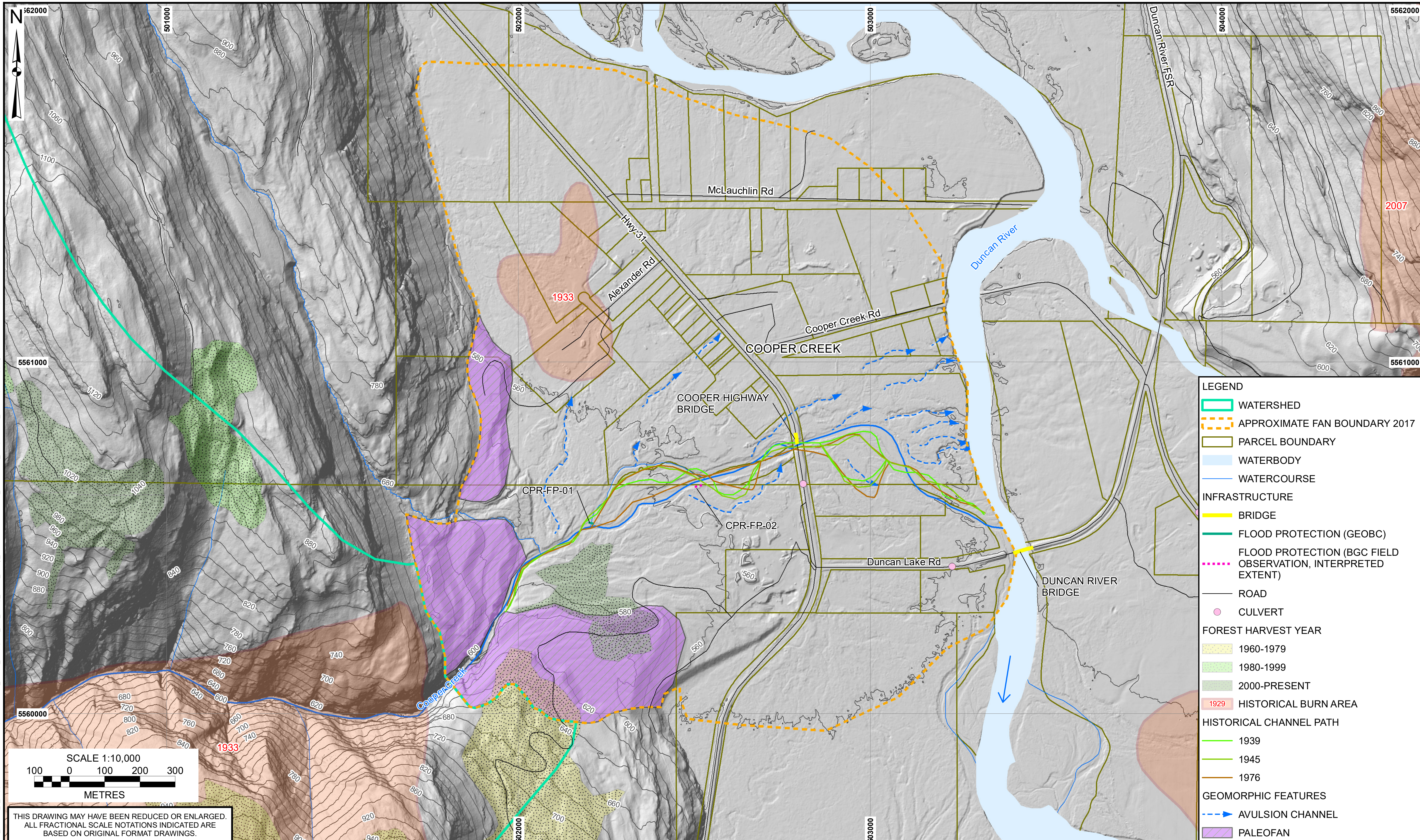

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3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY RDCK DATED 2017, AND GEOBASE CDED. CONTOUR INTERVAL IS 10m.
4. THE WATERSHED AND FAN BOUNDARY AS DRAWN ARE APPROXIMATE AND DELINEATE THE LANDFORMS BASED ON LIDAR DATED 2017. THE BOUNDARIES SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DO THEY SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
5. BUILDING FOOTPRINTS WERE NOT DIGITIZED FOR COOPER CREEK FAN. CULVERT LOCATIONS FROM BC MINISTRY OF TRANSPORTATION. ROADS DATA FROM BC DIGITAL ROAD ATLAS. PARCELS FROM PARCELMAP BC. BANK PROTECTION DATA FROM GEOBC AND BGC FIELD OBSERVATIONS.
6. PROJECTION IS NAD 1983 UTM ZONE 11N.
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APPROVED:	HW

