## RDCK FLOODPLAIN AND STEEP CREEK STUDY

# Redfish Creek

**Final**
**March 31, 2020**

BGC Project No.:
**0268007**

BGC Document No.:
**RDCK2-SC-003F**

Prepared by BGC Engineering Inc. for:
**Regional District of Central Kootenay**

BGC ENGINEERING INC. 500-980 Howe Street, Vancouver, BC Canada V6Z 0C8
Tel: 604.684.5900 Fax: 604.684.5909

## TABLE OF REVISIONS

| ISSUE | DATE | REV | REMARKS |
|---|---|---|---|
| DRAFT | February 27, 2020 | | Original issue (Drawings 07 and 08 not included) |
| FINAL | March 31, 2020 | | Final issue |
| | | | |
| | | | |
| | | | |
| | | | |

## LIMITATIONS

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

As a mutual protection to our client, the public, and ourselves, all documents and drawings are submitted for the confidential information of our client for a specific project. Authorization for any use and/or publication of this document or any data, statements, conclusions or abstracts from or regarding our documents and drawings, through any form of print or electronic media, including without limitation, posting or reproduction of same on any website, is reserved pending BGC's written approval. A record copy of this document is on file at BGC. That copy takes precedence over any other copy or reproduction of this document.

## ACKNOWLEDGEMENTS

BGC acknowledges the contributions of RDCK resident Rick Rodman and former RDCK Director, Josh Smienk to the present study.

# EXECUTIVE SUMMARY

This report and its appendices provide a detailed hydrogeomorphic hazard assessment of Redfish Creek. Redfish 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 Redfish Creek fan-delta. This work is the foundation for possible future quantitative risk assessments or conceptualization and eventual design and construction of mitigation measures, if required.

Redfish 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). Redfish Creek is considered a hybrid (i.e., subject to debris floods and debris flows) where rare debris flows from a near-fan tributary could continue to travel the main stem and reach the fan apex and beyond. This makes Redfish Creek a particularly dangerous creek as no debris flows have been recorded in the recent past (~ 80 years). The danger lies within the relative quiescence of the creek which, has led to development densification and the false perception that this creek is relatively 'harmless'. However, in BGC's opinion supported by field evidence, Redfish Creek is capable of delivering potentially destructive debris flows into the inhabited areas.

Multiple hazard scenarios were developed for specific event return periods. This included bulking of flow to allow for higher organic and mineral sediment concentrations and bridge blockage scenarios were also considered. Unlike any of the other priority steep creeks except from Kuskonook Creek, BGC identified debris-flow potential on the upper Redfish Creek fan-delta. A distinct, unvegetated coarse angular boulder lobe east of Feller Road and north of Marshall Road indicates that at least one potentially destructive debris flow has occurred in the past. BGC was unable to date the event, but using minimum ages of trees upstream, air photographs and geomorphic reasoning estimates the age of this event to be in the hundreds of years. BGC opines that it could lie within the 300 to 1000-year return period class and thus within the range of return periods considered for this study.

Two numerical hydro-dynamic models were employed to simulate debris flood hazard scenarios on the fan-delta. In addition, BGC simulated a debris flow from the closest eastern tributary given that this creek showed signs of having produced debris flows in the past. The reason for using multiple models was to simulate a range of results as both models have their distinct advantages and shortfalls. BGC also estimated bank erosion from a physically based model for different debris flood probabilities. Table E-1 provides key observations derived from the numerical modelling.

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

| Process | Key Observations |
|---|---|
| Clearwater Inundation (HEC-RAS results for all return periods) | • Redfish Creek likely remains in its current channel for return periods up to 50 years except downstream of Highway 3A where flows are prone to escape to the east and immediately upstream of Highway 3A where flows could escape to the west, but likely flow towards the highway bridge opening even for a 20-year event.<br>• Flow leaves the channel approximately 400 m upstream of Highway 3A, to the east and west, in the 200-year and 500-year return period scenarios.<br>• Downstream of the highway, flow spreads to the east and west from the 50-year return period and up. The flow leaving the channel corresponds to the locations of low points identified by BGC.<br>• Some avulsion channels upstream of the highway cause flow to pond against the highway embankment<br>• Avulsions are shallow (mostly less than 1 m).<br>• Developments east of Bryan Road to Kootenay Lake would likely be inundated with water up to approximately 1 m deep. |
| Sedimentation | • Sedimentation will likely occur on the main avulsion paths as well as the existing channel and will concentrate in the fan-delta area where the lowest gradients persist, and the floodplain has little confinement.<br>• Sedimentation associated with debris floods can occur on the eastern fan-delta sector upstream and downstream of the Highway 3A crossing. Deposition depth could be up to 1.5 m for the 200-year or 500-year debris floods and up to 4 metres in upper channel sections.<br>• Sedimentation associated with debris flows could reach up to 2.5 m height in the upper fan-delta and 3 m along the lower channel sections |
| Bank Erosion | • Bank erosion ranges between 0 m and 6 m (20-year) and 8 m to 30 m (500-year). Bank erosion potential generally increases downstream.<br>• The Highway 3A bridge and properties within the 50$^{th}$ percentile bank erosion corridor are subject to being affected by erosion if unprotected. |
| Auxiliary Hazards | • Forest service road instabilities (blocked culverts and fill-slope failures) upslope of the fan-delta at a small unnamed gully could lead to a small debris flow potentially blocking Redfish Creek on the fan-delta.<br>• The fact that Redfish Creek is subject to episodic debris flows makes the creek subject to a variety of auxiliary hazards. Debris (sediment and logs) lobes could direct flows into directions difficult to predict. The highway bridge would likely be destroyed in a debris flow and water would likely flow down Highway 3A and then escape towards the south and into the lake. |

The multiple process numerical modelling ensemble approach demonstrates the key hazards and associated risks stem from fan-delta avulsion that could occur duo to an exceedance of channel capacity, channel aggradation, log jams or bridge failure. This could result in widespread flooding particularly on the relatively unpopulated eastern active fan-delta portions.

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 (i.e., 500 years). 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/debris flows, 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 Redfish 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 map shows that the majority of the active fan-delta of Redfish Creek is located within the yellow (low) hazard area. Flow that is not confined to the main channel generally spreads across the entire fan-delta. The orange (moderate) hazard area highlights avulsion paths and areas of ponding around the highway. In the confined reach directly downstream of the fan apex, areas adjacent to the main channel have been interpreted to have a moderate hazard due to the unpredictable nature of debris flows. The red (high) hazard area is confined to the channel.

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

Hazard management at Redfish Creek would hinge primarily on the decision if rare debris flows are to be mitigated or not. If yes, then a major (i.e., expensive) structure would be required likely near the fan apex to halt the debris load from debris flows. If debris-flood hazard mitigation is the primary goal, a mix of setback berms/deflection berms, channel widening, and highway bridge upgrades may be most effective.

Some uncertainties persist in this study. As with all hazard assessments and corresponding maps, they constitute a snapshot in time. Re-assessment and/or re-modelling may be warranted due to significant alterations of the surface topography or scenario assumptions, such as future fan-delta developments, debris floods, formation or reactivation of landslide on tributary upstream of Redfish fan-delta that could impound Redfish Creek, bridge re-design or alteration to the existing dikes near the fan-delta apex. 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. Substantial changes of Kootenay Lake levels could alter the morphodynamics of the fan-delta and the upstream channel.

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

# TABLE OF CONTENTS

## LIST OF TABLES

## LIST OF FIGURES



## LIST OF APPENDICES

# LIST OF DRAWINGS

# 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 focused 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".

This report details the approach used by BGC to conduct a detailed steep creek geohazards assessment and mapping for Redfish Creek, located approximately 22 km northeast of Nelson, BC in Electoral Area E. The site lies on the north side of the West Arm of Kootenay Lake and Redfish Creek flows along the east side of the community of Redfish, BC into the lake (Drawing 01).

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 Redfish 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.

**Table 1-1. List of study areas.**

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

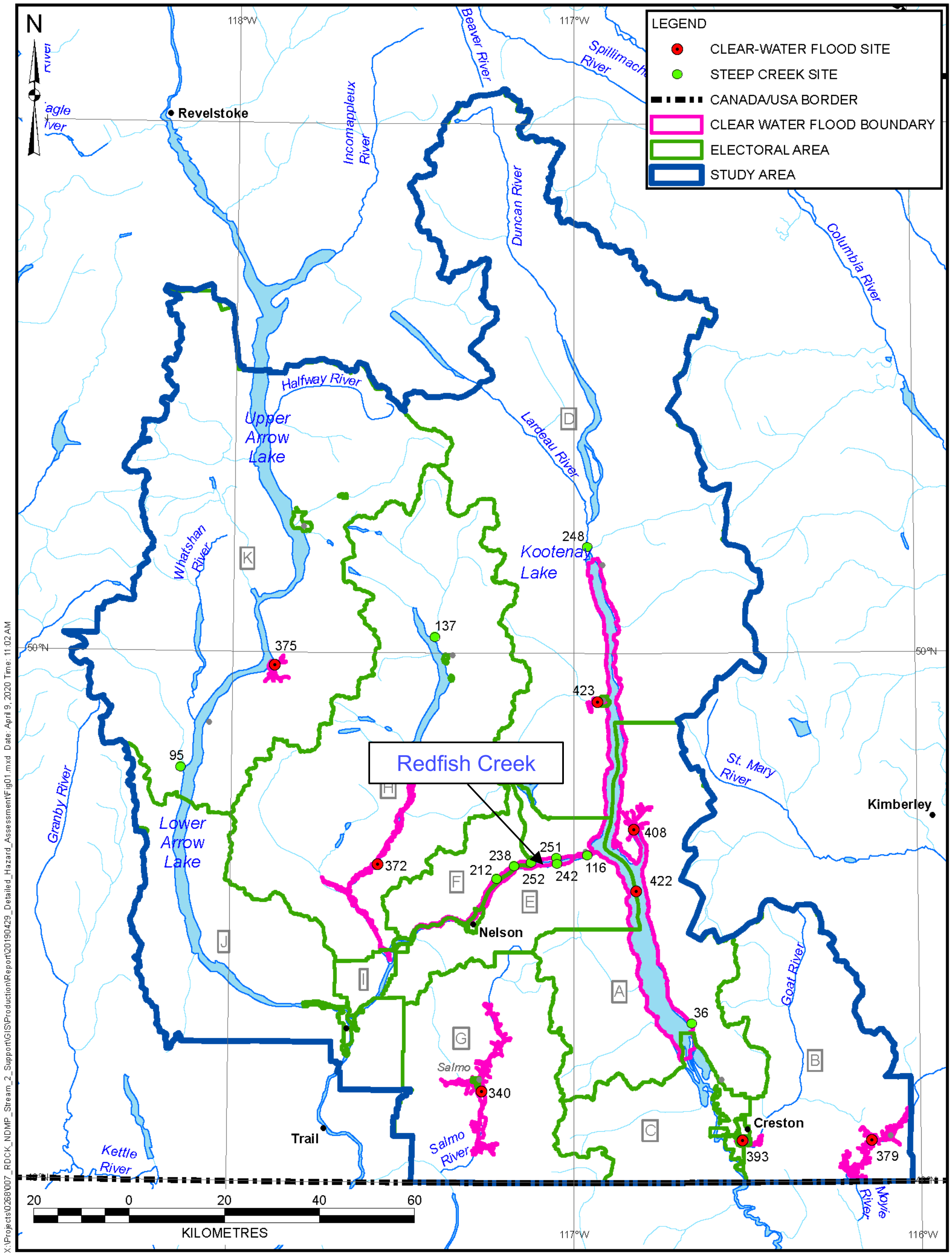



**Figure 1-1. Hazard areas prioritized for detailed flood and steep creek mapping. Site labels correspond to hazard identification numbers in Cambio Communities. Redfish Creek (No. 251) is labelled on the figure.**

## 1.2. Scope of Work

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

At Redfish Creek, the scope of work included:

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

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.

[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.

[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.

**Table 1-2. Return period classes.**

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

## 1.3. Deliverables

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

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

## 1.4. Study Team

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

- Kris Holm, M.Sc., P.Geo., Principal Geoscientist
- Sarah Kimball, M.A.Sc., P.Eng., P.Geo., Senior Geological Engineer
- Matthias Jakob, Ph.D., P.Geo., Principal Geoscientist
- Hamish Weatherly, M.Sc., P.Geo., Principal Hydrologist
- Lauren Hutchinson, M.Sc., P.Eng., Intermediate Geotechnical Engineer
- Beatrice Collier-Pandya, B.A.Sc., EIT, Geological Engineer
- Matthias Busslinger, M.A.Sc., P.Eng., Senior Geotechnical Engineer
- Carie-Ann Lau, M.Sc., P.Geo., Intermediate Geoscientist
- Jack Park, B.A.Sc., EIT, GIT, Junior Geological Engineer
- Hilary Shirra, B.A.Sc., EIT, Junior Hydrotechnical Engineer
- Phil LeSueur, M.Sc., P.Geo., Geological Engineer
- Patrick Grover, M.A.Sc., P.Eng., Senior Hydrotechnical Engineer
- Melissa Hairabedian, M.Sc., P.Geo., Senior Hydrologist
- Gemma Bullard, Ph.D., EIT, Junior Civil Engineer
- Midori Telles-Langdon, B.A.Sc., P.Eng., P.Geo., Intermediate Geological Engineer
- Sarah Davidson, Ph.D., P.Geo., Intermediate Geoscientist
- Toby Perkins, M.A.Sc., P.Eng., Senior Hydrotechnical Engineer
- Anna Akkerman, B.A.Sc., P.Eng., Hydrotechnical Engineer
- Elisa Scordo, M.Sc., P.Geo., P.Ag., Senior Hydrologist
- Matthew Buchanan, B.Sc., GISP, A.D.P., GIS Analyst

- Sophol Tran, B.A., A.D.P., GIS Analyst
- Lucy Lee, B.A., A.D.P., GISP, GIS Analyst/Developer
- Matthew Williams, B.Sc., A.D.P., GIS Analyst.
- Alistair Beck, B.S.F., Dip CST, Database/Web Application Developer
- Michael Porter, M.Eng., P.Eng., Director, Principal Geological Engineer

**Table 1-3. Study team.**

| | | |
|---|---|---|
| **Project Director** | Kris Holm | |
| **Project Manager** | Sarah Kimball | |
| **Overall Technical Reviewer(s)** | Matthias Jakob<br>Hamish Weatherly | |
| **Section** | **Primary Author(s)** | **Peer Reviewer(s)** |
| 1 | Lauren Hutchinson | Sarah Kimball;<br>Kris Holm |
| 2 | Beatrice Collier-Pandya | Matthias Busslinger;<br>Lauren Hutchinson |
| 3 | Beatrice Collier-Pandya | Lauren Hutchinson;<br>Carie-Ann Lau;<br>Matthias Busslinger;<br>Melissa Hairabedian |
| 4 | Jack Park | Carie-Ann Lau;<br>Matthias Busslinger |
| 5.1 | Beatrice Collier-Pandya | Lauren Hutchinson;<br>Matthias Jakob |
| 5.2 | Melissa Hairabedian | Lauren Hutchinson |
| 5.3 | Matthias Busslinger;<br>Matthias Jakob | Beatrice Collier-Pandya;<br>Lauren Hutchinson |
| 5.4 | Beatrice Collier-Pandya;<br>Gemma Bullard | Lauren Hutchinson;<br>Anna Akkerman |
| 5.5 | Gemma Bullard;<br>Midori Telles-Langdon | Sarah Davidson |
| 5.6 | Matthias Jakob | Lauren Hutchinson |
| 6.1 – 6.2 | Beatrice Collier-Pandya;<br>Lauren Hutchinson | Matthias Jakob |
| 6.3 | Melissa Hairabedian; | Lauren Hutchinson |
| 6.4 | Matthias Jakob | Lauren Hutchinson |
| 6.5 | Gemma Bullard;<br>Beatrice Collier-Pandya | Lauren Hutchinson;<br>Anna Akkerman |
| 6.6 | Gemma Bullard;<br>Midori Telles-Langdon, | Sarah Davidson |
| 6.7 | Beatrice Collier-Pandya;<br>Gemma Bullard | Lauren Hutchinson |
| 7 | Matthias Jakob | Lauren Hutchinson |

# 2. STEEP CREEK HAZARDS

## 2.1. Introduction

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

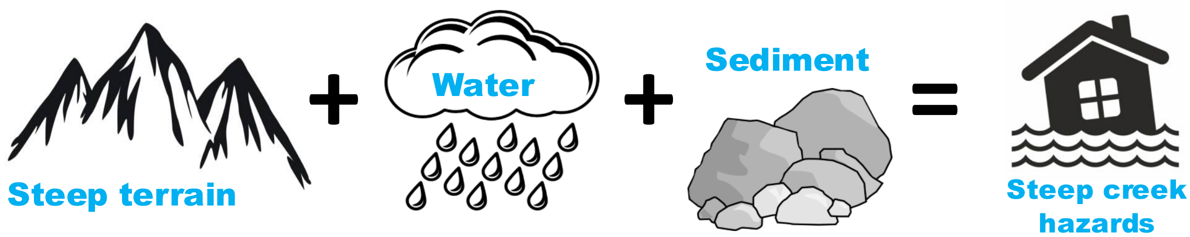



**Figure 2-1. Illustration of steep creek hazards.**

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

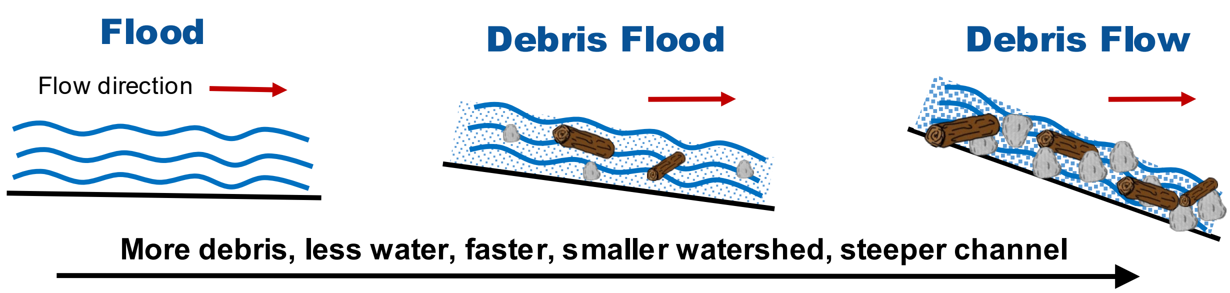



**Figure 2-2. Continuum of steep creek hazards.**

## 2.2. Clearwater Floods and Debris Floods

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

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

- Type 1 – Debris floods that are generated from rainfall or snowmelt runoff resulting in sufficient water depth to result in full bed mobilization.
- Type 2 – Debris floods that are generated from diluted debris flows (e.g., a debris flow that runs into a main channel in the upper watershed).
- Type 3 – Debris floods that are generated from natural (e.g., landslide dam) or artificial dam breaches.

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

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

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

## 2.3. Debris Flows

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

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

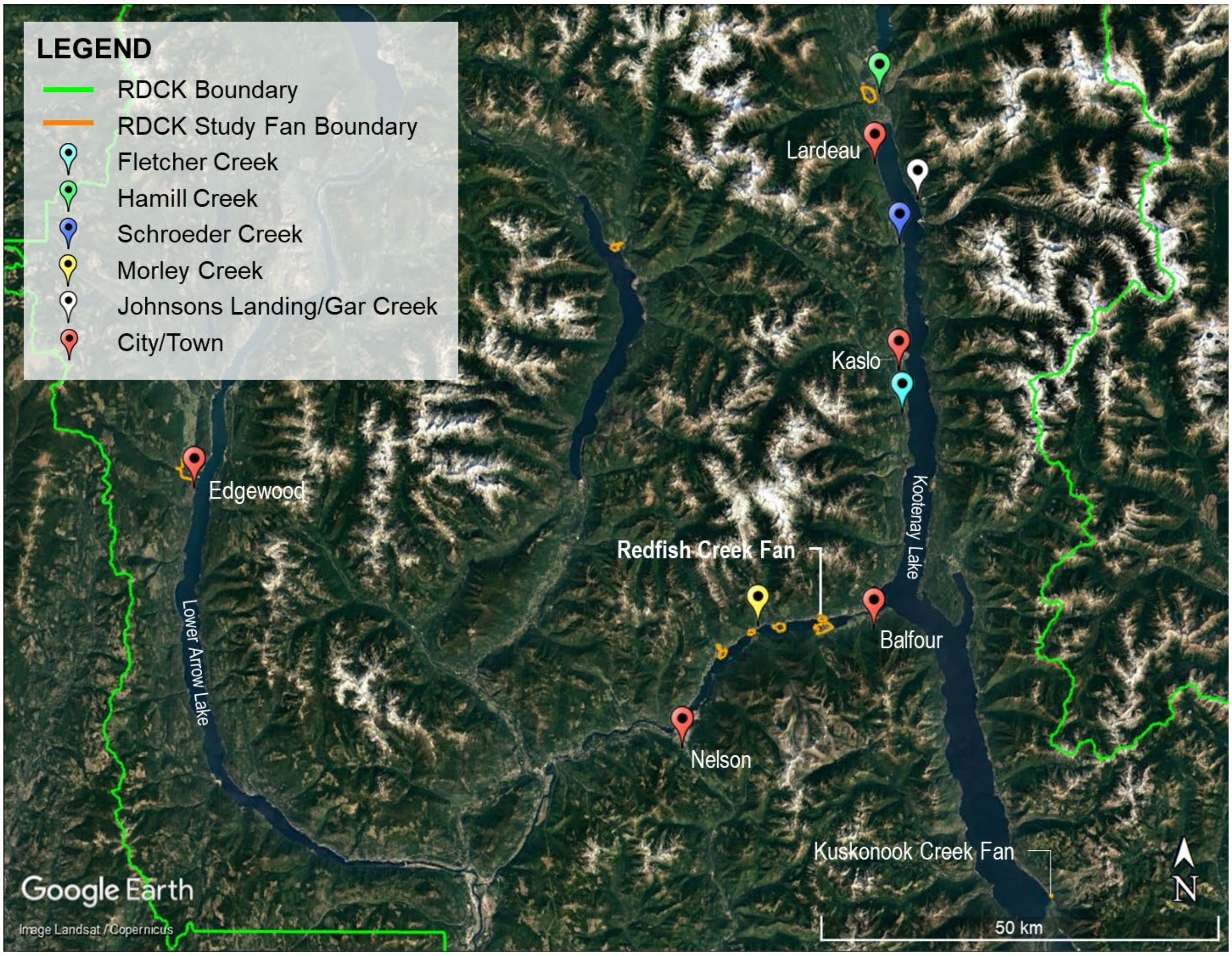



**Figure 2-3. Locations of RDCK fan-deltas and recent clearwater floods, debris flows, and debris floods (Google Earth Pro, 2016).**

## 2.4. Contextualizing Steep Creek Processes

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

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

- $Q_{max}$ 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.

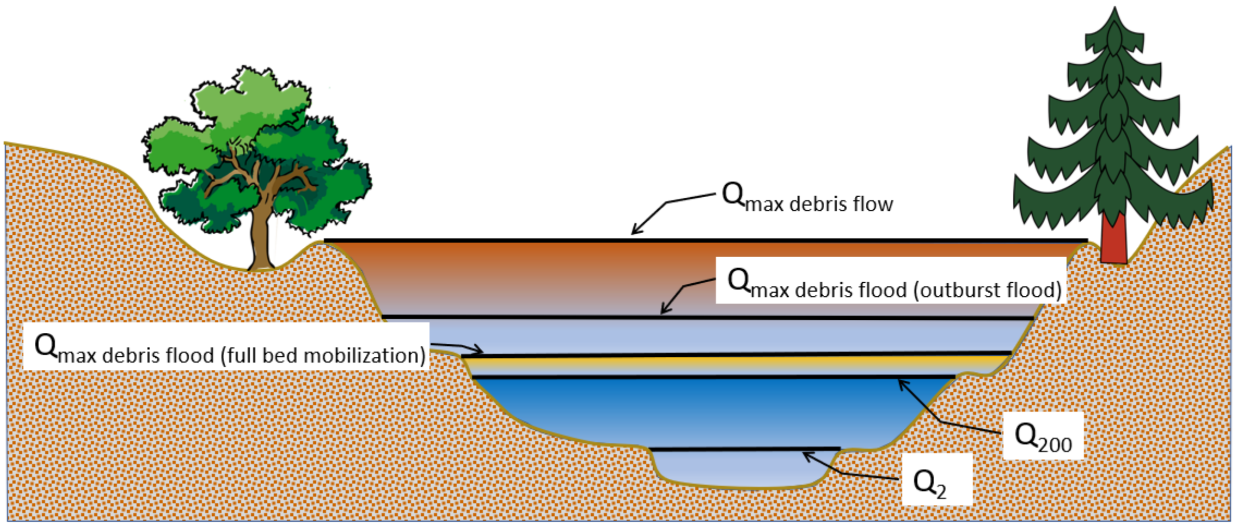



**Figure 2-4. Conceptual steep creek channel cross-section showing peak discharge levels for different events. Note that for some outburst floods or debris flows the discharge may well exceed what is shown here.**

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

## 2.5. Avulsions

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

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

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

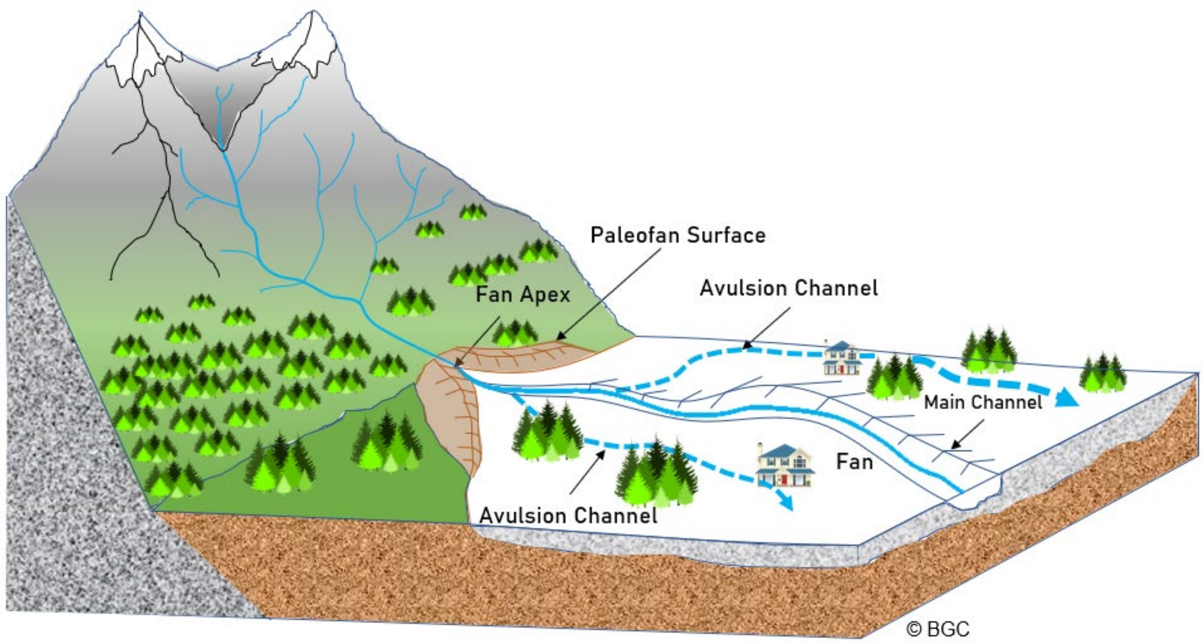



**Figure 2-5. Schematic of a steep creek channel with avulsions downstream of the fan apex. Artwork by BGC.**

# 3. STUDY AREA CHARACTERIZATION

The following section provides a characterization of the study area including physiography, geology, and geomorphology and a description of the Redfish Creek watershed and fan-delta (Drawing 01). Existing development (Drawings 02A, 02B) pertinent to this analysis along with hydroclimatic conditions and projected impacts of climate change are included.

