



FBC DETAILED FLOOD MAPPING STUDY

Hummingbird Creek

FINAL
January 31, 2023

BGC Project No.:
0511009

Prepared by BGC Engineering Inc. for:
Fraser Basin Council



Fraser Basin Council

January 31, 2023
Project No.: 0511009

Alex de Chantal
Regional Manager, Thompson-Okanagan
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200A – 1383 McGill Road
Kamloops, BC V2C 6K7

Dear Mr. de Chantal,

Re: FBC Detailed Flood Mapping Study, Hummingbird Creek – FINAL

Please find attached the above referenced report. The web application accompanying this report can be accessed at www.cambiocommunities.ca.

Should you have any further questions, please do not hesitate to contact the undersigned. We appreciate the opportunity to collaborate with you on this challenging and interesting study.

Yours sincerely,

BGC ENGINEERING INC.
per:



Kris Holm, M.Sc., P.Geo.
Principal Geoscientist

TABLE OF REVISIONS

ISSUE	DATE	REV	REMARKS
DRAFT	May 20, 2022		Original issue
FINAL	January 31, 2023		Final

CREDITS AND ACKNOWLEDGEMENTS

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Dr. Matthias Jakob, a coauthor on this assessment, worked on Hummingbird Creek and adjacent Sicamous Creek throughout his career – these streams informed many of his ideas and understandings of debris flow and debris flood hazards. This report was finalized after the untimely passing of Dr. Jakob. The project team is grateful for Dr. Jakob's contributions and acknowledges that the findings presented herein and the report benefitted from his contribution and review.

¹ "Professional Registrant" is a term used by Engineers and Geoscientists of British Columbia (EGBC) to describe a professional engineer or geoscientist registered with EGBC and authenticating this document.

LIMITATIONS

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SUMMARY

This report provides a detailed hazard assessment of Hummingbird Creek at Sicamous, British Columbia (BC). Hummingbird Creek is located on the east side of Mara Lake, 7 km south of Sicamous, BC. The Hummingbird Creek fan-delta, on which the community of Swansea Point resides, is densely developed and crossed by Highway 97A. The fan-delta has formed by debris floods and debris flows over the past approximately 9,000 years. On July 11, 1997, a major debris flow (with an estimated peak discharge of 1000 m³/s and sediment volume of 92,000 m³) damaged buildings and roads in Swansea Point. The debris flow was caused by drainage concentration that triggered a slope failure below a forestry road in the upper watershed. More recently a debris flood occurred on June 23, 2012 (estimated sediment volume of 22,000 m³), that damaged Highway 97A and caused sediment and water to enter several buildings.

The objective of this assessment was to quantify debris-flow- and debris-flood hazards to inform future hazard management at Swansea Point in the Columbia Shuswap Regional District (CSRD). Debris flows occur, on average, every 30 to 100 years (approximately 2% annual likelihood). Debris flows will preferentially affect the eastern portions of the fan upstream of the Highway 97A confluence and could result in life loss and building damage.

Debris floods occur, on average, every 10 to 30 years (3% to 10% annual likelihood). Hummingbird Creek channel is likely to fill with sediment during debris floods and channel avulsions. Debris floods can also damage the existing bank protection (riprap) due to bank erosion and threaten Highway 97A and properties along the southern banks of Hummingbird Creek. Debris floods are unlikely to result in life loss but could lead to substantial economic losses.

The effects of climate change are very likely to worsen the impacts of debris flows and debris floods on the fan-delta by creating more frequent and potentially larger debris floods and more frequent, and possibly larger debris flows in the future, primarily because more frequent and more intense rainfall is projected to occur in a warming climate. The frequency and size of debris flows and debris floods under a changing climate were considered in developing the frequency-magnitude model for Hummingbird Creek (Table E-1; Figure E-1).

Table E-1. Frequency-magnitude model for debris floods and debris flows on Hummingbird Creek.

Return Period (years)	Process	Debris Volume Best Estimate (m ³)	Peak Discharge (m ³ /s)
< 10	Flood	negligible	31
10 to 30	Type 1 debris flood	23,000	50
30 to 100	Debris flow	36,000	340
100 to 300	Debris flow	75,000	600
300 to 1000	Debris flow	170,000	1000
1000 to 3000	Debris flow	200,000	1200
>3000	Debris flow	200,000	1200

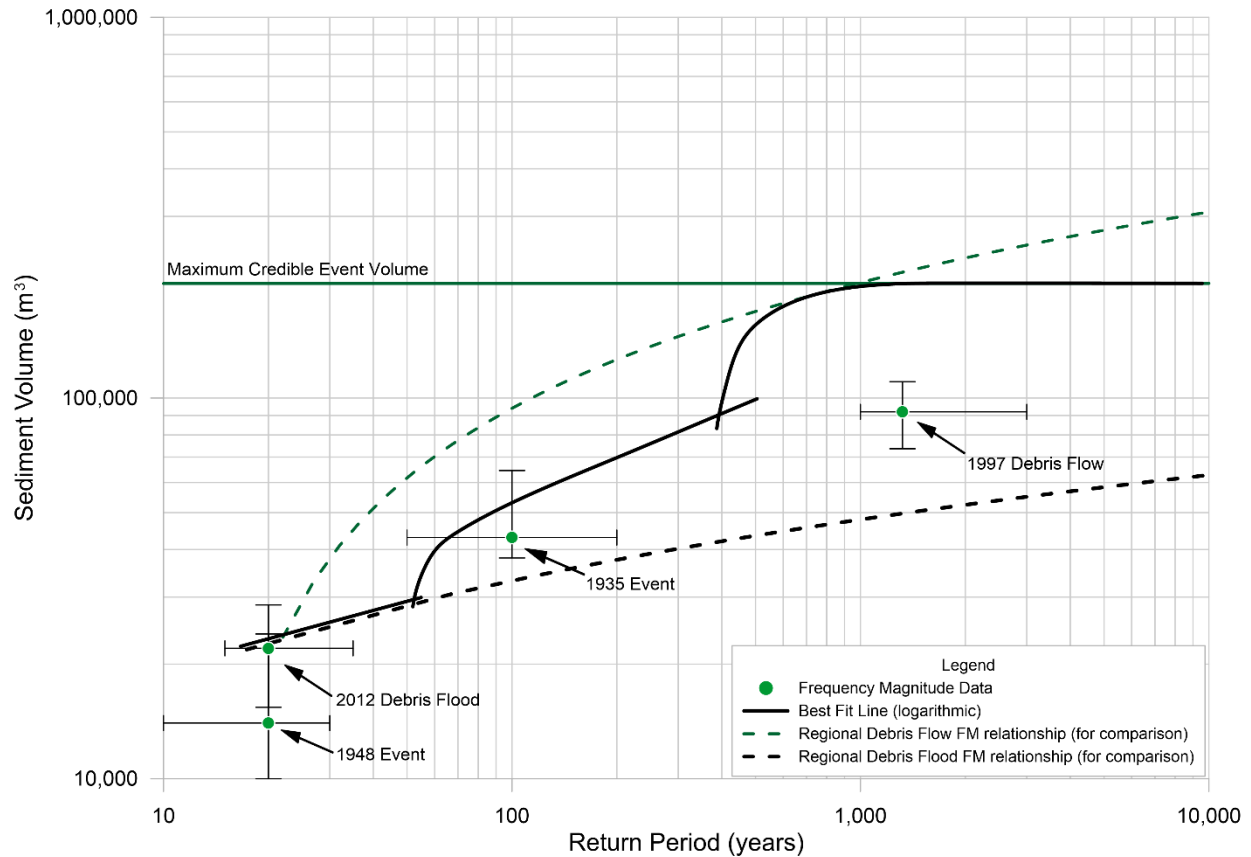


Figure E-1. The frequency-magnitude (F-M) model ensemble for Hummingbird Creek. The black solid curve shows F-M relationships for floods, debris floods and debris flows. The 1997 and 2012 events are shown for comparison, their respective frequencies are judgement-based.

A principal deliverable of this work is a “composite hazard map” that shows hazard zones that are based on impact intensity and frequency of said hazards. Frequently occurring destructive processes are mapped upstream of Highway 97A and along the channel downstream of Highway 97A. Life loss in these areas are likely should a debris flow occur. Other parts of the fan-delta are subject to lesser impact force and/or lesser frequency of impact, life loss is still possible, but less likely than for the areas at the fan-delta apex or near the channel.

Engineered mitigation measures are likely required to safeguard the population and infrastructure on Hummingbird Creek fan-delta, at potentially significant costs. The objective of such measures would be to stop as much debris as possible from reaching developed portions of the fan-delta and managing water flow and sediment down the channel to Mara Lake.

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1. INTRODUCTION

1.1. General

Hummingbird Creek is a debris flow- and debris flood²-prone creek located on the east side of Mara Lake, approximately 7 km south of the town of Sicamous, British Columbia (BC) (Drawing 01). Debris flows and debris floods have historically damaged buildings and roads in the community of Swansea Point, which is located on the fan-delta of Hummingbird Creek. Approximately 235 people live in Swansea Point (Statistics Canada, 2022) and Highway 97A runs through the community, forming a vital transportation link in the Shuswap Lake region.

On July 11, 1997, a 92,000 m³ debris flow transported sediment and water into populated areas of Swansea Point, damaging several cabins and damaging Highway 97A and surrounding roads into the community (Government of British Columbia, October 1997). At the time, the debris flow was one of the largest recorded in BC history (Jakob et al., 2000). While no one was killed by the debris flow, one person succumbed to a heart attack during emergency response. The cause of the debris flow was attributed to a slope failure below a forestry road approximately 2 km upstream of Swansea Point (Government of British Columbia, October 1997).

Following the 1997 event, a debris flood occurred in June 2012 that once again blocked the Highway 97A culvert, leading to damages to the highway and surrounding roads. This event was smaller than the 1997 event and no houses were structurally damaged, although highway and road damage occurred, and houses incurred flooding and minor sediment incursion. Following the 2012 debris flood, Swansea Point residents and Columbia Shuswap Regional District (CSR) successfully lobbied the provincial government to replace the Highway 97A culvert with a bridge, which was completed in 2015.

While considerable work has been completed to reduce debris-flow- and debris-flood hazards, Hummingbird Creek remains one of the highest alluvial fan hazards in the Thompson River watershed (TRW) and CSR (BGC, March 31, 2019; BGC, April 16, 2020; CSR, March 1, 2022). Given the high risk priority rating assigned in these reports, and number of people exposed to debris flows on Hummingbird Creek, Fraser Basin Council (FBC), in cooperation with CSR, applied to the federal Natural Disaster Mitigation Program (NDMP) to fund a hazard assessment for Hummingbird Creek and was successfully awarded in 2021.

A hazard assessment provides information on the hazard associated with debris flows and debris floods such as inundation area, water and sediment depth and velocity, and probability of occurrence. Other than to delineate a hazard boundary, no hazard maps exist for Hummingbird Creek prior to issue of this report. Such maps are important decision-making tools for local and regional governments to inform geohazard mitigation, land use planning, emergency management, and public awareness. The hazard assessment at Hummingbird Creek is being completed along with 14 other high hazard areas in the TRW including the adjacent Sicamous Creek (BGC, June 4, 2021).

² Debris flows and debris floods are kinds of steep creek geohazards with differing concentrations of sediment and water and result in various of hazards to people working and living near these creeks. Definitions of these hazards are provided in Section 3.

This report documents the results of a steep creek geohazards assessment for Hummingbird Creek (Drawing 01). This study supports community planning, bylaw development, and emergency response planning in developed areas subject to flood hazards, with consideration of climate change impacts. Recommendations include considerations for next steps from the study. The main body of this report is written concisely as a plain language summary and most of the technical information is provided in appendices.

1.2. Scope of Work

BGC Engineering Inc. (BGC's) scope of work is outlined in the proposed work plan for 15 study areas (BGC, January 7, 2021) and updated proposal (BGC, June 4, 2021) following confirmation from FBC in early May 2021 that the NDMP funding for FBC received full approval. The project was carried out under the terms of contract between FBC and BGC dated June 14, 2021.

The scope of work included:

- Desktop and field study to assist in the geohazard characterization (i.e., terrain interpretation, air photo interpretation, channel and watershed investigations on foot, dendrochronology where applicable, grain size measurements and other surface investigation)
- Detailed frequency-magnitude analysis based largely on empirical techniques
- Numerical modeling of debris floods and debris flows
- Hazard mapping.

BGC did not assess additional geohazards that could threaten the study area which may include lake flooding and earthquakes. While landslides (debris slides, rock fall, rock slides) were identified as part of the study area characterization, they were only considered in the hazard assessment if they contributed to the frequency and magnitude of debris flows and debris floods in the study area. Assessment of the frequency, magnitude, and runout of large landslides is beyond the scope of this work and all projects carried out under NDMP.

The study scope was informed by Engineers and Geoscientists of British Columbia (EGBC) professional practice guidelines for: flood map preparation (EGBC, 2017), Legislated Flood Assessments in a Changing Climate in BC (EGBC, 2018), and Guidelines for Landslide Assessments in BC (EGBC, 2022). The assessment is also consistent with the Federal Floodplain Mapping Framework (Natural Resources Canada [NRCAN], 2018). Within the NRCAN framework, this study provides the foundation to risk assessment and mitigation (Figure 1-1).

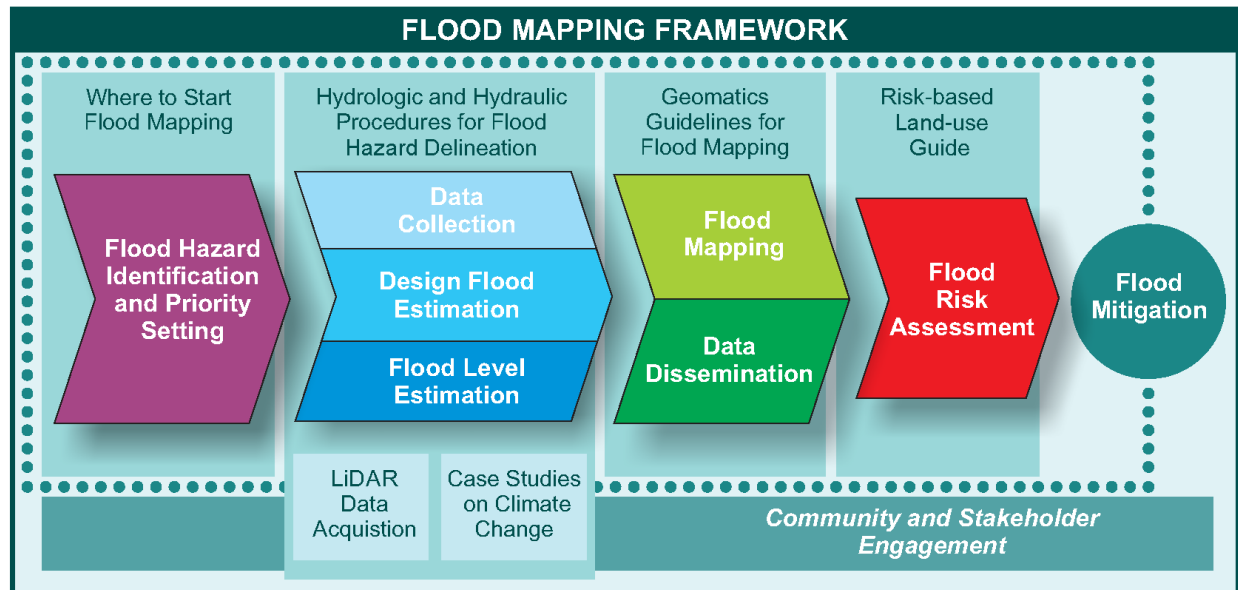


Figure 1-1. Federal flood mapping framework (NRCAN, 2018).

1.3. Report Outline

This report contains a summary of the results of the technical work done to support the hazard assessment. Where necessary, this assessment uses specific hazard terminology provided in Appendix A. Interested readers are encouraged to explore the technical appendices for further details as necessary. The summary includes the following major components:

- Section 2 describes the study area examined in this hazard assessment.
- Section 3 provides an overview of steep creek hazards (debris floods and debris flows) and how they differ from floods.
- Section 4 presents the Frequency-Magnitude Model for Hummingbird Creek supported by the data compilation in Appendix B and methods in Appendix C.
- Section 5 describes the results of the composite hazard mapping, which is generated from numerical flow modelling and methods outlined in Appendix D.
- Section 6 outlines the conclusions and considerations for hazard management.
- Appendix E provides discussion on the key uncertainties in this assessment.

1.4. Deliverables

Deliverables for this study include this report, static maps, and digital deliverables (steep creek hazard map) and are provided via the Cambio™ web application and as geospatial data provided to FBC.

Cambio displays the results of both this hazard assessment along with previous geohazard prioritization studies for FBC and CSRD (BGC, March 31, 2019; BGC, April 16, 2020). The application can be accessed at www.cambiocommunities.ca. Appendix F provides a Cambio user guide and covers the use of Cambio across the CSRD.

2. STUDY AREA CHARACTERIZATION

This section describes the physical setting of the Hummingbird and Mara Creek watersheds and the fan-delta at Mara Lake. Observations of the study area are supported by data compiled by BGC (Appendix B) and from field work completed by BGC (Matthias Jakob, Carie-Ann Lau, Kathleen Horita, and Hazel Wong) from October 5 to 8, 2021. Representative photographs of the study area are provided in the Photo Appendix.

2.1. First Nations

Hummingbird Creek is within the traditional and unceded territory of the Secwépemc people, specifically in the traditional territories of the Splatshin First Nation. BGC contacted the Splatshin First Nation to understand the traditional names and land knowledge of the study area and they politely declined to disclose this information. Therefore, out of respect for the authority of Splatshin First Nation in their traditional territory, we make no attempt to document the traditional land knowledge and use at Hummingbird Creek.

2.2. Watershed Characterization

2.2.1. Physical Setting

The study area is constrained to the watershed boundaries of Hummingbird and Mara creeks (which meet just upstream of Swansea Point) and the combined fan-delta of the two creeks (Drawings 01, 02A, 02B, and 03). The combined watersheds of Hummingbird and Mara creeks are approximately 8 km long and 6 km wide and have a watershed area of approximately 38 km². The topography of the Hummingbird and Mara creek watersheds is characterized by two landforms: relatively flat upland plateaus and steep slopes facing Mara Lake (Photo 1). The steep slopes adjacent to Mara Lake were created when huge glaciers carved out a deep valley trough in Mara Lake and flowed over the alpine plateaus approximately 25,000 to 17,000 years ago (Clague & Ward, 2011). These landforms developed a watershed profile that is classified in geomorphology colloquially as “gentle-over-steep”, with shallow slopes in the alpine plateaus overlying steep slopes along the margin of Mara Lake. This distinct landform can be seen in topographic profiles run along both creeks (Drawing 03).

The watersheds are underlain by metamorphic bedrock, which is generally strong except where disrupted by structural features such as faults and lineaments (Drawing 04; Cui et al., 2017). Based on field observations of a fault gouge approximately 400 m upstream of Swansea Point, we interpret that Hummingbird Creek follows such a fault. This type of rock and its associated faults and fractures can contribute sediment to steep tributary streams in Hummingbird Creek because of the weakened nature of adjacent rocks (EBA Engineering Inc. [EBA] and Kerr Wood Leidal [KWL], 1998).

The same glaciers that carved out Mara Lake valley also deposited glacial sediment (called “till”) that partially covered the bedrock surfaces. When the glaciers left the valley 9,000 years ago (Fulton, 1969), landslides and stream gullies began to move till and underlying bedrock slopes. Some of these landslides are still ongoing, with large landslides slowly deforming the bedrock slopes along Mara Creek, rockfall occurring in Hummingbird Creek, and slope failures below

forestry roads (Photos 2 to 6). Small lakes began to form in poorly drained areas and organic sediments filled these lakes. In addition to historical landslides, Drawing 04 shows the observations of landslides in the watersheds based on previous mapping (Terratech, 1998), BGC’s interpretation of lidar digital elevation models (DEMs), and field observations. BGC understands that more recent detailed mapping was completed for the watersheds to support logging operations, but this data was not made available to BGC.

Vegetation in the watershed is comprised of alpine fir, red cedar, western Hemlock, western larch, spruce, interior Douglas Fir, lodgepole pine, Wet Interior Cedar-Hemlock and Engelmann-Spruce forests (Government of British Columbia, 2021). Approximately 1 km² (3%) of the watershed burned in 2021 from the Two-Mile Road Fire (K42078). Drawing 04 shows the extent of the 2021 burn perimeter. Most of the burn occurred in the mid to upper reaches of Hummingbird Creek. Photo 7 shows an example of a burnt slope in the Hummingbird Creek watershed.