BGC ENGINEERING INC.
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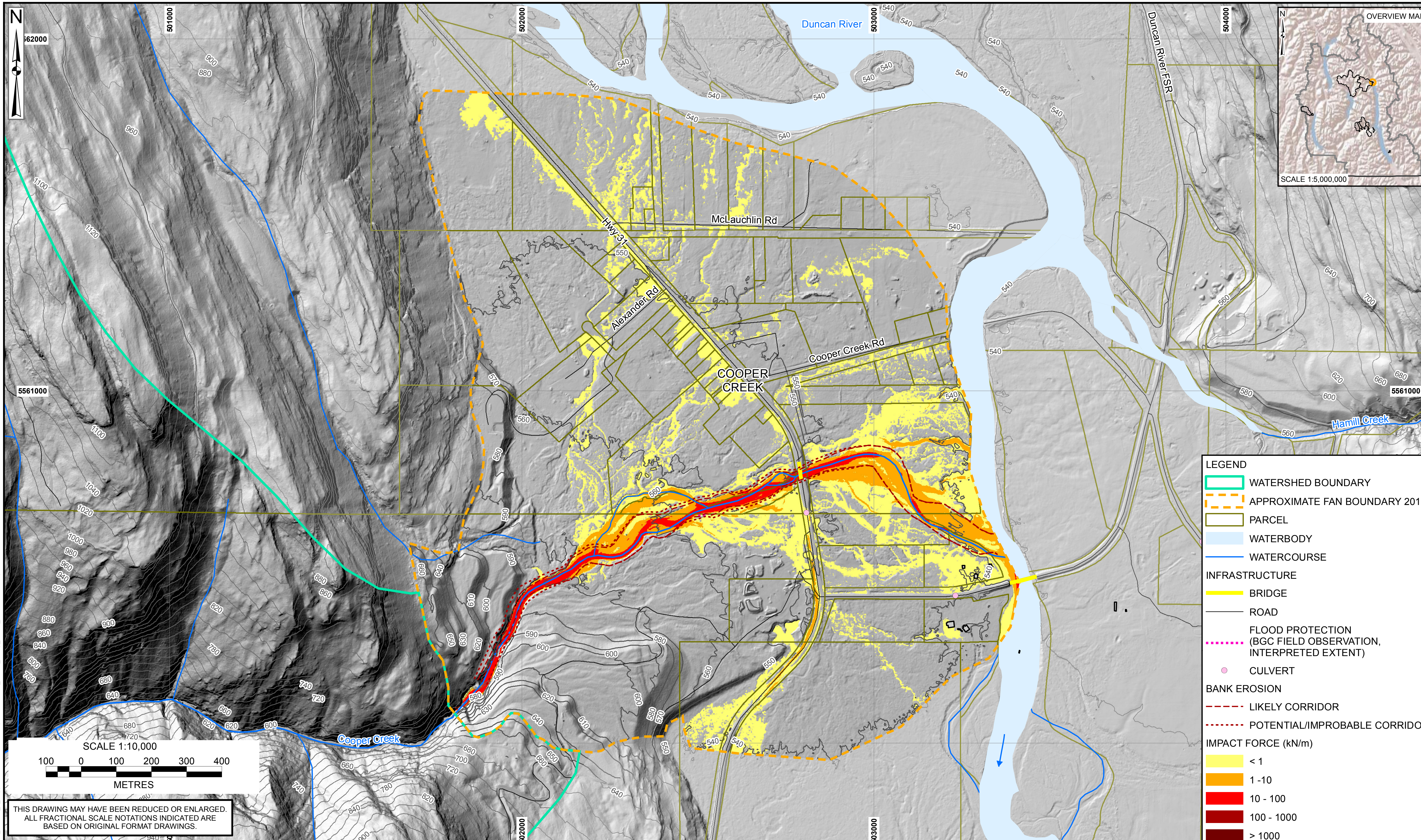
CLIENT:

PROJECT:
RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE:
COOPER CREEK
FAN GEOMORPHOLOGY

PROJECT No.:	DWG No:
0268007	06



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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. 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. ROADS DATA FROM BC DIGITAL ROAD ATLAS. FLOOD PROTECTION FROM GEOBC AND BGC FIELD OBSERVATIONS. PARCEL MAP FROM PARCELMAP BC.
6. SCENARIO MAP SHOWS CLEARWATER IMPACT FORCE BASED ON HEC-RAS MODEL RESULTS FOR THE 200-YEAR RETURN PERIOD COMPLETED BY BGC. THIS IS A REPRESENTATIVE MAP AND DOES NOT SHOW THE FULL SUITE OF MODELLED SCENARIOS. SCENARIO DETAILS ARE OUTLINED IN BGC REPORT.
7. THIS MAP REPRESENTS A SNAPSHOT IN TIME. FUTURE CHANGES (DEVELOPMENT, DEBRIS FLOOD MITIGATION, GEOHAZARD EVENTS) MAY WARRANT RE-DRAWING OF CERTAIN AREAS.
8. PROJECTION IS NAD 1983 UTM ZONE 11N. VERTICAL DATUM IS UNKNOWN.
9. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED OR USED FOR ANY PURPOSE OTHER THAN THE PURPOSE FOR WHICH BGC GENERATED IT. BGC SHALL HAVE NO LIABILITY FOR ANY DAMAGES OR LOSS ARISING IN ANY WAY FROM ANY USE OR MODIFICATION OF THIS DOCUMENT NOT AUTHORIZED BY BGC. ANY USE OF OR RELIANCE UPON THIS DOCUMENT OR ITS CONTENT BY THIRD PARTIES SHALL BE AT SUCH THIRD PARTIES' SOLE RISK.