## 3.1. Site Visit

Fieldwork on Redfish Creek was conducted from July 2 and 10, 2019 and on November 20, 2019 by the following BGC personnel: Kris Holm, Matthias Busslinger, Carie-Ann Lau, Matthias Jakob, Beatrice Collier-Pandya, and Hilary Shirra. Field work included channel hikes to look for evidence of high-water marks, measurement of grain size diameters (Wolman sampling) at the fan-delta apex and the channel mouth, measurement of cross-sections at bridge and other infrastructure crossing locations, and collection of tree core samples for dendrogeomorphic analysis. The upper watershed was flown by helicopter and numerous photographs were taken for later analysis of major sediment sources to the channel (Appendix B).

## 3.2. Physiography

Redfish Creek lies within the Selkirk Mountains, which is a subgroup of the Columbia Mountains in southeastern BC. Drawings 01, and 02A show the watershed and fan-delta boundaries on a shaded, bare earth digital elevation model (DEM) created from lidar. Drawing 03 shows a profile along the creek mainstem and tributary. Representative photographs of the watershed and fan-delta are provided in Appendix B.

The watershed is located within the Central Columbia Mountain ecosection of the Northern Columbia Mountains ecoregion, which is drained by numerous streams that flow into Kootenay Lake, the Slocan River, and the Arrow Lake reservoir (Demarchi, 2011). The ecosection is characterized by long, uniformly steep slopes that terminate at sharp ridges and mountain peaks sculpted by cirque glaciers with mostly narrow valleys (Holland, 1976). Precipitation is very high in the Central Columbia ecosection, as moisture from coastal areas arrives from the south and west, bringing high humidity and rain in summer, and deep snow in winter (Demarchi, 2011). Typical vegetation includes Western Red Cedar and Western Hemlock trees at lower elevations (from 500 m elevation) and Engelmann Spruce and Subalpine Fir trees along the mid-mountain slopes. The highest peaks in the Central Columbia ecosection reach up to approximately 3200 m and consist of barren rock. The highest elevation in the Redfish Creek watershed is about 2350 m along the northeast boundary of the watershed.

## 3.3. Geology

### 3.3.1. Bedrock Geology

The Redfish Creek watershed is underlain by granodioritic intrusive rocks of the Nelson Batholith, which formed in the Mid-Jurassic Period. The watershed is situated in the northern portion of the batholith, where subvertical to west-dipping foliation has been mapped north of the West Arm of Kootenay Lake (Vogl & Simony, 1992). Though there have been no faults mapped within the watershed, there are several northeast-trending normal and thrust faults that have been identified within 5 km, including the Midge Creek and Seeman Creek Faults (Moynihan & Pattison, 2013). These lineaments often provide preferential surface flow paths and represent locations of structural weakness.

### 3.3.2. Surficial Geology

Within the watershed, the surficial material is dominantly composed of glaciofluvial deposits and till in the valley bottom, with till and colluvium along valley walls (Figure 3-1). The highest ridges consist of mixed colluvium and bedrock outcrops (Jungen, 1980). Sediment within the channel is primarily derived from erosion of till and glaciofluvial materials along the channel banks in the V-shaped valley, and from colluvial processes in tributaries bordering the main channel. The abundant colluvium in the watershed indicates that the watershed is likely largely supply unlimited, which implies a quasi-unlimited amount of sediment available in the watershed to be mobilized during extreme hydroclimatic events. Debris flows sourced within till deposits are expected to contain a higher proportion of fine-grained sediment (fine sands, silts, and clays). All other factors being equal, these types of debris flows can flow further than those sourced from coarser-grained colluvial, fluvial, and glaciofluvial materials.

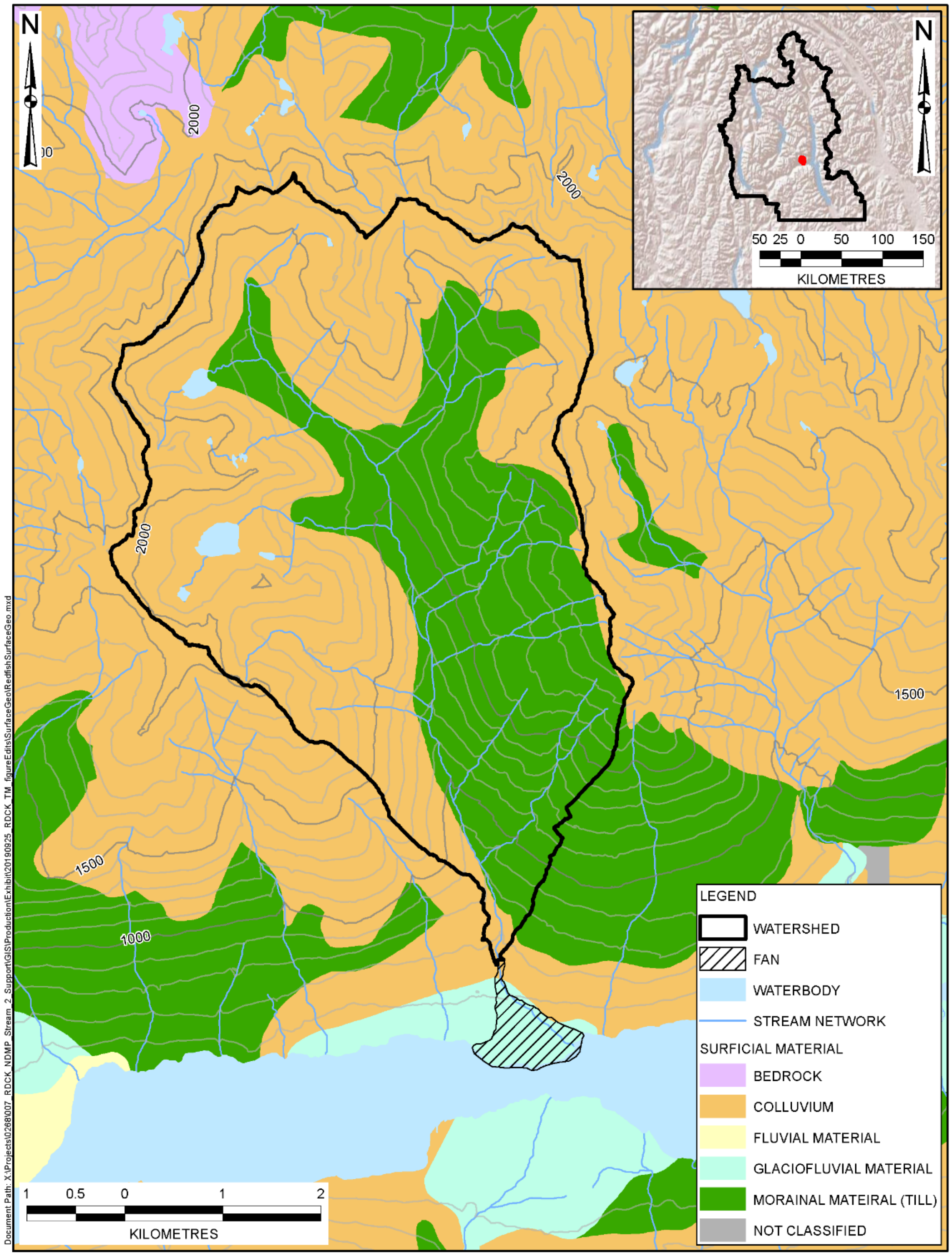



**Figure 3-1. Surficial geology of the Redfish Creek watershed (adapted from Ministry of Environment and Climate Change Strategy, 2016).**

## 3.4. Geomorphology

### 3.4.1. Watershed

Geomorphological analysis of Redfish Creek included characterization of the watershed and fan-delta using historical air photos (Drawings 04A and 04B) and lidar, supplemented by literature on the regional geology, geologic history and physiography, and a field visit.

Drawing 05 shows a geomorphic map of the study area, including specific landforms and sediment sources in the watershed. The headwaters of Redfish Creek are located on the mountainous slopes of Mount Yuill (approximate elevation of 2150 m) at the western edge of the watershed and the mountains to the northeast (peak elevation approximately 2350 m). The upper portion of the watershed is characterized by wide U-shaped valleys. The upper reaches of the watershed contain some active talus slopes that supply sediment to the channel. Several small lakes (e.g., Whitelady Lake, Ross Lake) are present on the flatter portions of the tributary valleys. The U-shaped valley transitions into the V-shaped mainstem valley that ultimately flows into the Kootenay Lake valley. Several debris avalanche paths related to logging roads are present, e.g., Photo 5 in Appendix B (see Drawing 05 for locations).

Based on review of lidar data, BGC identified the presence of tension cracks in bedrock at the crest of an unnamed ridge approximately 3.5 km north-northeast of the fan-delta apex, these are shown as landslide headscarps on Drawing 05 (see inset). While a helicopter reconnaissance did not reveal any obvious tension cracks, some bedrock outcrops and coarse talus were observed (see Photo 6 in Appendix B). Photos 7 and 8 show till slopes exposed by debris avalanches near the Redfish-Laird Creek FSR. A debris flow path is delineated below these debris avalanches (see Drawing 05).

The hillslopes are forested, and logging is abundant throughout the watershed. Apex (2016) estimated that approximately 14% of the total watershed has been logged (Drawing 05). Several debris flows and debris slides have also occurred in the watershed initiating from logging roads. For example, Photos 7 and 8 in Appendix B show till slopes exposed by debris avalanches near the Redfish-Laird Creek FSR. A debris flow path is delineated below these debris avalanches (see Drawing 05). No significant forest fires have been recorded in this watershed since 1919 (FLNRORD, 2019).

Tributary A joins Redfish Creek approximately 7.0 km upstream of the lake outlet (see location A in Drawing 03). Upstream of this confluence, the mainstem profile is somewhat stepped with alternating flatter and steeper reaches. The mainstem reach between 5.0 to 2.9 km from the lake outlet is steeper than 20%, which is approximately the threshold for debris flow conveyance in confined channels. Downstream of steep this reach, the gradient becomes flatter (to about 15%) toward the fan-delta apex at about km 1.4.

Table 3-1 summarizes relevant geomorphic characteristics of the Redfish Creek watershed which are indicators of the process type and anticipated behaviour of the watershed in response to high runoff. The Melton Ratio (watershed relief divided by square root of watershed area) and channel gradient both assist in determining if a creek is susceptible to flood, debris flood, or debris-flow processes (Section 6.1). The channel gradient above the fan-delta apex provides an indication of whether transportation of sediment is likely, and the fan-delta gradient approximates the angle where sediment deposition of larger flows from the watershed generally ensues.

**Table 3-1. Watershed characteristics of Redfish Creek.**

| Characteristic | Value |
|---|---|
| Watershed area ($km^2$) | 26 |
| Fan-delta area ($km^2$) | 0.74 |
| Active fan-delta area ($km^2$)[1] | 0.62 |
| Maximum watershed elevation (m) | 2,350 |
| Minimum watershed elevation (m) | 650 |
| Watershed relief (m) | 1,700 |
| Melton Ratio (km/km)[3] | 0.3 |
| Average channel gradient of mainstem above fan-delta apex (%) | 15 |
| Average channel gradient on fan-delta (%) | 10 |
| Average fan-delta gradient (%) | 12 |

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

### 3.4.2. Redfish Creek Fan-Delta

An overview of the Redfish Creek fan-delta is shown in Drawings 02A, 02B. The creek flows through an unincorporated community on the fan-delta. For the purposes of this report, the name Redfish is applied acknowledging that the community is referred to by other names by some sources (i.e., Harrop, Longbeach, Harrop Point). Drawing 06 shows geomorphic features of the fan-delta. Locations referred to in the text below are labelled on these drawings. The fan-delta areas delineated in the drawings have been interpreted by BGC based on lidar and field data; however, the extents of the fan-delta beyond the lidar data limits at Kootenay Lake are difficult to define due to changing lake levels.

Drawing 06 shows that the fan-delta comprises a paleofan/inactive fan-delta (purple shading) to the west and an active fan-delta (orange dashed polygon) to the east, and a submerged fan-delta (green shading) to the south. Redfish Creek flows southeasterly close to the eastern border of the fan-delta. The fan extends with a delta into the West Arm of Kootenay Lake and is therefore referred to as a fan-delta. Approximately 800 m upstream of the lake outlet the creek begins to flow through the developed part of the fan-delta. The active channel width on the fan-delta ranges from 10 to 20 m.

Avulsion channels (i.e., previous creek flow paths) predating the air photo record were delineated with blue dashed lines in Drawing 06 from lidar data. A previous report refers to a 1910 survey

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

delineating the creek channel approximately 80 m south-west of the present channel (NHC & Thurber, 1990). This location could not be verified with air photos or lidar (Figure 4-1). Air photos (Drawings 04A and 04B) show that the creek generally followed the current alignment since 1929, with the following exceptions:

- Possible avulsion to the east (1939 air photo)
- Possible avulsion near the channel outlet (1952 air photo)
- Construction of spawning channel downstream of the HWY 3A bridge to the east of the creek. The 1988 air photo (Drawing 04B) shows the area cleared for the spanning channel. With magnification the meandering channel is visible in the air photo. Water for the spanning channel is diverted by a weir from Redfish Creek (Figure 3-4), located approximately 25 m downstream of the Highway 3A bridge (Drawings 02A, 02B). Photos 11 and 12 (Appendix B) show features of the spawning channel. The spawning channel flows back into Redfish Creek at the weir (Figure 3-4) located approximately 100 m upstream of the lake outlet (Drawings 02A, 02B).

Drawing 03 shows that the channel gradient markedly flattens at 0.65 km from the lake outlet. Above this location, the average channel gradient to the fan-delta apex is 10 to 20% compared to less than 10% below. This flattening approximately coincides with the most distal location (about elevation 555 m, near Sykes Road) of surficial boulder deposits on the active fan-delta observed in the field by BGC. While the fan-delta is generally made from flood and debris flood deposits, it appears that upslope of elevation 555 m the fan-delta also comprises coarser deposits from debris flows. These features become more muted and shallower with distance from the fan-delta apex. The debris flow deposits are discussed in further detail in Section 6.1.

The Redfish Creek fan-delta has adjusted due to the raise of lake levels when Corra Linn Dam, located southwest of Nelson, was activated in 1938. The dam raised the lake levels by approximately 2 m (Touchstone Nelson, 2007) and BGC understands that this level will be held. The distal portions of the fan-delta, visible in historical air photos (Section 6.2.1), were flooded by the lake level raise. Where Redfish Creek flows into Kootenay Lake, the active channel width is approximately 30 m.

### 3.4.3. Steep Creek Process

BGC assessed the potential steep creek process types and hazards on Redfish 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, Redfish Creek plots in the zone of floods to debris floods (Figure 3-2). The points shown on the plot are subject to some error and watersheds can be subject to multiple processes at different timescales; for this reason, it is important to consider additional evidence to supplement the assessment of process type.

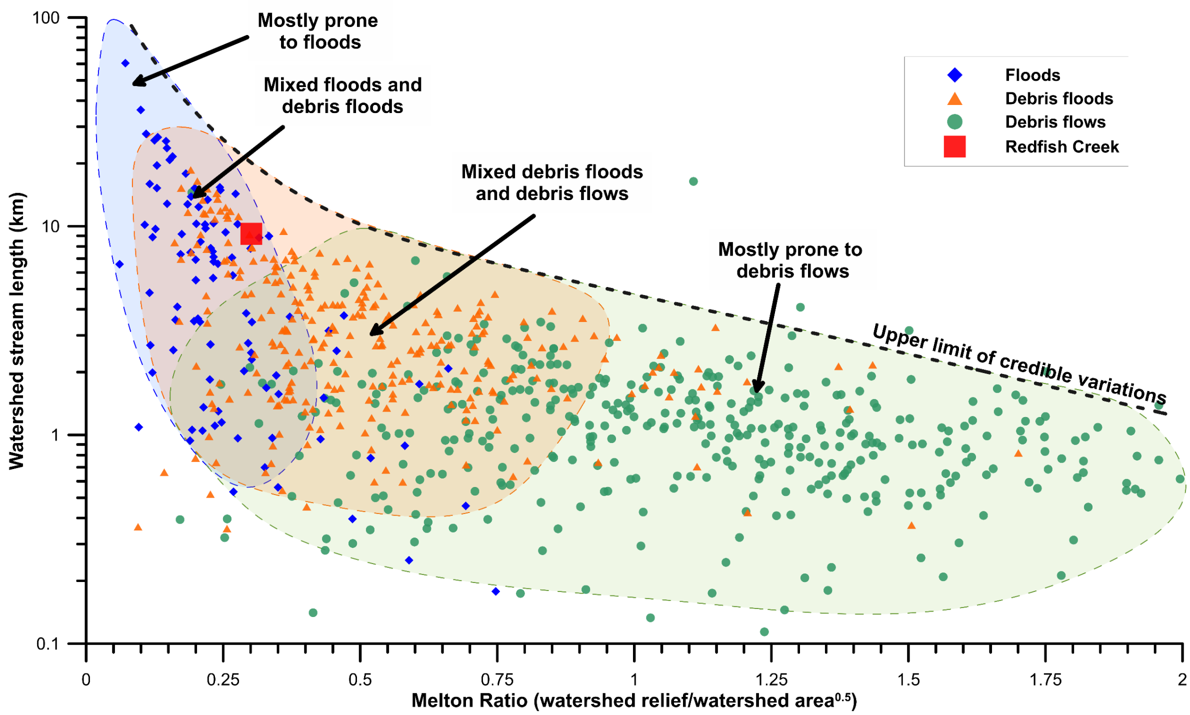



**Figure 3-2. Tendency of creeks to produce floods, debris floods and debris flows, as a function of Melton Ratio and stream length (data from Holm et al., 2016 and Lau, 2017). See Table 3-1 for Redfish Creek watershed data.**

Redfish Creek plots in the data cluster prone to debris floods and floods. Debris floods can be subdivided into three types, those triggered by the exceedance of a critical bed shear stress threshold (Type 1), those through transitions from debris flows (Type 2), and those triggered from outbreak floods (Type 3) (Section 1 of Methodology Report). This differentiation is not included in the above plot as such nuances are unknown for the data included above; however, it is included in this detailed assessment. See Section 6.1 for further details on the selection of hydrogeomorphic process for hazard analysis.

## 3.5. Existing Development

Development on the Redfish Creek fan-delta comprises the community of Harrop Point (Drawings 02A, 02B). Petroleum infrastructure transects the lower third of the fan-delta along Highway 3A and communications infrastructure transects across the fan-delta apex. Prominent development includes: The Redfish Elementary School located immediately south of Highway 3A and the Harrop Cable Ferry that launches from the south end of Harrop Ferry Road on the distal fan-delta. A majority of development is located to the south of Highway 3A.

The community of Redfish is not included in the 2016 census[4]. The closest location with population data is an unincorporated place by the name of Harrop/Procter. BGC interprets this to mean that the total population reported is for the communities of both Harrop and Procter but may also include smaller adjacent communities such as Redfish and Sunshine Bay. The

[4] Alternative names for the community (Harrop Point, Longbeach) are similarly missing from the 2016 census.

unincorporated communities of Harrop/Procter have a total population of approximately 600 people (Statistics Canada, 2016). The estimated total improvement value of parcels intersecting the Redfish Creek fan-delta based on 2018 BC Assessment Data is $17,604,600 (BGC, March 31, 2019).

### 3.5.1. Bridges

Bridge locations are shown on Drawings 02A, 02B. Redfish Creek passes under three bridge structures on the fan-delta and past the abutments of one removed bridge (Table 3-2, Figure 3-3). The Forestry Bridge and Marshall Road Bridge (removed) are not included in the public datasets (Government of British Columbia, 2020b). Redfish Highway Bridge is located in the mid-fan and is supported by vertical concrete abutments, which extend approximately 2 m on both the left and right banks.

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

| Bridge | Span (m) | Height Above Channel Center (m) | Notes |
|---|---|---|---|
| Forestry Bridge | Not measured | Not measured | At fan-delta apex |
| Marshall Road Bridge | N/A | N/A | Bridge removed, only abutments observed by BGC in July 2019. |
| Redfish Highway Bridge | 11.4 | 2.2 | Highway 3A, 2-lane road |
| Footbridge | 12.2 | 2.3 | 20 m downstream of fish weir |

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

**Forestry Bridge crossing on Redfish Creek near fan-delta apex. Looking east.**

**Standing on the upstream right bank looking east at the Redfish Highway Bridge (flow is into the bridge).**

**Standing on left bank looking south at the Footbridge. Creek flows from right to left in photo.**

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

### 3.5.2. Flood Protection Structures & Low Bank Observations

There are numerous flood protection structures along Redfish Creek that are noted in the BC Flood Protection Works Database and that were observed during BGC's field work. Approximately 250 m upstream of Highway 3A, a small (dimensions not measured) man-made berm (RFS-FP-01 on Drawings 02A, 02B) was observed on the left bank. This structure appears to have been built by a resident.

There are six flood protection structures (i.e., berms or dikes) on the Redfish Creek fan-delta noted in the BC Flood Protection Works Database[5] (Table 3-3); however, some of the structures are contiguous such that together they form three major flood protection structures (Drawings 02A, 02B). The upstream-most dike (RFS-FP-02) is located immediately downstream of Highway 3A on the right bank and extends for approximately 65 m downstream. RFS-FP-03 is located approximately 140 m downstream of Highway 3A and extends for 52 m downstream on the left bank. The most downstream dike/flood protection (Redfish Creek Dike (RFS-FP-04)) is located approximately 210 m downstream of Highway 3A and extends downstream on the right bank for approximately 93 m.

Redfish Creek Dike (RFS-FP-04) is the only structure listed in the Government of British Columbia's (2020) list of dikes by river/watercourse. The list states that this dike has "no local authority" as Owner/Administrator, rendering it an orphan dike, i.e., a flood protection structure which is not maintained by a diking authority[6].

Though not flood protection structures, there are two weirs (Drawings 02A, 02B) that connect to form an entry and exit for the fish spawning channel north of Redfish Creek.

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

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

**Table 3-3. Attributes of Redfish Creek Flood Protection Works.**

| Attribute[1] | Flood Protection Structure | | | |
|---|---|---|---|---|
| BGC ID | RFS-FP-01 | RFS-FP-02[3] | RFS-FP-03 | RFS-FP-04[3] (Redfish Creek Dike) |
| Source[1,2] | BGC Field Observation | iMapBC | iMapBC | iMapBC |
| Type | Berm | Dike | Protection | Dike/Protection |
| Orphan (Y/N)[4] | | Y | Y | Y |
| Comments | | | | Very thick veg. to 10 m, large rock 1 m wide |
| Survey Year(s) | - | 2003, 2004 | 2003 | 2003, 2004 |
| Erosion Protection Side | Left | Right | Left | Right |
| Length (m) | - | 66 | 52 | 157 |

Notes:
1. iMapBC data downloaded from Flood Protection Structural Works layer on February 23, 2020.
2. BGC Field Observation made on July 2 and 10, 2019.
3. Two or more contiguous segments.
4. Only the structures within iMapBC were classified as orphan structures.


**Looking downstream (south) at upstream weir on Redfish Creek with fish bypass to the left, and dike on right bank (RFS-FP-01). Arrows indicate dike crest.**


**Looking southwest across creek at downstream weir, and Redfish Creek Dike (RFS-FP-03 located on the right bank. Dashed line indicates approximate dike crest.**

**Figure 3-4. Flood protection measures encountered on Redfish Creek fan-delta during BGC's field work in July 2019. Refer to Drawings 02A, 02B for locations. No photo taken for RFS-FP-02.**

In addition to the man-made flood protection structures, there are natural levees formed from past debris flow lobes along Redfish Creek. Along these levees, there are low points where overtopping of the banks and avulsions are possible. Drawings 02A, 02B show the locations of these low points (RFS-LP-01 to -03) and Figure 3-5 shows the field photographs taken by BGC in July 2019. The NHC/Thurber (1990) report notes the locations of three low points – the west side of the fan-delta apex, the west side of Wightwick Road, and the west side of Marshall Road Bridge (now removed), which also is at Wightwick Road. RFS-LP-01 may correspond to one of the latter two low points noted by NHC/Thurber (1990).

**RFS-LP-01. On the right bank looking southeast at low point (i.e., walking trail) in natural berm.**

**RFS-LP-02. Looking south at headwall of the old water intake on the right bank. For reference, note arrow indicating same tree as in image below.**

**RFS-LP-03. Standing on right bank looking northeast at Redfish Creek. BGC personnel standing at the low point.**

**RFS-LP-02. Looking south valve of water intake and along pipe trench (pipe removed). For reference, note arrow indicating same tree as in image above.**

**Figure 3-5. Low levee spots encountered on Redfish Creek fan-delta during BGC's field work in July 2019. Refer to Drawings 02A, 02B for locations.**

## 3.6. Hydroclimatic Conditions

### 3.6.1. Existing Conditions

Climate normal data were obtained from Environment and Climate Change Canada's Kaslo station (600 m), located approximately 35 km north of the Redfish Creek outlet (Environment and Climate Change Canada, n.d.). Daily precipitation and temperature data are available from 1894 to 2015 at this station. Figure 3-6 shows the average monthly temperature and precipitation for this station from the 1981 to 2010 climate normals. Mean annual precipitation (rain and snow) is 886 mm (Table 3-4), and monthly precipitation peaks in November with an average of 113 mm.

The measured precipitation at the Kaslo station is lower than the precipitation in the Redfish Creek watershed, where the mountaintops extend more than 1600 m above Kootenay Lake. This difference in precipitation is due to orographic effects, which occur when an air mass is forced up over rising terrain from lower elevations. As it gains altitude it quickly cools down, the water vapour condenses (forming clouds), ultimately resulting in precipitation.