As the glaciers melted, they created an extensive lake system that stretched down the Okanagan Valley (Fulton, 1969). Eagle River (approximately 8 km north) began to deposit sediment into the lake near Sicamous and eventually blocked the valley so that Mara Lake was separated from Shuswap Lake. Hummingbird and Mara creeks carried glacial and landslide-generated sediment downhill towards the lake and formed the fan-delta now present at Mara Lake. The two creeks join approximately 1 km upstream of the lake at the highest point on the fan-delta (called “fan-delta apex”). Photos 8 to 11 show representative photos of the two channels above the fan apex and examples of in-channel sediment deposits. Below the fan-delta apex, the combined stream is called “Hummingbird Creek”.

Table 2-1 summarizes the Hummingbird Creek and Mara Creek watersheds and fan geographic characteristics.

Table 2-1. Watershed characteristics of Mara and Hummingbird Creeks.

Characteristic	Hummingbird Creek Subcatchment	Mara Creek Subcatchment	Combined Watershed
Watershed area (km ²)	15.6	22.6	38
Maximum watershed elevation (m)	2122	2169	2169
Minimum watershed elevation (m)	420	420	420
Watershed relief (m)	1702	1749	1749
Melton Ratio (km/km) ¹	0.43	0.37	N/A
Average channel gradient of mainstem above fan apex (%)	17	18	N/A
Fan area (km ²)	N/A	N/A	0.59
Fan area (including fan-delta) (km ²)	N/A	N/A	0.97
Average channel gradient on fan (%)	N/A	N/A	4.7
Average fan gradient (%)	N/A	N/A	3.8

Note:

- Melton Ratio is the ratio of elevation range to the square root of watershed area and an indicator of the relative susceptibility of a watershed to debris flows, debris floods or floods.

2.2.2. Forestry

Approximately 4.8 km² (approximately 13%) of the watershed has been logged (Government of BC, March 25, 2020). Most clearcut logging occurred between 1993 and 1998, with the most recent logging occurring in 2014. Drawing 04 shows the extents of forestry resource roads in the watershed. Photos 12 and 13 show examples of forestry culverts and bridges in the watershed. Select locations of observed forestry road related landslides are noted in Drawing 04, including the landslide that initiated the damaging 1997 debris flow. The potential for future debris flows due to forestry roads was incorporated into the frequency-magnitude model (Section 4).

2.3. Development on Fan-Delta

2.3.1. Swansea Point Community History

The first non-Indigenous settlers of the Hummingbird Creek area were farmers and homesteaders who arrived in the early 1900s (Sicamous-Eagle Valley Centennial Book Committee, 1985). After the onset of World War One, the fan-delta became the location of the Six Mile internment camp (Photo 14) which was in operation between 1915 and 1917 (Sicamous-Eagle Valley Centennial Book Committee, 1985; Ukrainian Canadian Civil Liberties Association, 2018). Prisoners at this camp were Ukrainian and other European Canadians forced to construct the road along Mara Lake between Sicamous and the south end of Mara Lake. Hummingbird Creek was also used for a relief camp during the depression in the 1930s (Cowan, 2011). After these camps closed, the land returned to homesteaders. The Swansea Resort opened in 1937 and was an early focal point for the community (Sicamous-Eagle Valley Centennial Book Committee, 1985).

Over the last 90 years, the community of Swansea Point has grown from homesteads and summer resorts to a community that now permanently houses 235 people (Statistics Canada, 2022). The community is also a popular destination for tourists drawn to Mara Lake.

2.3.2. Community Assets

The Hummingbird Creek fan-delta is host to approximately 420 buildings on 378 cadastral parcels in the CSRD (Drawing 02A and 02B). Total land values and improvements on Hummingbird Creek are approximately \$149,000,000 and \$74,000,000, respectively (BC Assessment, June 2019). Critical facilities and assets on the fan-delta include:

- Swansea Point Volunteer Fire Department
- Numerous private water wells, lake intakes, and a small water supply system
- Hummingbird Resort sewage system (CSRD, March 1, 2022)
- Power distribution lines
- Communication lines
- Highway 97A and associated infrastructure (bridges and culverts) (Ministry of Transportation and Infrastructure, n.d.).

2.3.3. Hummingbird Creek Infrastructure

The Hummingbird Creek channel on the fan-delta has been mitigated several times since the 1997 debris flow. This section summarizes many of the technical mitigation basis documents and

describes the status of the channel. Relevant observations are provided on Drawing 02A and 02B and the Photo Appendix.

For approximately 300 m from the fan-delta apex to the Highway 97A bridge, the creek flows down an excavated channel with its banks partially armoured with riprap (large angular boulders brought in to protect the bank from erosion; see Photo 15) installed in January 2013 (Golder Associates Ltd., August 23, 2013). BGC observed that the riprap upstream of the Highway 97A bridge was partially eroded and the underlying geotextile fabric was partially exposed (Photo 19). A similar deficiency was noted near the Highway 97A bridge following the 2017 and 2018 floods (nhc, August 7, 2020) and was repaired in October 2020 (Binnie Construction Services Ltd., October 24, 2020).

At Highway 97A, the Ministry of Transportation and Infrastructure (MOTI) constructed an 18 m long and 18 m wide bridge in 2015 (Photos 16 and 17). At the base of the bridge, the channel bottom width narrows to 6.5 m. Prior to the bridge construction, Highway 97A crossed over Hummingbird Creek with a 3.8 m by 2.3 m corrugated metal pipe culvert (Photo 18). Swansea Point residents and CSRD successfully lobbied MOTI to replace the culvert with a bridge as the existing culvert would not convey the 200-year flood (Golder Associates Ltd., August 23, 2013; Labere, August 27, 2013). The design basis for the current bridge is a 200-year flood of approximately 20 m³/s (Golder, December 19, 2013).

Below Highway 97A, Hummingbird Creek flows for approximately 700 m through a partially engineered channel to the outlet at Mara Lake (Photos 20 to 26). Approximately 2,900 m³ of channel bed sediment was removed in January 2013 from the lower 300 m of the channel (Golder Associates Ltd., August 23, 2013). Discontinuous riprap was later installed in the lower 400 m of the channel. However, in some locations no riprap is present adjacent to buildings (e.g., Photos 22 and 26).

More extensive mitigation measures (channel improvements and debris containment berm) were previously proposed for Hummingbird Creek to protect residents from the threat of future debris flows (EBA and KWL, March 11, 1998; Klohn Crippen Berger, June 24, 2003). Funding for these mitigations were proposed by the Province of BC in 2004 but ultimately not constructed because a referendum to approve the maintenance costs for these structures resulted in a rejection by the local population (Labere, July 4, 2012; CSRD, March 1, 2022). The official community plan for CSRD Electoral Area E “encourage[s] the Province [of BC] to construct and maintain a bridge, debris basin and berm at Hummingbird Creek to protect Swansea Point from another debris flow” (CSRD, March 1, 2022).

2.4. Climate and Climate Change

Figure 2-1 graphically summarizes the historical (1991 to 2020) monthly temperature and precipitation climate of the study area developed from climate reanalysis datasets (Appendix C). In the fan-delta area along Mara Lake, the estimated average total annual precipitation is 640 mm, but upslope in the watershed, that increases to 1030 mm, with the highest average monthly total of 123 mm in November and lowest (47 mm) in August. Average monthly temperature varies from around -5°C in January to 16°C in July. Snowfall normally occurs between November and April,

with the annual average snow of around 100 mm in the fan area to 344 mm (expressed as the equivalent amount of water as snow, or SWE) further upslope in the watershed. Summer months are drier but receive occasional heavy rainfall from thunderstorms. These precipitation events can be enhanced by nearby terrain (as air is forced to ascend slope faces); however, the same terrain can create rain shadows that limit precipitation. On average there are 202 dry days (days with less than 1 mm of precipitation) per year. Based on historical Environment and Climate Change Canada (ECCC) records in Sicamous (approximately 7 km north), the maximum historical one-day, three-day, and five-day precipitation accumulations are 44 mm (February 11, 1977), 51 mm (August 16, 1976), and 83 mm (August 19, 1976), respectively. A relatively short climatic record in Sicamous Creek (approximately 10 km northeast of Hummingbird Creek fan) showed a one-day maximum precipitation of 53 mm on July 11, 1997 (Jakob et al., 2000). Climate models estimate a one-day maximum precipitation of 55 mm in the watershed during the period 1971-2020 (Table 2-2).

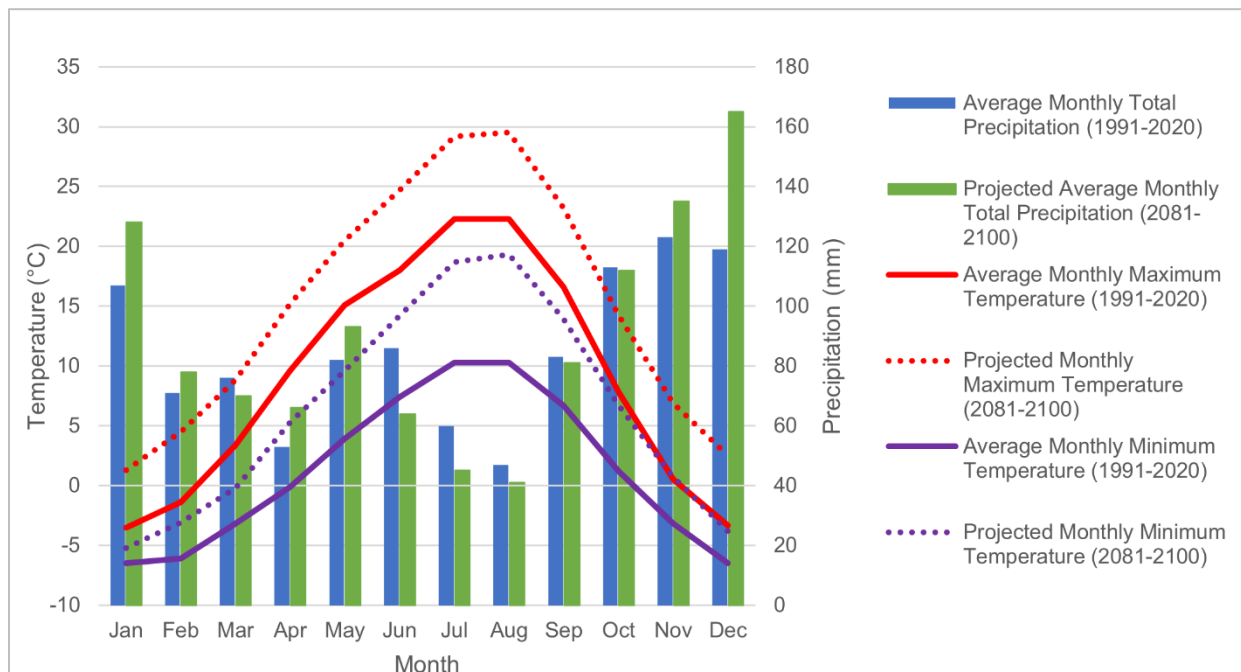


Figure 2-1. Historical and projected average monthly maximum and minimum temperature and average monthly total precipitation for the Hummingbird fan-delta. Source: Climate-BC.

Climate change is affecting every region on Earth and rising temperature will lead to increases in the frequency and severity of many extreme weather events, including heavy precipitation, droughts, and heatwaves that can contribute to geohazards such as wildfires, floods, and debris flows (IPCC, 2021, 2022). Using methods outlined in Appendix C, we projected the future climate conditions for the Hummingbird Creek watershed (upstream of the fan-delta) for two different future time periods (Figure 2-1; Table 2-2). The study area will experience an increase in average surface air temperature and total annual precipitation. These changes are accompanied by a small decrease in the number of dry days, as well as a large decrease in the amount of precipitation falling as snow (Table 2-2). Coupled with the increase in December and January

precipitation (Figure 2-1), this suggests that an increasing proportion of winter precipitation will fall as rain.

The frequency and intensity of heavy³ rainfall events will change through the remainder of the century. Most heavy sub-daily precipitation events occur during summer, which is expected to become drier. Over the remainder of the century, the watershed can expect the annual number of days experiencing heavy rainfall to more than double. When rain does occur, the hourly rainfall rate is expected to increase by 22% and the total daily rainfall is expected to increase by 10% relative to the historical estimates. This means today’s present 100-year hourly rainfall (33 mm) becomes a 75-year event by the 2050s and a 25-year event by the 2080s. Multi-day precipitation event totals increase the most in the spring, with 5-day totals for April and May increasing by approximately 40% by 2100. Similar increases in multi-day events occur are projected in the fall months, due in part to expected increases in the magnitude of atmospheric river events, where October 3-day totals are projected to increase 18% by 2100.

The implications of these changes in the climate are accounted for in the Hummingbird Creek frequency-magnitude relationship (Section 4.3).

Table 2-2. Projected change from historical (1991 to 2020) conditions for selected climate variables for two future time periods: 2041 to 2060 and 2081 to 2100 for the Hummingbird Creek watershed.

Climate Variable	Historical Value (1991-2020) ¹	Projected Change 2041 to 2060 ²	Projected Change 2081 to 2100 ²
Mean Annual Temperature (MAT)	5.1°C	+2.5°C (+49%)	+5.6°C (+110%)
Mean Annual Precipitation (MAP)	1030 mm	+96 mm (+9%)	+212 mm (+21%)
Precipitation as Snow (SWE)	344 mm	-72 mm (-21%)	-204 mm (-59%)
Magnitude of hourly rainfall extremes	--	+9%	+22%
Maximum 1-Day total precipitation	55 mm	-2.7 mm (-5%)	+5.4 mm (+10%)
Average number of days per year with ≥ 20 mm precipitation	5 days	+2.2 days (+45%)	+5.4 days (+109%)
Average number of dry days per year (< 1 mm precipitation)	202 days	-1.3 days (-0.6%)	-0.5 days (-0.3%)

Notes:

1. There is no weather station in the study area after 1994 and nearby weather stations have too much missing data. All historical values are estimated from climate model hindcasts.
2. Projections are from an ensemble of global climate models running the SSP5-8.5 emissions scenario. Data sources: Climate-BC and Microsoft Planetary Computer.

³ Heavy rainfall was defined by BGC as days experiencing 20 mm or more of total rainfall in one day.

3. STEEP CREEK HAZARDS

3.1. Introduction

Steep creek or hydrogeomorphic hazards are natural hazards that involve a mixture of water and debris or sediment (Figure 3-1). These hazards typically occur on creeks and steep rivers with small watersheds (usually less than 100 km²) in mountainous terrain, usually after intense or long rainfall events, sometimes aided by snowmelt and worsened by forest fires.

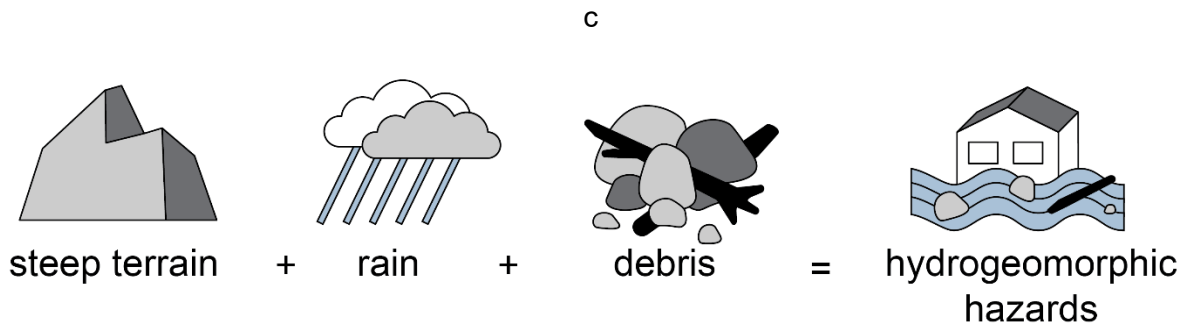


Figure 3-1. Illustration of steep creek hazards.

Steep creek hazards span a continuum of processes from clearwater floods (flood) to debris flows (Figure 3-2). The following two sections describe some general characteristics of debris floods and debris flows and how they differ from floods.

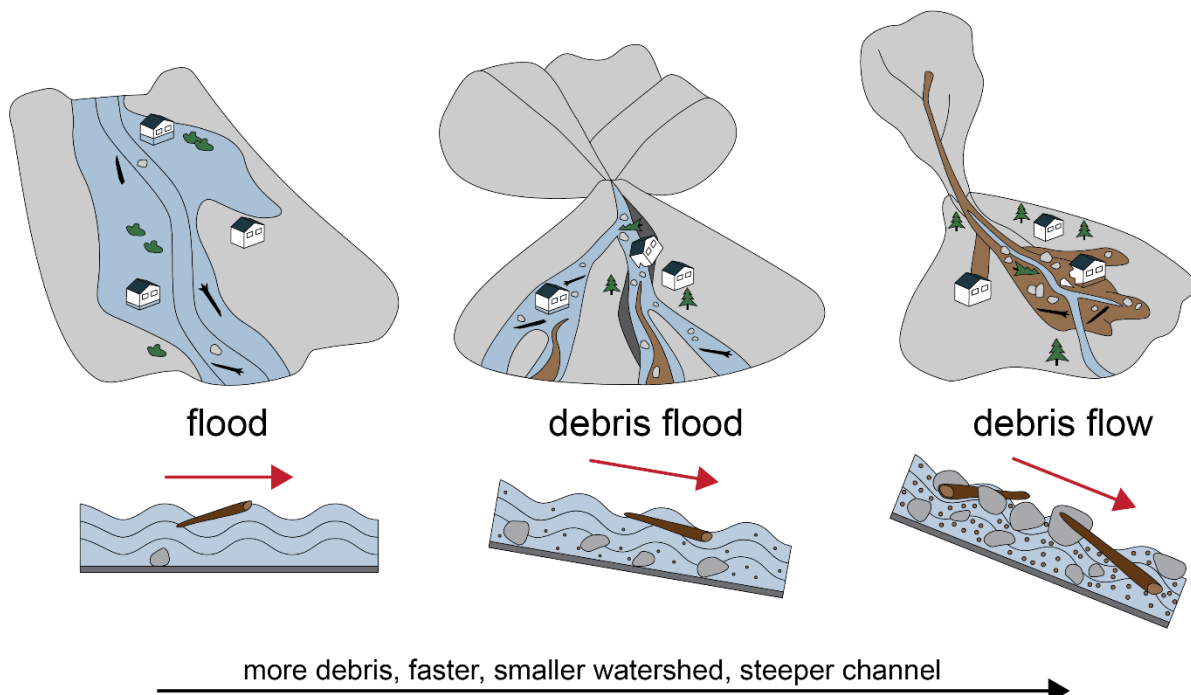


Figure 3-2. Continuum of steep creek hazards.

3.1.1. Debris Floods

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

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

Sediment and woody debris becoming entrained in floods leads to an increase in the volume of organic and mineral debris flowing down a channel, and an increase in peak discharge. This is referred to as flow bulking. Imagine a bucket of water spilled down a children’s slide. That’s a clearwater flood. Refill the bucket with 10 litres of water and a shovel of sand and some twigs. Now the water-sediment mixture occupies 12 litres worth of volume. It has bulked by a factor of 1.2. If the water-sediment mixture is spilled down the slide, this is a bulked debris flood with 20% sediment concentration by volume. The experiment can be repeated with increasing volumes of sediment until it becomes a debris flow (see Section 3.1.2).

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. A catastrophic level is reached when major infrastructure and building damage occurs due to erosion and results in sediment and water entering buildings, building and bridge foundation collapse, culvert blockage, and road surfaces being eroded. While relatively rare, injuries and/or fatalities occur when people are trying to escape these events.

A debris flood occurred on Hummingbird Creek on June 23, 2012.

3.1.2. 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 the bucket of water and fills it to the top, so that the fluid is half sand, half water, it is bulked by 100%, so it has a bulking factor of 2. If you spill it down the slide, you now have a debris flow that behaves more like liquid concrete than water.

Debris flows are typically faster than debris floods and have substantially higher velocities and flow depths, resulting in higher peak discharges and impact forces. They are particularly threatening to life and buildings due to these characteristics.

A debris flow occurred on Hummingbird Creek on July 11, 1997.

3.1.3. Comparing 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. Figure 3-3 demonstrates this concept with an example cross-section of a steep creek, including representative flood depths for the peak discharge (“Q”) of the following processes:

- Q_2 ; Clearwater flow with 2-year return period
- Q_{200} ; Clearwater flow with 200-year return period (i.e., a clearwater flood)
- $Q_{\text{max debris flood (full bed mobilization)}}$; Type 1 debris flood generated by full bed mobilization
- $Q_{\text{max debris flood (outburst flood)}}$; Type 3 debris flood generated by an outburst flood
- $Q_{\text{max debris flow}}$; Debris flow.