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SCALE:	1:10,000
DATE:	MAR 2020
DRAWN:	STT, LL, MIB
CHECKED:	LCH
APPROVED:	MJ

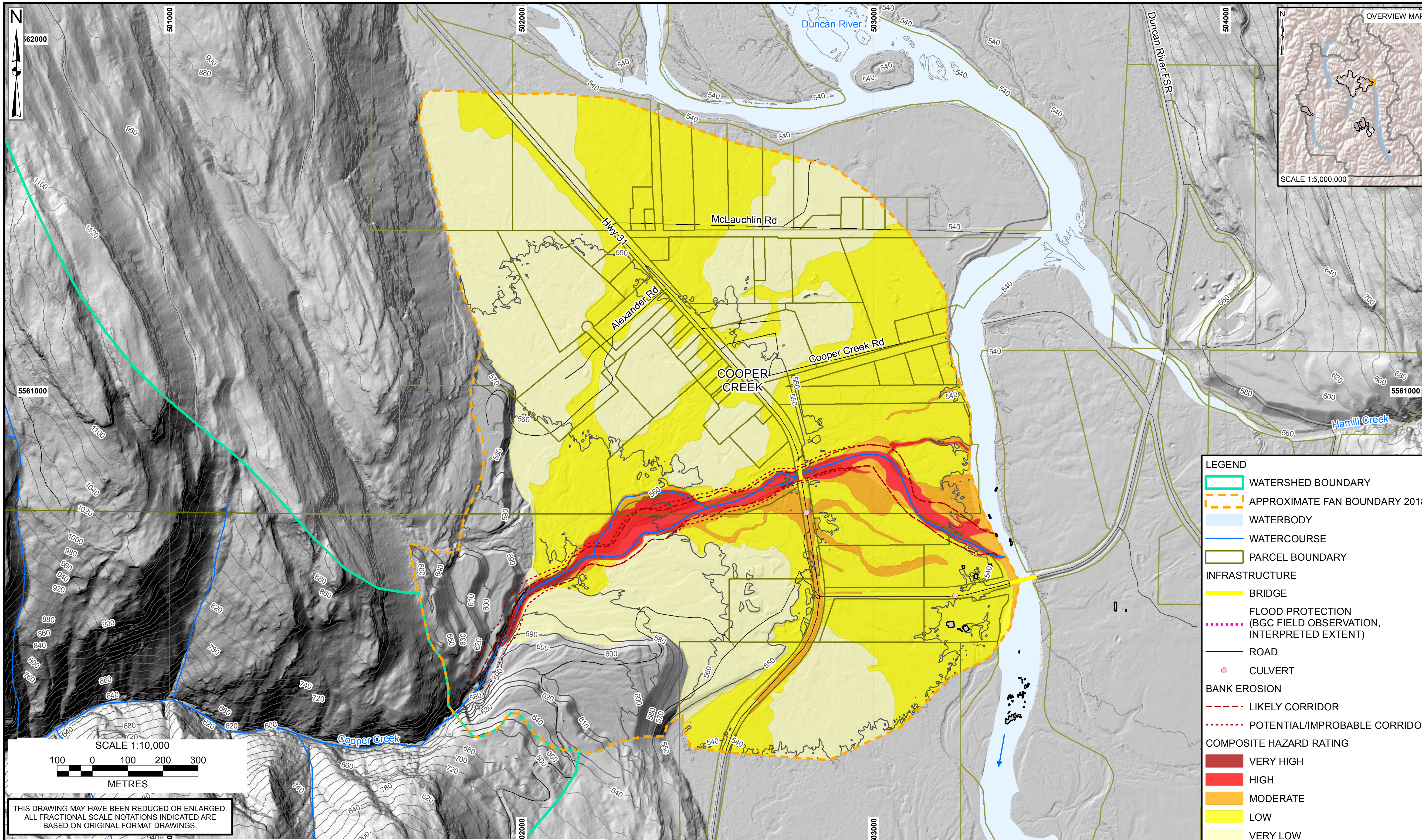
BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: COOPER CREEK 200 YEAR MODEL SCENARIO CPR-3a

PROJECT No.:	DWG No:
0268007	07



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

PROJECT No.:	DWG No:
0268007	08