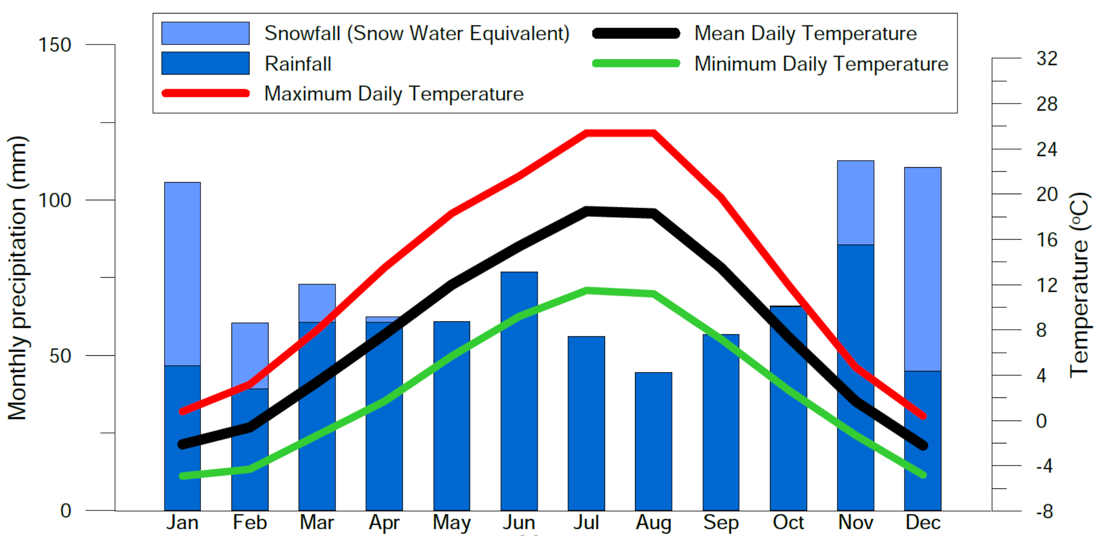



**Figure 3-6. Climate normal data for Kaslo station from 1981 to 2010.**

**Table 3-4. Annual total of climate normal data for Kaslo station from 1981 to 2010.**

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

To understand the regional distribution of precipitation and snowfall patterns and supplement the data from the Kaslo 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 1374 mm, varying as a function of elevation. The same trend is evident in the annual average precipitation as snow (PAS) over the watershed where the average precipitation as snow is 806 mm. PAS increases at the higher elevations; therefore, Redfish Creek watershed accumulates greater precipitation falling as snow compared to the Kaslo 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 Climate NA model provides downscaled climate projections for future conditions (Wang et al., 2016). The projections based on the Representative Carbon Pathway (RCP) 8.5 indicate that the mean annual temperature (MAT) in the Redfish Creek watershed is projected to increase from 2.1ºC (average between 1961 to 1990) to 5.6ºC by 2050 (average between 2041 to 2070). MAP is projected to increase from 1374 mm to 1454 mm, while PAS is projected to decrease from 806 mm to 546 mm by 2050 in the Redfish Creek watershed. Projected change in climate variables from historical conditions for the Redfish 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 conditions (1961 to 1990) for the Redfish Creek watershed (Wang et. al, 2016).**

| Climate Variable | Projected Change |
|---|---|
| Mean Annual Temperature (MAT) | +3.5 ºC |
| Mean Annual Precipitation (MAP) | +81 mm |
| Precipitation as Snow (PAS) | -260 mm |

# 4. SITE HISTORY

## 4.1. Introduction

Redfish Creek flows through the unincorporated community of Redfish and into Kootenay Lake at Harrop Narrows. Residents have lived on the fan-delta since the late 1800s, and the area has served as an important ferry connection for the communities on opposing shores of Kootenay Lake.

## 4.2. Document Review

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

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

BGC's review of the above work is not aimed as a critique but rather a brief summary of the findings of each report. Each scientific or engineering/geoscientific study builds on the preceding one benefitting from the added knowledge. In the case of the NHC-Thurber (1990) study, the different methodologies used by that study and this one are discussed, as the former is frequently quoted by practitioners working on single lot hazard assessments. 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 Redfish Creek.**

| Year | Month/Day | Source | Purpose |
|---|---|---|---|
| 1990 | April | Northwest Hydraulic Consultants Ltd. and Thurber Consultants Ltd. | Hazard Assessment |
| 1998 | February 23 | Klohn Crippen Consultants Ltd. | Alluvial and debris torrent fan-delta inventory |
| 2001 | March | Jordan | Research article |
| 2001 | May | Boyer and Jordan | Summary of November 1999 storm event |
| 2003 | | Whitaker, Alila, Beckers, and Toews | Research article |
| 2003 | June 13 | Intermountain Engineering & Surveying Ltd. | Precondition for Building Permit |
| 2003 | July 22 | Integrated Hydropedology Ltd. | Precondition for Building Permit |
| 2004 | | Schnorbus and Alila | Research article |
| 2004 | July 21 | Klohn Crippen Consultants Ltd. | Precondition for Building Permit |
| 2006 | | Jordan | Research article |
| 2009 | September 30 | Deverney Engineering Services Ltd. | Precondition for Building Permit |
| 2010 | September 12 | Deverney Engineering Services Ltd. | Precondition for Subdivision |
| 2011 | June 17 | Deverney Engineering Services Ltd. | Precondition for Building Permit |
| 2012 | October 12 | Green and Alila | Research article |
| 2015 | February 15 | Lasca Group Technical Services Ltd. | Precondition for Building Permit |
| 2016 | April | Apex Geoscience Consultants Ltd. | Hydrogeomorphic Assessment |
| 2016 | July 21 | Perdue Geotechnical Services Ltd. | Precondition for Building Permit |
| 2017 | January 15 | Apex Geoscience Consultants Ltd. | Hazard Assessment |

### 4.2.1. NHC/Thurber (1990)

In 1990, a detailed report was authored by a team of Northwest Hydraulic Consultants Ltd (NHC) and Thurber Consultants (Thurber), titled: Alluvial Fan Hazard Assessment, Regional District of Central Kootenay Electoral Area "E" & "F". This assessment included Duhamel, Sitkum, Kokanee, Redfish, Harrop, Procter, Laird, and Narrows creeks. Except for the latter two (Laird and Narrows), these same creeks were prioritized for detailed study by BGC. A detailed comparison of the NHC/Thurber study with the present work is included in Section 6.7.2.

### 4.2.2. Deverney Engineering Services Ltd. (2011)

In 2011, a letter report authored by Deverney Engineering Services Ltd. (Deverney) assessed the natural hazards to Lot A, Plan NEP89540, DL 1313, Kootenay Land District on the Redfish Creek fan-delta. The lot is located approximately 400 m southwest of Redfish Creek, south of Highway 3A. This report was requested by the owner of the subject property. Deverney assessed the hazard due to lake shoreline erosion, clearwater flood hazard, and debris flood hazard. Deverney reported that land to the west of Redfish Creek is vulnerable to avulsions due to log or debris jams in the creek, relatively poor channel confinement at sites with potential blockages (bridges), and areas with low stream banks. The avulsion hazard for Redfish Creek was estimated to have an annual probability of 1:50 years and that the area north of Highway 3A is more vulnerable to debris flows, and the debris-flow hazard to the property in question was very low. A PDI (probability of death of an individual) risk assessment was completed which indicated that the potential for life loss risk at the subject property is approximately 1:170,000 and thus well below the thresholds indicated by MoTI (2010) of < 1:100,000 for a new proposed development.

### 4.2.3. Apex Geoscience Consultants Ltd. (2016)

In 2016, Apex Geoscience Consultants (Apex) conducted a hydrogeomorphic assessment of Redfish Creek to provide guidance for forest management. In that report, hydrology and flood frequency were assessed, along with sediment mobility. Apex also completed a detailed review of previous sediment transport research for Redfish Creek.

To analyze sediment mobility, Apex examined the $D_{90}$[7] of the bed material found throughout the watershed. Their measured $D_{90}$ values varied between approximately 20 and 450 mm and found that the $D_{90}$ increased as the channel gradient decreased. This was interpreted to relate to the increased turbulence and associated velocity decrease in steep reaches.

In the 2016 report, Apex completed a detailed characterization of individual reaches connecting to the mainstem of Redfish Creek. The channel was subdivided into six reaches (Figure 11, Apex (2006)). The reach of Redfish Creek upstream of its confluence with Tributary B (Drawing 03) was interpreted to have the greatest amount of channel bed mobility. The two reaches immediately upstream of the fan-delta were noted to contain large colluvial boulders and bedrock, which served to stabilize the channel. The reach immediately upstream of the Redfish Creek fan-delta was noted to contain many woody debris jams. In the lower reaches of Redfish Creek, Apex noted that the two main elements at risk are water intakes and the spawning channel (Section 3.5.2). The risk associated with the water intakes is in part from upstream hazards that could be impacted by forest development. Apex assessed that forest harvesting of less than 20% below 1725 m, and distributed over a range of elevations, should not increase the existing hazards to the water intake. During Apex's field investigation, most of the existing debris slides in Redfish Creek were found to have occurred in the past 20 years as a results of forest roads with inadequate drainage control.

---

[7] $D_{90}$ refers to the diameter of the 90$^{th}$ percentile in a grain size distribution.

#### 4.2.4. Perdue Geotechnical Services (2016)

In 2016, Perdue Geotechnical Services (PGS) conducted a flood hazard assessment of Lot 9, Plan NEP5817, District Lot 1313, Kootenay District. This assessment was requested by RDCK, prior to issuing a building permit for the land in question. The lot is located along the north shore of the West Arm of Kootenay Lake between Redfish Creek and Bryan Road. The northwest boundary of the lot is flanked by Redfish Road. In this report, PGS assessed clearwater and debris-flood hazards to this lot including a review of several previous studies conducted on the Redfish Creek alluvial fan-delta. The debris-flood hazard was assessed by searching for morphological evidence of past debris floods on Lot 9 and surrounding areas. The clearwater flooding hazard was assessed through analysis of Redfish Creek stream gauge data collected by Environment and Climate Change Canada. The probability of a clearwater flood having negative impacts on Lot 9 was found to be greater than 1 in 200. The probability of a debris flood having negative impacts on Lot 9 was found to be less than 1 in 475. A number of recommendations are provided in Perdue (2016) pertaining to the proposed building and geodetic surveys.

### 4.3. Historic Timeline

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

- At least five notable hydrogeomorphic events (2012, 2011, 1999, 1968 and possibly at least two more events between the 1929 and 1939 and 1945 and 1952 air photo dates) have occurred on Redfish Creek in the past century. Recent flood events (2011 and 2012) have occurred during freshet conditions, when snowmelt was elevated due to several days of high temperatures, with runoff augmented by the concurrence of rainstorm events (Apex, 2016).
- The 2012 flood event is interpreted to be a debris flood, due to the description of bank erosion and in-channel sediment mobilization. At the time, residents raised concerns regarding the potential avulsion of the channel upstream of the highway bridge that could impact the highway, houses, and Redfish School.
- The watershed has been logged on both sides of the valley (Drawing 05).
- Previous studies have highlighted the presence of large boulders and debris levees near the fan-delta apex. The presence of such boulders implies that a large historical debris flow event occurred at an unknown time since the area was deglaciated (see Section 6.1).
- Water levels at the toe of the fan-delta are influenced by the reservoir levels on Kootenay Lake.
- Approximately 350 m upstream of Highway 3A, a resident recalls a landslide coming down on the left bank, which pushed the creek to the south. According to the resident, the underlying “blue clay” may have acted as an aquitard (Drawings 02A, 02B).

## Geohazard History

*Redfish WSC stream gauge, 2002 (Copyright Province of British Columbia. All rights reserved. Reproduced with permission from the Province of British Columbia)*

*Mouth of Redfish Creek, 1975 (Image I-19895 courtesy of the Royal BC Museum and Archives)*

**June 2019 -** Lighting sparked a small wildfire between Redfish Creek and Laird Creek

**June 2012 -** Largest flood on record (1968 to 2016) at Redfish Creek gauge (12.3 $m^3/s$); residents concerned about potential avulsion upstream of bridge. Interpreted to be a debris flood based on observations of in-channel sediment mobilization and bank erosion

**June 2011 -** Second largest flood on record at gauge (11.7 $m^3/s$)

**2006 -** Landslide deposited roughly 1000$m^3$ of sediment into creek approximately 4 km upstream of fan apex

**Mid-2000s -** Resident recalls a landslide coming down on the left bank, which pushed the creek to the south. Tree stumps from slide are still evident in the creek in 2019. The landslide was triggered when sewage test holes were dug into gravel. According to the resident, the underlying "blue clay" may have acted as an aquitard

**August 2002 -** Approximately 2 ha wildfire in upper watershed (not included in GeoBC dataset)

**November 13, 1999 -** Fall flooding due to rain on snow storm event (6.6 $m^3/s$)

**March 27, 1997 -** Landslide deposited sediment into the creek in upper watershed

**Approximately 1990 -** Two landslides observed in the upper watershed

**1968 -** Third largest flood on record at gauge (11.2 $m^3/s$)

**1966 -** Survey verifies creek near its present channel on fan

**Pre-1952 -** Fresh event deposit visible in air photo

**Pre-1939 -** Fresh sediment deposit in channel visible in air photo

**1910 -** Survey shows creek up to 80 m southwest of its present channel. BGC notes that this survey location may be erroneous, as this location could not be verified in historical aerial photographs or from lidar interpretation

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

## Mitigation

**1975 -** Bridge over Redfish Creek on Highway 3A widened and concrete deck constructed

**Late 1960s to early 1970s -** Resident notes of Ministry of Highways excavating sediments out of the stream and placing them on the side of the creek.

**1935 -** 40-foot steel I-beam bridge constructed across Redfish Creek

## Development

**2002 to 2017 -** Logging in watershed

**1992 to 2002 -** West Arm Demonstration Forest in Redfish Creek operated by BC Ministry of Forests

**1987 -** Redfish School opened

**1982 -** Kokanee spawning channel constructed in Redfish Creek with funding from the Habitat Conservation Trust Fund and the Nature Trust of BC

**August 1979 -** Province of BC leases property near the mouth of Redfish Creek from the National Second Century Fund of BC to preserve valuable spawning grounds for Kokanee

**Late 1960s through early 1970s** - Logging and forestry road development in watershed

**1938 -** Corra Linn Dam activated downstream of Redfish Creek

**1925 -** Approval granted for the development of the Harrop-Procter ferry with dock on Redfish Creek fan

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

**Figure 4-1. Summary of recorded geohazard, mitigation, and development history at Redfish 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 Redfish Creek. Figure 5-1 shows the workflow to develop frequency-magnitude (F-M) relationships for Redfish Creek and other flood and debris flood prone creeks in the RDCK. In addition to the flood and debris flood assessment, the potential for a debris flow originating on a tributary upstream of the fan-delta apex was assessed and modelled as described in the coming sections.

## 5.1. Debris Flood and Debris Flow Frequency Assessment

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

### 5.1.1. Air Photo Interpretation

Air photos dated between 1929 and 2006 were examined for evidence of past sediment transport events on Redfish 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 (Section 4.3).

### 5.1.2. Dendrogeomorphology

Six tree core samples were collected for dendrogeomorphological analysis from Redfish Creek (Drawings 02A, 02B). Characteristics of the samples including the tree type, minimum establishment date[8], and features that indicate physical damage to the tree are presented in the results section (Section 6.2.2). The presence of features indicating a tree sustained damage in a given year can supplement the historical records, and air photo interpretation in the development of a record of historical events, as well as the extents of such events.

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

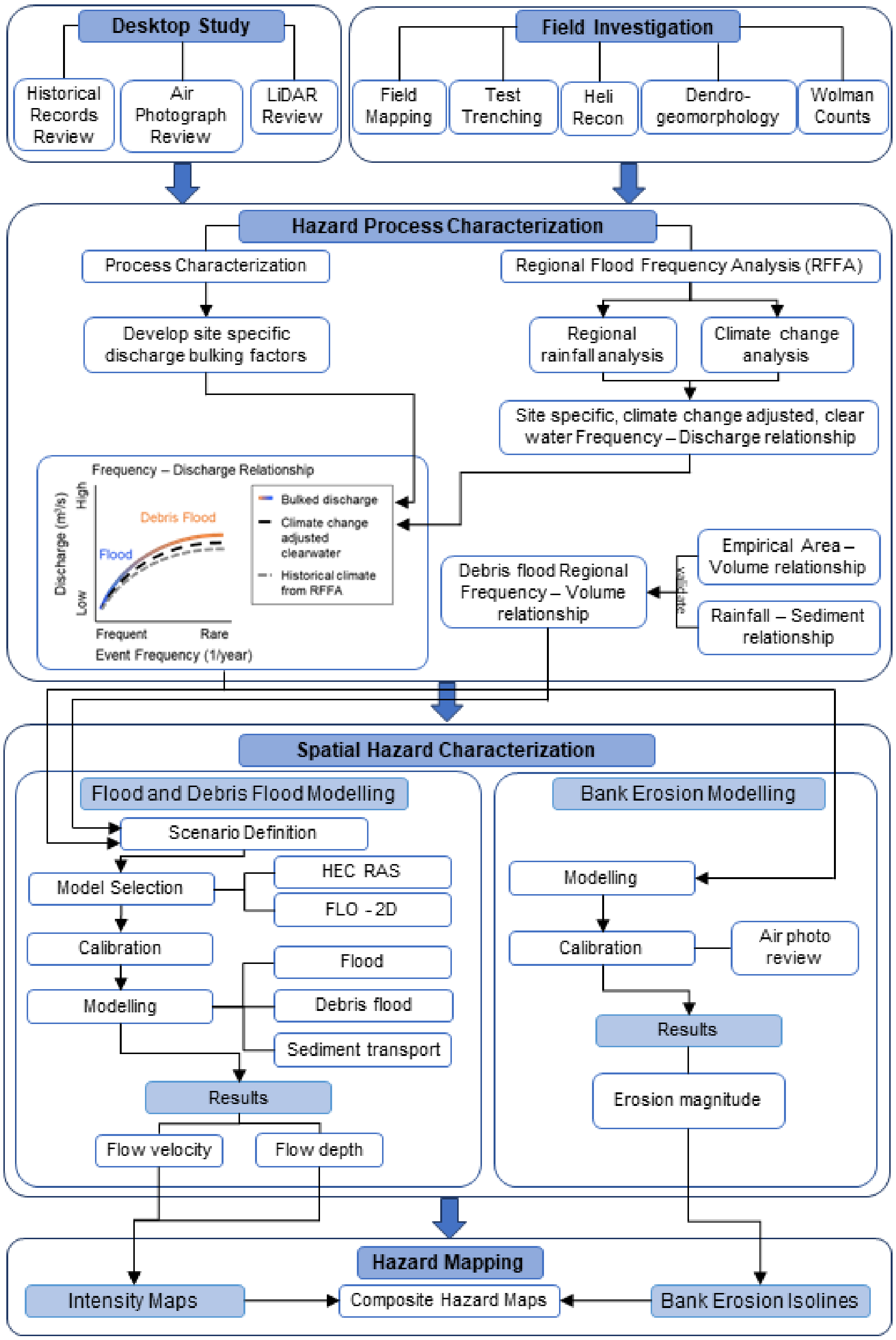



**Figure 5-1. Flood and debris flood prone steep creeks workflow used for developing frequency-magnitude relationships, modelling, and preparing hazard maps.**

## 5.2. Peak Discharge Estimates

### 5.2.1. Clearwater Peak Discharge Estimation

Peak discharge (flood quantile) estimates were calculated using a station flood frequency analysis (FFA) because historical streamflow data are recorded at the *Redfish Creek near Harrop* (08NJ061) hydrometric station maintained by the Water Survey of Canada. The peak discharge estimates calculated at the hydrometric station were applied directly to the Redfish Creek watershed because the hydrometric station is located approximately at the outlet. The peak discharge estimates for Redfish Creek were compared to results using a regional FFA based on the index-flood method and with historical estimates published by previous studies (e.g., NHC, 1990; Apex, 2016; DES, 2011; and PGS, 2016). For the Regional FFA, the Redfish Creek watershed was assigned to the 4 East hydrologic region for watersheds less than 500 $km^2$ based on its watershed characteristics. The methodology for the Regional FFA as well as the estimation of peak discharge at the hydrometric station are described in Section 3 of the Methodology Report (BGC, March 31, 2020b).

### 5.2.2. Climate-Change Adjusted Peak Discharges

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

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

### 5.2.3. Sediment Concentration Adjusted Peak Discharges

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

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

BGC assessed Redfish 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 clearwater discharges need to be bulked accordingly. To produce a bulked frequency-discharge relationship, a bulking factor was applied to the peak discharge for each return period, based on sediment availability and debris flood process type. The bulked frequency-discharge relationship was then used in numerical runout modelling.

In addition to the 20- to 500-year return period debris floods, a 500-year return period debris flow was modelled on Redfish Creek because of the observation of a large debris flow boulder lobe on the upper fan-delta (Section 5.5).

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 (Rickenmann, 2001). A detailed discussion of the methodology is provided in Section 2 of the Methodology Report.

## 5.4. Numerical Debris Flood Modelling

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

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

9 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 HEC-RAS and FLO-2D models; 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 | FLO-2D |
|---|---|---|
| Topographic Input | Lidar (2018) | Lidar (2018) |
| Grid cells | Variable (2- 20 m) | 5 m |
| Manning' n | 0.12 (channel), 0.02 (main roads), 0.1 (fan-delta) | 0.06 (channel), 0.02 (main roads), 0.1 (fan-delta) |
| Upstream boundary condition | Steady Flow ($Q_{20}$ and $Q_{50}$) | Steady Flow ($Q_{200}$ and $Q_{500}$) |
| Downstream boundary condition | Steady stage at Kootenay Lake (534.6 m) | |

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

A series of modelling scenarios were developed for Redfish 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.

Dikes were removed from topography when the bank erosion was predicted to reach the dike footprint and the critical shear stress to shear stress ratio reached or exceeded two ($\tau/\tau_c \geq 2$). For Redfish Creek, the following flood protection or weir structures were assumed eroded away for the 200- and 500-year modelled return periods: both weirs, RFS-FP-02, RFS-FP-03 and RFS-FP-04.

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

## 5.5. Numerical Debris Flow Modelling

Debris flows were modeled on Redfish Creek because of the observation of a large debris flow boulder lobe on the upper fan-delta (Figure 5-2). In addition, a conspicuous feature was located on lidar imagery at an elevation of approximately 1150 m in the upper first eastern tributary (Tributary J, Drawing 03) which is confluent with Redfish Creek approximately 1.1 km upstream of the fan-delta apex. This feature is a well-defined depression outside of the current channel with an approximate volume of missing sediment of 85,000 $m^3$. This feature is interpreted to be the legacy of a static liquefaction failure in glacial sediments. It is not believed to be a retrogressive erosional feature as it does not display the typical dendritic upstream fingering. For the purpose of modelling, the missing sediment volume was further bulked by another 5000 $m^3$ due to sediment entrainment in the 700 m long reach of the tributary leading to Redfish Creek (assumed entrainment rate of 7 $m^3/m$). The corresponding peak discharge was calculated via an equation developed by Bovis and Jakob (1999) that relates peak discharge to total volume for coarse-granular debris flows (Equation 5-1).

$$Q_{max} = (0.036\,V)^{0.901} \quad \text{[Eq. 5-1]}$$

Using 90,000 $m^3$ total debris flow volume, the expected peak discharge is approximately 1400 $m^3/s$, which was used as model input.

The event return period was conservatively estimated to be associated with a 500-year return period event as BGC were unable to find datable material to establish an F-M relationship for debris-flow events on this creek.

**Figure 5-2. Boulder lobe on the upper Redfish Creek fan-delta estimated to be hundreds of years old. BGC photograph of July 10, 2019.**

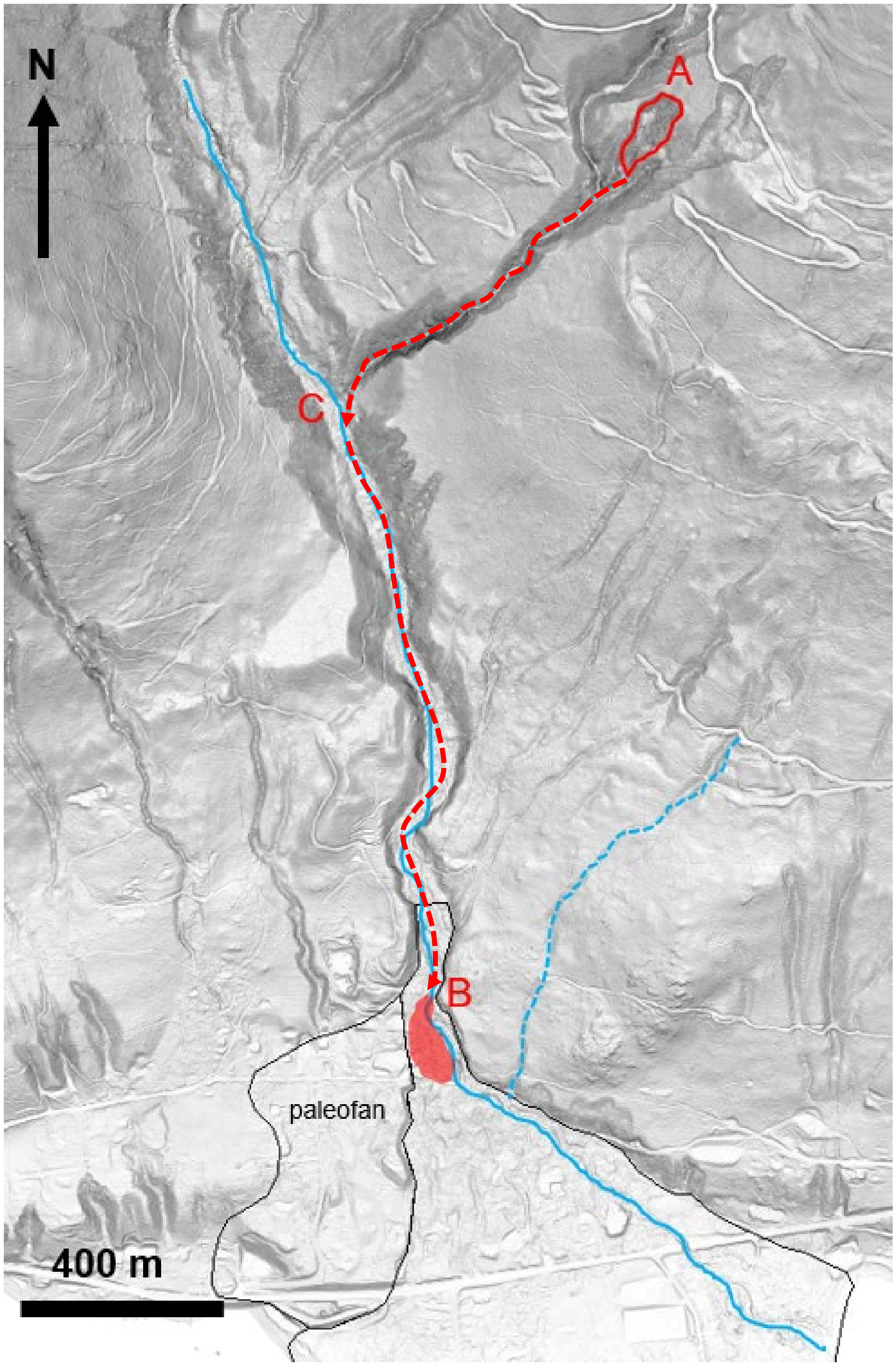



**Figure 5-3. Screenshot of the Redfish fan-delta and tributary with landslide scarp (A) to which the debris flow deposit at location B is attributed. The debris flow model was started with a total volume of 90,000 $m^3$ and a peak flow of 1400 $m^3/s$ at location C. Also shown is the potential path of a small debris flow (blue dashed line) that could block Redfish Creek channel on the fan-delta.**

Modelling was completed using FLO-2D, whose merits have been discussed in the previous section.

### 5.5.1. Basic Setup and Input Parameters

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

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

Table 5-2 summarizes the basic input parameters that were used to set up the models.

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

| Parameter | | Value |
|---|---|---|
| Manning's n | Fan-delta | 0.1 |
| | Streets | 0.02 |
| | Channel | 0.06 |
| Floodplain Limiting Froude number | Debris flows | 2 |
| Sediment concentration (by volume) | Debris flows | 50% |
| Surface detention[10] | | 0.03 m |

BGC conservatively assumed that there is negligible infiltration on fan-deltas.