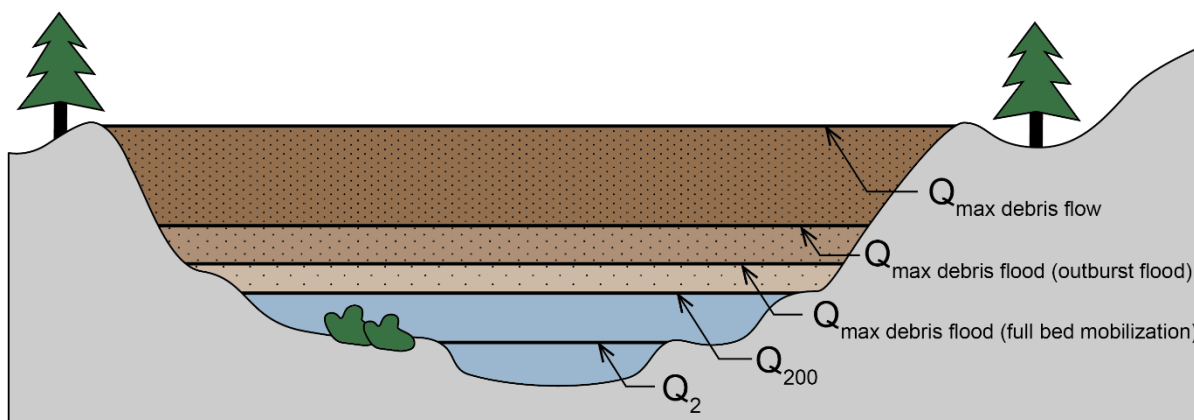


Figure 3-3. Conceptual steep creek channel cross-section showing peak discharge levels for different events. Note that for some outburst floods or debris flows the discharge may exceed what is shown here.

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 debris floods, the longer duration of the event will also affect the total volume of sediment transported, the amount the channel may aggrade, and the amount of bank erosion occurring.

4. FREQUENCY-MAGNITUDE MODEL

This section summarizes the frequency and magnitude model for steep creek hazards at Hummingbird Creek and answers the following questions:

- How frequently do steep creek hazards occur?
- When they occur, how large are they in terms of their volume of sediment and water (called “magnitude”) and the peak discharge flowing down the channel?
- How will the frequency-magnitude relationship above change with climate change?

We present the answers to these questions in the form of a frequency-magnitude (F-M) model for specific return periods. Getting the F-M relationships right is of considerable importance, as it influences the outcome of numerical modeling, informs follow-up risk assessments, and instructs the design of potential mitigation measures. Therefore, considerable effort was expended on this task.

In this section, we summarize the steep creek processes at Hummingbird Creek (Section 4.1) and documented historical steep creek events (Section 4.2), describe how these events may change with climate change (Section 4.3), and summarize the results of the F-M model for Hummingbird Creek (Sections 4.4 and 4.5) that was used to generate the composite hazard map (Section 5). The results presented in this section are supported by methods described in Appendix C. An overview of the methods is shown in Figure 4-1. Representative photos of past debris flows and debris floods are provided in the Photo Appendix.

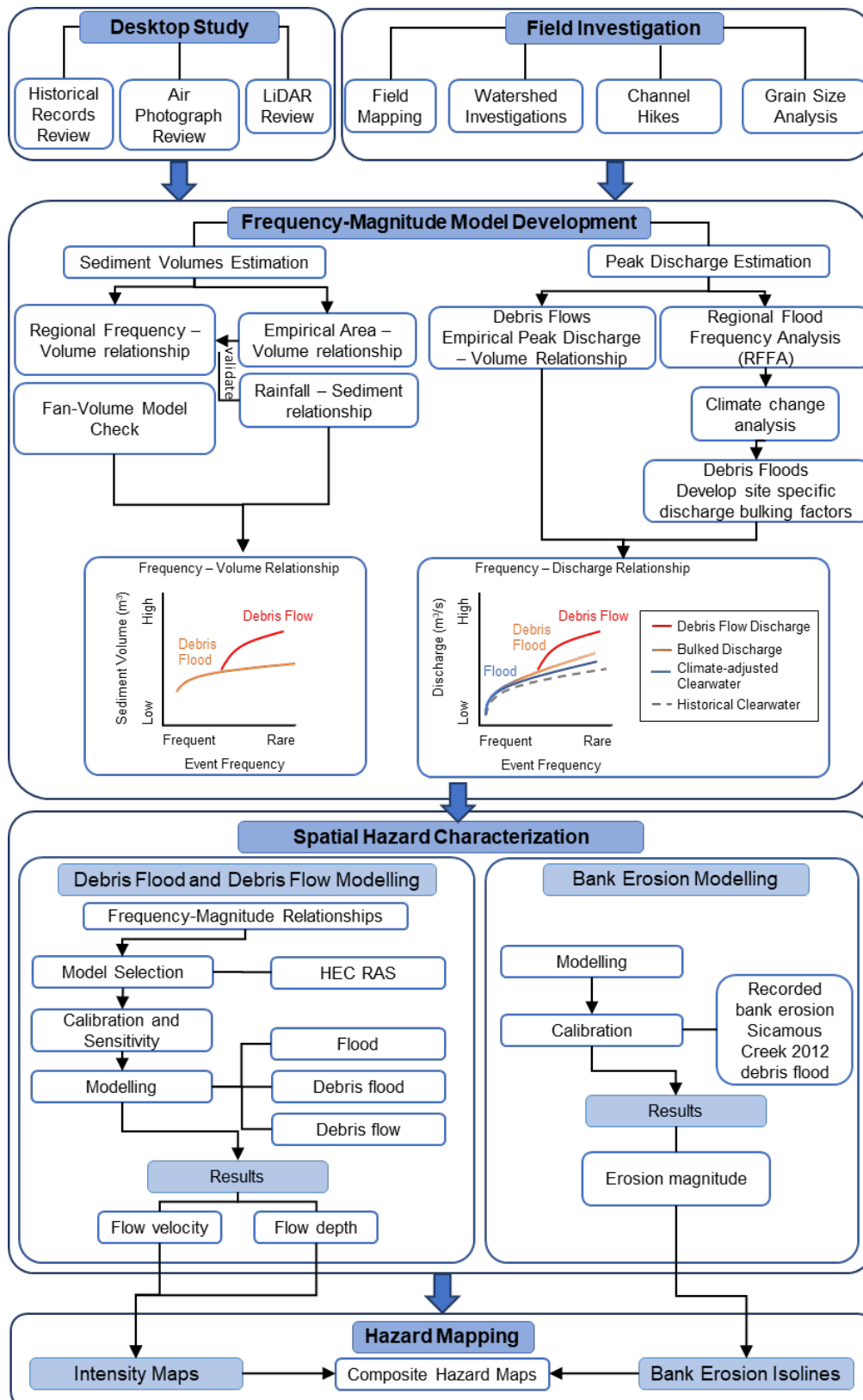


Figure 4-1. Flood- and debris flow-prone steep creeks workflow used for developing frequency-magnitude relationships, modeling, and preparing hazard maps.

4.1. Hummingbird Creek Steep Creek Processes

Hummingbird Creek is subject to floods, debris floods, and debris flows all at specific return periods. We interpret this from the following evidence:

- Empirical analyses (Figure 4-2) suggest that both debris floods and debris flows are possible on Hummingbird Creek and Mara Creek watersheds.
- The creek produced a debris flow on July 11, 1997, and a debris flood on June 23, 2012. These events are further discussed in Section 4.2.
- BGC observed evidence of past debris floods in the upper watersheds of both Mara and Hummingbird Creeks (Photos 10 and 11).

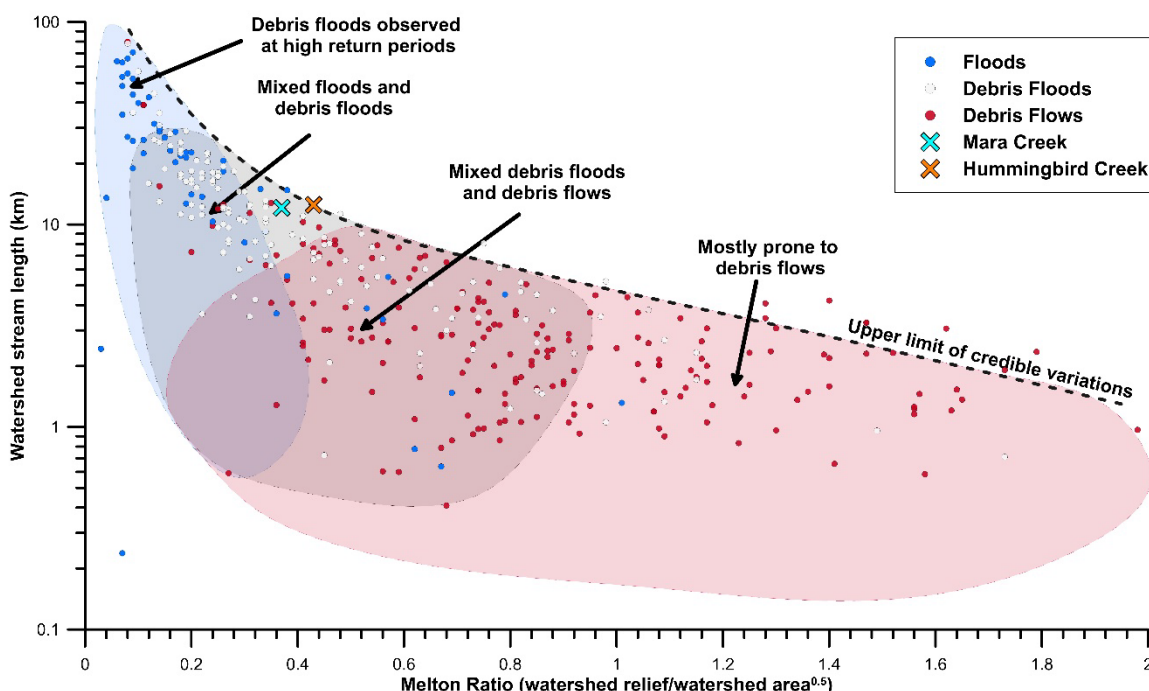


Figure 4-2. Steep creek classification into floods, debris floods and debris flows from field observations across Alberta and British Columbia compiled by BGC. Melton ratio is the ratio of elevation range to the square root of watershed area and an indicator of the relative susceptibility of a watershed to debris flows, debris floods or floods.

While both creeks plot in the “typical” debris flood range of Figure 4-2, the “gentle-over-steep” topography of the watersheds creates steep and unstable channels in the mid to lower watersheds that have generated debris flows in the past. These start as debris avalanches on the steep side slopes that transition to debris flows upon impact with the main channel. This can be exacerbated by drainage along forestry roads and cutblocks as evidenced by the debris flow on July 11, 1997.

Debris floods are interpreted to be triggered by high-intensity rainfall that mobilizes in-channel sediment, which is a type I debris flood (Section 3.1.2). The frequency of these events is influenced by the abundance of colluvial sediments and landslide processes in these watersheds and the frequency of high intensity rainfall events. These watersheds can also produce type II debris floods through the dilution of debris flows by incorporating in-channel water volume. The

type II process is interpreted to occur less frequently on Hummingbird Creek because the channel is sufficiently steep ($> 10^\circ$) to convey debris flows to the fan-delta apex.

4.2. Historical Events

Table 4-1 summarizes the records of floods, debris floods, and debris flows at Hummingbird Creek from historical records, air photos, dendrochronology, and test trenches (methods described in Appendix C). Interpretations from these events are provided on the fan-delta geomorphic map (Drawing 05) and the air photo comparison (Drawing 06). Representative photographs from these sources are provided in the Photo Appendix. From the recorded flood, debris flow, and debris flood events, we can make some observations about the occurrence and types of steep creek processes at Hummingbird Creek:

- Debris flows have occurred on average, every 50 to 100 years (two recorded events between 1928 to present), depending to some degree on human watershed alterations.
- Debris floods have occurred on average, every 10 to 30 years (five recorded events between 1928 to present)
- Some recorded events occurred during late in the freshet (May or June) when snow would have been present in the watershed and subject to snowmelt during rainstorms.
- Most events occurred during high daily rainfall (greater than 20 mm/day). However, tying specific event occurrence to daily or hourly rainfall thresholds is not possible due to lack of consistent rainfall data near the site. Moreover, antecedent moisture conditions play a role in preparing the watershed soils for landsliding in case of a high intensity rainfall event.
- Most events coincided with high lake levels. Observations of high lake level occurrence coinciding with debris floods and debris flows was carried into the assumptions used to generate the composite hazard map (Appendix D).
- The largest event on record (July 11, 1997) was a debris flow that was triggered by artificial drainage concentration downstream of a culvert that resulted in a debris avalanche below a forestry road (Government of BC, October 1997).
- The main channel across the fan-delta has changed course (termed an “avulsion”) at least two times since the first air photo in 1928. These avulsions are thought to occur during large debris flows and debris floods.

Table 4-1. Summary of observed steep creek events at Hummingbird Creek. Where date ranges are approximated, recorded rainfall is provided for ECCC station Salmon Arm (approximately 20 km west), deactivated ECCC station Sicamous (approximately 7 km north), or the deactivated Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD) station Sicamous Creek (approximately 10 km northeast).

Event Date	Type of Event	Source of Event	Sediment volume (m ³)	Peak discharge (m ³ /s)	Damages	Notes
580 years before present	Unknown	Radiocarbon date from HUM-TP-02 SA-01 (Drawing 05)	Unknown	Unknown	Unknown	A prehistoric debris flow or debris flood reached the fan-delta margin near Mara Lake. The deposit was approximately 1.0 m below the surface (Photo 27) and indicates that prehistoric events were large enough to deposit thick sediment far away from the fan-delta apex.
150 years before present	Unknown	Radiocarbon date from HUM-TP-02 SA-01 (Drawing 05)	Unknown	Unknown	Unknown	A prehistoric debris flow or debris flood reached the fan-delta margin near Mara Lake. The deposit was approximately 0.7 m below the surface (Photo 28) and indicates that prehistoric events were large enough to deposit thick (approximately 0.3 m) sediment far away from the fan-delta apex. Regional high water and flood event occurred around this time in 1894.
1925, 1926, or 1928	Unknown	EBA and KWL (March 11, 1998); Fuller (2002); air photo record	Unknown	Unknown	Unknown	In the 1928 air photo, the channel is very bright, indicating recent debris deposition. No recorded events describe an event occurring during this time frame, although the brightness of the channel suggests it occurred recently (within the last 10 years). Dendrochronology reported in EBA and KWL (1998) suggests a date of 1925 or 1926. More than 20 mm/day of rain fell in Salmon Arm on May 17, 1927, August 11, 1927, and June 16, 1928. EBA and KWL (1998) mapped the pre-1930 channel flowing across the northern sector of the fan (towards Swanbeach Road). However, BGC notes that the channel was primarily flowing west (Drawing 06).
June 30, 1935 ¹	Debris flow or debris flood	EBA and KWL (March 11, 1998); Jakob et al. (2000); Fuller (2002)	43,000	Unknown	Two bridges destroyed, severe erosion along the two channels.	During this event, Hummingbird Creek flowed as two channels across the fan-delta (Drawing 06 based on EBA and KWL, 1998). The channel mouth avulsed approximately 350 m south compared to the 1928 air photo. The event occurred during the night of June 30 based on historical accounts. EBA and KWL (1998) interpret the event was sourced from Mara Creek although Jakob et al (2000) could not detect evidence for a debris flow source in air photos. Based on boulder sizes recalled by residents, EBA and KWL (1998) classified this event as a debris flow. Approximately 55 mm of rain fell in Salmon Arm from June 29 to 31, 1935.
1948	Lake flooding, debris flood	Airphoto record; Sicamous-Eagle Valley Centennial Book Committee (1985); EBA and KWL (March 11, 1998)	14,000	Unknown	Cabins at Swansea Resort had water due to flooding. Hummingbird Creek eroded channel banks below Highway 97A and destroyed a small hydroelectric dam.	In the 1951 air photo, the channel is very bright, indicating recent debris deposition. Sicamous-Eagle Valley Centennial Book Committee (1985) describe that the spring of 1948 was very hot and melted the thick snowpack quickly, resulting in flooding. Hummingbird Creek reportedly moved large boulders.
1964/1965	Debris flood?	EBA and KWL (March 11, 1998)	Unknown	Unknown	Unknown	Dendrochronology reported in EBA and KWL (1998) suggests a date of 1964 or 1965, although no events are historically recorded around these dates. More than 20 mm/day of rain fell in Sicamous on May 9, June 26, July 8, July 14, August 3, and September 7, 1964.
June 1972	Lake flooding and debris flood?	Septer (2008); Shuswap Lake Watch (n.d.); EBA and KWL (March 11, 1998)	Unknown	Unknown	Overland lake flooding.	Mara Lake rose to its highest record level on June 14, 1972. Dendrochronology reported in EBA and KWL (1998) suggests a debris flood occurring in 1971 or 1972. No events are historically recorded around these dates. More than 20 mm/day of rain fell in Sicamous on March 22 and July 11, 1972.
1976/1977	Debris flood?	EBA and KWL (March 11, 1998)	Unknown	Unknown	Unknown	Dendrochronology in EBA and KWL (1998) suggests a date of 1976 or 1977, although no events are historically recorded around these dates. In mid-August 1976, the highest recorded three- and five-day rainfall occurred in Sicamous (Section 2.4).

Event Date	Type of Event	Source of Event	Sediment volume (m ³)	Peak discharge (m ³ /s)	Damages	Notes
July 11, 1997	Debris flow	Government of BC (October 1997); EBA and KWL (March 11, 1998); Jakob et al. (2000)	92,000	1,000	Upstream of Highway 97A, direct impact of debris flow against five homes (Photos 29 to 31), and water wells were buried or destroyed. Highway 97A culvert crossing was overtopped, and the road base was damaged from erosion. Downstream of Highway 97A, overland flow and avulsions caused road damage (Photos 32 and 33) and damaged septic fields. One person died of a heart attack during recovery efforts.	The debris flow originated on a steep (greater than 35°) slope below the Ashton-Mara East Forest Service Road (locally known as "Skyline Road") approximately 2 km upstream of the fan-delta apex on Hummingbird Creek (Forest Practices Board, August, 2011). Jakob et al. (2000) note that 1997 was abnormally wet year, with higher-than-normal snowpack in the months leading up to the debris flow. On the day of the event, peak rainfall intensity reached 6 mm/hr with 85 mm of rainfall recorded in the adjacent watershed of Sicamous Creek on the day of the event (Jakob et al., 2000). Salmon Arm received 18 mm of rain on this day and 22 mm of rain the day preceding the debris flow.
June 23, 2012	Debris flood and lake flooding	Shuswap Lake Watch (n.d.); Golder (August 23, 2013)	22,000	N/A	Highway 97A culvert crossing was overtopped, and the road base was damaged from erosion. Downstream of Highway 97A, overland flow and avulsions caused road damage (Photos 34 to 38)	The debris flood coincided with the second highest lake level recorded on Mara Lake. BGC observed evidence of this debris flood in Mara Creek (location shown in Drawing 05). Salmon Arm received 25 mm of rain. A major and destructive debris flood occurred on nearby Sicamous Creek.
2017	Flood	Northwest Hydraulic Consultants (NHC, August 7, 2020)	Unknown	Unknown	High flows damaged riprap protection upstream of Highway 97A bridge.	NHC (August 7, 2020) attributed the flooding to high snowpack, warmer than normal temperatures, and heavy precipitation. High intensity (more than 20 mm/day) rain fell in Salmon Arm on May 4 and May 11, 2012.

Note:

1. KWL and EBA (March 11, 1998) deduced the year of this event from interviews with Hummingbird Creek residents and monthly rainfall magnitudes. The recollected year of this event ranged from 1930 to 1933. Jakob et al. (2000) narrow the date range from historical reports to 1935. BGC agrees with this interpretation based on rainfall records from Salmon Arm ECCC climate station.

4.3. Climate Change Considerations

Given the findings in Section 2.4, the following assumptions were made to adjust the F-M considering climate change effects:

- Debris flows are possible for the 30 to 100-year return period given the projected increase in the frequency and magnitude of high intensity rainfall.
- A 35% increase in runoff by the end of the 21st century (see Appendix C).
- An increasing likelihood of wildfires and tree mortality through drought and heat stress as well as beetle infestations, given the projected increases in air temperature. This last effect was out of the current scope of work and is difficult to quantify. It was not explicitly accounted for in the F-M adjustment.

The relative effects of these factors are captured in Table 4-2.

Table 4-2. Summary of climate change effects on debris flood and debris flow F-M relationships.

Effect	F-M impact	Confidence
Increases in extreme rainfall frequency	Moves the F-M curve to the left	Very High
Increases in extreme rainfall intensity	Moves the F-M curve upwards	Very High
Increase in wildfire burn severity	Not accounted for in the F-M curve	High

4.4. Return Periods for Frequency Magnitude Model

Debris flows and debris floods, like any geophysical phenomenon, occur at irregular intervals. Their frequency is approximated from various proxy data sources that allow reconstruction of the average recurrence interval. Table 4-3 outlines the Annual Exceedance Probabilities (AEPs) chosen by BGC for this hazard assessment that generally represent the spectrum of observed or reconstructed event magnitudes. These AEPs are consistent with those listed in the EGBC Guidelines for Legislated Flood Assessments in a Changing Climate (2018) and Guidelines for Landslide Assessments in BC (2022).