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

### 5.5.2. Sediment Model Setup and Calibration

In FLO-2D, sediment and water inputs are defined using inflow hydrographs, which can be assigned to grid cells at the fan-delta apex. The peak discharge of the hydrograph is changed between model scenarios to model different event sediment volumes. The debris-flow input hydrographs use a constant hydrograph shape and sediment concentration (50%), and the length of the hydrograph is adjusted to match the estimated sediment volume and peak discharge. In general, because of the high peak discharges, the hydrographs are very short (<10 minutes). The inflow hydrograph parameters are summarized in Table 5-3 The sediment volume was calculated by measuring the volume missing in the lidar from a previous event as described and shown in Section 5.5 above.

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

**Table 5-3. Simulated debris-flow scenario volume and peak discharge.**

| Return Period (years) | Sediment volume ($m^3$) | Peak discharge at fan-delta apex ($m^3/s$) |
|---|---|---|
| 500 | 90,000 | 1400 |

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

For Redfish Creek, the above-described undated event was used for calibration. BGC used the event delineations shown on Figure 6-1 and deposition depths from field observations to calibrate the models. The rheological parameters are presented in Table 5-4.

**Table 5-4. Rheological parameters**

| Parameters Set | Viscosity Coefficient | Viscosity Exponent | Yield Stress Coefficient | Yield Stress Exponent |
|---|---|---|---|---|
| Aspen Natural Soil | 0.00136 | 28.4 | 0.152 | 18.7 |

These parameters match the Aspen Natural Soil rheology from the FLO-2D reference manual (FLO-2D, 2017). The rheology was estimated iteratively through attempting different combinations until the modeled debris flow extent was similar to the observed boulder lobes as mapped in the field. The Aspen Natural Soil rheology was closest to the observed boulder distribution realizing that it is rather difficult to exactly reconstruct an event that has occurred likely hundreds of years ago with substantial erosion of the event since its occurrence.

## 5.6. 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 six creek cross-sections between the fan-delta apex and the mouth of the creek. The assessment methods are outlined in Section 2 of the Methodology Report. Sediment size sample results used as inputs to the modelling are included in Appendix C. The location of each bank erosion cross-section is delineated on Drawings 02A, 02B. Refer to Appendix D for the full list of air photos consulted during the calibration process.

## 5.7. 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 Redfish Creek: debris flood/flow model result maps and a composite hazard rating map. The model result maps support emergency planning and risk analyses, and the composite hazard rating map supports communication and policy implementation, as described further below.

### 5.7.1. Debris Flood and Debris Flow Model Result Maps

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

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

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

### 5.7.2. Composite Hazard Rating Map

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

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

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

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

where v is flow velocity (m/s), $d_f$ is the fluid's flow depth (m), $\rho_f$ is the fluid density (kg/m$^3$) to obtain a unit of force per metre flow width for the three left terms in Equation 5-2 and $P(H)$ is the annual probability of the geohazard. The unit of $IIF$ is then Newton or kilo Newton per metre per year (kN/m per yr).

Equation 5-2 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 5-4).

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 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 5-4 displays a wider range of return periods and intensities than are relevant to debris flood and debris flow hazards on Redfish 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 | | | | | |

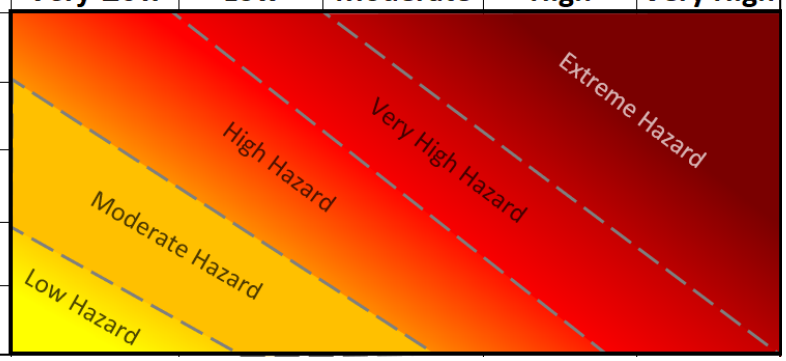



**Figure 5-4. Simplified geohazard impact intensity frequency matrix.**

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 for elements of concern, which also depends on their vulnerability and their being present in the hazard area at the time of impact.

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

# 6. RESULTS

## 6.1. Hydrogeomorphic Process Characterization

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

- The average channel gradient above the fan-delta apex is 15% (Drawing 03), which is insufficient for sustained debris flow transport. Tributary A has an overall gradient of 17% before it meets Redfish Creek 5 km above the fan-delta apex, from where on the gradient is about 15% to the fan-delta.
- The average fan-delta gradient of 12% which within the range of debris flows with high bedload transport rates.
- The west side of the fan-delta is dissected by a number of small, shallow avulsion channels (Drawing 06).
- The surficial expression of previous fan-delta deposits (sheets of gravel) are typical of debris floods.
- Accounts of previous flood events and analysis of historic air photos (see Section 4.3) are consistent with debris-flood activity due to associated erosion and observed movement of sediment in air photos.

Together, this evidence indicates that Redfish Creek is subject to supply unlimited Type 1 debris floods for lower return periods (20- and 50-year). For higher return periods (200- and 500-year), Type 2 debris floods are interpreted as the dominant process. The presence of a debris flow tributary (Redfish Creek Trib J) approximately 1 km upstream of the fan-delta apex (Drawings 03, 05) indicates that Type 3 debris floods are possible. BGC compared the anticipated peak discharge of a Type 3 debris flood with the climate-adjusted bulked discharge for a Type 2 debris flood and the latter was greater, and thus was treated as the dominant hazard.

While the preponderance of evidence suggest that debris floods are the dominant hydrogeomorphic hazard on the fan-delta, multiple boulder lobes and levees were identified on the west side of Redfish Creek during BGC's field visit in July 2019. The boulders observed in lobes and levees were primarily granitic and rounded. Figure 6-1 shows the locations of the boulder lobe observations and Table 6-1 shows the images and what was observed at each location. Of note is that Table 6-1 refers to dendrogeomorphology results that are described in more detail in Section 6.2.2.

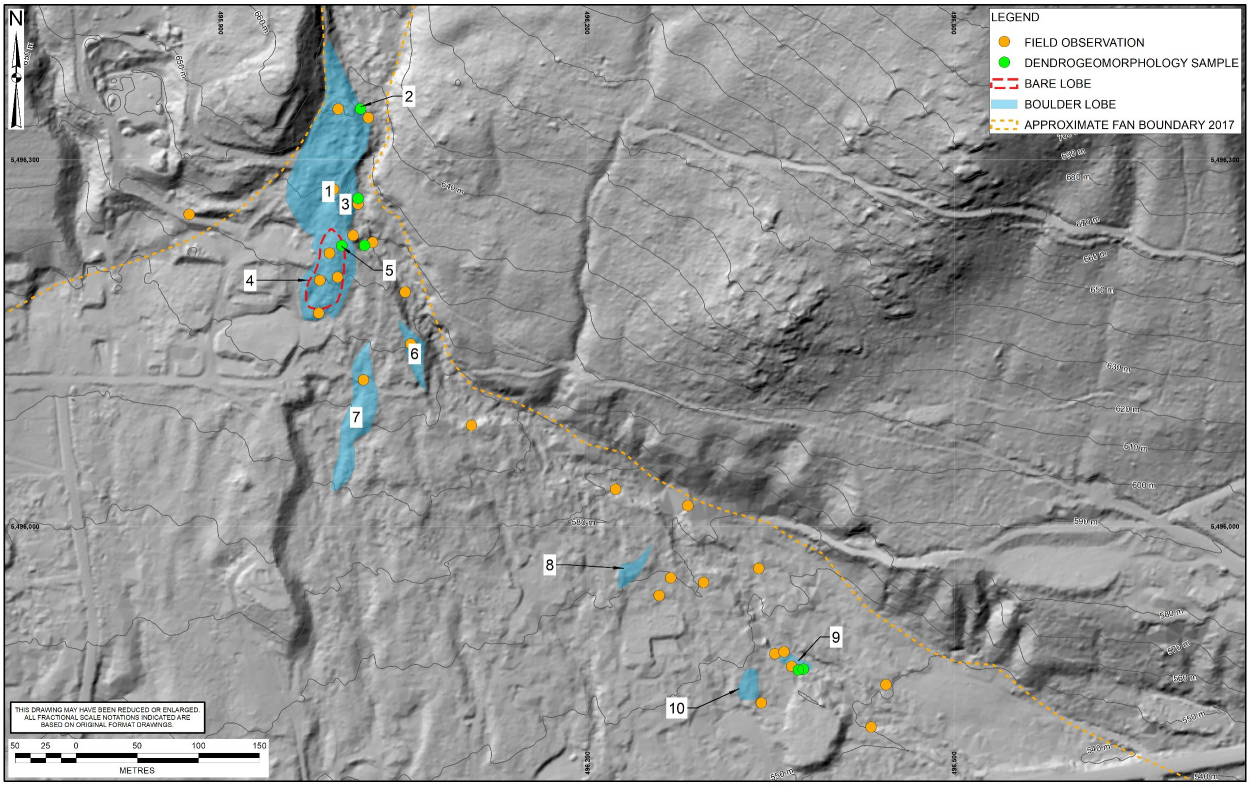
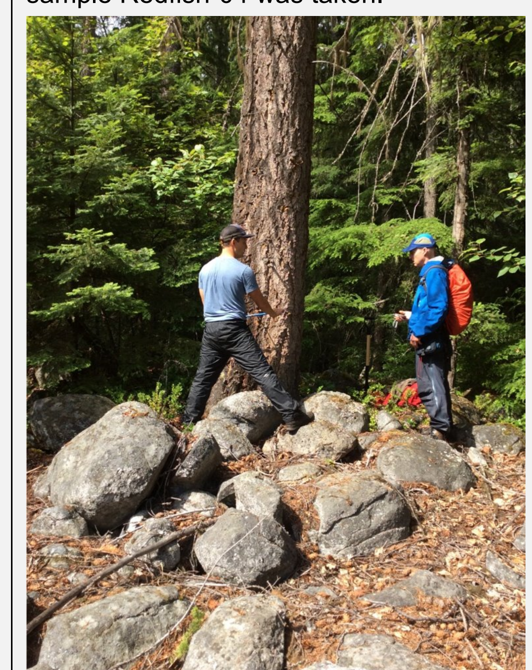
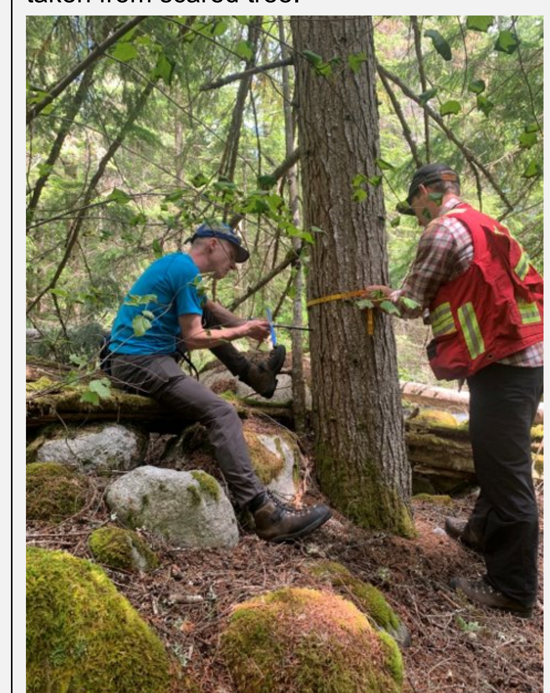



**Figure 6-1. Boulder lobe locations observed during BGC's field visit in July 2019.**

**Table 6-1. Boulder lobes observed at Redfish Creek.**

| Location | Comment | Image | Location | Comment | Image |
|---|---|---|---|---|---|
| 1 | Multiple boulder lobes and levees delineated blue shading. | See Figure 6-1. | | | |
| 2 | Minimum age of boulder deposit from dendrogeomorphology sample (Redfish-03) is 73 years (oldest visible ring in 1946). Boulder diameter up to 2 m. | Looking downslope (south) along boulder levee.  | 4 | Approximate outline of bare lobe (i.e., no trees) of boulders. Boulders are 0.3 to 2.5 m in diameter and overgrown with moss. “Weathered rind” can be peeled off some boulders.<br>Also visible in 1929 air photo in Drawing 04A. | Field personnel standing on granitic boulder where “weathered rind” was peeled off by hand (see brown patch).  |
| 3 | Minimum age of boulder levee from dendrogeomorphology sample (Redfish-02) is 106 years (oldest visible ring in 1913). | Looking upslope (north) from about mid-point of the bare boulder lobe indicated with red dashed line in Figure 6-1.   | 5 | Minimum age of bare boulder deposit from dendrogeomorphology sample (Redfish-04) is 104 years (oldest visible ring in 1915). | Looking north at largest pine tree on at upper edge of bare boulder deposit where dendrogeomorphology sample Redfish-04 was taken.  |

| Location | Comment | Image | Location | Comment | Image |
|---|---|---|---|---|---|
| 6 | Boulder lobe on the right bank of Redfish Creek. Boulders from 0.5 to 2.0 m in diameter. | Looking downstream (southeast) along boulder lobe located on right bank of Redfish Creek.<br> | 8 | Most distal boulder lobes observed by BGC in July 2019. Change in vegetation noted. Lobes are 0.5 m tall. | Looking downstream (southeast) along boulder levee on right bank of Redfish Creek. Scared tree is shown in Photo below.<br><br> |
| 7 | Boulder lobe with 2 to 3 m diameter boulders. | Looking upslope (north) at large boulders. Note field personnel for scale.<br> | 9 | Debris flow levee on the right bank. Boulders surrounding the tree. Minimum age of the levee from dendrogeomorphology samples (Redfish-05 and Redfish-06) are 63 years (oldest visible ring in 1956) and 65 years (oldest visible ring in 1954), respectively. Redfish-06 sample cored through a suspected scar with moderate TRDs noted in year 1983 (36 years ago), which may indicate when the tree was impacted.<br>BGC notes that the levee and/or the later tree impact be due to a debris flow but could also be related to:<br>A. Instream works (sediment cleanout, side casting), rather than debris flow activity. See Figure 4-1 mitigation comment: “Late 1960s to early 1970’s – Resident notes of Ministry of Highways excavating sediments out of the stream and placing them on the side of the creek for approximately 500 m to 600 m along the creek”, or<br>B. Works related to the nearby water intake.<br>NHC/Thurber (1990) did not report any evidence of recent activity. | Looking downstream (southeast) at scared tree located on boulder levee on right bank of Redfish Creek. Dendrogeomorphology sample Redfish-06 was taken from scared tree.<br> |

| Location | Comment | Image | Location | Comment | Image |
|---|---|---|---|---|---|
| 10 | Boulder lobe with 0.5 to 1.0 m diameter boulders. | Looking downslope (southeast) at moss-overgrown boulder lobe where field personnel is standing.  | | | |

## 6.2. Debris Flood Frequency Assessment

Results of the debris flood F-M assessment are presented in this section. Based on historical accounts, field evidence, and analysis of remote sensing data, Redfish Creek is believed to be subject to supply-limited Type 1 debris floods for lower return periods (20- and 50-year), Type 2 debris floods at a 200-year, return period, and Type 3 debris floods for higher return periods (500-year) assessed, due to the presence of a debris flow tributary approximately 1 km upstream of the fan-delta apex (Drawing 05).

### 6.2.1. Air Photo Interpretation

At least four notable hydrogeomorphic events have occurred since 1929 as identified from the air photo interpretation. Drawings 04A and 04B show air photos with events delineated. The interpreted deposition area and characteristics of the sediment transport events are described in Table 6-2. BGC interprets that all the noted events are likely Type 1 debris flood events due to the erosion and observed movement of sediment in air photos. Evidence of debris-flood activity during the 1999, 2011, and 2012 events (Section 4.3) was not observed in the air photo record as the available air photos are from multiple years after the events (2006, 2017) and the channel is well vegetated.

The deposition areas delineated from the air photos were combined with the Scheidl and Rickenmann (2010) debris flood area-volume relationship to estimate event volumes (Section 2 of the Methodology Report).

**Table 6-2. Summary of Redfish Creek sediment transport events in air photo record (1929-2014).**

| Event Year[1] | Air Photo Year | Deposition Area ($m^2$) | Estimated Event Volume ($m^3$) | Event Characteristics |
|---|---|---|---|---|
| 1929-1939 | 1939 | 12,600 | 3,000 | Fresh sediment deposited in channel from mid to distal fan-delta. |
| 1945-1952 | 1952 | 8,600 | 2,000 | Fresh sediment deposited in channel, potential avulsion near channel outlet. |
| 1968 | 1974 | 12,300 | 3,000 | Fresh sediment deposited from fan-delta apex to channel outlet, sediment plume into Kootenay Lake. |
| 1997 | 1997 | 17,300 | 5,000 | Sediment deposited along channel, mostly around creek outlet at Kootenay Lake. |

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.

### 6.2.2. Dendrogeomorphology

Results for the 6 dendrogeomorphological samples on Redfish Creek are presented in Table 6-3 and tree locations are shown on Drawings 02A, 02B.

**Table 6-3. Summary of Redfish Creek dendrogeomorphology sample features.**

| Sample[1] | Tree type | Minimum establishment date (first ring) | Features[2] |
|---|---|---|---|
| Redfish-01 | Cedar | 1900 | Pith not reached due to rot in centre of tree |
| Redfish-02 | Pine | 1913 | Strong TRDs in 1968 |
| Redfish-03 | Douglas Fir | 1946 | Strong TRDs in 2016 |
| Redfish-04 | Pine | 1915 | Moderate TRDs in 1940, 1958, 1959 and 1994 |
| Redfish-05 | Spruce | 1956 | Strong TRDs in 2000 |
| Redfish-06 | Hemlock | 1954 | Moderate TRDs in 1983 |

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

The dendrogeomorphological analysis did not identify any trees sampled with strong TRDs or scars; therefore, no events can be inferred from the dendrogeomorphology analysis alone for this creek. Instead, the analysis has been used to corroborate known events to support the development of the F-M relationship as well as to support assessment of the boulder lobes and debris flow levees identified in the proximal fan-delta (Table 6-1).

### 6.2.3. Summary

Notable Type 1 debris floods have occurred approximately every 12 to 14 years on Redfish Creek (Table 6-4). Sediment deposition depths back calculated from the Scheidl and Rickenmann (2010) equation give an average depth of 0.2 to 0.3 m for the four events delineated from air photos.

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

| Event Year | Description |
|---|---|
| 1929 – 1939 | Fresh sediment deposited in channel from mid- to distal fan-delta. |
| 1945 - 1952 | Fresh sediment deposited in channel, potential avulsion near channel outlet. |
| 1968 | Third largest flood on record at gauge. |
| 1997 | Landslide deposited sediment into the creek in upper watershed. Sediment deposited along channel mostly around creek outlet at Kootenay Lake as observed in air photo. BGC does not know if these two events are connected. |
| 1999 | Fall flooding due to rain on snow event. |
| 2011 | Second largest flood on record at gauge. |
| 2012 | Largest flood on record. Residents observed in-channel sediment mobilization and bank erosion |

## 6.3. Peak Discharge Estimates

Peak discharges for different return periods were estimated to serve as input to the numerical modelling. For debris floods (20-year to 500-year return period), the workflow entailed an estimate of clearwater peak discharges, followed by a climate-change adjustment, and finally an adjustment for sediment bulking. For the 500-year return period debris flow, the workflow entailed estimating the volume of the debris flow based on the source area from lidar, bulking the volume using a sediment entrainment rate, and then calculating the associated peak discharge using the Bovis and Jakob (1999) equation that relates peak discharge to total volume for coarse-granular debris flows. Results of the analysis are presented in Figure 6-2 and Table 6-5. With respect to these results, the reader should note the following:

- Historical peak discharges are based on an FFA at the hydrometric station (08NJ061).
- The climate change impact assessment results were difficult to synthesise in order to select climate-adjusted peak discharges on a site-specific basis. Consequently, a 20% increase in peak discharge was adopted as per Section 4 of the Methodology Report (BGC, March 31, 2020b).
- The climate-adjusted, bulked peak discharges were used in the numerical modelling of debris floods.
- The debris-flow discharge was used in the debris flow modelling.

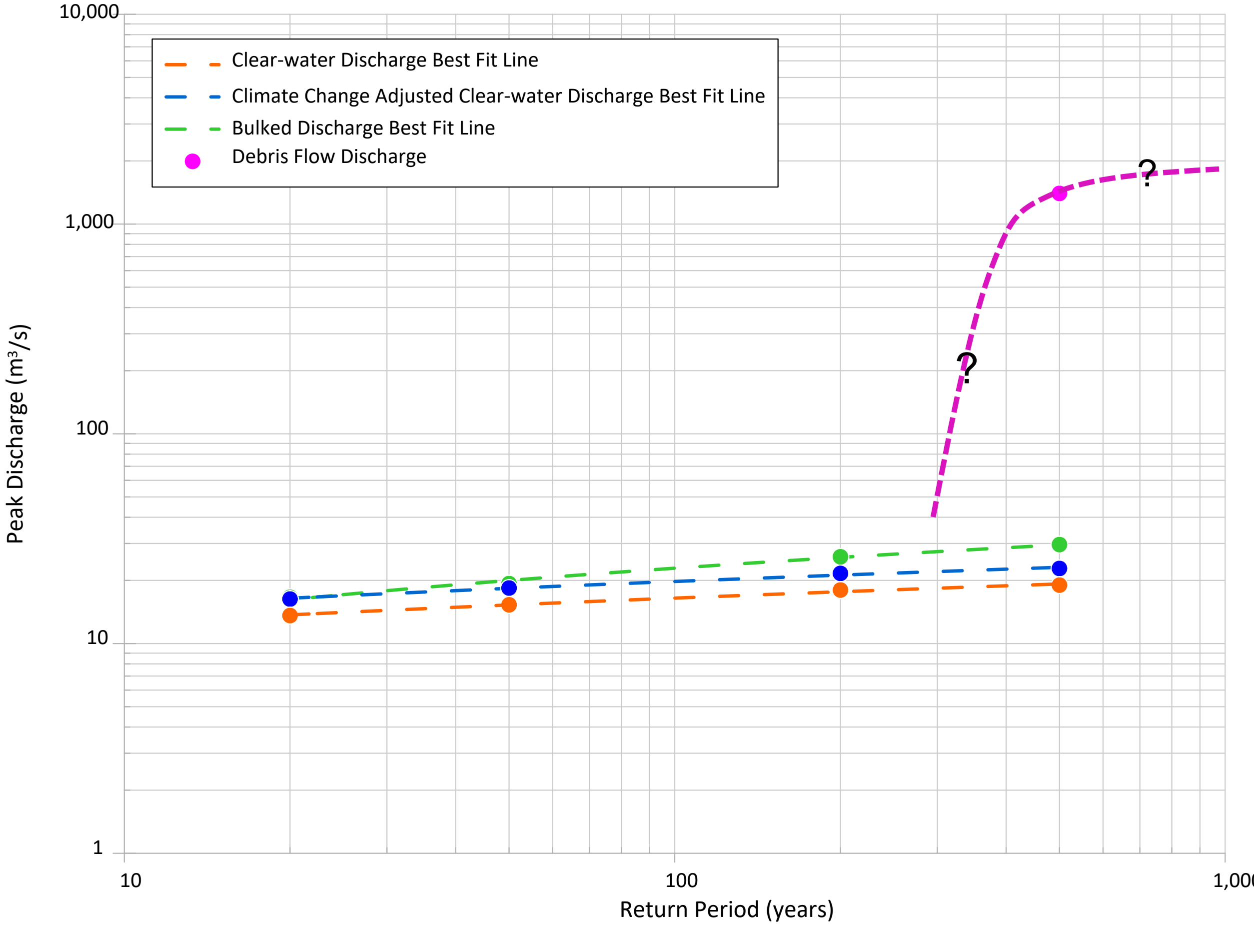



**Figure 6-2. Frequency-discharge relationship for Redfish Creek. The upper purple dashed line indicates a hypothetical debris-flow frequency-magnitude curve with a pronounced bend indicating supply limitations at high return periods.**

**Table 6-5. Bulking factors for each return period's debris flood peak discharge and justification.**

| Return Period (years) | AEP | Historical Peak Discharge ($m^3/s$) | Climate-adjusted Peak Discharge ($m^3/s$) | Bulking Factor | Bulked Peak Discharge ($m^3/s$) | Debris Flood Type | Comments |
|---|---|---|---|---|---|---|---|
| 2 | 0.5 | 10 | 10 | 1.0 | 10 | n/a | Flood |
| 20 | 0.05 | 15 | 15 | 1.02 | 15 | 1 | Few active landslides in lower 20% of watershed |
| 50 | 0.02 | 15 | 20 | 1.05 | 20 | 1 | Increased landslide activity from "few" to "several" in lower 20% of watershed, some woody debris. |
| 200 | 0.005 | 20 | 20 | 1.2 | 25 | 2 | Debris flow tributary exists 1 km upstream of fan-delta apex (Drawing 05). |
| 500 | 0.002 | 20 | 25 | 1.3 | 30 | 3 | Investigated the potential peak flows associated with a landslide dam outbreak flood (LDOF) on the debris flow tributary creek upstream. However, peak discharges estimated for the sediment bulked, climate-change adjusted peak flows were higher than the LDOF scenario, and, therefore the modelling considered the bulked, climate adjusted peak flows to be conservative. |

Note:

1. Refer to Section 2 of the Methodology Report 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 Redfish Creek debris floods. These included air photo analysis of sediment deposits, dendrogeomorphology, sediment transport equations, and application of regional relationships for fan-delta area – sediment volume and watershed area – sediment volume. The different methods were compared. Debris volume results from the air photo analysis for debris floods are shown in Table 6-2 and the results of the regional relationship and sediment transport equations are shown in Table 6-6. The volume estimates from the Rickenmann (2001) analysis are not credible for debris floods given that events greater than 50,000 m$^3$ do not appear in the air photo record and are 11 to 13 times higher than those obtained from the regional F-M debris flood analysis. They are also four times higher than the 500-year return period debris flow volume. This overestimate for debris flood volumes could be attributable to either BGC's hydrographs not being representative, or the critical discharge being underestimated (Section 2 of Methodology Report). Therefore, for numerical modelling of debris floods, the regional relationships were applied as they appear to provide more reasonable results. Sediment volumes for the 20- and 50- year return period events are associated with Type 1 debris floods, while the sediment volumes for the 200- and 500- year return period events are associated with Type 2 debris floods.

**Table 6-6. Summary of event volumes for debris floods for each return period based on the regional frequency-volume curve and Rickenmann (2001) analysis.**

| Return Period (years) | Event Volume (m$^3$) | |
|---|---|---|
| | Regional Frequency Volume | Rickenmann (2001) |
| 20 | 17,000 | 225,000 |
| 50 | 22,000 | 275,000 |
| 200 | 29,000 | 354,000 |
| 500 | 34,000 | 383,000 |

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

The 500-year return period debris flow was tentatively assessed to have an event volume of 90,000 m$^3$ with a corresponding peak discharge of approximately 1500 m$^3$/s (Section 5.5).

### 6.4.2. Wildfire Effects on Debris Flood Sediment Volumes

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

## 6.5. Numerical Debris Flood and Debris Flow Modelling

A summary of the key observations from the debris flood and debris flow modelling is included in Table 6-7. The model results are presented in Cambio Communities and a representative example from the 200-year return period is included in Drawing 07.

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

**Table 6-7. Summary of modelling results.**

| Process | Key Observations |
|---|---|
| Clearwater inundation | • Flow leaves the channel approximately 400 m upstream of Highway 3A, to the east and west, in the 200- and 500-year return period scenarios.<br>• Downstream of the highway, flow spreads to the east and west from the 50-year return period and up. The flow leaving the channel corresponds to the locations of low points identified by BGC (Section 3.5.2).<br>• Some avulsion channels upstream of the highway cause flow to pond against the highway embankment. |
| Sedimentation | • Sedimentation will likely occur on the main avulsion paths as well as the existing channel and will concentrate in the fan-delta area where the lowest gradients persist, and the floodplain has little confinement.<br>• Sedimentation associated with debris flows could reach up to 2.5 m height in the upper fan-delta and 3 m along the lower channel sections. |
| Auxiliary Hazards | • Forest service road instabilities (blocked culverts and fill-slope failures) upslope of the fan-delta at a small unnamed gully could lead to a small debris flow potentially blocking Redfish Creek on the fan-delta.<br>• The fact that Redfish Creek is subject to episodic debris flows makes the creek subject to a variety of auxiliary hazards. Debris (sediment and logs) lobes could direct flows into directions difficult to predict. The highway bridge would likely be destroyed in such scenario and water would likely flow down Highway 3A and then escape towards the south and into the lake. |

## 6.6. Bank Erosion Assessment

The air photo assessment compared available air photos from 1929 to 2006 to determine the historical changes in channel width at the six cross-sections considered in the bank erosion assessment (Drawings 02A, 02B). At Redfish Creek, cross sections 1 and 4 did not have visible banks in the air photos, therefore these sections were excluded from the air photo assessment. Table 6-8 summarizes the maximum channel width change between successive pairs of air photos and the cross-section at which it was observed. The maximum observed change in channel width between two successive air photos on Redfish Creek was 5 m, between 1968 and 1974 at cross-section 6. To provide context for these values, the average current bankfull width is 6 m at the cross sections analyzed. Potential error or uncertainty in these measurements may be introduced by shadows from vegetation, poor image quality, or distortion during rectification. BGC estimates the total error associated with the above factors is less than 5 m.

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

| Air Photo Interval | Maximum Channel Width Change Between Photos (m) | Cross-Section of Maximum Channel Width Change (Drawings 02A, 02B) |
|---|---|---|
| 1929-1958 | 2 | 3 |
| 1958-1968 | 0 | - |
| 1968-1974 | 5 | 6 |
| 1974-1979 | 2 | 2 |
| 1979-1988 | 3 | 5 |
| 1988-1997 | 0 | - |
| 1997-2006 | 3 | 2 |

A summary of the bank erosion model results by return period is outlined in Table 6-9. This table displays the minimum, maximum, and average erosion modelled across all cross-sections considered at each of the four return periods modelled. Cambio Communities shows bank lines indicating the 50% exceedance probability of the modelled erosion (i.e., the bank erosion that is predicted to be exceeded in 50% of the model runs) for each return period as two corridors: the likely erosion corridor and the potential/improbable erosion corridor.

**Table 6-9. Summary of bank erosion model results by return period.**

| Return Period (years) | Minimum Erosion (m) | Average Erosion (m) | Maximum Erosion (m) |
|---|---|---|---|
| 20 | 0 | 3 | 6 |
| 50 | 0 | 6 | 10 |
| 200 | 1 | 11 | 15 |
| 500 | 8 | 21 | 30 |

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

Figure 6-3 shows the 50% percentile modelled bank erosion at each cross-section. The predicted erosion differs between cross-sections based on the cross-section characteristics (e.g., channel geometry, channel slope, $D_{84}$ grain size). Erosion-peaks at cross-section 6 for all return periods except the 200-year, which peaked at cross section 3.

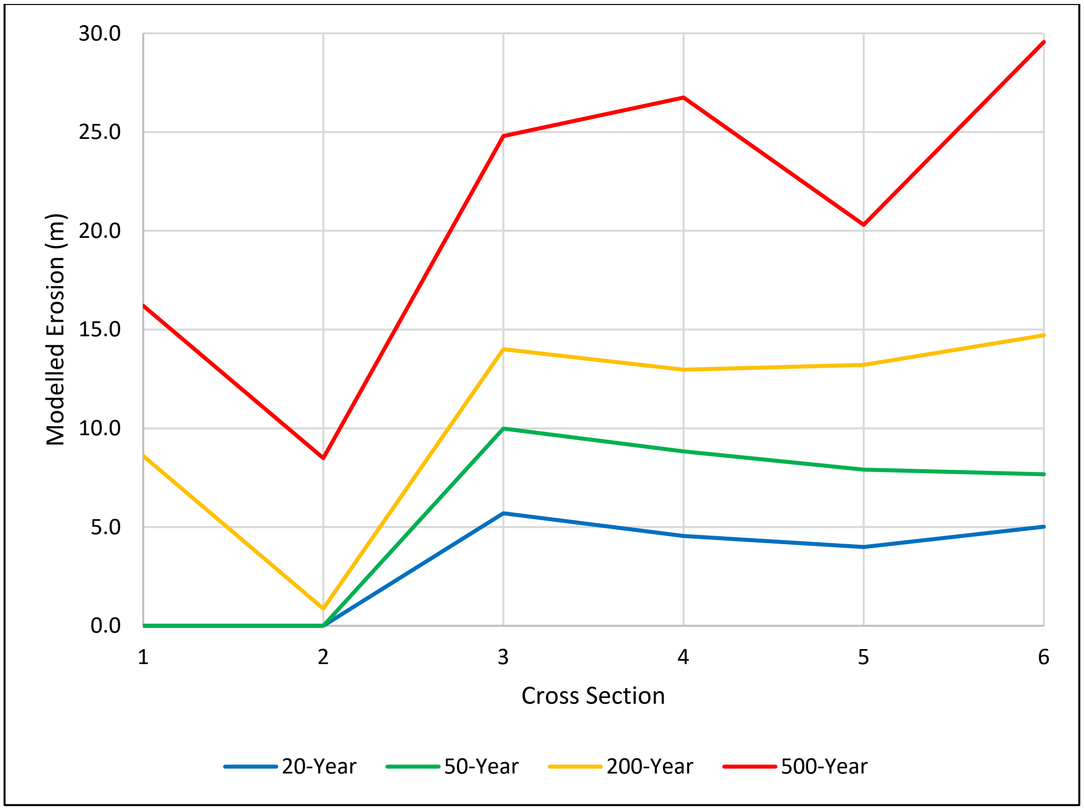



**Figure 6-3. Redfish Creek 50th percentile bank erosion model results at each cross-section.**

All return periods have the potential to impact the bridge abutments at the Highway 3A crossing. Longer-term progressive erosion could impact the property at the east end of Redfish Road.

## 6.7. Hazard Mapping

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

### 6.7.1. Composite Hazard Rating Map

As noted in Section 5.7.2, hazard rating zones shown on the composite hazard rating map reflect categorization applicable to a wide range of hazard types, from clearwater floods to large landslides. The choice of categorization may affect interpretation by the map user and is subject to review and discussion with RDCK.

The composite hazard rating map demonstrates that the majority of the active fan-delta of Redfish Creek is located within the yellow (low) hazard area. Flow that is not confined to the main channel generally spreads across the entire fan-delta. The orange (moderate) hazard area highlights avulsion paths and areas of ponding around the highway. In the confined reach directly downstream of the fan apex, areas adjacent to the main channel have been interpreted to have a moderate hazard due to the unpredictable nature of debris flows. The red (high) hazard area is confined to the channel. The dotted zones indicate areas that will likely be inundated with sediment to depths up to 1 m and up to 3 m in the active channel due to debris floods. During a debris flow event, areas adjacent to the channel could be inundated with up to 2 m of sediment and up to 4 m in the active channel.

### 6.7.2. Comparison with NHC/Thurber (1990)

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

#### 6.7.2.1. Methodological Differences

The NHC/Thurber (1990) assessment considered debris torrents[11], avulsions or channel shifts, and inundation. For each fan-delta investigated, hazard areas were codified between 0 (lowest hazard) and 5 (highest hazard). However, since NHC/Thurber (1990) also included loss of life consequences as a second dimension in their hazard mapping, their hazard maps provided information on relative levels of risk. Specific risk zones were defined as those where individual life loss risk exceeds or falls below specified values. Areas with a hazard (risk) code of 3 or higher were interpreted to have a significant threat to loss of life defined as the annual probability of death of a select individual of > 1:20,000. Figure 6-4 shows the NHC/Thurber risk map for Redfish Creek.

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

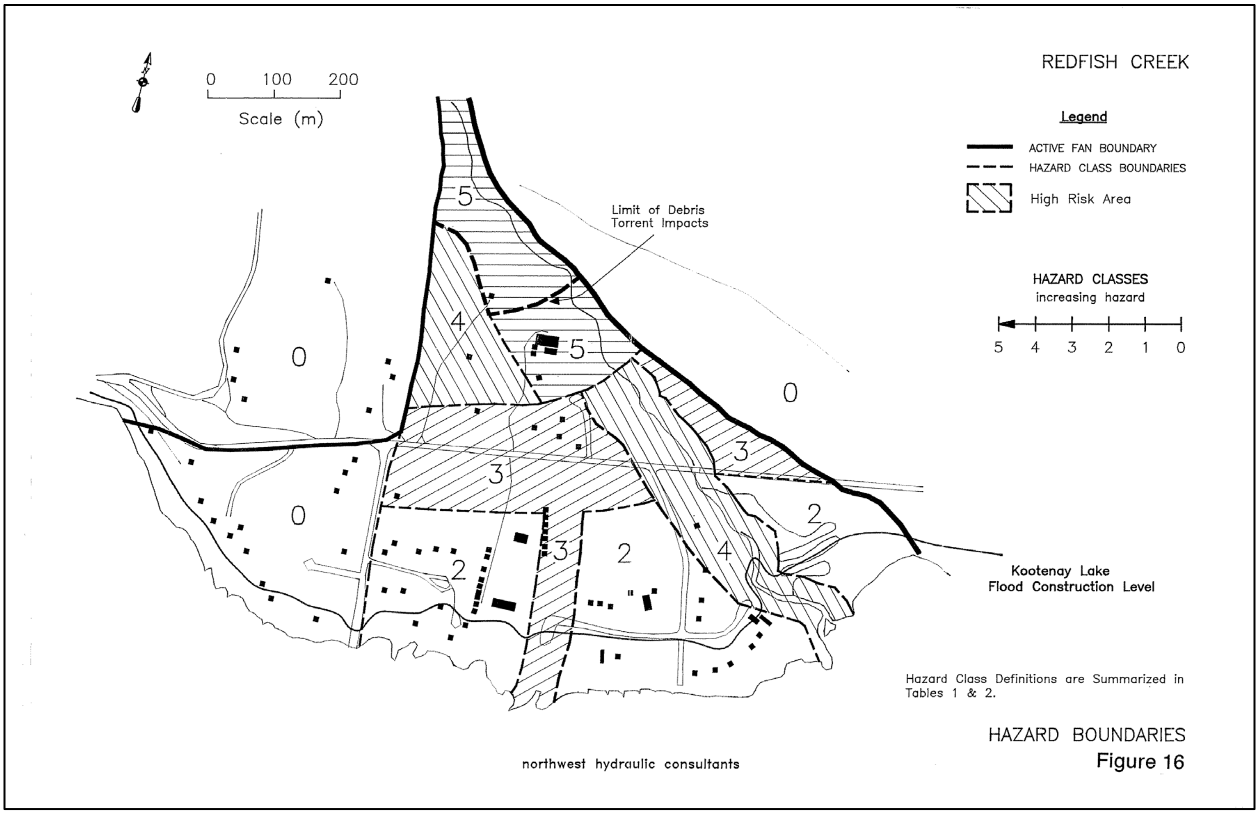



**Figure 6-4. NHC/Thurber's (1990) Redfish Creek individual life risk map. Class 4 and 5 imply individual life loss risk values exceeding 1:10,000. Class 3 1:10,000 to 1:20,000. Class 0, 1 and 2 < 1:20,000.**

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

**Table 6-10. Method comparison between NHC/Thurber (1990) and this report (BGC, 2020).**

| Technique/Data | NHC/Thurber (1990) | BGC (2020) | Comment |
|---|---|---|---|
| Process | Debris torrents (debris flows and debris floods) | Debris floods (20 to 500-year return periods); Debris flows (500-year return period) | BGC encountered evidence of a past debris flow of unknown age and integrated numerical modelling of a debris flow on a Redfish tributary. |
| Process Severity | Classification into debris floods, indirect and direct impacts | Impact quantified and independent of process | BGC (2020) is a more comparable and transparent approach to evaluate impact intensity |
| Topography | 2 m contours | Lidar DEM | Substantially higher resolution in BGC (2020) |
| Fan-delta activity designation | Into “active” and “inactive” | Into “paleofans” and “active” | Given the better DEM resolution, BGC’s classification is a refinement to N/T |
| Return Periods Considered | <100, 100-1000, >1000 | 20, 50, 200, 500 | Return periods greater than 500 years are associated with very high uncertainties and were thus not included in BGC (2020) |
| Frequency Estimates | Historical air photos, maps, records, watershed characteristics | As N/T, but also dendrochronology, 30 years more historical data, flood and debris flood frequency analysis. | Substantially greater effort by BGC (2020) compared to N/T, thus higher confidence in BGC (2020) |
| Magnitude Estimates | Relative assessments of sediment supply. | Two types of sediment transport calculations, regional F-M sediment volume relationships, air photo delineation of deposition area and application of Bovis and Jakob (1999) equation empirical relationships between peak discharges and sediment volumes | Substantially greater effort by BGC (2020) compared to N/T, thus higher confidence in BGC (2020) |
| Probability of Avulsion | Method by Dawdy (1979) to determine probability of avulsion based on historical information and geomorphology | Numerical modelling-assisted with assumptions of bridge and/or culvert blockages at critical locations based on capacity exceedances | Lesser reliance on expert judgement for BGC (2020) and hence more replicable and transparent than N/T. |
| Impact Intensity | Based on flow velocity and depth*. Note that those were estimated, not modelled. | Based on modelled flow velocity, depth and fluid density | The key difference is the association of given impact intensity groupings to severity of impact. |
| Hazard Mapping | Classification into 5 groups based on hazard type, frequency and severity | Based on frequency and impact force (severity) including bank erosion | More transparent approach based on numerical modelling rather than pure expert judgement |
| Risk to Loss of Life | Calculated via standard probability of loss of life for an individual formula | No loss of life risk calculations | In N/T, risk to loss of life calculations were reported under hazard mapping. Risk and hazard are distinctly different. BGC’s (2020) did not attempt to calculate risk to loss of life. |

Note: * See Table 6-11

**Table 6-11. Comparison of NHC/Thurber (1990) and this report (BGC, 2020) hazard mapping methods. Note that the categories of flow depth and flow velocity of NHC/Thurber (1990) do not exactly match the impact force as determined by BGC (2020).**

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

#### 6.7.2.2. Redfish Creek Specifics

NHC/Thurber (1990) indicated that the boulder and debris levees near the fan-delta apex (Section 6.1) were a minimum of 80 years old based on the age of adjacent trees but interpreted the deposits to be significantly older. An event of sufficient magnitude to mobilize boulders of the size identified was interpreted to be an extremely rare event. The fan-delta gradient near the apex (approximately 18%) was interpreted to be sufficient for debris-flow / debris-flood activity. Downstream of the fan-delta apex, the potential for overbank flows in pre-existing flow channels was identified due to low channel banks; however, these flows were directed back to the main channel. The water intake and access road at the fan-delta apex (referred to herein as the “Forestry Bridge” Drawing 06) were identified as a potential avulsion site as modelled by BGC (Appendix E). The hazard classification at Redfish Creek was highest in the proximal fan-delta and along the main channel with an area of elevated hazard at mid-fan-delta and down an avulsion channel west of the main channel (NHC and Thurber, April 1990). In total 48% of the fan-delta was classified as hazard code 3, 4, or 5.

#### 6.7.2.3. Summary

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

# 7. SUMMARY AND RECOMMENDATIONS

## 7.1. Introduction

This report provides a detailed hazard assessment of the Redfish Creek fan-delta. Redfish 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 Redfish Creek.

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

## 7.2. Summary

### 7.2.1. Air Photo Interpretation and Dendrogeomorphology

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

- The largest debris flood visible in the air photo record occurred sometime between 1988 and 1997 as 1997 air photos show an area of freshly deposited debris of approximately 17,300 $m^2$.
- The largest flood events in the gauge record (2012, 2011) are not visible in the air photo record due to the vegetation cover and the time post-event of available air photos.
- Dendrochronological investigations proved unsuitable for the development of the frequency-volume curve as trees on the fan-delta were not old enough to allow spatial extrapolation of old debris flood events.
- At least four notable hydrogeomorphic events have occurred since 1929. BGC interprets that all the noted events are likely Type 1 debris flood events due to their erosion and observed movement of sediment in air photos.

### 7.2.2. Peak Discharge Estimates

In recognition of the impacts of climate change and potential bedload and suspended sediment loads, the clearwater peak flows estimated from an 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 Redfish Creek range from 15 $m^3/s$ (20-year clearwater flood) to 25 $m^3/s$ (500-year clearwater flood).

- Sediment bulking factors of 1.02 (2% increase for the 20-year debris flood) to 1.3 (30% increase for the 500-year return period event) were adopted as input to numerical modelling.
- Consideration of climate change and sediment bulking increase the clearwater discharge estimate from 20 to 30 $m^3/s$ for the 500-year debris flood event, but do not significantly impact the 20-year event.
- Peak discharge of a 500-year return period debris flow was estimated to 1400 $m^3/s$.

### 7.2.3. Frequency-Magnitude Relationships

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

**Table 7-1. Redfish Creek debris flood frequency-magnitude relationship.**

| Return Period (years) | Adjusted Peak Discharge ($m^3/s$) |
|---|---|
| 20 | 15 |
| 50 | 20 |
| 200 | 25 |
| 500 | 30 |

### 7.2.4. Numerical Flood, Debris Flood and Debris Flow Modelling

Two numerical models were employed to simulate the chosen hazard scenarios on the Redfish Creek fan-delta. The two models were complimentary, in that results could be compared to facilitate flexibility in the interpretation of results in consideration of the advantages and shortcomings of the individual models. Table 7-2 provides key observations derived from the numerical modelling.

**Table 7-2. Key findings from numerical modelling of Redfish Creek debris floods.**

| Process | Key Observations |
| --- | --- |
| Clearwater Inundation (HEC-RAS results for all return periods) | • Redfish Creek likely remains in its current channel for return periods up to 50 years except downstream of Highway 3A where flows are prone to escape to the east and immediately upstream of Highway 3A where flows could escape to the west, but likely flow towards the highway bridge opening even for a 20-year event.<br>• Flow leaves the channel approximately 400 m upstream of Highway 3A, to the east and west, in the 200-year and 500-year return period scenarios.<br>• Downstream of the highway, flow spreads to the east and west from the 50-year return period and up. The flow leaving the channel corresponds to the locations of low points identified by BGC.<br>• Some avulsion channels upstream of the highway cause flow to pond against the highway embankment<br>• Avulsions are shallow (mostly less than 1 m).<br>• Developments east of Bryan Road to Kootenay Lake would likely be inundated with water up to approximately 1 m deep. |
| Sedimentation | • Sedimentation will likely occur on the main avulsion paths as well as the existing channel and will concentrate in the fan-delta area where the lowest gradients persist, and the floodplain has little confinement.<br>• Sedimentation associated with debris floods can occur on the eastern fan-delta sector upstream and downstream of the Highway 3A crossing. Deposition depth could be up to 1.5 m for the 200-year or 500-year debris floods and up to 4 metres in upper channel sections.<br>• Sedimentation associated with debris flows could reach up to 2.5 m height in the upper fan-delta and 3 m along the lower channel sections |
| Auxiliary Hazards | • Forest service road instabilities above the fan-delta could come down and block the creek temporarily.<br>• The fact that Redfish Creek is subject to episodic debris flows makes the creek subject to a variety of auxiliary hazards. Debris (sediment and logs) lobes could direct flows into directions difficult to predict. The highway bridge would likely be destroyed in such scenario and water would likely flow down Highway 3A and then escape towards the south and into the lake. Portions of Highway 3A could be eroded. |

The multiple process numerical modelling ensemble approach demonstrates that the key hazards and associated risks at Redfish Creek stem from the multiple avulsion paths the flow takes as the main channel is over capacity at higher return periods as well as the deposition of the sediment across the fan-delta.

### 7.2.5. Bank Erosion Assessment

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

- The erosion predicted by modelling was calibrated with the air photo record, accounting for likelihood of a 50-year return period flood having occurred within the record span.
- Total bank erosion (both channel sides) is predicted to range between a maximum of 6 m for a 20-year debris flood event to approximately 30 m for a 500-year return period debris flood.
- Key locations where bank erosion could lead to greater risk include the abutments of the bridge crossing on Highway 3A, and the property at the east end of Redfish Road through progressive erosion.

#### 7.2.6. Hazard Mapping

Model results are cartographically expressed in two ways:

- The individual debris flood model results are captured through an index of impact force that combines flow velocity, bulk density and flow depth. These maps are useful for assessments of development proposals and emergency planning. These hazard scenarios are shown on Cambio Communities and a representative example is shown on Drawing 07.
- A composite hazard rating map (impact intensity frequency map) that combines the debris flood 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 debris flood/flow model results and the composite impact intensity frequency map serve as decision-making tools to guide subdivision and other development permit approvals.

### 7.3. Limitations and Uncertainties

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

- Future fan-delta development
- Substantial flood or debris flood events
- Development of large landslides in the watershed with the potential to impound Redfish Creek
- Bridge re-design
- Alteration to the spawning channels downstream of the highway.
- Substantial changes to Kootenay Lake levels.
- Significant wildfire events in the watershed.

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

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

## 7.4. Considerations for Hazard Management

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

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

1. Stopping organic and mineral debris near the fan apex to avoid downstream aggradation and concordant avulsions. Note that this strategy, while being effective, is very expensive and requires regular maintenance. In some cases, it may also lead to stream downcutting downstream which may or may not be a desirable consequence.
2. Most creeks on fans or fan-deltas 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. Deepening the channel through excavation will invariably be followed by infill causing a cycle of expensive and disruptive gravel excavations. This is being done at the Resort Municipality of Whistler on Fitzsimmons Creek at a cost of several hundred thousand dollars per year. Instead, setback berms that provide maximum room for the creek to shift and build up sediment is preferred.
3. Riprapping confined channels is of limited use as aggradation over time will render the riprap ineffective.

Redfish Creek fan-delta hosts the third highest value of assets in comparison with the steep creek fan-deltas studied in detail (Table 1-1); however, the highest hazard areas on the Redfish Creek fan-delta are in the upper fan where there is little to no development (Drawing 08). For this reason, the above options may not achieve a desirable cost-benefit ratio when compared to the asset values currently located in the areas affected by higher hazard.

Redfish Creek fan-delta has been established as being subject to rare (300 to 1000-year return period), but highly destructive debris flows potentially impacting the upper fan-delta, defined as the fan-delta portion north of Highway 3A. This is anomalous compared to most other study creek fan-deltas as the morphometry of the watershed indicates it is mostly prone to debris floods. If the RDCK chooses to mitigate debris flows (rather than sterilize development) on the upper fan-delta, then massive and very costly engineered structures would likely be required to reduce risk to tolerable levels.

The following site-specific mitigation measures could be considered. 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 7-3. Options (a1) to (d) pertain to debris flood hazards (in yellow) and options (a2) and (e) pertain to debris flows (in red).

**Table 7-3. Preliminary, conceptual-level, site specific mitigation options for Redfish Creek. Note that none of the options have been examined in detail.**

| Option | Description | Effect on Steep Creek Hazard Reduction |
|---|---|---|
| a1 | Construction of deflection berm on southern side of active channel near 600 m elevation (former extension of Marshall Road with Wightwick Road).<br>This should be considered in combination with options b, c, d. | Reduction in potential for avulsion at specific location on the western half of the active fan-delta. |
| a2 | Debris-flow mitigation: Construction of deflection berm on right (south) bank would be approximately 700 m long and several meters high | Contain debris flows in channel upstream of Highway 3A to protect the western fan from debris-flow impacts. |
| b | Highway 3A bridge replacement. | Increased bridge capacity to prevent flows overtopping the bridge and associated erosion. |
| c | Channel widening | Reduction in avulsion potential by increasing the channel capacity. |
| d | Construction of setback berms that tie into and reinforce existing flood protection downstream of Highway 3A (Drawings 02A, 02B) | Reduction in avulsion potential to protect development west of channel downstream of Highway 3A from inundation and sedimentation. |
| e | Debris-flow mitigation: Construction of debris basin north of Marshall Rd. | Storage of sediment and reduction in downstream sedimentation and impacts. |

Selection of appropriate mitigation options should also consider the following:

- Debris-flow mitigation structures are likely to exceed the improvement values on the upper fan-delta and possibly of the entire fan-delta.
- Unintentional risk transfer to downstream properties needs to be carefully considered with any structural (i.e., constructed) measures, for example, a debris-flow deflection berm (Figure 7-1(f (a2)) could potentially transfer the risk towards the current highway crossing east of Bryan Road as well as downstream development on the eastern portions of Redfish Road.
- The fan-delta segment south of Highway 3A and east of Redfish Creek currently contains the fish spawning channel, this area should remain sterilized for future land use.
- Bank erosion could encroach on existing development, especially for properties on the eastern portion of Redfish Road with total erosion reaching up to 50 m in the lower channel sections. Setback restrictions are key to avoid future losses due to bank erosion.
- The application of the composite hazard rating map 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.