Table 4-3. Return period classes (AEPs) used to associate specific debris volumes and peak flows for the hazard assessment on Hummingbird Creek.

Return Period Range (years)	Representative Return Period (years)	AEP (%)
1 to 3	2	50
3 to 10	5	20
10 to 30	20	5
30 to 100	50	2
100 to 300	200	0.5
300 to 1000	500	0.2
>1000	2000	0.05

Note: The 5-, 50- and 500-year events do not precisely fall at the mean of the return period ranges but were chosen as round figures due to uncertainties and because these return periods have a long tradition of use in BC.

4.5. Hummingbird Creek Frequency-Magnitude Model

BGC assumed the following in developing the F-M model:

- Post-wildfire debris flows following the Two-Mile Road Fire are possible, but unlikely due to the relatively small amount of the watershed (2%) burnt at moderate to high intensity (Hope et al., 2015; FLNRORD, March 15, 2022).
- The re-occurrence of a debris flow originating downslope of a forest road may be reduced due to changes to forestry road management made after the 1997 debris flow (Forestry Practices Board, August 2001) but is still possible (Photo 6, Drawing 05). Therefore, BGC included the potential for logging road related debris flows in the estimate of debris flow return periods.
- Previous estimates of flood frequency used a regional hydrologic analysis (EBA and KWL, 1998). BGC updated the regional hydrologic analysis to include additional years of discharge data collected in nearby watersheds that would include any high flow years (e.g., 2012). It also included an ensemble of methods including the regional index flood method and a pro-rated calibrated hydrologic model on the nearby Sicamous Creek watershed (Appendix C). Values presented below are the result of the regional index flood method.

Table 4-4 and Figure 4-3 summarize the F-M model for Hummingbird Creek developed from these assumptions. A discussion of the uncertainties inherent to the F-M model are provided in Appendix E. Of note on Figure 4-3 is that the previous documented events fall below the F-M curve, as the curve accounts for projected climate change impacts.

Table 4-4. Frequency-magnitude analysis results on Hummingbird Creek.

Return Period Class (years)	Dominant Geomorphic Process	Debris Volume (m ³)	Flood Discharge (m ³ /s)	Bulked, Climate Change Adjusted Discharge ¹ (m ³ /s)	Bulking Factor Comments
1 to 3	Flood	-	16	21	-
3 to 10	Flood	-	23	31	-
10 to 30	Debris Flood	23,000	31	42	Type 1 debris flood
30 to 100	Debris Flood /Debris Flow	36,000	n/a	340	n/a
100 to 300	Debris Flow	75,000	n/a	600	n/a
300 to 1000	Debris Flow	170,000	n/a	1000	n/a
1000 to 3000	Debris Flow	200,000	n/a	1200	n/a
3000 to 10,000	Debris Flow	200,000	n/a	1200	n/a

Note:

1. Bulked, climate change adjusted discharges were used as the peak discharge for debris-flood modeling.

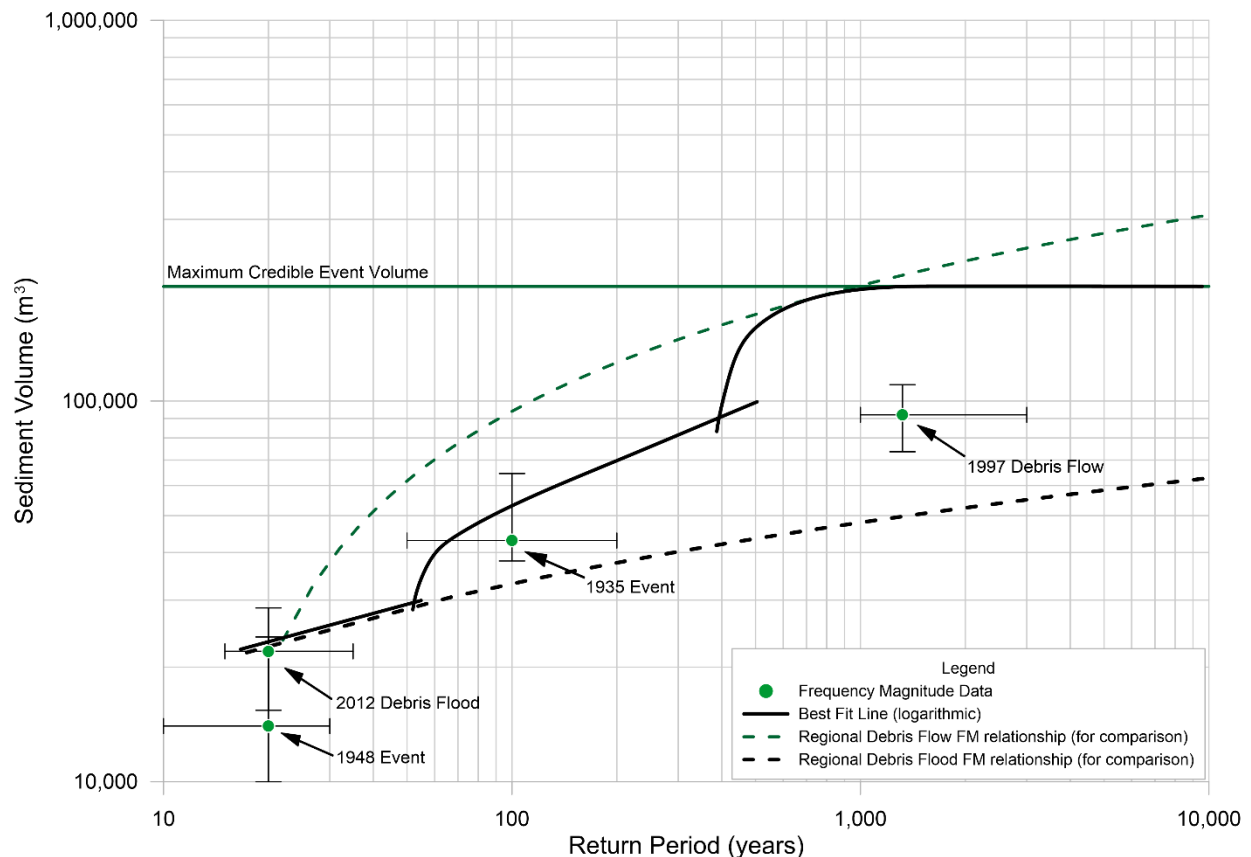


Figure 4-3. The frequency-magnitude (F-M) model ensemble for Hummingbird Creek. The black solid curve shows F-M relationships for floods, debris floods and debris flows. The 1997 and 2012 events are shown for comparison. Error bars are based on judgement.

5. COMPOSITE HAZARD MAP

5.1. Introduction

This section summarizes the results of flood-, debris flood-, and debris-flow computer simulation from the frequency and magnitude model of steep creek hazards at Hummingbird Creek (Section 4). These models and subsequent calculations answer the following questions:

- When steep creek hazards occur, how far do they spread across the fan-delta?
- How deep, and fast, is the flow during a steep creek event?
- What are the impact forces⁴ produced during these events?

We present the answers to these questions in the form of a composite hazard map which combines impact force and frequency for each simulated scenario. In other words, for any location on the fan it informs on the hazard by combining the damage potential with the likelihood of the event affecting a specific area. The warmer the colours, the higher the hazard. The results were generated from the methods outlined in Appendix D. The composite hazard map is meant to provide a tool for land use planners and regulators to identify hazards and inform zoning and development permit application responses.

The composite hazard map does not resolve the specific frequency, impact force or bank erosion of such events; this information is contained in the hazard scenario maps, as outlined below.

5.2. Results of Hazard Scenarios

Drawing 07 shows the maximum impact forces of each of the six individual hazard maps for each of the return period classes. Table 5-1 provides a description of the likelihood and severity of structural damage based on the impact forces provided in Drawing 07 with example photos documented from previous debris floods and debris flows on the fan-delta of Hummingbird Creek. Table 5-2 summarizes the findings⁵ of the individual modelling scenarios.

The existing bridge over Hummingbird Creek was modelled to be overtopped when the peak discharge of the flows exceeded its capacity. Additional blockage and avulsion scenarios were not simulated. The precise flow behavior of each modelled scenario is uncertain because of nuances during each event that cannot all be modelled with confidence. These nuances include channel aggradation, bank and highway erosion, bridge and/ or channel blockages, and fences or other obstacles that may influence the flow path and affect its impact.

⁴ Impact force is the product of the flow depth, the square of the flow velocity, and the density of the flow.

⁵ Confidence and likelihood terminology are used in Table 5-1 and defined in Appendix A.

Table 5-1. Description of the likelihood and severity of building damage based on the modelled impact forces shown in the hazard maps in Drawing 07. Example photos are provided from previous events at Hummingbird Creek.





Impact Force (kN/m)	Colour	Potential Consequence Severity	Description	Example Photo
< 1	Yellow	Minor	Slow flowing shallow or deep water carrying little or no debris. High likelihood of water damage. Potentially dangerous to people in buildings, in areas with greater water depths.	 <p>Sedimentation and damages on the lower fan-delta of Hummingbird Creek following a debris flood in June of 2012. Photo courtesy of CSRD June 2012.</p>
1 to 10	Orange	Moderate	Mostly slow but potentially fast flowing shallow or deep flow with some debris. High likelihood of sedimentation and water damage. Potentially dangerous to people in the basement or first floor of buildings without elevated concrete foundations.	 <p>Looking west on the lower fan-delta of Hummingbird Creek following the debris flow on July 11, 1997. Photo courtesy of Sicamous Museum July 1997.</p>
10 to 100	Pale Red	High	Fast moving and deep water carrying debris and/or large boulders. High likelihood of major structural damage and severe sedimentation and water damage. Very dangerous to people.	 <p>Looking at damages to an unknown building on the fan-delta of Hummingbird Creek following the debris flow on July 11, 1997. Photo courtesy of Sicamous Museum July 1997.</p>
100 to 1000	Red	Severe	Very fast moving and deep water carrying debris and large boulders. High likelihood of total building destruction and very high likelihood of major structural damage. Extremely dangerous to people.	
> 1000	Brown	Complete Destruction	Very fast moving and deep water carrying significant amounts of debris and large boulders. Very high likelihood for total building destruction. Extremely dangerous to people.	 <p>Looking at damages to an unknown building on the upper fan-delta of Hummingbird Creek following the debris flow on July 11, 1997. Photo courtesy of Sicamous Museum July 1997.</p>

Table 5-2. Summary of modeling results. Explanations on confidence definitions can be found in Appendix A.

Process and Return Period Range (years)	Key Predictions
Floods (< 10 years) (not shown in Drawing 07)	<ul style="list-style-type: none"> Floods will likely be fully contained within the existing channel and unlikely to result in appreciable damage on the fan-delta reaches (very high confidence). Bank erosion is unlikely to impact existing development at those return periods (high confidence). Over time, accumulation of sediment (if not artificially removed) especially in the lower fan-delta reaches will decrease conveyance and hence freeboard (very high confidence).
Debris flood (10 to 30 years)	<ul style="list-style-type: none"> Debris floods are associated with substantial bank erosion along unprotected or poorly protected channel reaches on the fan-delta and major (> 10,000 m³) sediment transport (high confidence). Assuming that the Highway 97A bridge remains un-blocked, debris floods are expected to cause substantial bank erosion especially along the North bank upstream of Highway 97 and along the lower reaches of the channel opposite of Hummingbird Resort. Erosion of the riprap protection on the south side of the creek at Hummingbird Resort, is possible especially if the water level in Mara Lake is low (medium confidence). Portions of Hummingbird Resort could be inundated with water with depths of up to 0.5 m (medium confidence).
Debris flow (30 to 100-year return periods)	<ul style="list-style-type: none"> Debris flows will overwhelm the channel capacity of Hummingbird Creek and may inundate approximately 30% of the fan-delta surface. Debris flows will avulse upstream of Highway 97A and impact homes on the north side of the creek with impact forces likely to cause major structural damage to such homes (high confidence). Flow depths are likely to range up to 6 m in the channel and up to 3 m outside of the channel on the north side of the creek. Flow velocities are likely to reach up to 7 m/s near the fan apex diminishing to some 3 m/s near the Highway 97A bridge. Flow velocities outside the channel diminish to the north from 3 to 1 m/s (high confidence). Debris flows will block the Highway 97A bridge and lead to further avulsions mainly affecting the northern fan portions downstream of Highway 97A (very high confidence) and partly to the south likely to cross the highway immediately upstream of Hummingbird Resort with water and debris entering Hummingbird Resort from the north (high confidence). Avulsion flow depths will be mostly less than one metre and result mostly in nuisance flooding. Local substantial damage could occur where homes are located in former channels where flow is deeper and faster (high confidence). The channel of Hummingbird Creek is likely to fill with sediment and subsequent flood flows may cause erosion along its banks throughout the fan reaches, especially along the north banks due to flow concentration on the outside of the channel bend (high confidence).
Debris flow (100 to 300-year return periods)	<ul style="list-style-type: none"> Similar impacts as for the 30 to 100-year return period debris flow, but with somewhat higher flow depths and flow velocities. Debris flows may inundate approximately 35% of the total fan-delta surface. Entire Hummingbird Resort affected by the debris flow with damage expected to structures attributable to water inundation and localized erosion (high confidence).
Debris flow (300 to 1000-year return periods)	<ul style="list-style-type: none"> Similar impacts as for the 100 to 300-year return period debris flow, but with somewhat higher flow depths and flow velocities. Debris flows may inundate approximately 55% of the total fan-delta surface. Likely destruction of buildings on the upstream of Highway 97A on the north bank (very high confidence). Additional avulsions are also possible towards the north along Highway 97A. Most of the highway across the Hummingbird Creek fan-delta will likely be eroded or become otherwise impassable cutting access to the fan-delta (high confidence). Some structural damage to buildings in avulsions paths especially in low-lying areas of former channels due to erosion (high confidence). At this return period, multiple initiating failures in the watershed are conceivable which implies several debris flow surges whose behaviour cannot be reliably modeled.
Debris flow (> 1000-year return period)	<ul style="list-style-type: none"> Similar impacts as for the 300 to 1000-year return period debris flow, but with somewhat higher flow depths and flow velocities. Debris flows may inundate approximately 60% of the total fan-delta surface. Likely destruction of buildings on the upstream of Highway 97A on the north bank (very high confidence) At this return period, multiple initiating failures in the watershed are conceivable which implies several debris flow surges whose behaviour cannot be reliably modeled.

5.3. Composite Hazard Map Results

The composite hazard map incorporates the ensemble of modelled hazard scenarios into a single map. It represents the current hazard on the fan-delta by combining the modelled impact forces from all hazard scenarios and the annual probability of occurrence for each hazard (i.e., debris flood or debris flow). The highest return bank erosion corridor modelled is also provided in the composite hazard map and is colour coded according to Figure 5-1 assuming bank erosion damage is approximately equivalent to an impact force of 1 to 10 kN/m. Figure 5-1 illustrates how the colour scheme and final hazard rating provided in the composite hazard map are estimated based on the probability of occurrence of difference classes of impact forces (examples of impact force potential damage provided in Table 5-1).

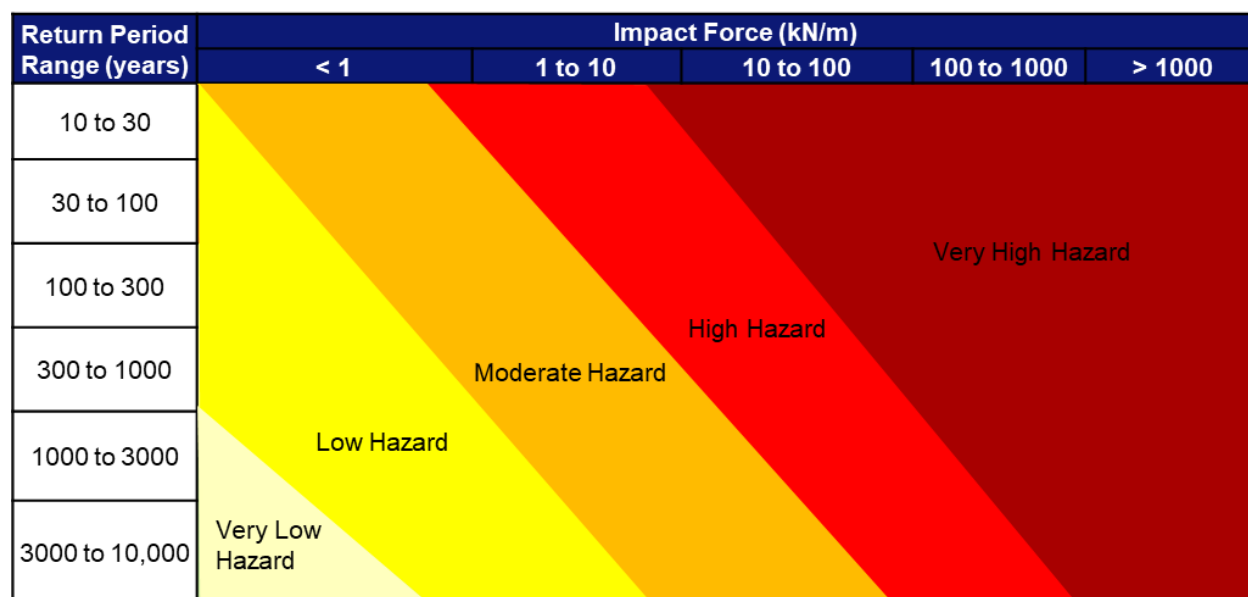


Figure 5-1. Matrix illustrating the colour scheme and final hazard rating provided in the composite hazard map. The composite hazard map combines the modelled impact force from each hazard scenario and the annual probability of occurrence of the hazard.

The composite hazard map for Hummingbird Creek (Drawing 08) indicates the following:

- Most of the fan-delta of Hummingbird Creek is subject to some flooding hazard.
- The upper fan-delta (upstream of Highway 97A) is characterized by high to very high composite hazard rating, which suggests frequently occurring high impact forces creating a substantial hazard to homes and potential risk to loss of life.
- High to moderate bank erosion hazards exist along the existing channel of Hummingbird Creek downstream of Highway 97A, including the densely developed lots at Hummingbird Resort.
- High to moderate hazard exists along two avulsion channels on the central and northern fan portions. These two channels follow Swansea Point Road and a topographically low part of the fan-delta.

- At least half of Highway 97A and some of the local roads are subject to moderate hazards, meaning that portions of Swansea Point may be inaccessible in an event due to scour, erosion, and/or debris deposition.

6. CONCLUSIONS AND CONSIDERATIONS FOR HAZARD MANAGEMENT

6.1. Conclusions

Hummingbird Creek fan-delta is subject to considerable debris-flood- and debris-flow hazard, as demonstrated during the 1997 debris flow (Jakob et al., 2000) and the 2012 debris flood. Given the hazards and the high development density in the high hazard zones, Hummingbird Creek fan-delta is one of the highest risk fans within the CSRD (BGC, April 16, 2020).

During the 1997 and 2012 events damage occurred to buildings and roads, but fortuitously neither event led to injury or direct loss of life. The lack of reported injuries and fatalities during these events should not lead one to believe that the hazard is manageable under the current channel configuration, even with a recently (2015) constructed bridge. Debris flows are certain to eventually re-occur and reach the Hummingbird Creek fan-delta. When they occur, debris flows will exit the existing channel and inundate development, where they can cause substantial damage and may lead to injury and loss of life. The highest hazard area exists on the upper fan-delta upstream of Highway 97A.

It may be argued that the chance of logging-road related failures is a legacy of the past and that these events are unlikely to re-occur due to improved logging road and watershed management. However, it cannot be guaranteed that similar circumstances to the 1997 debris flow could not occur and lead to renewed landslide activity. Furthermore, the effects of climate change will likely increase both the frequency and magnitude of debris floods and debris flows in the Mara and Hummingbird Creek watersheds.

A primary deliverable of this assessment is the composite hazard map (Section 5.3, Drawing 08). Compared to a development permit area defined by a hazard boundary, this map provides a more detailed basis on which to make planning and permitting decisions that may vary depending on the level of hazard. As these maps represent the first of their kind within the CSRD, additional work should be considered to develop recommendations for the application of these maps in decision making. BGC notes that policy review for composite hazard maps is related to the subject of risk tolerance policy and the roles and responsibilities of Qualified Professionals in development permitting. BGC suggests further engagement with the CSRD about policy integration of results, beyond the conclusion of this project. Guidance on suggested land use planning within each hazard zone is provided in EGBC Professional Practice Guidelines "*Landslide Assessments in British Columbia*" (EGBC, September 29, 2022).

6.2. Considerations for Hazard Management

This section notes specific considerations given the findings of this report that may be considered for future hazard management of the hazards from Hummingbird Creek and Mara Creek. These considerations would require further analysis by BGC to refine and require more in-depth discussion with the CSRD and other interested parties who own assets on the Hummingbird Creek fan-delta.