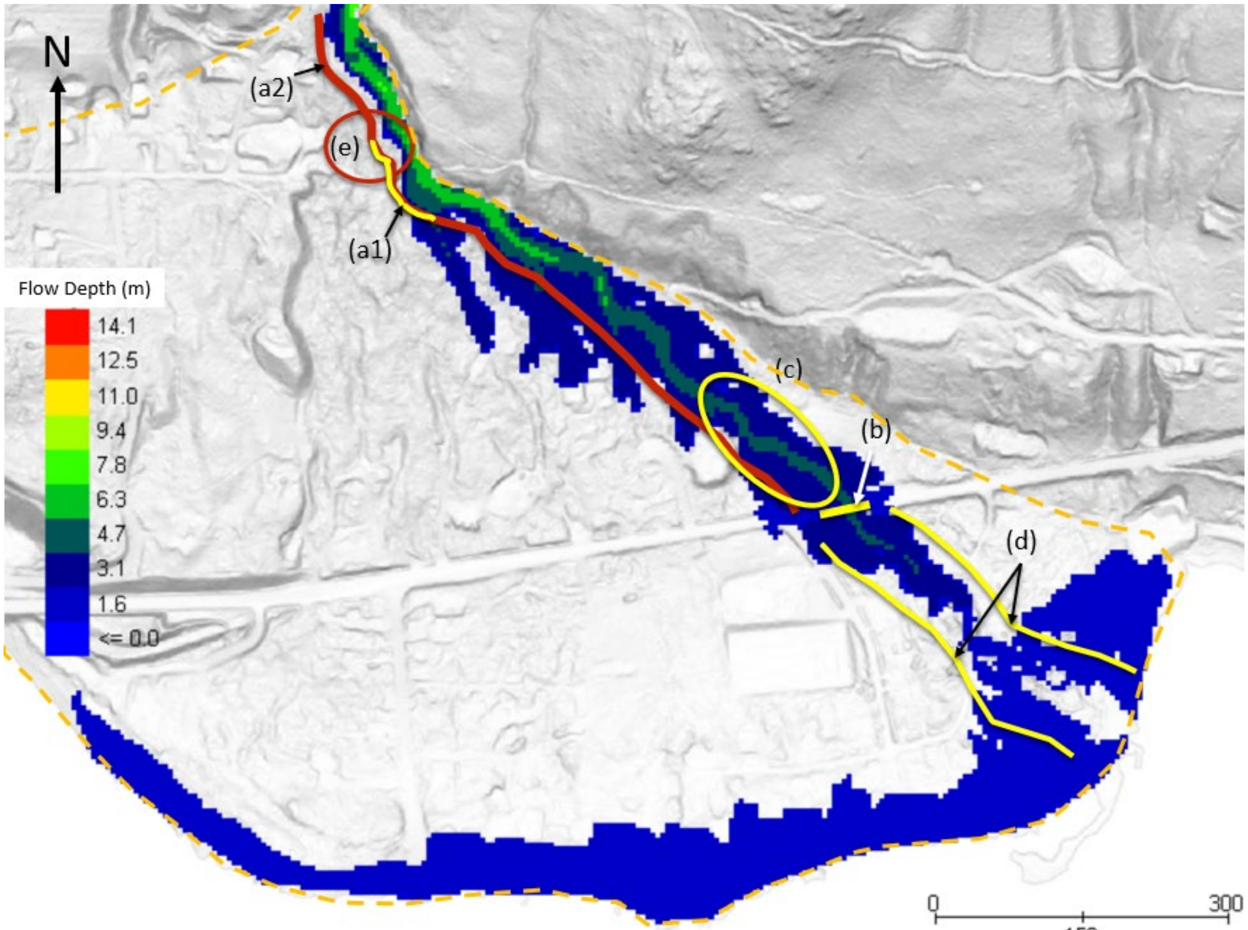



**Figure 7-1. Debris flow inundation map showing flow depths for a 300- to 1000-year return period debris flow on Redfish Creek and conceptual-level mitigation options for Redfish Creek fan-delta. Debris-flow mitigation options are in red, and debris flood mitigation options are in yellow. Note that 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,

**BGC ENGINEERING INC.**
**per:**

Matthias Jakob, Ph.D., P.Geo.
Principal Geoscientist

Matthias Busslinger, M.A.Sc., P.Eng.
Senior Geotechnical Engineer

Melissa Hairabedian, M.Sc., P.Geo.
Senior Hydrologist

Reviewed by:

Hamish Weatherly, M.Sc., P.Geo.
Principal Hydrologist

KH/HW/mp/mm

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

# REFERENCES

11 projects aided for fish, wildlife. (1981, August 20). *Times-Colonist*, p. 6.

Apex Geoscience Consultants Ltd. (2016, April). *Redfish Creek hydrogeomorphic assessment* [Report]. Prepared for Kalesnikoff Lumber Co. Ltd.

Apex Geoscience Consultants Ltd. (2017, January 15). Response to email from Tyler Hodgkinson from January 13, 2017. Prepared for Kalesnikoff Lumber Co. Ltd.

BGC Engineering Inc. (2019, March 31). *Flood and Steep Creek Geohazard Risk Prioritization* [Report]. Prepared for Regional District of Central Kootenay.

BGC Engineering Inc. (2019, May 24). *NDMP Stream 2: Flood Mapping Program* [Proposal]. Prepared for Regional District of Central Kootenay.

BGC Engineering Inc. (2019, June 20). *Consulting Services Agreement – RDCK Flood Hazard Risk Assessment* [Contract]. Prepared for Regional District of Central Kootenay.

BGC Engineering Inc. (2019, November 15). *NDMP Stream 2 Project Deliverables – Revised* [Letter]. Prepared for Regional District of Central Kootenay.

BGC Engineering Inc. (January 15, 2020). *Kootenay Lake Flood Impact Analysis* [Report]. Prepared for Regional District of Central Kootenay.

BGC Engineering Inc. (2020a, March 31). *Summary Report* [Report]. Prepared for the Regional District of Central Kootenay.

BGC Engineering Inc. (2020b, March 31). *Steep Creek Assessment Methodology Report* [Report]. Prepared for the Regional District of Central Kootenay.

Boivin, J. (2019, June 13). West Kootenay afternoon storms spark fires. *Nelson Star*. Retrieved from https://www.nelsonstar.com/

Boyer, D. & Jordan, P. (2001). November 1999 fall storm: Kootenay region. Changing Water Environments: Research and Practice. CWRA BC Branch conference proceedings. May 8-11, 2001, Whistler, BC.

Bovis, M., & Jakob, M. (1999). The role of debris supply conditions in predicting debris flow activity. *Earth Surface Processes and Landforms, 24*(11), 1039-1054. https://doi.org/10.1002/(SICI)1096-9837(199910)24:11<1039::AID-ESP29>3.0.CO;2-U

British Columbia Minister of Highways and Public Works. (1936). *Report for the fiscal year 1935/36*. Victoria, BC: Author.

British Columbia Minister of Highways and Public Works. (1976). *Report for the fiscal year 1975/76*. Victoria, BC: Author.

British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD). (2019, December 17). *Fire Perimeters - Historical* [GIS Data]. Retrieved from https://catalogue.data.gov.bc.ca/dataset/fire-perimeters-historical

Cui, Y., Miller, D., Schiarizza, P., & Diakow, L.J. (2017). *British Columbia digital geology*. British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Open File 2017-8, 9p.

Davidson, D. (2002, August 26). Valhalla Park fire burning wild. *Nelson Daily News*, p. 1.

Demarchi, D.A. (2011, March). *An introduction to the ecoregions of British Columbia* (3rd ed.). Victoria, BC: British Columbia Ministry of Environment, Ecosystem Information Section. Retrieved from https://www2.gov.bc.ca/assets/gov/environment/plants-animals-and-ecosystems/ecosystems/broad-ecosystem/an_introduction_to_the_ecoregions_of_british_columbia.pdf

Deverney Engineering Services Ltd. (2009, September 30). *Natural Hazard Assessment, Lot 2, Plan 8398, D.L. 1313, Kootenay Land District, 286 Harrop Ferry Road, Balfour, BC* [Precondition for Subdivision]. Prepared for David Dever and Abigail Dever.

Deverney Engineering Services Ltd. (2010, September 12). *Natural Hazard Assessment, Lot A, Plan 7634, DL 1313, Kootenay Land District, 6103 Highway 3A, Balfour, BC* [Precondition for Building Permit]. Prepared for Barry Riehl.

Deverney Engineering Services Ltd. (2011, June 17). *Natural Hazard Assessment and Building Setback Variance Application, Lot A, Plan NEP89540, DL 1313, Kootenay Land District, 6126 Pippers Lane, Nelson, BC* [Precondition for Building Permit]. Prepared for Michael McGillvrey and Janet McGillvrey.

Environment and Climate Change Canada. (n.d.). *Canadian Climate Normals 1981-2010 Station Data – Kaslo* [Data]. Extracted August 14, 2019, from the Environment and Climate Change Canada Canadian Climate Normals website: http://climate.weather.gc.ca/climate_normals/results_1981_2010_e.html?searchType=stnName&txtStationName=kaslo&searchMethod=contains&txtCentralLatMin=0&txtCentralLatSec=0&txtCentralLongMin=0&txtCentralLongSec=0&stnID=1124&dispBack=1

Government of British Columbia. (2020a). *Flood Protection Structures in B.C.* Internet webpage. URL last accessed February, 2020: https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/drought-flooding-dikes-dams/integrated-flood-hazard-management/dike-management/flood-protection-structures.

Government of British Columbia. (2020b). *Flood Protection Works – Appurtenant Structures.* Internet webpage. URL last accessed February, 2020: https://catalogue.data.gov.bc.ca/dataset/4639cc3d-93dd-4ff2-ae77-0aae4f3cd588

Green, K.C. & Alila, Y. (2012). A paradigm shift in understanding and quantifying the effects of forest harvesting on floods in snow environments. *Water Resources Research, 48*(10), W10503. https://doi.org/10.1029/2012WR012449

Holland, S.S. (1976). *Landforms of British Columbia – A physiographic outline* (Bulletin 48). Victoria, BC: British Columbia Department of Mines and Petroleum Resources.

Integrated Hydropedology Ltd. (2003, July 22). *Proposed second house on Parcel A, (SC U3340), Plan 5239, L.L. 1313 KD* [Precondition for Building Permit]. Prepared for Ben Martin and Debbie Gail Jervis-Legate.

Intermountain Engineering & Surveying Ltd. (2003, June 13). *Report Pursuant to Floodplain Management By-Law No. 1000, 1993* [Precondition for Building Permit]. Prepared for Regional District of Central Kootenay.

Jakob, M. (2005). Debris-flow hazard analysis. In M. Jakob, and O. Hungr (Ed.), *Debris-flow Hazards and Related Phenomena* (pp. 411-437). Berlin, Germany: Springer-Verlag Berlin and Heidelberg GmbH & Co.

Jordan, P. (2001). Sediment budgets in the Nelson Forest Region. In D.A.A. Toews and S. Chatwin (Eds). *Watershed Assessment in the Southern Interior of British Columbia*: Workshop Proceedings March 9 - 10, 2000. Penticton B.C. Canada. B.C. Min. For. Working Paper 57.

Jordan, P. (2006). The use of sediment budget concepts to assess the impact on watersheds of forestry operations in the southern interior of British Columbia. *Geomorphology ,79*(1-2), 27-44. https://doi.org/10.1016/j.geomorph.2005.09.019

Jungen, J.R. (1980). *Soil resources of the Nelson map area (82F)* [RAB Bulletin 20, British Columbia Soil Survey Report No. 28]. Kelowna, BC: British Columbia Ministry of Environment, Resource Analysis Branch.

Klohn-Crippen Consultants Ltd. (1998, February 23). *Terrain Stability Inventory: Alluvial and Debris Torrent Fans Kootenay Region* [Report]. Prepared for the Ministry of Environment, Lands and Parks.

Klohn Crippen Consultants Ltd. (2004, July 21). *Flood Hazard Assessment Redfish Creek Property* [Precondition for Building Permit]. Prepared for Robert Osler Haggar.

Lasca Group Technical Services Ltd. (2015, February 15). *6160 Redfish Road – Alluvial Fan Flood Hazard Assessment Report* [Precondition for Building Permit]. Prepared for Patrice Mauro and Joseph Mauro.

Local and personal. (1925, August 28). *The Creston Review*, p. 8.

Moynihan, D.P. & Pattison, D.R.M. (2013, April 3). Barrovian metamorphism in the central Kootenay Arc, British Columbia: Petrology and isograd geometry. *Canadian Journal of Earth Sciences, 50,* 769-794. http://dx.doi.org/10.1139/cjes-2012-0083

Navigable Waters' Protection Act. (1925, May 22). *The Creston Review*, p. 4.

Northwest Hydraulic Consultants Ltd. and Thurber Consultants Ltd. (1990, April). *Alluvial Fan Hazard Assessment: Regional District of Central Kootenay Electoral Area "E" & "F"* [Report]. Prepared for Regional District of Central Kootenay.

Perdue Geotechnical Services Ltd. (2016, July 21). *Redfish Creek Alluvial Fan Hazard Assessment Lot 9, Plan NEP5817, District Lot 1313, Kootenay District* [Precondition for Building Permit]. Prepared for Simone Michelle Campbell.

Province of British Columbia. (2016). Terrestrial Ecosystem Information (TEI) Spatial Data - Dist_Pkg_NonPEM_Cariboo_Okanagan_Kootenay2016.zip. Data available from the British Columbia Ministry of Environment, Ecosystem Information Section at: http://www.env.gov.bc.ca/esd/distdata/ecosystems/TEI/TEI_Data/2016-09-14.

Rickenmann, D. (2001). Comparison of bed load transport in torrents and gravel bed streams. *Water Resources Research, 37*(12), 3295-3305.

Schafer, T. (2012, June 7). Rainfall warning adds to flood concerns. *Trail Times*, p. 1.

Schafer, T. (2012, June 25). West Kootenay weather turns deadly. *Trail Times*, p. 3.

Scheidl, C., & Rickenmann, D. (2010). Empirical prediction of debris-flow mobility and deposition on fans. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group, 35*(2), 157-173.

Schnorbus, M. & Alila, Y. (2004). Forest harvesting impacts on the peak flow regime in the Columbia Mountains of southeastern British Columbia: An investigation using long-term numerical modeling. *Water Resources Research, 40*(5). https://doi.org/10.1029/2003WR002918

Spawning creek saved by preservation fund. (1979, August 18). *The Vancouver Sun*, p. B12.

Touchstone Nelson, Museum of Art and history. (2007). Corra Linn Dam, Kootenay River [Web page]. Retrieved from https://web.archive.org/web/20111004041631/http://virtualmuseum.ca/Exhibitions/Hydro/en/dams/?action=corralinn

Vogl, J.J. & Simony, P.S. (1992). *The southern tail of the Nelson batholith, southeast British Columbia: emplacement and deformation along a terrane accretion zone.* Retrieved from http://users.clas.ufl.edu/jvogl/Vogl_Simony_Nelson.pdf

Whitaker, A., Alila, Y., Beckers, J., & Toews, D. (2003). Application of the distributed hydrology soil vegetation model to Redfish Creek, British Columbia: model evaluation using internal catchment data. *Hydrological Processes, 17*(2), 199-224. https://doi.org/10.1002/hyp.1119

# 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:<br>a) To describe things of value (e.g., people, infrastructure, environment) that could potentially suffer damage or loss due to a **geohazard**.<br>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:<br>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"**<br>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**.<br>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.<br>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:<br>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**.<br>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.<br>There are two main interpretations:<br>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.<br>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:<br>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.<br>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 |

# REFERENCES

American Geosciences Institute. (2011). *Glossary of Geology* (5th ed.). Virginia: Author.

American Geological Institute. (1972). *Glossary of Geology*. Washington, DC.: Author.

Bates, R.L. & Jackson, J.A. (1995). *Glossary of Geology* (2nd ed.). Virginia: American Geological Institute.

Canadian Avalanche Association (CAA). (2016). Technical Aspects of Snow Avalanche Risk Management – Resources and Guidelines for Avalanche Practitioners in Canada (C. Campbell, S. Conger, B. Gould, P. Haegeli, B. Jamieson, & G. Statham Eds.). Revelstoke, BC, Canada: Canadian Avalanche Association.

Canadian Standards Association (CSA). (1997). *CAN/CSA – Q859-97 Risk Management: Guideline for Decision Makers*. CSA Group, Toronto, ON, pp. 55.

Fell, R., Ho., K.K.S., LaCasse, S., & Leroi, E. (2005). A framework for landslide risk assessment and management. In Hungr, O., Fell, R., Couture, R. (Eds.) *Landslide Risk Management:* Proceedings *of the International Conference on Landslide Risk Management.* Vancouver, BC.

Fell, R., Whitt, G. Miner, A., & Flentje, P.N. (2007). Guideline for Landslide Susceptibility, Hazard and Risk Zoning for Land Use Planning. *Australian Geomechanics Journal* 42: 13-36.

International Organization for Standardization (ISO). (2018). *ISO 31000:2018 Risk Management – Guidelines*. Retrieved from https://www.iso.org/standard/65694.html

Ministry of Water, Land and Air Protection. (MWLAP) (2004). *Flood Hazard Area Land Use Management Guidelines*.

National Oceanic and Atmospheric Administration. (n.d.) What is LIDAR? [Web page]. Retrieved from https://oceanservice.noaa.gov/facts/lidar.html

Oxford University Press. (2008). *A dictionary of Earth Sciences* (3rd ed.). Oxford, England: Author.

Porter, M., Jakob, M., & Holm, K. (2009, September). Proposed Landslide Risk Tolerance Criteria. *GeoHalifax 2009*. Paper presented at the meeting of the Canadian Geotechnical Society, Halifax, Canada.

Whitfield, P.H., Cannon, A.J., & Reynolds, C.J. (2002). Modelling Streamflow in Present and Future Climates: Examples from the Georgia Basin, British Columbia. *Canadian Water Resources Journal, 27*(4), 427 – 456. https://doi.org/10.4296/cwrj2704427

# APPENDIX B
# SITE PHOTOGRAPHS


**Photo 1.**

**Overview photo taken during helicopter flight looking east along West Kootenay Lake Arm and the main body of Kootenay Lake in the background. Highway 3A crosses Redfish Creek fan (left or north). Harrop Creek fan is located to the (right or south). Photo: BGC, July 6, 2019.**


**Photo 2.**

**Overview photo taken during helicopter flight looking south at the Redfish Creek fan with Harrop Creek fan across the lake. Photo: BGC, July 6, 2019.**

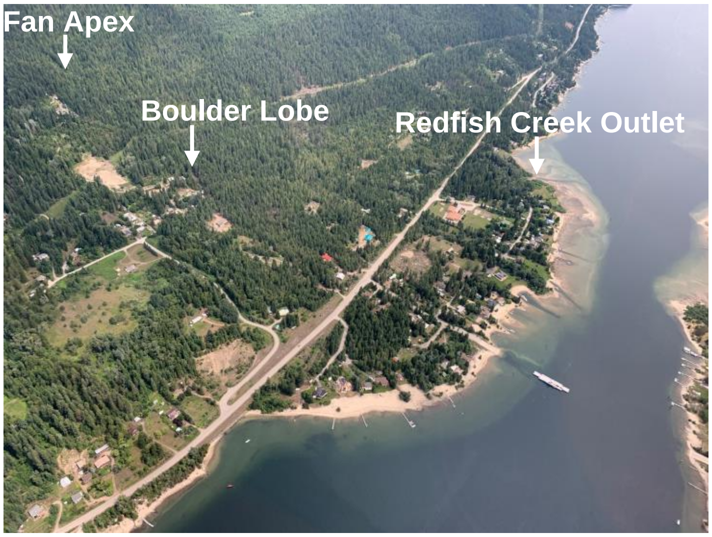



**Photo 3.**

**Overview photo taken during helicopter flight looking north-east at Redfish Creek. A boulder lobe located west of the creek is indicated. Locations of fan apex and Redfish Creek outlet into the West Arm of Kootenay Lake are shown. Photo: BGC, July 6, 2019.**


**Photo 4.**

**Overview photo during helicopter flight looking down (north is up) at the Redfish Creek Fan with Highway 3A (left to right) running across Redfish Creek. Redfish Creek Outlet labeled. Photo: BGC, July 6, 2019.**

**Photo 5.**

**Overview photo during helicopter flight looking northeast at debris avalanche paths on the eastern valley side of Redfish Creek, approximately 5.3 km upstream of lake outlet. Initiation zones are indicated with arrows. See Drawing 05 for debris flow paths. Photo: BGC, July 6, 2019.**


**Photo 6.**

**View from helicopter looking down in southeastern direction (towards Grandview Drive near Laird Creek) at approximate elevation 1900 m on eastern ridge along Redfish Creek. Some bedrock outcrops and coarse talus were observed between the trees. See Drawing 05 for location. Photo: BGC, July 6, 2019.**

**Photo 7.**

**Looking southeast on Redfish-Liard Creek FSR at exposed till escarpment (approximately 20 m tall), possibly related to a debris avalanche that released from here. Note arrow pointing to rounded granitic boulders contained in till. See Drawing 05 for location. Photo: BGC, July 10, 2019.**

**Photo 8.**

**Looking east on Redfish-Liard Creek FSR at overgrown side scarp (dashed line) of debris avalanche. Note arrow pointing to rounded granitic boulders contained in till. See Drawing 05 for location. Photo: BGC, July 10, 2019.**

**Photo 9.**

**Looking downstream (south) at woody debris accumulation on Redfish Creek near fan apex. Photo: BGC, July 2, 2019.**

**Photo 10.**

**Natural berm approximately 2 m high extending along the right bank approximately 400 m downstream from fan apex. Photo: BGC, July 2, 2019.**


**Photo 11.**

**Looking upstream (north) at gate regulating flows diverted from Redfish Creek. In the foreground of the photo is the uppermost pool of the Redfish Creek spawning channel, partially built with prefabricated concrete blocks. Photo: BGC, July 3, 2019.**

**Photo 12.**

**Standing approximately 120 m downstream of the gate shown in photo above and looking downstream, along the Redfish Creek spawning channel crossing with arch culvert. The arch culvert is approximately 3 m wide with 1.5 m of clearance to the water at the time of photo. Photo: BGC, July 3, 2019.**

**Photo 13.**

**Standing on the shore of Kootenay Lake looking east at the outlet of Redfish Creek. Photo: BGC, July 3, 2019.**

# APPENDIX C
# SEDIMENT SIZE SAMPLING

## C.1. SAMPLING LOCATIONS

At Redfish Creek, two Wolman Samples were taken, one upstream of the fan apex, and the other downstream of Highway 3A near the outlet to Kootenay Lake. The sampling locations (referred to as Redfish 1 and Redfish 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 | Redfish 1 | Redfish 2 |
|---|---|---|
| Location | Upstream of fan apex | Downstream of Highway 3A, near the outlet to Kootenay Lake |
| Longitude | 117° 3'23.43"W | 117° 2'49.34"W |
| Latitude | 49°37'17.99"N | 49°36'50.44"N |
| Number of stones measured | 102 | 99 |


**Figure C-1. Wolman sampling locations along Redfish Creek. Google Earth image of April 7, 2012.**

**Figure C-2. Photograph taken of Wolman sampling location Redfish 1. BGC photograph of November 22, 2019.**

**Figure C-3. Photograph taken of Wolman sampling location Redfish 2. BGC photograph of July 3, 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. Redfish Creek sediment distribution from Wolman Count Data.**

| Grain Size | Redfish 1 | Redfish 2 |
|---|---|---|
| $D_{95}$ (mm) | 173 | 228 |
| $D_{84}$ (mm) | 122 | 160 |
| $D_{50}$ (mm) | 51 | 69 |
| $D_{15}$ (mm) | 16 | 24 |
| $D_{5}$ (mm) | 6 | 15 |

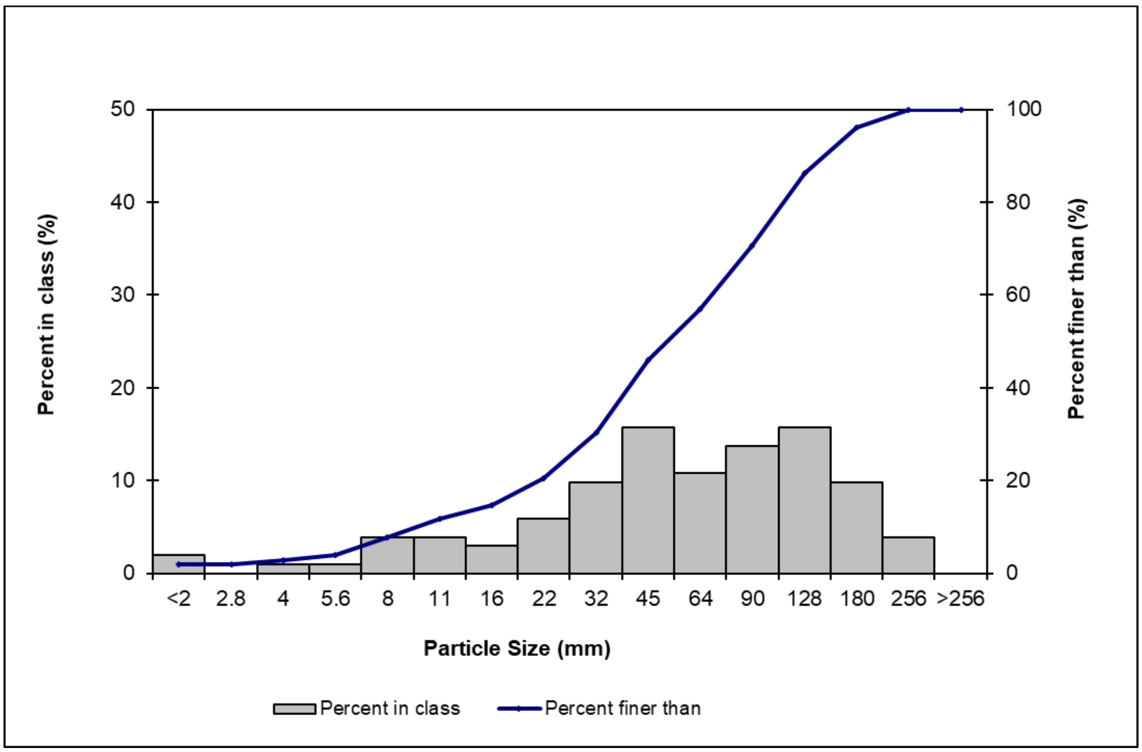



**Figure C-4. Redfish Creek grain size distribution at Redfish 1 (upstream of fan apex) from Wolman count.**

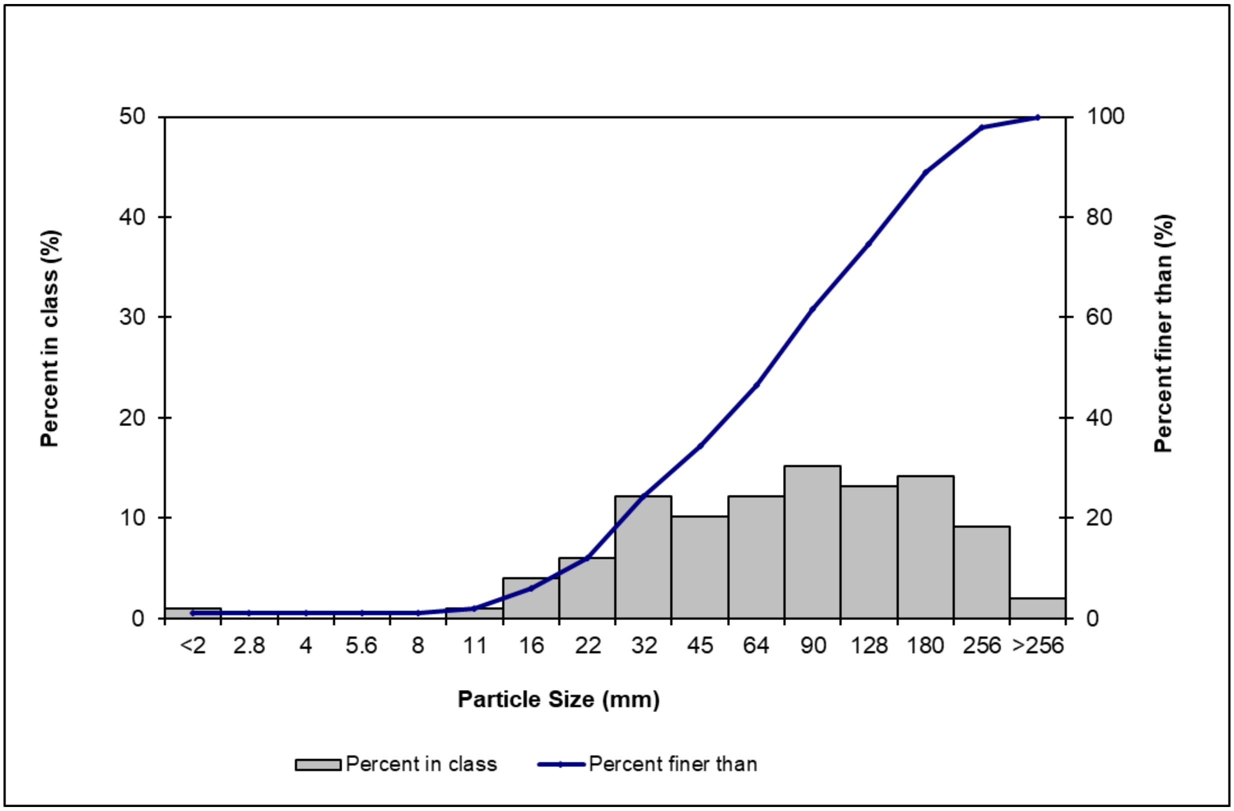



**Figure C-5. Redfish Creek grain size distribution at Redfish 2 (Downstream of Highway 3A, near the outlet to Kootenay Lake) from Wolman count.**

The channel gradient decreases downstream, as such, it would be expected that bed material size would decrease as well. Instead, bed material size at Redfish 2 (on distal fan) has a higher proportion of bed material larger than 8 mm as compared with Redfish 1 (above fan apex) where there is generally finer bed material.

In order to predict sediment size distributions at locations not sampled, linear interpolation between the $D_{84}$ values collected at the sampling locations and distance from fan apex was used.

# APPENDIX D
# AIR PHOTO RECORDS

Table D-1 presents airphoto records from the Redfish Creek analysis.

**Table D-1. Redfish Creek airphoto records.**

| Year | Date | Roll Number | Photo Number | Scale |
|---|---|---|---|---|
| 2006 | 9/1/2006 | BCC06135 | 205-207 | 20,000 |
| 2006 | 7/21/2006 | BCC06061 | 36-37 | 20,000 |
| 2000 | 9/17/2000 | BCB00038 | 121, 163-165 | 15,000 |
| 1997 | 8/22/1997 | BCB97047 | 163-165, 262-264 | 15,000 |
| 1988 | 7/22/1988 | BC88090 | 54-56, 105-107 | 15,000 |
| 1979 | 8/2/1979 | BC79134 | 11-16, 32-36 | 10,000 |
| 1974 | 6/17/1974 | BC7568 | 137-141, 148-154 | 8,000 |
| 1968 | 8/31/1968 | BC7109 | 12-15 | 16,000 |
| 1968 | 8/8/1968 | BC7111 | 25-27 | 16,000 |
| 1958 | 7/24/1958 | BC2478 | 8-10, 50-52 | 15,840 |
| 1952 | 6/14/1952 | BC1455 | 13 -16 | 31,680 |
| 1945 | 6/5/1945 | A7735 | 3-4 | 25,000 |
| 1939 | 7/24/1939 | BC146 | 71-73, 90-92 | 31,680 |
| 1929 | 4/18/1929 | A1015 | 16-18 | 10,000 |

# APPENDIX E
# MODELLING SCENARIOS

## E.1. MODELLING SCENARIOS

The scenarios analyzed for Redfish 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. Example modeling scenario summaries for Redfish Creek.**

| Scenario Name | Return Period (yrs) | Process Type | Bulking Factor | Bulked Peak Discharge ($m^3/s$) | Conveyance Structures | | | Flood Protection Structures | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Name | Estimated Capacity ($m^3/s$) | Assumption | Name | Type | Bank Erosion Encroaching | $\tau/\tau c \geq 2$ | Assumption |
| RFS-1 | 20 | Debris Flood (Type 1) | 1.02 | 17 | Forestry Bridge | N/A | Destroyed when over capacity due to condition | RFS-FP-02 | Dike, not orphaned | N | Y | Left in as is, bank erosion not encroaching |
| | | | | | Redfish Highway Bridge | 80 | Functioning as intended | RFS-FP-02 | Dike, not orphaned | N | Y | Left in as is, bank erosion not encroaching |
| | | | | | | | | RFS-FP-03 | Bank protection on left bank | N | Y | Left in as is, bank erosion not encroaching |
| | | | | | Footbridge | 60 | Functioning as intended | RFS-FP-04 | Bank protection (large rocks) on right bank. | N | Y | Left in as is, bank erosion not encroaching |
| | | | | | | | | RFS-FP-04 | Bank protection (large rocks) on right bank. | N | Y | Left in as is, bank erosion not encroaching |
| | | | | | | | | RFS-FP-04 | Orphaned, vegetated dike on right bank. | N | Y | Left in as is, bank erosion not encroaching |
| RFS-2 | 50 | Debris Flood (Type 1) | 1.05 | 19 | Forestry Bridge | N/A | Destroyed when over capacity due to condition | RFS-FP-02 | Dike, not orphaned | N | Y | Left in as is, bank erosion not encroaching |
| | | | | | Redfish Highway Bridge | 80 | Functioning as intended | RFS-FP-02 | Dike, not orphaned | N | Y | Left in as is, bank erosion not encroaching |
| | | | | | | | | RFS-FP-03 | Bank protection on left bank | N | Y | Left in as is, bank erosion not encroaching |
| | | | | | Footbridge | 60 | Functioning as intended | RFS-FP-04 | Bank protection (large rocks) on right bank. | N | Y | Left in as is, bank erosion not encroaching |
| | | | | | | | | RFS-FP-04 | Bank protection (large rocks) on right bank. | N | Y | Left in as is, bank erosion not encroaching |
| | | | | | | | | RFS-FP-04 | Orphaned, vegetated dike on right bank. | N | Y | Left in as is, bank erosion not encroaching |

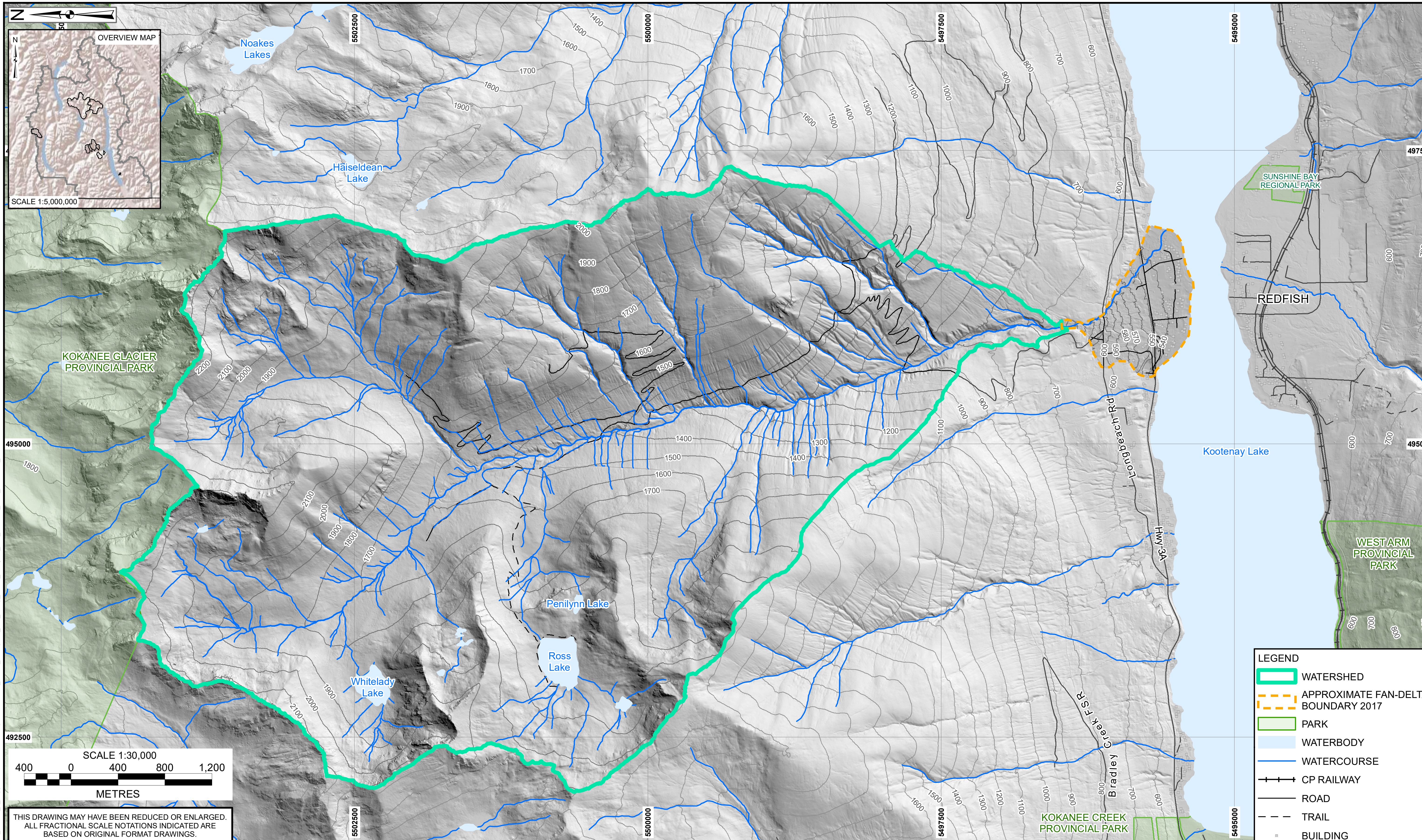
| Scenario Name | Return Period (yrs) | Process Type | Bulking Factor | Bulked Peak Discharge ($m^3/s$) | Conveyance Structures | | | Flood Protection Structures | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Name | Estimated Capacity ($m^3/s$) | Assumption | Name | Type | Bank Erosion Encroaching | $\tau/\tau c \geq 2$ | Assumption |
| RFS-3 | 200 | Debris Flood (Type 2) | 1.2 | 26 | Forestry Bridge | N/A | Destroyed when over capacity due to condition | RFS-FP-02 | Dike, not orphaned | Y | Y | Will not function as intended, removed from topography |
| | | | | | Redfish Highway Bridge | 80 | Functioning as intended | RFS-FP-02 | Dike, not orphaned | Y | Y | Will not function as intended, removed from topography |
| | | | | | | | | RFS-FP-03 | Bank protection on left bank | Y | Y | Will not function as intended, removed from topography |
| | | | | | Footbridge | 60 | Functioning as intended | RFS-FP-04 | Bank protection (large rocks) on right bank. | N | Y | Left in as is, bank erosion not encroaching |
| | | | | | | | | RFS-FP-04 | Bank protection (large rocks) on right bank. | N | Y | Left in as is, bank erosion not encroaching |
| | | | | | | | | RFS-FP-04 | Orphaned, vegetated dike on right bank. | N | Y | Left in as is, bank erosion not encroaching |
| RFS-4a | 500 | Debris Flood (Type 2) | 1.3 | 30 | Forestry Bridge | N/A | Destroyed when over capacity due to condition | RFS-FP-02 | Dike, not orphaned | Y | Y | Will not function as intended, removed from topography |
| | | | | | Redfish Highway Bridge | 80 | Functioning as intended | RFS-FP-02 | Dike, not orphaned | Y | Y | Will not function as intended, removed from topography |
| | | | | | | | | RFS-FP-03 | Bank protection on left bank | Y | Y | Will not function as intended, removed from topography |
| | | | | | Footbridge | 60 | Functioning as intended | RFS-FP-04 | Bank protection (large rocks) on right bank. | N | Y | Left in as is, bank erosion not encroaching |
| | | | | | | | | RFS-FP-04 | Bank protection (large rocks) on right bank. | N | Y | Left in as is, bank erosion not encroaching |
| | | | | | | | | RFS-FP-04 | Orphaned, vegetated dike on right bank. | N | Y | Left in as is, bank erosion not encroaching |

| Scenario Name | Return Period (yrs) | Process Type | Bulking Factor | Bulked Peak Discharge ($m^3/s$) | Conveyance Structures | | | Flood Protection Structures | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Name | Estimated Capacity ($m^3/s$) | Assumption | Name | Type | Bank Erosion Encroaching | $\tau/\tau c \geq 2$ | Assumption |
| RFS-4b | 500 | Debris Flow | N/A | 1400* | Forestry Bridge | N/A | Destroyed when over capacity due to condition | RFS-FP-02 | Dike, not orphaned | Y | Y | Will not function as intended, removed from topography |
| | | | | | Redfish Highway Bridge | 80 | Over capacity, bridge destroyed | RFS-FP-02 | Dike, not orphaned | Y | Y | Will not function as intended, removed from topography |
| | | | | | | | | RFS-FP-03 | Bank protection on left bank | Y | Y | Will not function as intended, removed from topography |
| | | | | | Footbridge | 60 | Over capacity, bridge destroyed | RFS-FP-04 | Bank protection (large rocks) on right bank. | N | Y | Left in as is, bank erosion not encroaching |
| | | | | | | | | RFS-FP-04 | Bank protection (large rocks) on right bank. | N | Y | Left in as is, bank erosion not encroaching |
| | | | | | | | | RFS-FP-04 | Orphaned, vegetated dike on right bank. | N | Y | Left in as is, bank erosion not encroaching |

Note:

1. No bulking factor was applied as peak discharge was calculated from Bovis and Jakob (1999) equation as detailed in report.

# DRAWINGS




X:\Projects\0268007_RDCK_NDMP_Stream_2_Support\GIS\Production\Report\20191018_RDCK_Floodplain_and_Steep_Creek_Study\01_Site_Location_DDP_REDFISH_V3.mxd

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

| | |
|---|---|
| SCALE: | 1:30,000 |
| 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: REDFISH CREEK SITE LOCATION MAP

PROJECT No.: 0268007

DWG No: 01


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 - REDFISH 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. BUILDING FOOTPRINTS DIGITIZED BY BGC BASED ON LIDAR AND REPRESENT ONLY A SUBSET OF TOTAL BUILDINGS ON THE FAN-DELTA. CULVERT LOCATIONS FROM BC MINISTRY OF TRANSPORTATION. FLOOD PROTECTION DATA FROM GEOBC. ROADS DATA FROM BC DIGITAL ROAD ATLAS. WATER RIGHTS LICENSE DATA FROM GEOBC. PARCELS FROM PARCELMAP BC. PARKS DATA FROM GOVERNMENT OF BC.
6. BRIDGE REMOVED ON MARSHALL ROAD. ONLY ABUTMENTS OBSERVED BY BGC IN JULY 2019.
7. PROJECTION IS NAD 1983 UTM ZONE 11N.
8. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED OR USED FOR ANY PURPOSE OTHER THAN THE PURPOSE FOR WHICH BGC GENERATED IT. BGC SHALL HAVE NO LIABILITY FOR ANY DAMAGES OR LOSS ARISING IN ANY WAY FROM ANY USE OR MODIFICATION OF THIS DOCUMENT NOT AUTHORIZED BY BGC. ANY USE OF OR RELIANCE UPON THIS DOCUMENT OR ITS CONTENT BY THIRD PARTIES SHALL BE AT SUCH THIRD PARTIES' SOLE RISK.

| | |
|---|---|
| SCALE: | 1:5,000 |
| DATE: | MAR 2020 |
| DRAWN: | LL |
| CHECKED: | JJHP |
| APPROVED: | MJ |

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

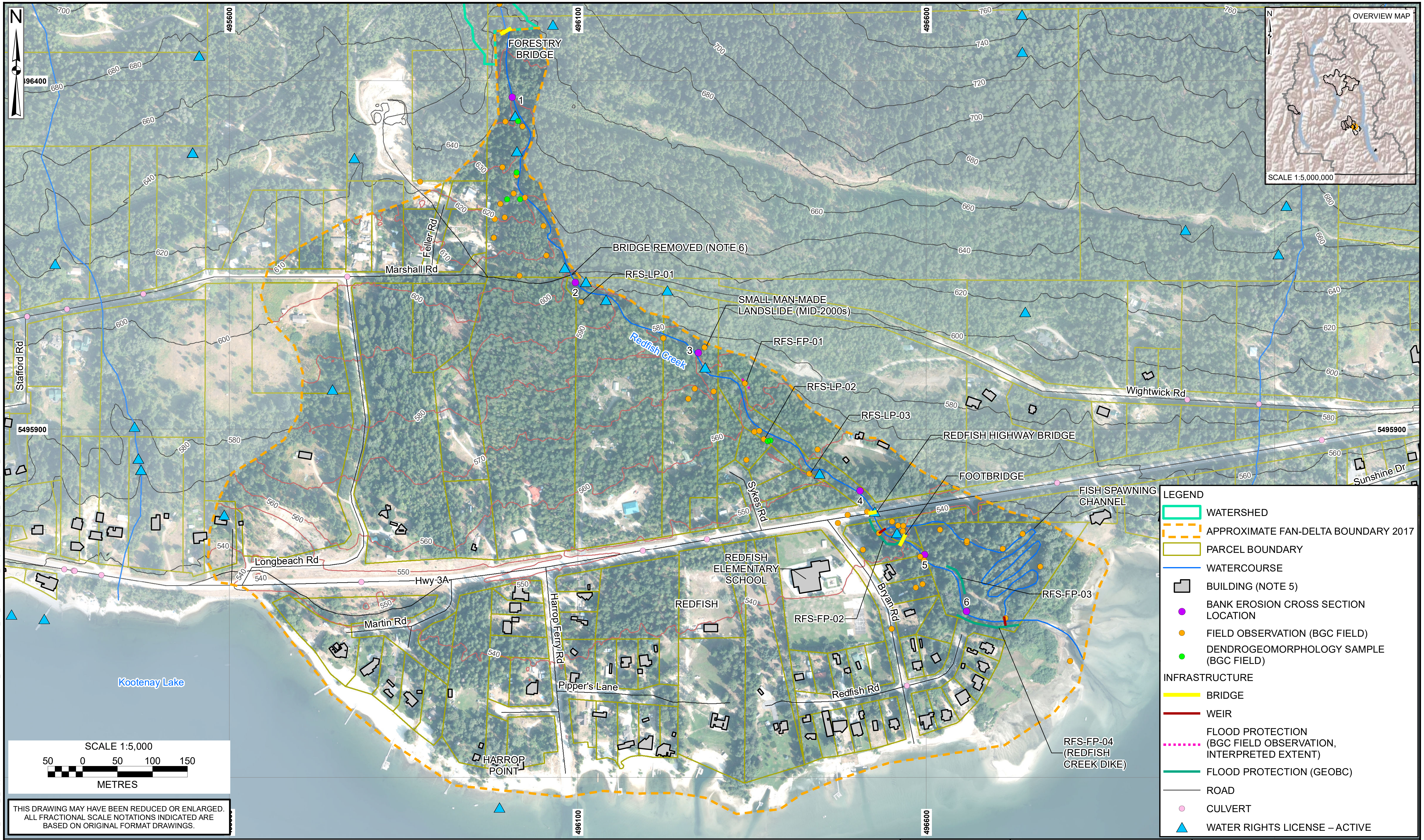
PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: REDFISH CREEK FAN-DELTA SITE MAP

PROJECT No.: 0268007

DWG No: 02A

X:\Projects\0268\007_RDCK_NDMP_Stream_2_Support\GIS\Production\Report\20191018_RDCK_Floodplain_and_Steep_Creek_Study\02A_Fan_Delta_Site_Map_DDP_REDFISH.mxd




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 - REDFISH CREEK", AND DATED MARCH 2020.
3. BASE TOPOGRAPHIC DATA AND ORTHOPHOTO BASED ON LIDAR PROVIDED BY RDCK, DATED 2017. CONTOUR INTERVAL IS 20 m AND 10 m ON FAN.
4. THE FAN BOUNDARY AS DRAWN IS APPROXIMATE AND DELINEATES THE LANDFORM BASED ON LIDAR DATED 2017. THE BOUNDARY SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DOES IT SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
5. WATER DATA FROM CANVEC, UPDATED BASED ON BGC FIELD OBSERVATIONS, WHERE APPLICABLE. BUILDING FOOTPRINTS DIGITIZED BY BGC BASED ON LIDAR AND REPRESENT ONLY A SUBSET OF TOTAL BUILDINGS ON THE FAN-DELTA. CULVERT LOCATIONS FROM BC MINISTRY OF TRANSPORTATION. FLOOD PROTECTION DATA FROM GEOBC. ROADS DATA FROM BC DIGITAL ROAD ATLAS. WATER RIGHTS LICENSE DATA FROM GEOBC. PARCELS FROM PARCELMAP BC. PARKS DATA FROM GOVERNMENT OF BC.
6. BRIDGE REMOVED ON MARSHALL ROAD. ONLY ABUTMENTS OBSERVED BY BGC IN JULY 2019.
7. PROJECTION IS NAD 1983 UTM ZONE 11N.
8. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED OR USED FOR ANY PURPOSE OTHER THAN THE PURPOSE FOR WHICH BGC GENERATED IT. BGC SHALL HAVE NO LIABILITY FOR ANY DAMAGES OR LOSS ARISING IN ANY WAY FROM ANY USE OR MODIFICATION OF THIS DOCUMENT NOT AUTHORIZED BY BGC. ANY USE OF OR RELIANCE UPON THIS DOCUMENT OR ITS CONTENT BY THIRD PARTIES SHALL BE AT SUCH THIRD PARTIES' SOLE RISK.

| | |
|---|---|
| SCALE: | 1:5,000 |
| DATE: | MAR 2020 |
| DRAWN: | LL |
| CHECKED: | JJHP |
| APPROVED: | MJ |

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT: REGIONAL DISTRICT CENTRAL KOOTENAY

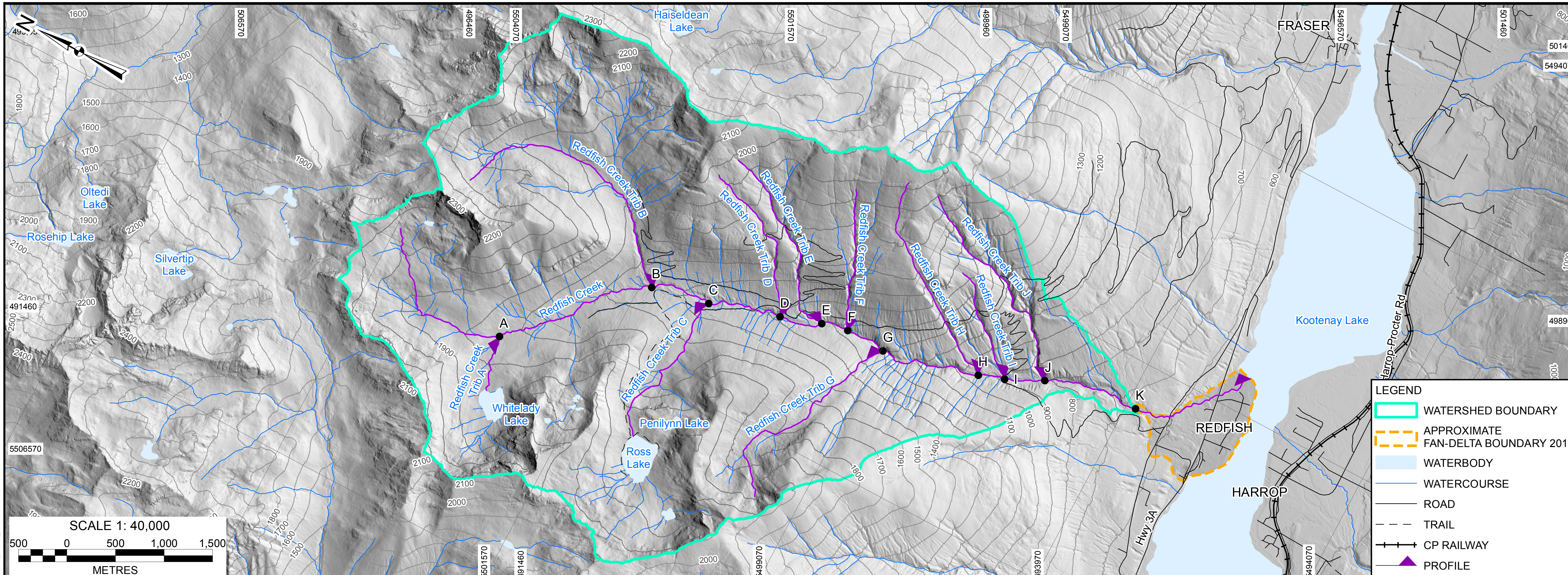
PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

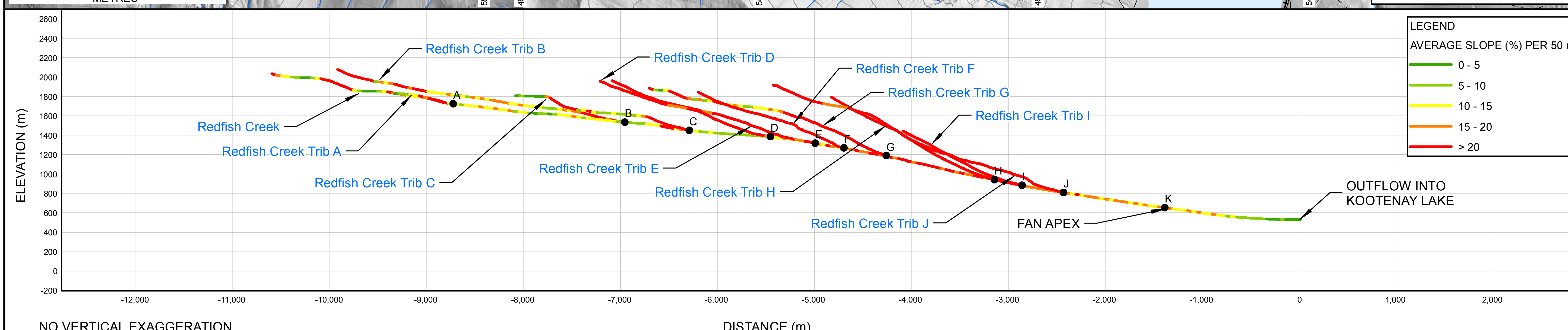
TITLE: REDFISH CREEK FAN-DELTA SITE MAP

PROJECT No.: 0268007

DWG No: 02B

X:\Projects\0268\007_RDCK_NDMP_Stream_2_Support\GIS\Production\Report\20191018_RDCK_Floodplain_and_Steep_Creek_Study\02B_Fan_Delta_Site_Map_DDP_REDFISH.mxd