The CSRD has recently enacted a new Official Community Plan for Electoral Area E, which includes Swansea Point (CSRD, March 1, 2022). These new bylaws (CSRD bylaw No. 840 and

841) classify Hummingbird Creek as a “Steep Creek Hazard Area”. The objective of the new Bylaw No. 840 is to “minimize the risk to life, and to minimize the potential for damage to property and the natural environment (CSRD, March 1, 2022)”. The Official Community Plan encourages “the Province [of BC] to construct and maintain a bridge, debris basin and berm at Hummingbird Creek to protect Swansea Point from another debris flow” (CSRD, March 1, 2022). Given the results of this assessment, BGC agrees with the intent of this statement that mitigation works are required to protect Swansea Point from another debris flow.

This report’s scope did not include the development of mitigation concepts. However, it is helpful to understand the type and scale of mitigation measures that may be considered to reduce debris-flood and debris-flow risk on the Hummingbird Creek fan-delta. The following key strategies ought to be acknowledged when trying to achieve successful risk reduction for existing and future developments:

1. Sediment retention: Trap organic debris and sediment near the fan apex to avoid aggradation and downstream avulsions. Note that this strategy, while it is effective, is expensive and requires regular maintenance. Such structures must also consider potential consequences such as stream downcutting downstream of the structure and impacts to downstream fish habitat.
2. Conveyance: Most creeks on fan-deltas tend to be wide and laterally unstable, causing frequent avulsions. Confining the creek between berms on the channel edge is undesirable as the channel will infill with sediment during sediment transport events, thus reducing the channel’s flow and sediment capacity. Alternatively, berms set back from the main channel can provide room for the creek to shift and build up sediment. Unfortunately, setback berms could infringe on existing properties. Given the length of the fan delta (approximately 1000 m), such setback berms would be very expensive. The berms would have to be owned and operated by local government, which will require access easements. Occasional sediment removal from the stream channel might still be required.

A variety of potential mitigation measures for Hummingbird Creek are listed in Table 6-1 and shown in Figure 6-1. The identified measures require more analysis before they can be considered conceptual design options. These concepts are separated into global mitigation (measures 1 and 2), mitigation specific to Highway 97A (measures 3a to 3g), and measures aimed at improving the channel of Hummingbird Creek through channel bank hardening and channel widening (measures 4a and 4b). Other measures such as property-specific measures and warning systems are also listed (measures 5, 6, and 7). Property-specific measures could be implemented to increase resilience of developments to debris flood and debris-flow impact; e.g., flood construction levels or specific measures to avoid water or debris entry into basements and ground floors via doors and/or windows. Lastly, a hydro-climatic warning system could be implemented alongside emergency management procedures to reduce the potential for loss of life.

Measures 1 and 2 will have the most impact on reducing debris-flow risk as they aim to capture a large proportion of the modelled debris flows. A combination of measures 3, 4, 5, 6 and 7 are meant to complement measures 1 and 2 should those be constructed.

Other measures often used in steep creek mitigation work that are not possible on the Hummingbird Creek fan-delta include:

- Deflection berms: The Hummingbird Creek fan-delta is densely developed and flow cannot simply be deflected to another area on the fan-delta.
- Fully armoured continuous channel: Hummingbird Creek is not steep enough to convey the sediment volumes expected from debris floods or debris flows from the fan-delta apex to Mara Lake.

Table 6-1. Mitigation measures that may be considered for the Hummingbird Creek fan-delta

Focus	Measure	Description	Effect on Debris Flood or Debris Flow Hazard Reduction	Relative Cost
Global Mitigation	1	Debris barrier near the fan apex	Reduction in debris load, reduced chance of downstream avulsions. Minor clearwater flood attenuation.	Very High
	2	Debris basin between the fan apex and Highway 97A	As above and avoidance of outflanking of structure.	Very High
Highway-Related Mitigation	3a	Grouting riprap beneath Highway 97A bridge	Reduces chance of highway failure by foundation erosion.	Low
	3b	Raised road	Reduces water and debris flow erosion, avulsion potential down Swansea Point Road.	Very Low
	3c	Armoured overflow channels along Highway 97A	Allows water flowing down Highway 97A to flow north or south along armoured channels or ditches and enter Mara Lake without highway washout.	Low
	3d	Lock-blocks or jersey barriers	Redirects water and debris flowing down Highway 97A to flow north or south while reducing the chance of road embankment erosion and road surface failure.	Low
	3e	Armoured overflow channel on Swansea Point Road	Allows water and debris to be redirected from Swansea Point Road back into Hummingbird Creek without eroding the road.	Low
	3f	Avulsion relief channel	Constructed channel to relieve water and some sediment from Highway 97A.	Moderate
	3g	Road swale	Reduces the potential of water and debris entering Hummingbird Resort.	Very Low
Hummingbird Creek Channel Improvements	4a	Riprap grouting	Reduces the bank erosion potential along the existing channel.	Low
	4b	Channel widening with grouted riprap or stone pitching bank protection	Reduces the bank erosion and avulsion potential, while allowing for some sediment storage. May require property acquisition and regular maintenance for sediment removal in channel.	Moderate
Other measures	5	Establishing flood construction level for new and redevelopments as per this report	Provides minimum elevation requirements for new developments on the Hummingbird Creek fan-delta where overland flooding is a concern. This is less applicable to areas at risk to debris flow impact.	Low ³
	6	Home-specific mitigation	Reduction of damage to buildings on Hummingbird Creek fan-delta from debris flows or debris floods.	Low ³
	7	Hydroclimatic warning system	Reduction of life loss potential.	Low

Notes:

1. Costs will vary depending on the scale of mitigation.
2. Very High: > \$10M, High: \$1M-\$10M, Moderate: \$100,000-\$1M, Low: \$10,000-\$100,000, Very Low: <\$10,000.
3. Cost estimate for individual properties.

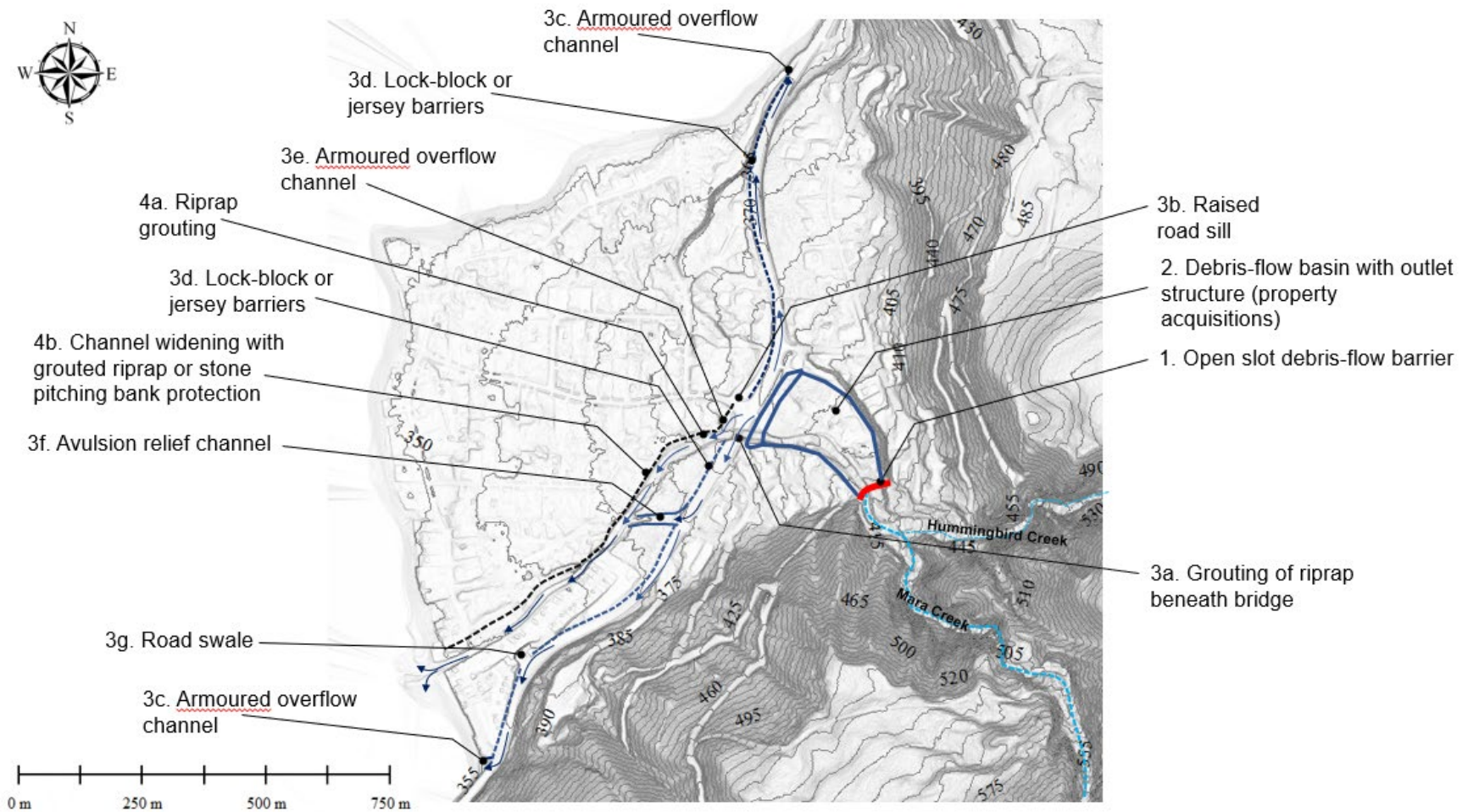


Figure 6-1. Potential debris-flood or debris-flow mitigation measure alternatives that may be considered to achieve risk reduction. Mitigation measures in combination are likely more effective than any single mitigation measure.

7. CLOSURE

This report contains sections under the supervision of different individuals. Carie-Ann Lau is the responsible author for Study Area Characterization (Section 2). Kathleen Horita is the responsible author for Frequency-Magnitude Model (Section 4), Composite Hazard Map (Section 5), and Conclusions and Considerations for Hazard Management (Section 6).

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

Yours sincerely,

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PHOTOGRAPHS

1.0 Photos of the Mara and Hummingbird Creek watersheds



Photo 1.

Looking northeast at Hummingbird Creek fan-delta and upslope watershed. Note the relatively flat plateau in the upper watershed and the steep channel flowing down to the fan-delta.

Photo by BGC on October 4, 2012.



Photo 2.

Looking south at steep bedrock cliffs interpreted to be large landslide headscarps in Mara Creek approximately 1.8 km southeast of the fan-delta apex (see location in Drawing 05).

Photo by BGC on October 6, 2021.



Photo 3.

Looking west (downstream) at steep bedrock slopes adjacent to Hummingbird Creek approximately 150 m upstream of the fan-delta apex. The steep slopes are subject to rockfalls (see location in Drawing 05).

Photo by BGC on October 7, 2021.



Photo 4.

Looking north at the source of the 1997 debris flow below the Skyline forestry road in the Hummingbird Creek watershed (see location in Drawing 05). Note the rip rap placed on the slope below the forestry road.

Photo by BGC on October 6, 2021.



Photo 5.

Looking northeast at the source of the 1997 debris flow below the Skyline forestry road in the Hummingbird Creek watershed (see location in Drawing 05). Note the rip rap placed on the slope below the forestry road and the moderately burnt trees on either side of the debris slide path.

Photo by BGC on October 6, 2021.



Photo 6.

Looking south at a debris slide triggered by forestry road failure in the Mara Creek watershed (see location in Drawing 05). The large boulders on the left photo demark the top of the debris slide.

Photo by BGC on October 6, 2021.



Photo 7.
Looking north at moderately burnt vegetation on bedrock-controlled slopes of Hummingbird Creek. The burn is approximately 10 m downslope of the forestry road.

Photo by BGC on October 6, 2021.

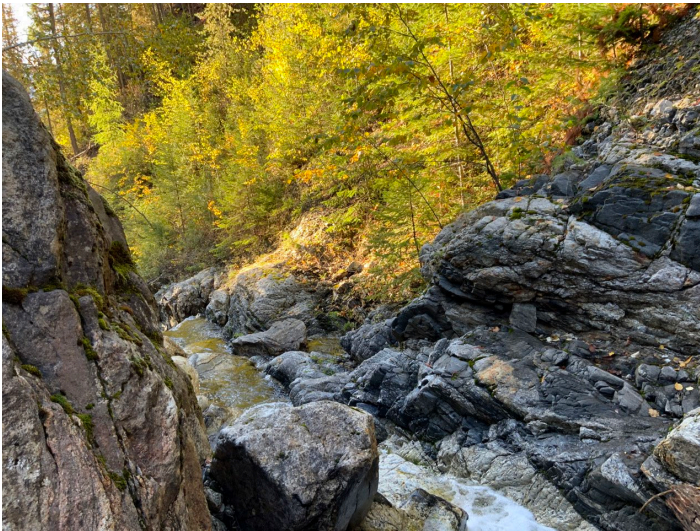


Photo 8.
Looking west (downstream) at bedrock-controlled channel of Hummingbird Creek approximately 400 m upstream of the fan-delta apex.

Photo by BGC on October 7, 2021.



Photo 9.
Looking north (downstream) at bedrock-controlled channel of Mara Creek approximately 150 m upstream of fan-delta apex.

Photo by BGC on October 8, 2021.



Photo 10.

Looking north at debris flood deposits downstream of a forestry road crossing in the Hummingbird Creek watershed approximately 4 km upstream of the fan-delta apex. Note the yellow notebook (approximate 15 cm tall) for scale compared to the size of the gravels and boulders in the deposit.

Photo by BGC on October 5, 2012.



Photo 11.

Looking south (upstream) at approximately 10-year-old debris flood deposits in Mara Creek approximately 1.6 km upstream of the fan-delta apex. Note the yellow notebook (approximate 15 cm tall) for scale compared to the size of the boulders in the channel.

Photo by BGC on October 6, 2021.



Photo 12.

Looking south at an approximately 1.8 m diameter culvert under a forestry road in the Mara Creek watershed.

Photo by BGC on October 6, 2021.



Photo 13.
Looking northeast at an approximately 11 m long forestry road bridge approximately 3.9 m above Hummingbird Creek. The bridge is approximately 4 km upstream of the fan-delta apex.

Photo by BGC on October 6, 2021.

2.0 Photos of the fan-delta

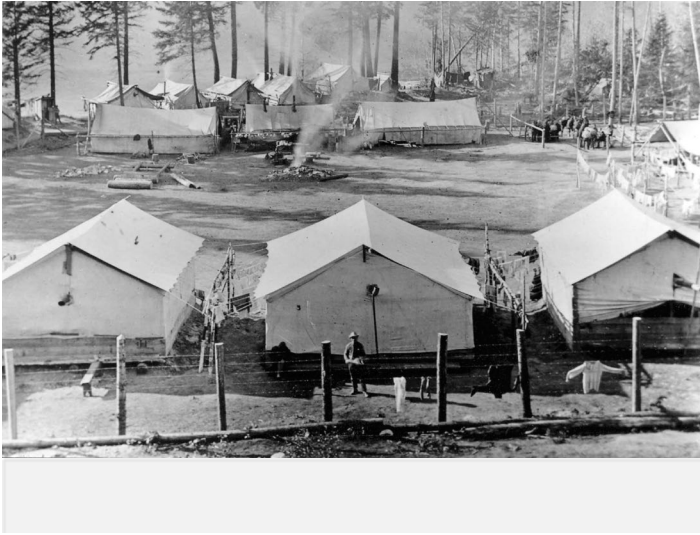


Photo 14.
Looking west at the internment camp at Six Mile (present-day Swansea Point). Note Mara Lake in the background of the photo.

Photo courtesy of the Enderby and District Museum and Archives ca. 1917.



Photo 15.
Looking east (upstream) at the Hummingbird Creek channel between the fan-delta apex and Highway 97A. Note the presence of large angular rip rap along the channel banks.

Photo by BGC on October 7, 2021.



Photo 16.
Looking west (downstream) at the Highway 97A bridge over Hummingbird Creek.

Photo by BGC on October 7, 2021.



Photo 17.
Looking east (upstream) at the Highway 97A bridge over Hummingbird Creek.

Photo by BGC on October 8, 2021.



Photo 18.
Looking west (downstream) at the former culvert under Highway 97A bridge at Hummingbird Creek. Note the difference at the Highway 97A crossing compared to Photo 16.

Photo by BGC on October 5, 2012.



Photo 19.
Looking south (across channel) at the condition of the rip rap along the south (left) bank of Hummingbird Creek upstream of the Highway 97A bridge. Note the black fabric (geotextile) visible next to the riprap.

Photo by BGC on October 7, 2021.



Photo 20.

Looking west (downstream) at the Hummingbird Creek channel downstream of the Highway 97A bridge. Note the presence of large angular boulders in the channel placed during mitigation in 2020 (Binnie Construction Services Ltd., October 24, 2020).

Photo by BGC on October 8, 2012.



Photo 21.

Looking east (upstream) at the Hummingbird Creek channel approximately 300 m downstream of the Highway 97A bridge. Note the lack of rip rap lining the channel banks.

Photo by BGC on October 8, 2012.



Photo 22.

Looking north at right (north) bank of Hummingbird Creek approximately 350 m downstream of the Highway 97A bridge. Note the approximately 0.75 m freeboard between the channel and the top of the bank and the buildings behind the bank.

Photo by BGC on October 8, 2012.



Photo 23.

Looking west (downstream) at the Hummingbird Creek channel approximately 400 m downstream of the Highway 97A bridge. Note the approximately 2.0 m freeboard between the channel and the top of the south (left) bank and the buildings behind the bank. The south (left) bank is armoured by rip rap.

Photo by BGC on October 8, 2012.



Photo 24.

Looking east (upstream) at the Hummingbird Creek channel approximately 400 m downstream of the Highway 97A bridge. Note the approximately 1.75 m freeboard between the channel and the top of the south (left) bank and the buildings behind the bank. The south (left) bank is armoured by rip rap.

Photo by BGC on October 8, 2012.



Photo 25.

Looking east (upstream) at the Hummingbird Creek channel approximately 450 m downstream of the Highway 97A bridge. Note the approximately 1.6 m freeboard between the channel and the top of the south (left) bank and the buildings behind the bank. The south (left) bank is armoured by rip rap.

Photo by BGC on October 8, 2012.



Photo 26.

Looking east (upstream) at the Hummingbird Creek channel approximately 650 m downstream of the Highway 97A bridge and near the outlet at Mara Lake. Note the approximately 1.6 m freeboard between the channel and the top of the south (left) bank and the buildings behind the bank. The south (left) bank is not armoured by rip rap.

Photo by BGC on October 8, 2012.

3.0 Photos of past debris flow and debris floods



Photo 27.

Looking east at HUM-TP-02 SA-01 (see location in Drawing 06). A radiocarbon date from this prehistoric debris flow or debris flood deposit dated this sediment to approximately 580 years before present.

Photo by BGC on October 8, 2021.



Photo 28.

Looking west at HUM-TP-02 SA-01 (see location in Drawing 06). A radiocarbon date from this prehistoric debris flow or debris flood deposit dated this sediment to approximately 150 years before present.

Photo by BGC on October 8, 2021.



Photo 29.

Looking north at homeowner excavation on the upper fan-delta comprised of approximately 1.2 m of 1997 debris flow deposits. Note the size of the boulders near the top of the excavation compared to the 15 cm yellow notebook.

Photo by BGC on September 23, 2021.



Photo 30.
Looking at damages to an unknown building on the upper fan-delta due to the Hummingbird Creek debris flow on July 11, 1997.

Photo courtesy of the Sicamous Museum taken in July 1997.



Photo 31.
Looking at damages to unknown buildings on the upper fan-delta due to the Hummingbird Creek debris flow on July 11, 1997.

Photo courtesy of the Sicamous Museum taken in July 1997.



Photo 32.
Looking south from Highway 97A at the damages from the Hummingbird Creek debris flow on July 11, 1997.

Photo courtesy of the Sicamous Museum taken in July 1997.



Photo 33.
Looking west at 718 Swansea Point Road on the lower fan-delta and the damages from the Hummingbird Creek debris flow on July 11, 1997.

Photo courtesy of the Sicamous Musuem taken in July 1997.



Photo 34.
Looking south at the Highway 97A Hummingbird Creek culvert crossing following the 2012 debris flood.

Photo by CSRD in June 2012.



Photo 35.
Looking west at Swansea Point Road and the Hummingbird Creek avulsion channel following the 2012 debris flood.

Photo by CSRD in June 2012.



Photo 36.
Looking east at Swansea Point Road, Highway 97A, and the Hummingbird Creek avulsion channel following the 2012 debris flood.

Photo by CSRD in June 2012.



Photo 37.
Looking at debris deposition at an unknown house on the lower fan-delta following the 2012 debris flood.