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

| | |
|---|---|
| SCALE: | 1:40,000 |
| DATE: | MAR 2020 |
| DRAWN: | STT |
| CHECKED: | JJHP, LCH |
| APPROVED: | MJ |

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

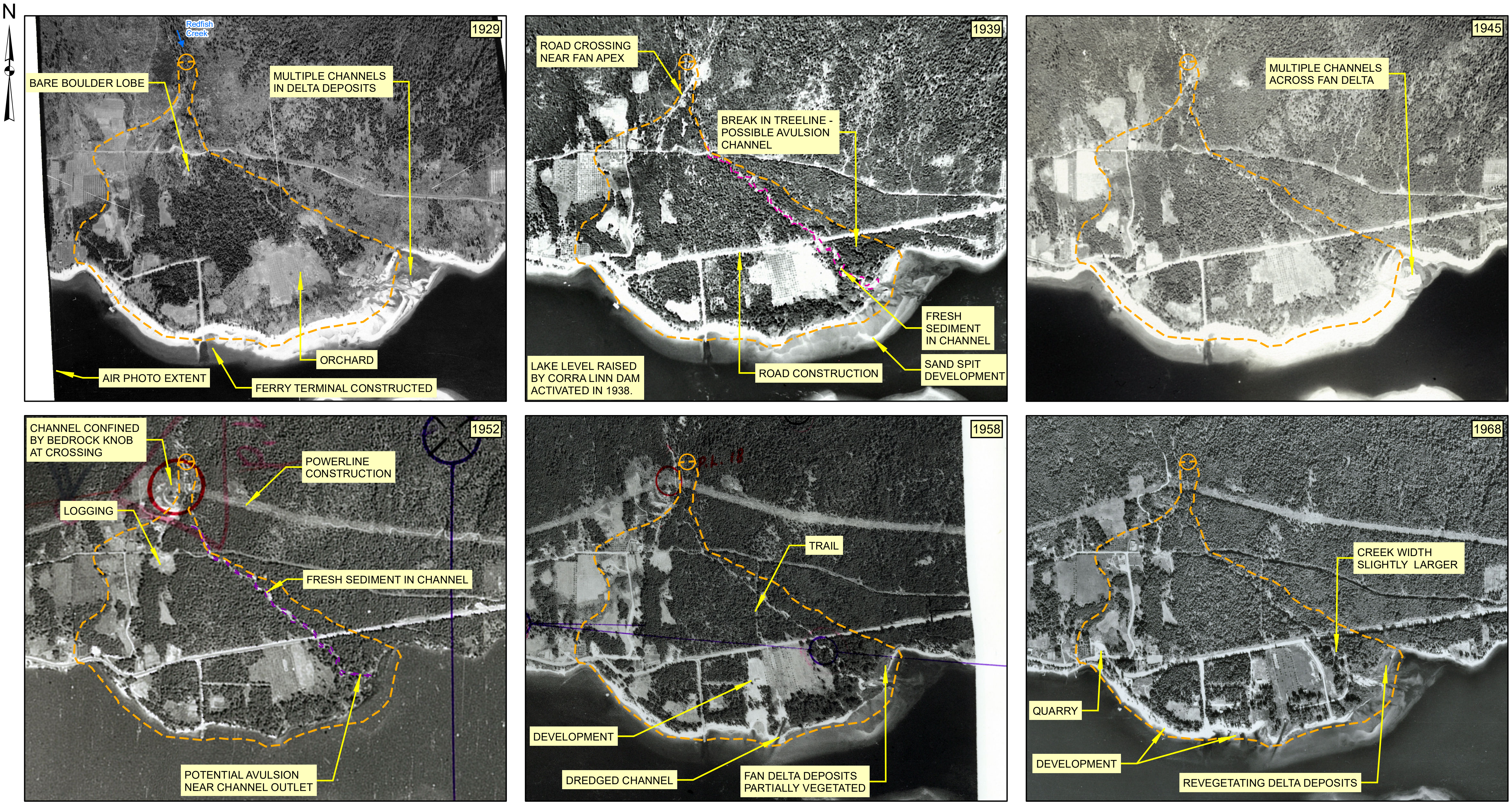
PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: REDFISH CREEK PROFILE

PROJECT No.: 0268007

DWG No: 03

X:\Projects\0268007_RDCK_NDMP_Stream_2_Support\GIS\ProductionReport\20191018_RDCK_Floodplain_and_Steep_Creek_Study\Profile\03_Redfish_Creek_Profile.mxd




SCALE 1:15,000

200 0 200 400 600

METRES

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

**LEGEND**

- APPROXIMATE FAN-DELTA BOUNDARY 2017
- FAN APEX
- APPROXIMATE EXTENT OF PRE-1939 EVENT
- APPROXIMATE EXTENT OF PRE-1952 EVENT

X:\Projects\0268\007_RDCK_NDMP_Stream_2_Support\GIS\Production\Report\20190716_RDCK_Airphoto_Comparison\Air Photo Map 6 panels.mxd

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 - REDFISH CREEK", AND DATED MARCH 2020.
3. BASE TOPOGRAPHIC DATA BASED ON AIR PHOTOS PROVIDED BY BC AIR PHOTO LIBRARY AND NATIONAL AIR PHOTO LIBRARY.
4. THE FAN BOUNDARY AS DRAWN IS APPROXIMATE AND DELINEATES THE LANDFORM BASED ON LIDAR DATED 2017. THE BOUNDARY SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DOES IT SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
5. AIR PHOTO FROM YEARS 1952 AND 1958 WERE MARKED ON PHYSICAL COPIES PRIOR TO BGC'S AIR PHOTO INTERPRETATION.
6. LAKE LEVEL RAISED BY CORRA LINN DAM ACTIVATED IN 1938.
7. COORDINATE SYSTEM IS UTM ZONE 11 NAD 1983. VERTICAL DATUM IS UNKNOWN.
8. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED OR USED FOR ANY PURPOSE OTHER THAN THE PURPOSE FOR WHICH BGC GENERATED IT. BGC SHALL HAVE NO LIABILITY FOR ANY DAMAGES OR LOSS ARISING IN ANY WAY FROM ANY USE OR MODIFICATION OF THIS DOCUMENT NOT AUTHORIZED BY BGC. ANY USE OF OR RELIANCE UPON THIS DOCUMENT OR ITS CONTENT BY THIRD PARTIES SHALL BE AT SUCH THIRD PARTIES' SOLE RISK.

| | |
|---|---|
| SCALE: | 1:15,000 |
| DATE: | MAR 2020 |
| DRAWN: | MIB, LL |
| CHECKED: | JJHP, LCH |
| APPROVED: | MJ |

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

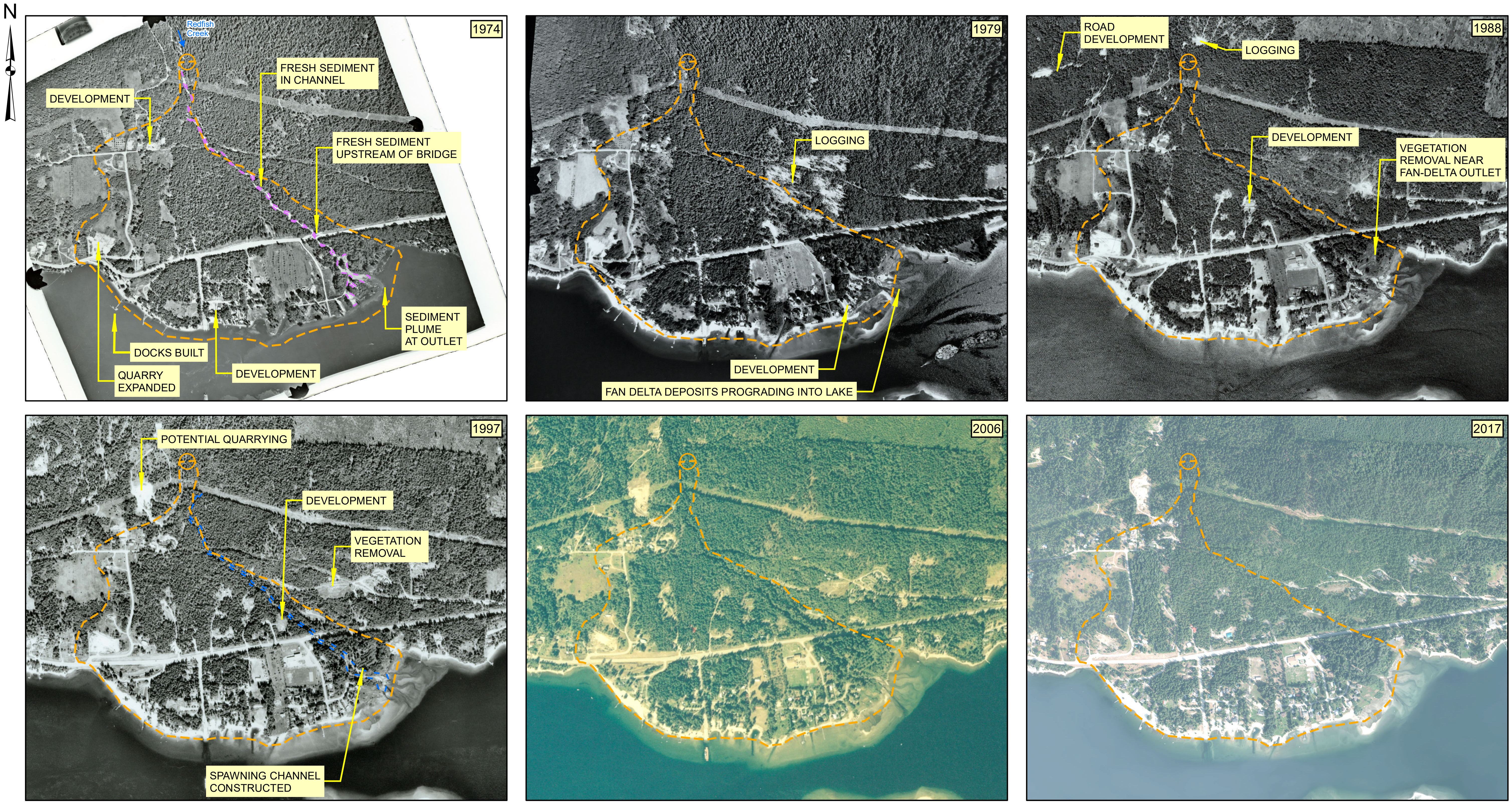
CLIENT: REGIONAL DISTRICT CENTRAL KOOTENAY

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: REDFISH CREEK AIR PHOTO COMPARISON

PROJECT No.: 0268007

DWG No: 04A




SCALE 1:15,000

200 0 200 400 600

METRES

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

LEGEND

- APPROXIMATE FAN-DELTA BOUNDARY 2017
- FAN APEX
- APPROXIMATE EXTENT OF 1968 EVENT
- APPROXIMATE EXTENT OF 1997 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 - REDFISH 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.

| | |
|---|---|
| SCALE: | 1:15,000 |
| DATE: | MAR 2020 |
| DRAWN: | MIB, LL |
| CHECKED: | JJHP, LCH |
| APPROVED: | MJ |

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

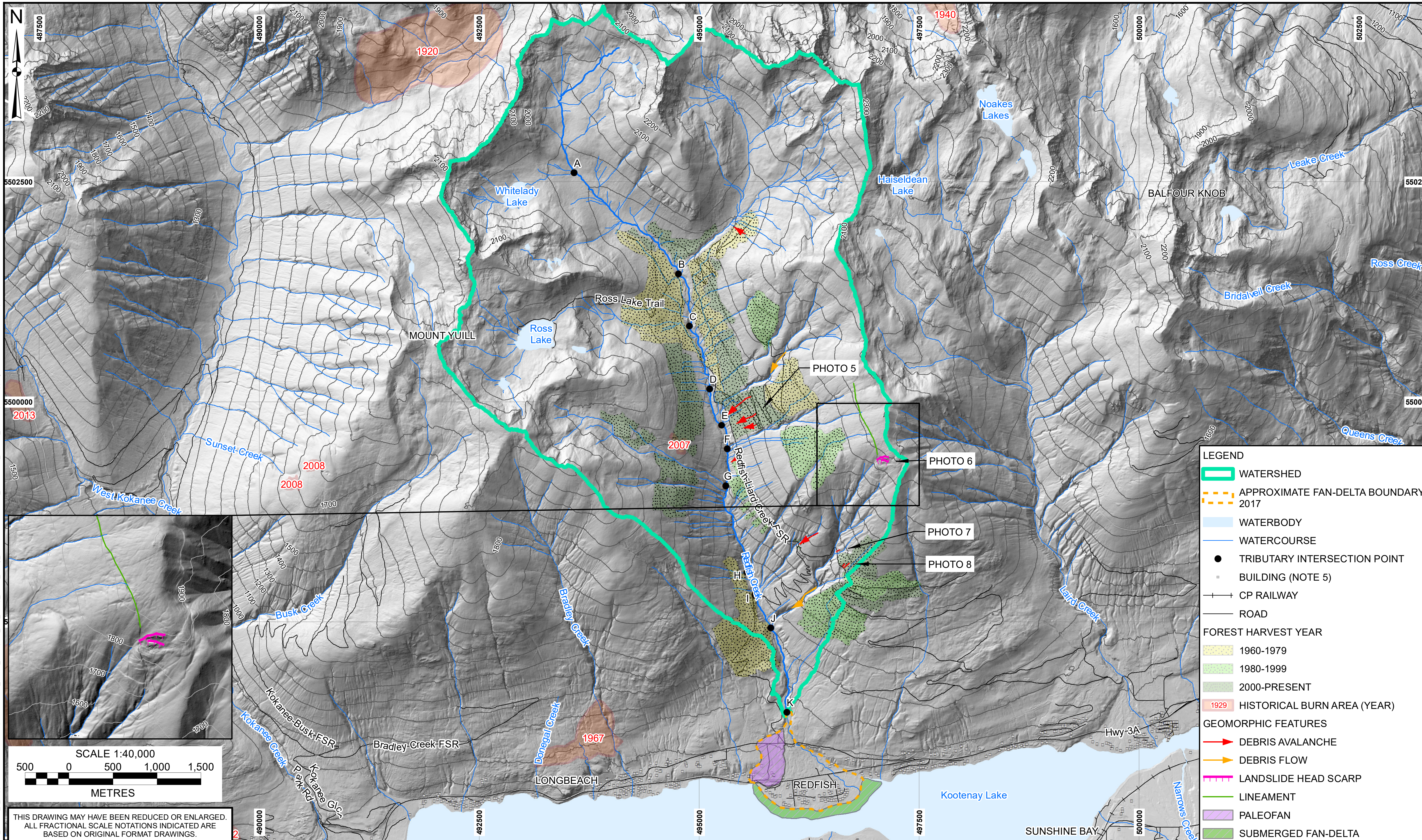
CLIENT:

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: REDFISH CREEK AIR PHOTO COMPARISON

PROJECT No.: 0268007

DWG No: 04B




NOTES:
1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "RDCK FLOODPLAIN AND STEEP CREEK STUDY - REDFISH CREEK", AND DATED MARCH 2020.
3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY RDCK DATED 2017. CONTOUR INTERVAL IS 100m.
4. THE WATERSHED AND FAN-DELTA BOUNDARY AS DRAWN IS APPROXIMATE AND DELINEATES THE LANDFORM. THE BOUNDARY SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DOES IT SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
5. BUILDING FOOTPRINTS DIGITIZED BY BGC BASED ON LIDAR AND REPRESENT ONLY A SUBSET OF TOTAL BUILDINGS ON THE FAN-DELTA. ROADS DATA FROM BC DIGITAL ROADS ATLAS. RAILWAY DATA FROM GEOBASE NATIONAL RAILWAY NETWORK.
6. HISTORICAL CUT BLOCK DATA FROM GEOBC DATASET DATED 2019 AND ONLY REPRESENTATIVE OF AREAS THAT INTERSECT WATERSHED BOUNDARY. HISTORICAL BURN AREA FROM GEOBC DATASET DATED 2019.
7. PROJECTION IS NAD 1983 UTM ZONE 11N.
8. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED OR USED FOR ANY PURPOSE OTHER THAN THE PURPOSE FOR WHICH BGC GENERATED IT. BGC SHALL HAVE NO LIABILITY FOR ANY DAMAGES OR LOSS ARISING IN ANY WAY FROM ANY USE OR MODIFICATION OF THIS DOCUMENT NOT AUTHORIZED BY BGC. ANY USE OF OR RELIANCE UPON THIS DOCUMENT OR ITS CONTENT BY THIRD PARTIES SHALL BE AT SUCH THIRD PARTIES' SOLE RISK.

| | |
|---|---|
| SCALE: | 1:40,000 |
| DATE: | MAR 2020 |
| DRAWN: | MW |
| CHECKED: | JJHP, LHC |
| APPROVED: | MJ |

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: REDFISH CREEK WATERSHED GEOMORPHOLOGY

| PROJECT No.: | DWG No.: |
|---|---|
| 0268007 | 05 |


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

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 - REDFISH CREEK", AND DATED MARCH 2020.
3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY RDCK DATED 2017. CONTOUR INTERVAL IS 10m.
4. THE WATERSHED AND FAN 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. CULVERT LOCATIONS FROM BC MINISTRY OF TRANSPORTATION. ROADS DATA FROM BC DIGITAL ROAD ATLAS. PARCELS FROM PARCELMAP BC. BUILDING FOOTPRINTS DIGITIZED BY BGC BASED ON LIDAR AND REPRESENT ONLY A SUBSET OF TOTAL BUILDINGS ON THE FAN-DELTA.
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.

| | |
|---|---|
| SCALE: | 1:5,500 |
| DATE: | MAR 2020 |
| DRAWN: | MW |
| CHECKED: | JJHP |
| APPROVED: | MJ |

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

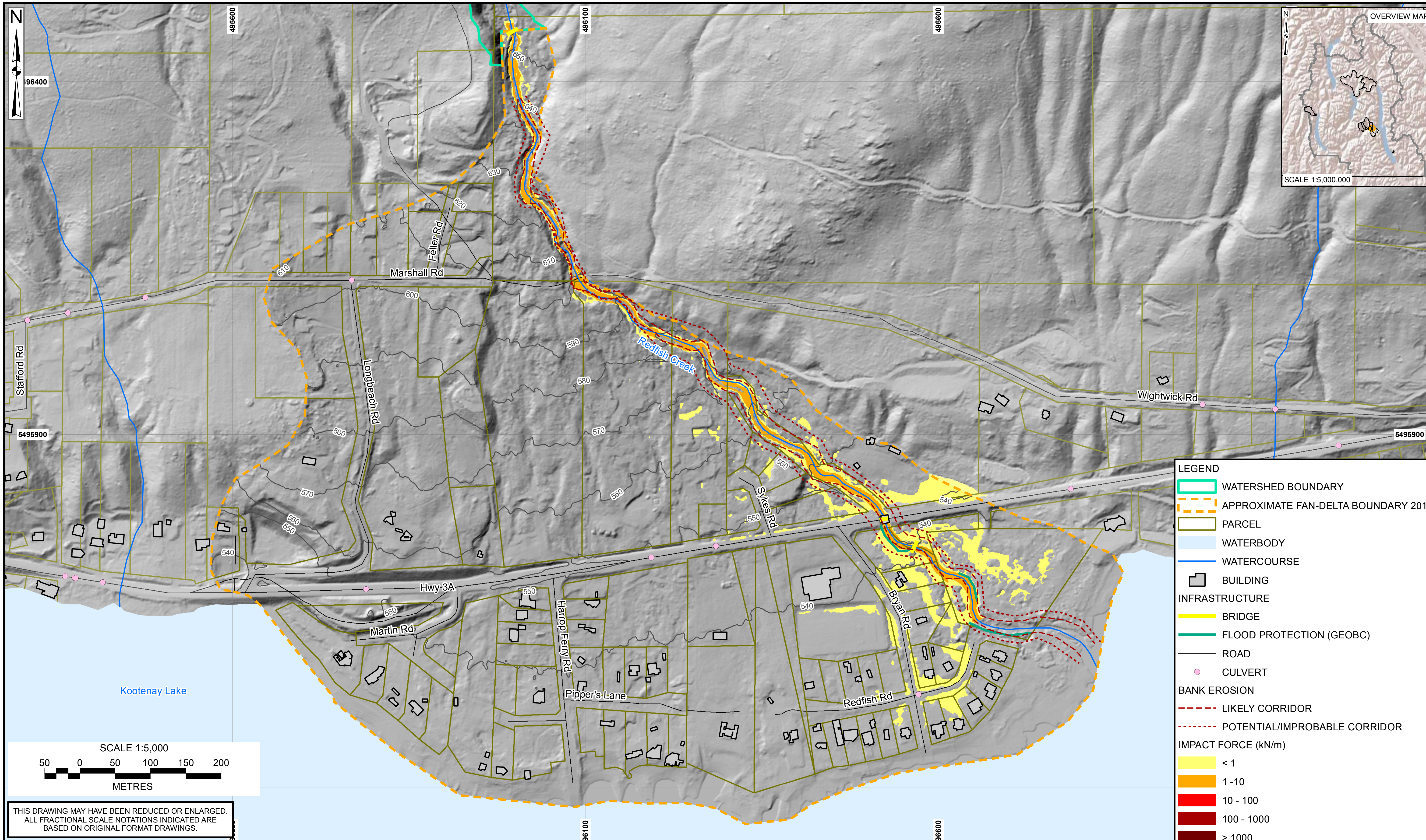
CLIENT:

PROJECT:
RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE:
REDFISH CREEK
FAN-DELTA GEOMORPHOLOGY

| PROJECT No.: | DWG No: |
|---|---|
| 0268007 | 06 |

X:\Projects\0268\007_RDCK_NDMP_Stream_2_Support\GIS\Production\Report\20191112_RDCK_Floodplain_and_Steep_Creek_Study_STEEPCREEK\FINAL_COPIES\06_Redfish_GeomorphicMappingofFan.mxd Date: April 15, 2020 Time: 10:59 AM




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

X:\Projects\0268\007_RDCK_NDMP_Stream_2_Support\GIS\Production\Report\20200207_RDCK_Steep_Creek_Hazards\07 Redfish Creek 200 Year Model Scenario.mxd

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

| | |
|---|---|
| SCALE: | 1:5,000 |
| DATE: | MAR 2020 |
| DRAWN: | LL, MIB, STT |
| CHECKED: | LCH |
| APPROVED: | MJ |

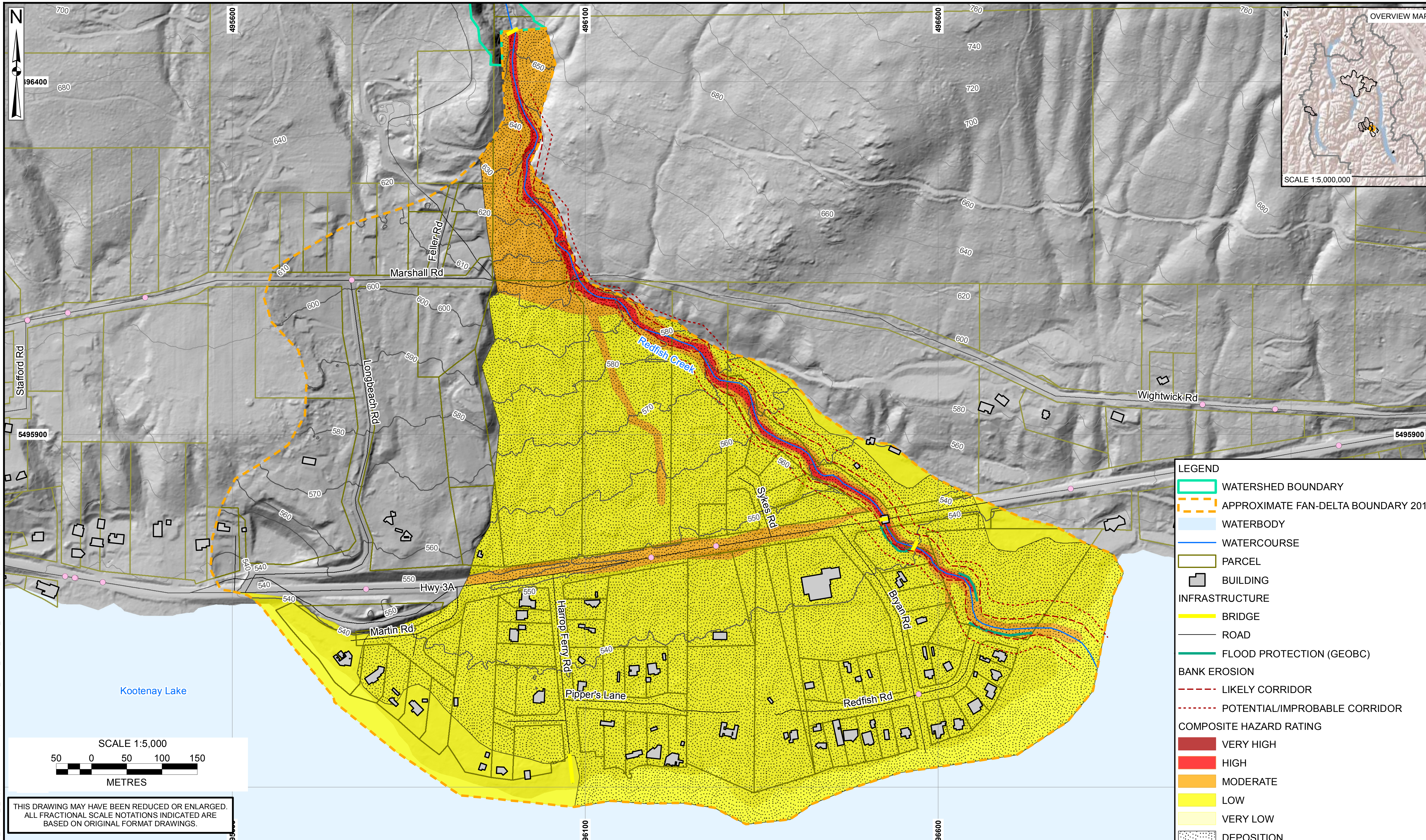
BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT: REGIONAL DISTRICT CENTRAL KOOTENAY

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY

TITLE: REDFISH CREEK 200 YEAR MODEL SCENARIO RFS-3

| PROJECT No.: | DWG No: |
|---|---|
| 0268007 | 07 |




NOTES:
1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORTS TITLED "RDCK FLOODPLAIN AND STEEP CREEK STUDY - REDFISH CREEK", AND DATED MARCH 2020.
3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY RDCK, DATED 2017. CONTOUR INTERVAL IS 20 m AND 10 m ON FAN. THE FAN BOUNDARY AS DRAWN IS APPROXIMATE AND DELINEATES THE LANDFORM BASED ON LIDAR DATED 2017.
4. COMPOSITE HAZARD RATINGS PORTRAYED ON THIS DRAWING ONLY REPRESENT HAZARDS STUDIED WITHIN THE FAN-DELTA BOUNDARY.
5. SURFACE FLOW ON PALEO SURFACES WITHIN THE FAN-DELTA BOUNDARY HAVE NOT BEEN ASSESSED IN THIS STUDY.
6. MODELLED BANK EROSION IS SHOWN AS A LIKELY CORRIDOR (DIVIDED BETWEEN CHANNEL BANKS BASED ON CHANNEL GEOMETRY) AND POTENTIAL/IMPROBABLE CORRDIOR (APPLIED EQUALLY TO BOTH BANKS).
7. THIS MAP REPRESENTS A SNAPSHOT IN TIME. FUTURE CHANGES (DEVELOPMENT, DEBRIS FLOOD MITIGATION, GEOHAZARD EVENTS) MAY WARRANT RE-DRAWING OF CERTAIN AREAS.
8. BUILDING FOOTPRINTS DIGITIZED BY BGC. CULVERT LOCATIONS FROM BC MINISTRY OF TRANSPORTATION. ROADS DATA FROM BC DIGITAL ROAD ATLAS. BANK PROTECTION FROM GEOBC AND BGC FIELD OBSERVATIONS. PARCEL MAP FROM PARCELMAP BC.
9. PROJECTION IS NAD 1983 UTM ZONE 11N.
10. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED OR USED FOR ANY PURPOSE OTHER THAN THE PURPOSE FOR WHICH BGC GENERATED IT. BGC SHALL HAVE NO LIABILITY FOR ANY DAMAGES OR LOSS ARISING IN ANY WAY FROM ANY USE OR MODIFICATION OF THIS DOCUMENT NOT AUTHORIZED BY BGC. ANY USE OF OR RELIANCE UPON THIS DOCUMENT OR ITS CONTENT BY THIRD PARTIES SHALL BE AT SUCH THIRD PARTIES' SOLE RISK.

| | |
|---|---|
| SCALE: | 1:5,000 |
| 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: REDFISH CREEK COMPOSITE HAZARD RATING MAP

PROJECT No.: 0268007

DWG No: 08