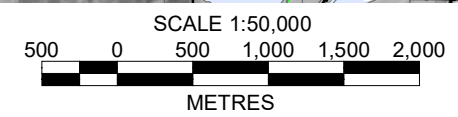
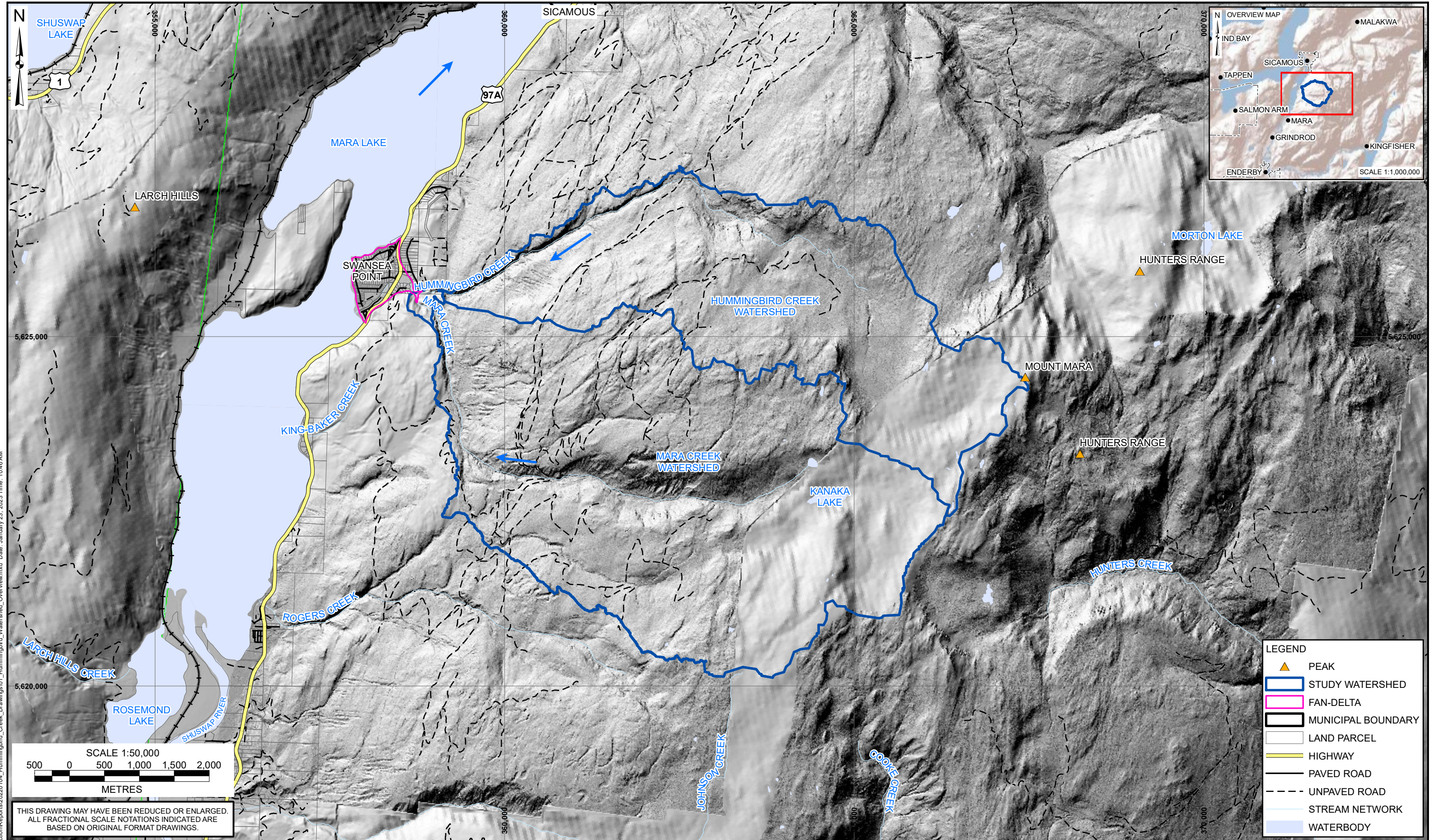
Photo by CSRD in June 2012.



Photo 38.
Looking south at sediment deposited into pool at 718 Swansea Point Road on the lower fan-delta following the 2012 debris flood.

Photo by CSRD in June 2012.

DRAWINGS



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

LEGEND	
	PEAK
	STUDY WATERSHED
	FAN-DELTA
	MUNICIPAL BOUNDARY
	LAND PARCEL
	HIGHWAY
	PAVED ROAD
	UNPAVED ROAD
	STREAM NETWORK
	WATERBODY

NOTES:
 1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
 2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "FBC DETAILED FLOOD MAPPING STUDY, HUMMINGBIRD CREEK", AND DATED JANUARY 2023.
 3. PARCEL DATA FROM PARCELMAP BC.
 4. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY TERRA REMOTE (2019), FORSITE (2014, 2018) AND GEOBASE (2013).
 5. THE WATERSHED AND FAN BOUNDARIES AS DRAWN ARE APPROXIMATE AND DELINEATE THE LANDFORM BASED ON LIDAR DATED 2019. THE BOUNDARIES SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DO THEY SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.

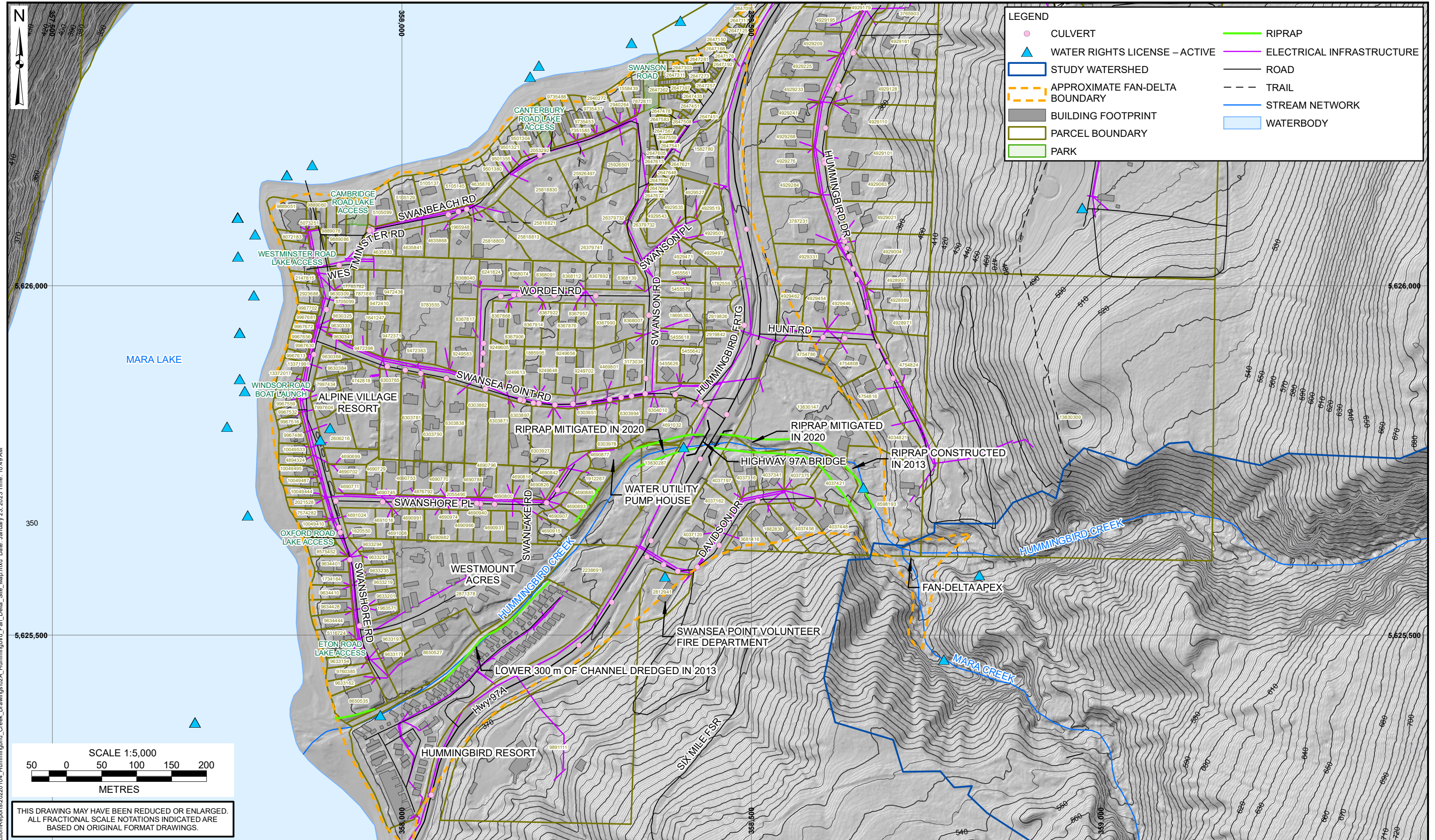
6. WATERBODIES SOURCED FROM CANVEC, WATERCOURSES SOURCED FROM BGC'S RIVER NETWORK TOOLS AND CANVEC, ROADS AND TRAILS SOURCED FROM GEOBC DIGITAL ROAD ATLAS.
 7. PROJECTION IS UTM ZONE 11 NAD 1983. VERTICAL DATUM IS CGVD2013.
 8. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED 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:	1:50,000
DATE:	JAN 2023
DRAWN:	SW, MIB
REVIEW:	CAL
APPROVED:	KH

CLIENT:
 Fraser Basin Council

PROJECT: FBC DETAILED FLOOD MAPPING STUDY, HUMMINGBIRD CREEK	
TITLE: WATERSHED OVERVIEW	
PROJECT No.: 0511 009	DWG No.: 01

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 2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "FBC DETAILED FLOOD MAPPING STUDY, HUMMINGBIRD CREEK", AND DATED JANUARY 2023.
 3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY TERRA REMOTE (2019), FORSITE (2014, 2018) AND GEOBASE (2013). CONTOUR INTERVAL 1 m.
 4. PARCEL DATA FROM PARCELMAP BC. RIPRAP OBSERVED BY BGC OCTOBER 2021 AND REFLECTS MULTIPLE CONSTRUCTION AGES OUTLINED IN REPORT.
 5. THE WATERSHED AND FAN BOUNDARIES AS DRAWN ARE APPROXIMATE AND DELINEATE THE LANDFORM BASED ON LIDAR DATED 2019. THE BOUNDARIES SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DO THEY SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
 6. PROJECTION IS UTM ZONE 11 NAD 83. VERTICAL DATUM IS CGVD2013.
 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:	1:5,000
DATE:	JAN 2023
DRAWN:	SW, MIB
REVIEW:	CAL
APPROVED:	KH

CLIENT:



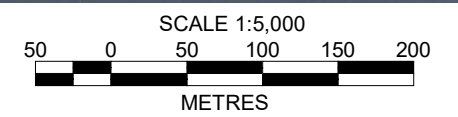
CLIENT:



PROJECT:		FBC DETAILED FLOOD MAPPING STUDY, HUMMINGBIRD CREEK	
TITLE:		FAN DELTA SITE MAP (1 OF 2)	
PROJECT No.:	0511 009	DWG No.:	02A



LEGEND	
	CULVERT
	WATER RIGHTS LICENSE – ACTIVE
	STUDY WATERSHED
	APPROXIMATE FAN-DELTA BOUNDARY
	BUILDING FOOTPRINT
	PARCEL BOUNDARY
	PARK
	RIPRAP
	ELECTRICAL INFRASTRUCTURE
	ROAD
	TRAIL
	STREAM NETWORK



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NOTES:
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 3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY TERRA REMOTE (2019), FORSITE (2014, 2018) AND GEOBASE (2013). CONTOUR INTERVAL 1 m.
 4. PARCEL DATA FROM PARCELMAP BC. RIPRAP OBSERVED BY BGC OCTOBER 2021 AND REFLECTS MULTIPLE CONSTRUCTION AGES OUTLINED IN REPORT.
 5. THE WATERSHED AND FAN BOUNDARIES AS DRAWN ARE APPROXIMATE AND DELINEATE THE LANDFORM BASED ON LIDAR DATED 2019. THE BOUNDARIES SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DO THEY SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
 6. PROJECTION IS UTM ZONE 11 NAD 83. VERTICAL DATUM IS CGVD2013.
 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.

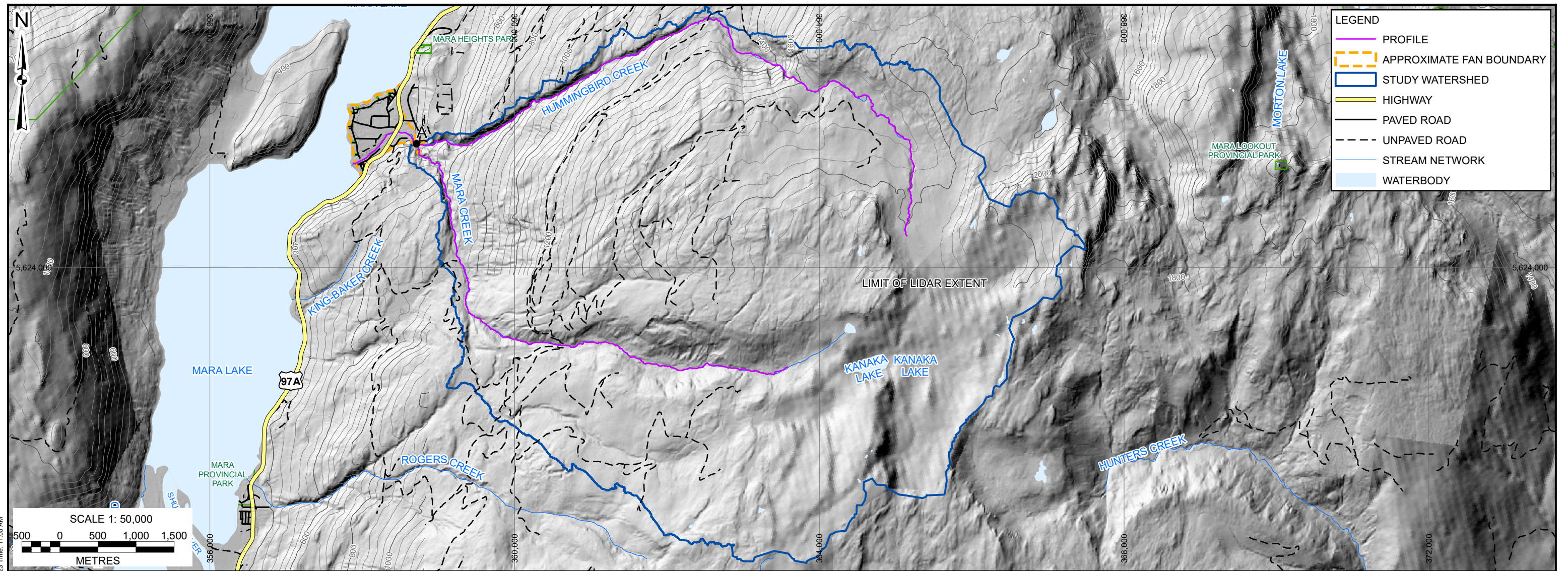
SCALE:	1:5,000
DATE:	JAN 2023
DRAWN:	SW, MIB
REVIEW:	CAL
APPROVED:	KH

CLIENT:

BGC

PROJECT: FBC DETAILED FLOOD MAPPING STUDY, HUMMINGBIRD CREEK	
TITLE: FAN DELTA SITE MAP (2 OF 2)	
PROJECT No.: 0511 009	DWG No.: 02B

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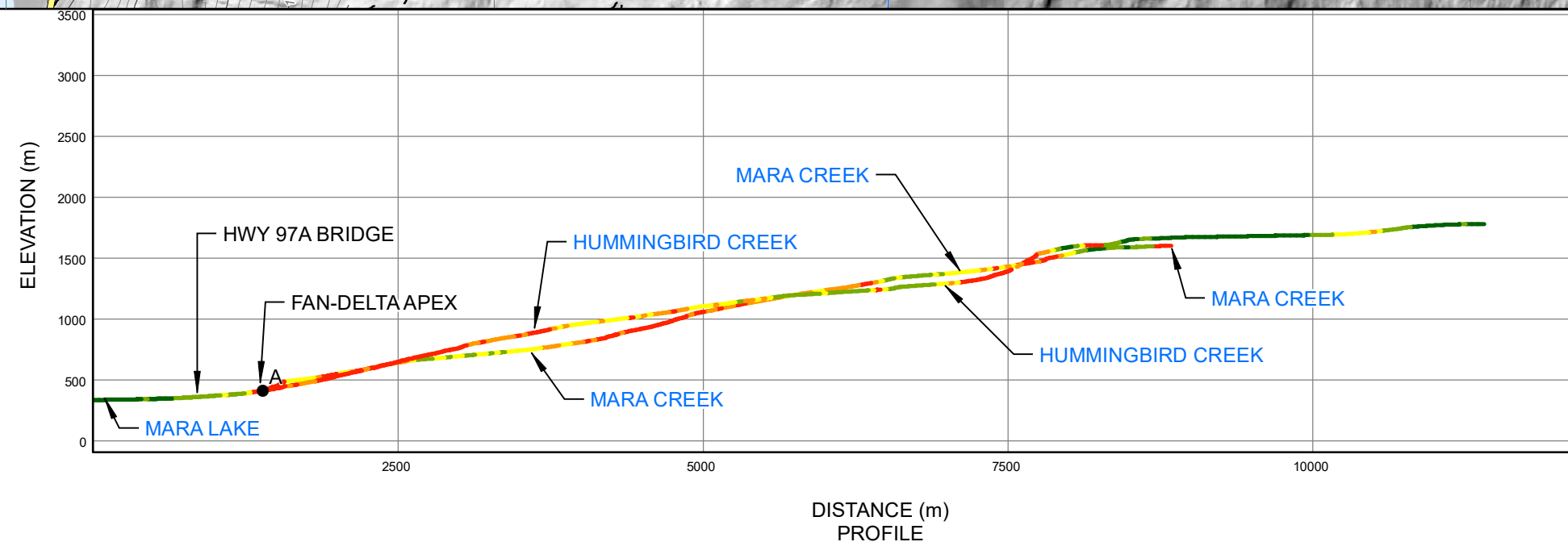


LEGEND

- PROFILE
- APPROXIMATE FAN BOUNDARY
- STUDY WATERSHED
- HIGHWAY
- PAVED ROAD
- UNPAVED ROAD
- STREAM NETWORK
- WATERBODY

SCALE 1: 50,000

METRES



LEGEND

AVERAGE SLOPE (%) PER 50 m

- 0 - 5
- 10 - 15
- 5 - 10
- 15 - 20
- > 20

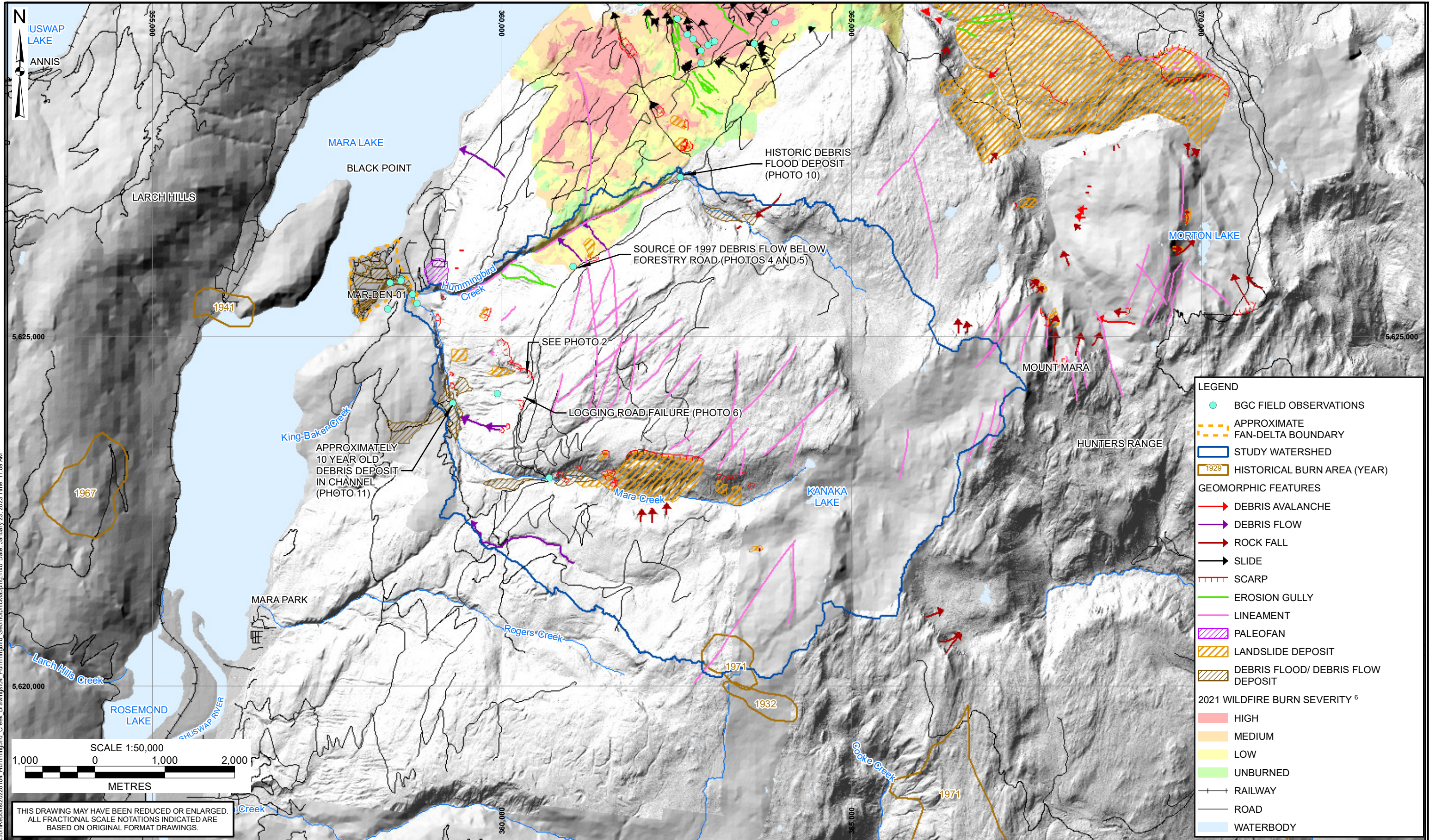
NO VERTICAL EXAGGERATION

NOTES:

1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "FBC DETAILED FLOOD MAPPING STUDY, HUMMINGBIRD CREEK", AND DATED JANUARY 2023.
3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY TERRA REMOTE (2019), FORSITE (2014, 2018) AND GEOBASE CDED (2013).
4. THE WATERSHED AND FAN BOUNDARIES AS DRAWN ARE APPROXIMATE AND DELINEATE THE LANDFORM BASED ON LIDAR DATED 2019. THE BOUNDARIES SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DO THEY SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
5. WATERBODIES SOURCED FROM CANVEC, WATERCOURSES SOURCED FROM BGC'S RIVER NETWORK TOOLS AND CANVEC, ROADS AND TRAILS SOURCED FROM GEOBC DIGITAL ROAD ATLAS.
6. ELEVATION PROFILE SHOWS DISTANCE RELATIVE TO THE CREEK OUTLET ON X-AXIS AND ELEVATION DERIVED FROM THE BASE TOPOGRAPHIC DATA ON Y-AXIS
7. PROJECTION IS NAD 1983 UTM ZONE 11N. VERTICAL DATUM IS CGVD2013.
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: 1:50,000	CLIENT: Fraser Basin Council	PROJECT: FBC DETAILED FLOOD MAPPING STUDY, HUMMINGBIRD CREEK
DATE: JAN 2023		TITLE: HUMMINGBIRD CREEK PROFILE
DRAWN: MIB		PROJECT No.: 0511009
REVIEW: CAL		DWG No.: 03
APPROVED: KH		

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LEGEND

- BGC FIELD OBSERVATIONS
- APPROXIMATE FAN-DELTA BOUNDARY
- STUDY WATERSHED
- 1929 HISTORICAL BURN AREA (YEAR)

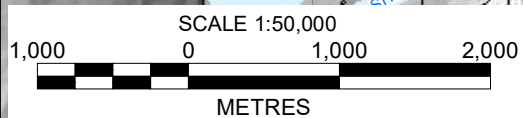
GEOMORPHIC FEATURES

- DEBRIS AVALANCHE
- DEBRIS FLOW
- ROCK FALL
- SLIDE
- ⋈ SCARP
- EROSION GULLY
- LINEAMENT
- PALEOFAN
- LANDSLIDE DEPOSIT
- DEBRIS FLOOD/ DEBRIS FLOW DEPOSIT

2021 WILDFIRE BURN SEVERITY ⁶

- HIGH
- MEDIUM
- LOW
- UNBURNED

- +— RAILWAY
- ROAD
- WATERBODY



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NOTES:

1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "FBC DETAILED FLOOD MAPPING STUDY, HUMMINGBIRD CREEK", AND DATED JANUARY 2023.
3. BASE TOPOGRAPHIC DATA BASED ON LIDAR FROM TERRA REMOTE SENSING, DATED 2019.
4. PARCEL DATA FROM PARCELMAP BC.
5. THE WATERSHED AND FAN BOUNDARIES AS DRAWN ARE APPROXIMATE AND DELINEATE THE LANDFORM BASED ON LIDAR DATED 2019. THE BOUNDARIES SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DO THEY SHOW THE SPATIAL EXTENT

OF POTENTIAL FLOODING.

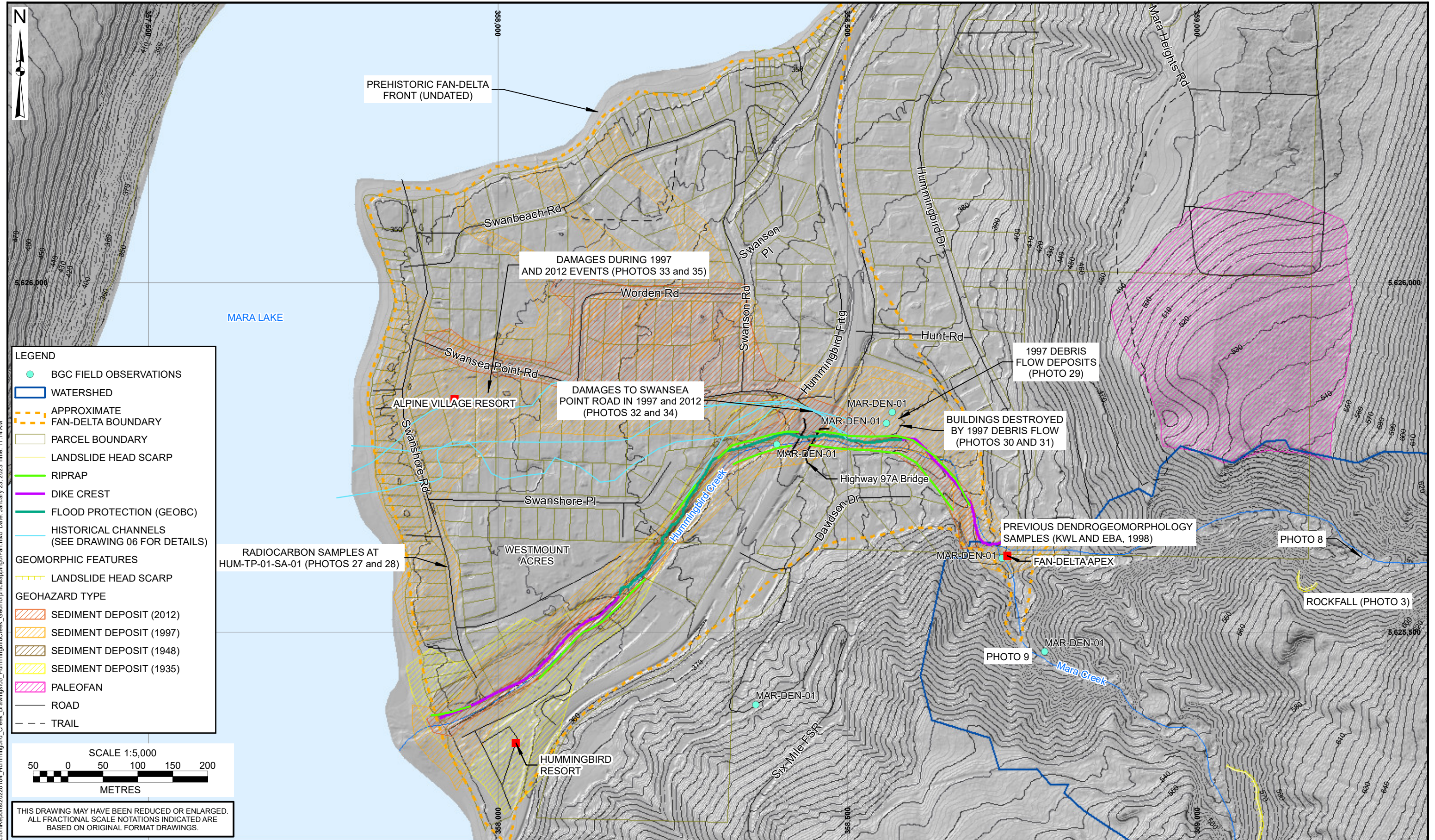
6. BURN SEVERITY RATINGS BASED ON PROVINCIAL DATA PROVIDED ON NOVEMBER 10, 2021.
7. PROJECTION IS UTM ZONE 11 NAD 1983. VERTICAL DATUM IS CGVD2013.
8. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED OR USED FOR ANY PURPOSE OTHER THAN THE PURPOSE FOR WHICH BGC GENERATED IT. 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:	1:50,000
DATE:	JAN 2023
DRAWN:	SW, MIB
CHECKED:	CAL
APPROVED:	KH

CLIENT:

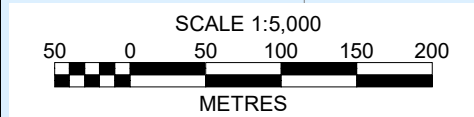
BGC

PROJECT: FBC DETAILED FLOOD MAPPING STUDY, HUMMINGBIRD CREEK	
TITLE: WATERSHED GEOMORPHOLOGY	
PROJECT No.: 0511 009	DWG No.: 04



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- LEGEND**
- BGC FIELD OBSERVATIONS
 - WATERSHED
 - APPROXIMATE FAN-DELTA BOUNDARY
 - PARCEL BOUNDARY
 - LANDSLIDE HEAD SCARP
 - RIPRAP
 - DIKE CREST
 - FLOOD PROTECTION (GEOBC)
 - HISTORICAL CHANNELS (SEE DRAWING 06 FOR DETAILS)
- GEOMORPHIC FEATURES**
- LANDSLIDE HEAD SCARP
- GEOHAZARD TYPE**
- SEDIMENT DEPOSIT (2012)
 - SEDIMENT DEPOSIT (1997)
 - SEDIMENT DEPOSIT (1948)
 - SEDIMENT DEPOSIT (1935)
 - PALEOFAN
 - ROAD
 - TRAIL



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- NOTES:**
1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
 2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "FBC DETAILED FLOOD MAPPING STUDY, HUMMINGBIRD CREEK", AND DATED JANUARY 2023.
 3. BASE TOPOGRAPHIC DATA BASED ON LIDAR FROM TERRA REMOTE SENSING, DATED 2019. CONTOUR INTERVAL IS 1 m.
 4. THE WATERSHED AND FAN-DELTA BOUNDARY AS DRAWN ARE APPROXIMATE AND DELINEATE THE LANDFORMS BASED ON LIDAR DATED 2019. THE BOUNDARIES SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DO THEY SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING. RIP RAP OBSERVED BY BGC OCTOBER 2021 AND REFLECTS MULTIPLE CONSTRUCTION AGES OUTLINED IN REPORT.
 5. HISTORICAL CUT BLOCK DATA FROM GEOBC DATASET DATED 2019 AND ONLY REPRESENTATIVE OF AREAS THAT INTERSECT

WATERSHED BOUNDARY, HISTORICAL BURN AREA FROM GEOBC DATASET DATED 2019. ROADS DATA FROM BC DIGITAL ATLAS. PARCELS FROM PARCELMAP BC. RETAINING WALL FROM MINISTRY OF TRANSPORTATION DATASET DATED 2012. SOLE RISK.

6. PROJECTION IS NAD 1983 UTM ZONE 11N. VERTICAL DATUM IS CGVD2013.

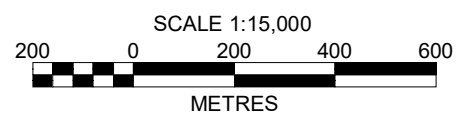
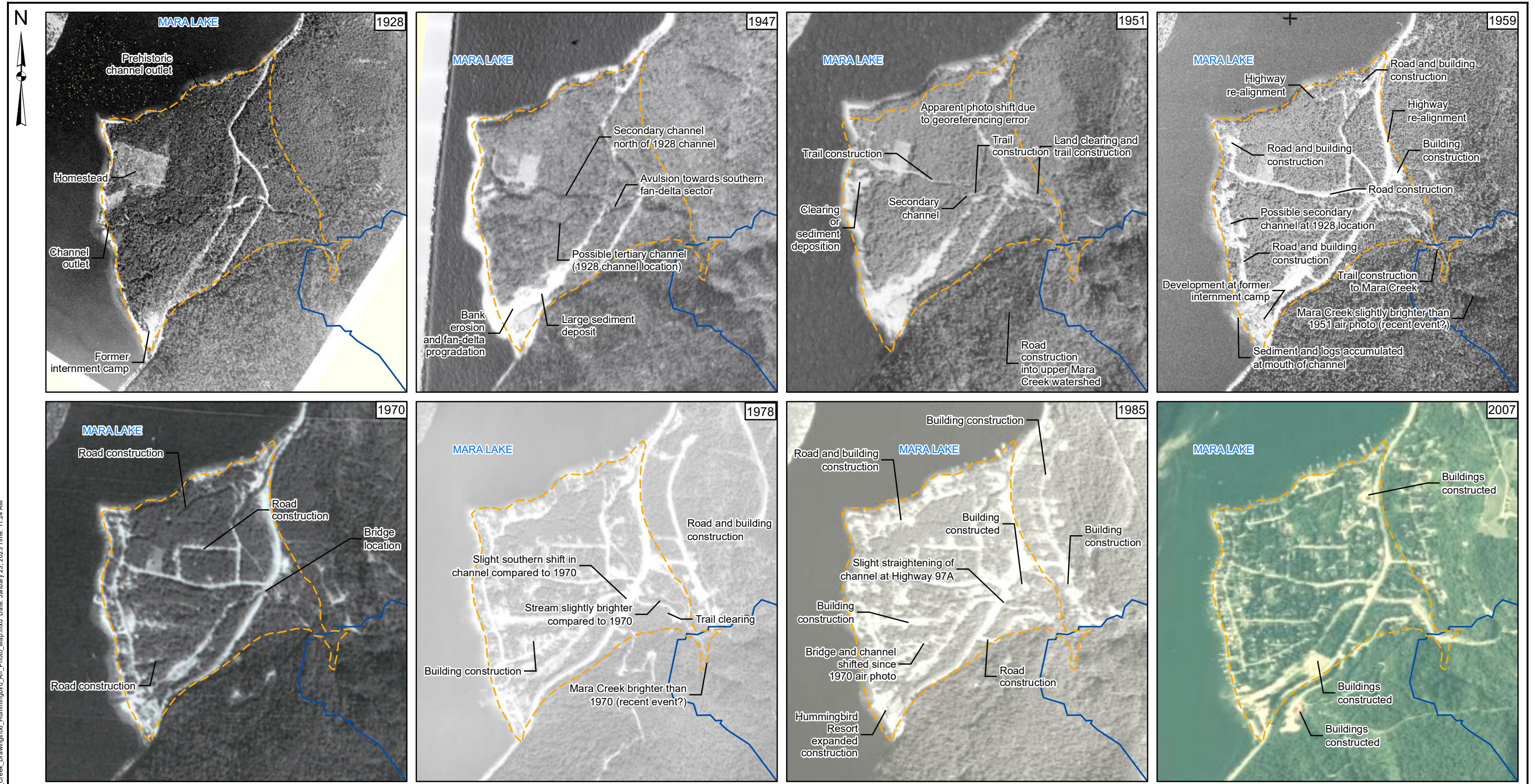
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SCALE:	1:5,000
DATE:	JAN 2023
DRAWN:	SW
REVIEW:	CAL
APPROVED:	KH

CLIENT:

BGC

PROJECT: FBC DETAILED FLOOD MAPPING STUDY, HUMMINGBIRD CREEK	
TITLE: FAN-DELTA GEOMORPHOLOGY	
PROJECT No.: 0511 009	DWG No.: 05



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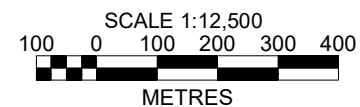
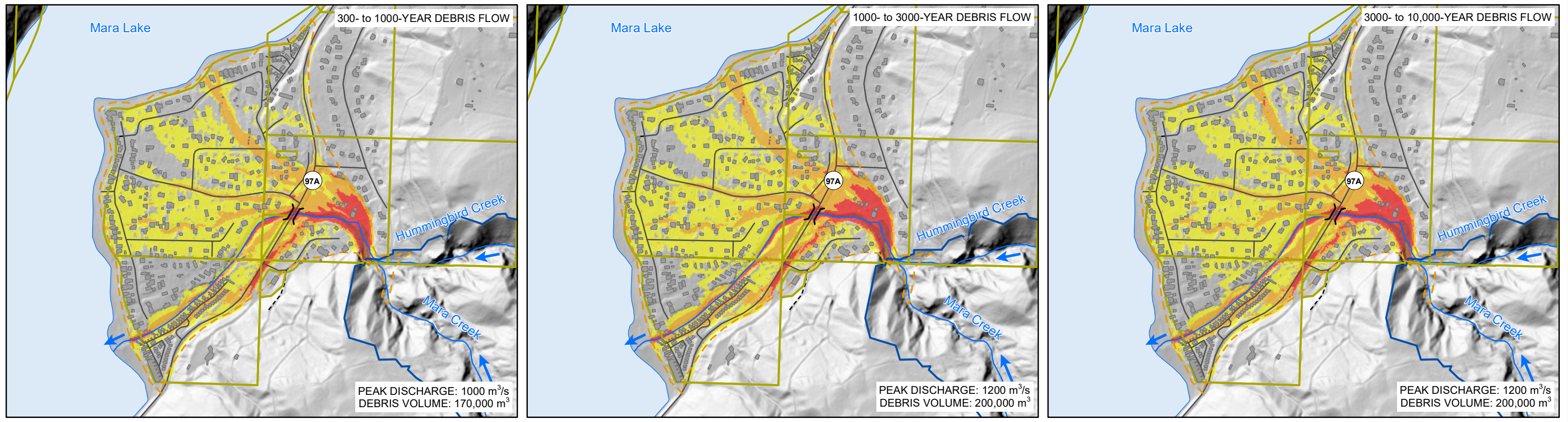
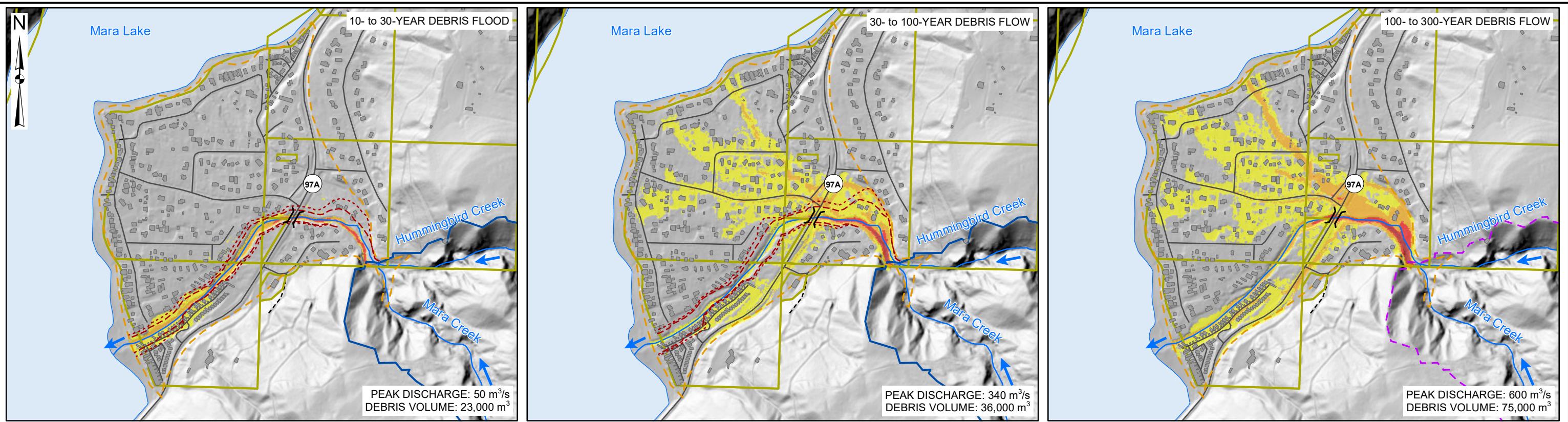
NOTES:

1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "FBC DETAILED FLOOD MAPPING STUDY, HUMMINGBIRD CREEK", AND DATED JANUARY 2023.
3. THE WATERSHED AND FAN BOUNDARIES AS DRAWN ARE APPROXIMATE AND DELINEATE THE LANDFORM BASED ON LIDAR DATED 2018. THE BOUNDARIES SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DO THEY SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
4. WATERSHED BOUNDARIES DELINEATED FROM BGC'S RIVER NETWORK TOOLS, WATERBODIES SOURCED FROM CANVEC, WATERCOURSES SOURCED FROM BGC'S RIVER NETWORK TOOLS AND CANVEC.
5. PROJECTION IS NAD 1983 UTM ZONE 11N. VERTICAL DATUM IS CGVD2013.
6. 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.

LEGEND	
	APPROXIMATE FAN BOUNDARY
	STUDY WATERSHED

SCALE: 1:15,000	CLIENT:	PROJECT: FBC DETAILED FLOOD MAPPING STUDY, HUMMINGBIRD CREEK
DATE: JAN 2023		TITLE: AIR PHOTO COMPARISON
DRAWN: MIB, LL		PROJECT No.: 0511009
REVIEW: CAL		DWG No.: 06
APPROVED: KH		

X:\Projects\0511009\GIS\Production\Reports\2020104_Hummingbird_Creek_Drawings\06_Hummingbird_Air_Photo_Map.mxd Date: January 23, 2023 Time: 11:24 AM



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LEGEND

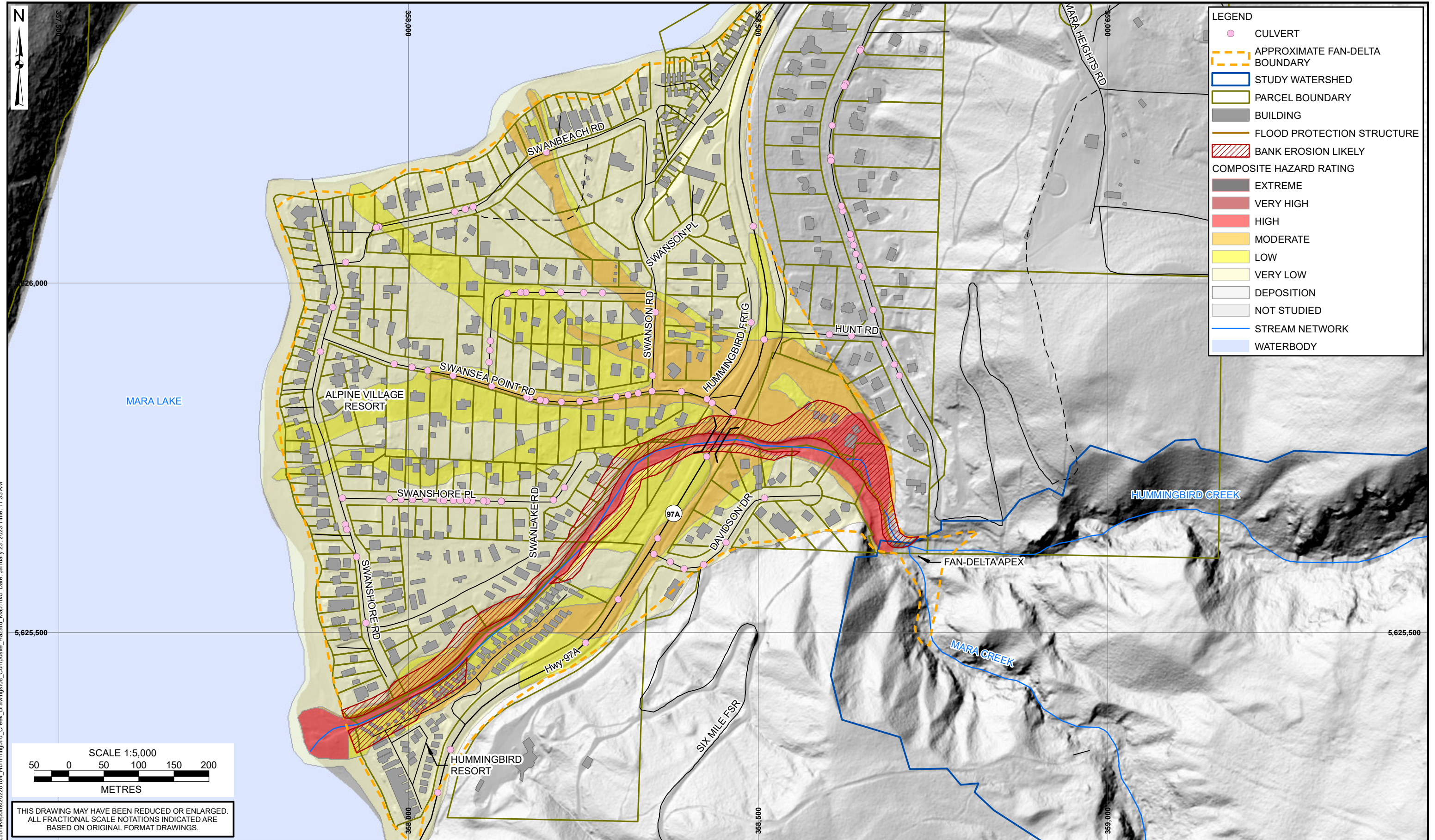
APPROXIMATE FAN BOUNDARY	SURVEY PARCEL	PAVED ROAD	BANK EROSION	IMPACT FORCE (kN/m)
STUDY WATERSHED	STREAM	TRAIL	BANK EROSION LIKELY	< 1
BUILDING			BANK EROSION POTENTIAL	1 - 10
				100 - 1000
				> 1000

NOTES:

- ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
- THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "FBC DETAILED FLOOD MAPPING STUDY, HUMMINGBIRD CREEK" DATED JANUARY 2023.
- BASE TOPOGRAPHIC DATA BASED ON LIDAR FROM TERRA REMOTE SENSING, DATED 2019.
- ROADS, STREAM AND WATERBODY DATA FROM CANVEC. SURVEY PARCEL DATA FROM TANTALIS. BUILDING FOOTPRINT DATA FROM TERRA REMOTE LIDAR.
- THE FAN BOUNDARY AS DRAWN IS APPROXIMATE AND DELINEATES THE LANDFORM BASED ON LIDAR DATED, 2019. THE BOUNDARY SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DOES IT SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
- SCENARIO MAPS SHOW DEBRIS FLOOD OR DEBRIS FLOW IMPACT FORCE CALCULATED BASED ON HEC-RAS MODEL RESULTS. THE MODEL IS INITIATED UPSTREAM OF THE FAN-DELTA APEX AND RESULTS HAVE BEEN TRIMMED TO MARA LAKE AND THE DOWNSTREAM FAN BOUNDARY. THESE MAPS REPRESENT A SNAPSHOT IN TIME. FUTURE CHANGES (DEVELOPMENT, MITIGATION, GEOHAZARD EVENTS) MAY WARRANT THE RE-DRAWING OF CERTAIN AREAS.
- PROJECTION IS NAD 1983 UTM ZONE 11N. VERTICAL DATUM IS CGVD2013.
- 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: 1:12,500	CLIENT: Fraser Basin Council	PROJECT: FBC DETAILED FLOOD MAPPING STUDY, HUMMINGBIRD CREEK
DATE: JAN 2023		TITLE: SELECTED MODEL SCENARIOS
DRAWN: MIB		PROJECT No.: 0511009
REVIEW: CAL		DWG No.: 07
APPROVED: KH		

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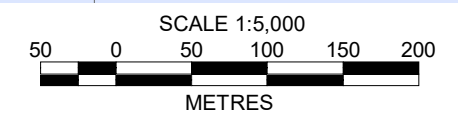


LEGEND

- CULVERT
- APPROXIMATE FAN-DELTA BOUNDARY
- STUDY WATERSHED
- PARCEL BOUNDARY
- BUILDING
- FLOOD PROTECTION STRUCTURE
- BANK EROSION LIKELY

COMPOSITE HAZARD RATING

- EXTREME
- VERY HIGH
- HIGH
- MODERATE
- LOW
- VERY LOW
- DEPOSITION
- NOT STUDIED
- STREAM NETWORK
- WATERBODY



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 "FBC DETAILED FLOOD MAPPING STUDY, HUMMINGBIRD CREEK", AND DATED JANUARY 2023.
3. BASE TOPOGRAPHIC DATA BASED ON LIDAR FROM TERRA REMOTE SENSING, DATED 2019.
4. PARCEL DATA FROM PARCELMAP BC. DIKE DATA FROM DATABC.
5. PROJECTION IS UTM ZONE 11 NAD 1983. VERTICAL DATUM IS CGVD2013.
6. HAZARDS SHOWN ON THIS MAP MAY CHANGE WITH SUBSTANTIAL CONSTRUCTION ACTIVITIES AND/OR FUTURE DEBRIS FLOODS OR DEBRIS FLOWS AND MAY REQUIRE REDRAWING.

7. THIS MAP IS A SIMPLIFICATION FROM VARIOUS NUMERICAL MODEL RUNS AND SHOULD NOT BE INTERPRETED AS PRECISE.
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REVIEW:	CAL
APPROVED:	KH

CLIENT:




PROJECT: FBC DETAILED FLOOD MAPPING STUDY, HUMMINGBIRD CREEK	
TITLE: COMPOSITE HAZARD MAP	
PROJECT No.: 0511009	DWG No.: 08

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APPENDIX A TERMINOLOGY

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

Table A-1. Geohazard terminology.

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

Term	Definition	Source
Debris Flow	Very rapid to extremely rapid surging flow of saturated, non-plastic debris in a steep channel (Hung, Leroueil & Picarelli, 2014). Debris generally consists of a mixture of poorly sorted sediments, organic material and water (see Appendix B of this report for detailed definition).	BGC
Debris Flood	A very rapid flow of water with a sediment concentration of 3-10% in a steep channel. It can be pictured as a flood that also transports a large volume of sediment that rapidly fills in the channel during an event (see Appendix B of this report for detailed definition).	BGC
Elements at Risk (E)	This term is used in two ways: a) To describe things of value (e.g., people, infrastructure, environment) that could potentially suffer damage or loss due to a geohazard . b) For risk analysis, as a measure of the value of the elements that could potentially suffer damage or loss (e.g., number of persons, value of infrastructure, value of loss of function, or level of environmental loss).	BGC
Encounter Probability	This term is used in two ways: a) Probability that an event will occur and impact an element at risk when the element at risk is present in the geohazard zone. It is sometimes termed “ partial risk ” b) For quantitative analyses, the probability of facilities or vehicles being hit at least once when exposed for a finite time period L, with events having a return period T at a location. In this usage, it is assumed that the events are rare, independent, and discrete, with arrival according to a statistical distribution (e.g., binomial or Bernoulli distribution or a Poisson process).	BGC
Erosion	The part of the overall process of denudation that includes the physical breaking down, chemical solution and transportation of material.	Oxford University Press (2008)
Fan-delta	Alluvial fans that prograde into standing bodies of water from adjacent highlands	Westcott and Ethridge (1987)
Flood	A rising body of water that overtops its confines and covers land not normally under water.	American Geosciences Institute (2011)

Term	Definition	Source
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)
Frequency (f)	<p>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.</p> <p>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</p>	Adapted from Fell et al. (2005)

Term	Definition	Source
	<p>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.</p>	
Hazard	<p>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.</p>	BGC
Hazardous flood	<p>A flood that is a source of potential harm.</p>	BGC
Geohazard	<p>Geophysical process that is the source of potential harm, or that represents a situation with a potential for causing harm.</p> <p>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.</p>	Adapted from CSA (1997), Fell et al. (2005).
Geohazard Assessment	<p>Combination of geohazard analysis and evaluation of results against a hazard tolerance standard (if existing). Geohazard assessment includes the following steps:</p> <ol style="list-style-type: none"> a. Geohazard analysis: identify the geohazard process, characterize the geohazard in terms of factors such as mechanism, causal factors, and trigger factors; estimate frequency and magnitude; develop geohazard scenarios; and estimate extent and intensity of geohazard scenarios. b. Comparison of estimated hazards with a hazard tolerance standard (if existing) 	Adapted from Fell et al. (2007)
Geohazard Event	<p>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).</p>	Adapted from ISO (2018)
Geohazard Intensity	<p>A set of parameters related to the destructive power of a geohazard (e.g. depth, velocity, discharge, impact pressure, etc.)</p>	BGC
Geohazard Inventory	<p>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.</p>	Adapted from CSA (1997)

Term	Definition	Source
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)
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)

Term	Definition	Source
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
Probability	<p>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.</p> <p>There are two main interpretations:</p> <ul style="list-style-type: none"> i) Statistical – frequency or fraction – The outcome of a repetitive experiment of some kind like flipping coins. It includes also the idea of population variability. Such a number is called an “objective” or relative frequentist probability because it exists in the real world and is in principle measurable by doing the experiment. ii) Subjective (or Bayesian) probability (degree of belief) – Quantified measure of belief, judgement, or confidence in the likelihood of an outcome, obtained by considering all available information honestly, fairly, and with a minimum of bias. Subjective probability is affected by the state of understanding of a process, judgement regarding an evaluation, or the quality and quantity of information. It may change over time as the state of knowledge changes. 	Fell et al. (2005)
Return Period (Recurrence Interval)	Estimated time interval between events of a similar size or intensity . Return period and recurrence interval are equivalent terms. Inverse of frequency .	BGC
Risk	Likelihood of a geohazard scenario occurring and resulting in a particular severity of consequence. In this report, risk is defined in terms of safety or damage level.	BGC

Term	Definition	Source
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
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	<p>Indeterminacy of possible outcomes. Two types of uncertainty are commonly defined:</p> <ul style="list-style-type: none"> a) Aleatory uncertainty includes natural variability and is the result of the variability observed in known populations. It can be measured by statistical methods, and reflects uncertainties in the data resulting from factors such as random nature in space and time, small sample size, inconsistency, low representativeness (in samples), or poor data management. b) Epistemic uncertainty is model or parameter uncertainty reflecting a lack of knowledge or a subjective or internal uncertainty. It includes uncertainty regarding the veracity of a used scientific theory, or a belief about the occurrence of an event. It is subjective and may vary from one person to another. 	BGC
Waterbody	Ponds, lakes and reservoirs	BGC
Watercourse	Creeks, streams and rivers	BGC

The standard terms used to define levels of confidence in this report are as given in the International Panel on Climate Change (IPCC) Uncertainty Guidance Note (IPCC, 2010), namely:

Confidence Terminology	Chance of confidence in being correct
Very high confidence	At least 9 out of 10
High confidence	About 8 out of 10
Medium confidence	About 5 out of 10
Low confidence	About 2 out of 10
Very low confidence	Less than 1 out of 10

Note that 'low confidence' and 'very low confidence' are only used for areas of major concern and where a risk-based perspective is justified.

The standard terms used in this report to define the likelihood of an outcome or result where this can be estimated probabilistically are:

Likelihood Terminology	Likelihood of the occurrence/ outcome
Virtually certain	> 99% probability
Extremely likely	> 95% probability
Very likely	> 90% probability
Likely	> 66% probability
More likely than not	> 50% probability
About as likely as not	33 to 66% probability
Unlikely	< 33% probability
Very unlikely	< 10% probability
Extremely unlikely	< 5% probability
Exceptionally unlikely	< 1% probability

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APPENDIX B DATA COMPILATION

B.1. PREVIOUS REPORTS

The following data sources, organized by date of publication, were reviewed by BGC for the Sicamous and Hummingbird Creek hazard assessments:

- Geological map of Vernon including the Kamloops, Osoyoos, and Kootenay districts (Geological Survey of Canada, 1960).
- Report on the glacial lake history of the southern interior plateau (Fulton, 1969).
- Surficial geology map of the Kootenay Lake area (Geological Survey of Canada, 1984).
- Guide on estimating peak flows for ungauged basins in the Okanagan region (Government of BC, 1988).
- Study on the geology of the Shuswap Metamorphic Complex (Johnson, 1990).
- District of Sicamous zoning bylaws (1993).
- Geotechnical review of the south Sicamous Creek road crossing (Terratech, 1993).
- Proceedings from the Sicamous Creek Silvicultural Systems Project workshop (Hollstedt and Vyse, 1997).
- Inter-agency hazard analysis report on the July 11, 1997 Hummingbird Creek debris flow (Government of British Columbia, 1997).
- Fish habitat and stream channel assessment on the watersheds of the Sicamous-Grinrod area (Summit Environmental Consultants, 1997).
- Impact assessment and restoration recommendations for Hummingbird Creek after the 1997 debris flow (EBA & KWL, 1998).
- Terrain stability mapping of the Sicamous Creek watershed by Terratech (1998).
- Watershed assessment of the Sicamous Creek watershed (Dobson Engineering, 1998).
- Terrain stability mapping of the Hummingbird and Mara creek watersheds (Terratech, 1999).
- Paper on the 1997 Hummingbird Creek debris flow and discussion on the risk to development on the fan (Jakob et al., 2000).
- Study on including geomorphic processes in flood frequency estimates of mountain streams used for design purposes (Jakob & Jordan, 2001).
- Investigation report on complaints to the Forest Practices Board following the destruction from the 1997 debris flow (2001).
- Regional study on frequency, cause, and sediment source of landslides in the Arrow Forest District and the Kootenay Lake Forest District (Jordan, 2001).
- A study on using soil coring at Swansea Point to date historical debris flow events that have impacted the Mara Creek alluvial fan (Fuller, 2002).
- Decision analysis report of debris flow potential risk at Hummingbird Creek by Klohn Crippen (2003).
- Study on the microclimate at Sicamous Creek by the Ministry of Forests (Government of British Columbia, 2004).
- Debris flow and flood hazard assessment for a proposed development on Sicamous Creek (EBA, 2006).
- Rural land use bylaw number 2000 for Sicamous (CSRD, 2009).
- Official community plan for the District of Sicamous (2009).

- Watershed mapping of Shuswap Lake, Mara Lake, Little Shuswap Lake, and Little River (EEC, 2009).
- Lidar digital elevation data for Sicamous Creek fan-delta flown in 2011 and provided by MOTI.
- Provincial flood forecasts and warnings, watches, and advisories (MFLNRO, 2012).
- Report and hydrological data from HEC-RAS modelling of Sicamous Creek under pre- and post-event conditions by Golder Associates following the flooding events of June 2012 (2012).
- Invoices for the costs associated with maintenance and repairs to infrastructure following the 2012 debris flow events at Hummingbird and Sicamous creeks (2013).
- Detailed design report of the Hummingbird Creek channel repairs following flooding and damage to infrastructure in June 2012 (Golder Associates, 2013a).
- Hydrotechnical specifications for the replacement of the Hwy 97A culvert with a bridge (Golder Associates, 2013b).
- Detailed design and record drawings of the Hummingbird Creek bridge project (Government of British Columbia, 2014).
- Engineering drawings of the Sicamous Creek bridge design and site plan from Stantec Consulting (2015).
- Annual water system report produced by District of Sicamous (2016).
- A review of fisheries resources for the South Thompson – Shuswap habitat management area, including Shuswap, Little Shuswap, and Mara lakes (FBC, 2016).
- Presentation on the effects of riparian retention on alluvial fans (Giles, 2017).
- Geohazard risk prioritization for the Thompson River watershed (BGC, 2019).
- Statistically downscaled climate model scenarios from 1950 to 2100 (Pacific Climate Impacts Consortium, 2019).
- Supreme court decision from the legal suit between Waterway Houseboats Ltd. (plaintiff) and the province of BC, District of Sicamous, and Bryan and Constance McLaughlin (defendants) (2019).
- Lidar digital elevation data for Sicamous and Hummingbird Creek watersheds flown in 2019 for Natural Disaster Mitigation Program.
- Geohazard risk prioritization for the Columbia Shuswap Regional District (BGC, 2020).
- Hydrotechnical assessment of Hummingbird Creek and design of riprap mitigation following damage to the existing protection upstream of the Hummingbird Creek bridge during the 2017 and 2018 freshet (NHC, 2020).
- Construction status reports from Binnie Construction Services during the Highway 97A Hummingbird Creek riprap repair (2020).
- Court of appeal decision from the legal suit between Waterway Houseboats Ltd. (plaintiff) and the province of BC, District of Sicamous, and Bryan and Constance McLaughlin (defendants) (2020).
- Lidar data for the Sicamous and Hummingbird Creek watersheds flown in 2020 and provided by Tolko.
- Environmental monitoring report of the Sicamous refuse disposal facility (EEC, 2021).
- Community plans for Electoral Area E within the regional district (CSR, 2022).

- Wiseman Creek emergency post-wildfire debris flow assessment (BGC, 2022).
- Post-wildfire risk assessment of the Two-Mile Road fire by Westrek Geotechnical Services (2022).
- Historical and real time hydrometric discharge data from Environment and Climate Change Canada (n.d.) used to support the index flood regional flood frequency analysis and provide a check on flood quantiles estimated for Sicamous and Hummingbird creeks. Notable Water Survey of Canada gauges reviewed include 08LC027, 08LC023, and 08LC024.
- Published Intensity-Duration-Frequency curves for the Salmon Arm A (1166R45, 1964 to 2016) weather station and historical precipitation records (Environment and Climate Change Canada, 2021)
- Bathymetry map of Mara Lake derived from Canadian Hydrographic Service (CHS) charts (GPS Nautical Charts, n.d.)
- Snow survey data from automated snow stations Celistra (1F06P, 2004 to present) and Enderby (1F04, 2017 to present) (Government of British Columbia, n.d.).
- Daily lake levels of Shuswap Lake from 1994 to present (Shuswap Lake Watch, n.d.)
- Precipitation and temperature record for June of 2012 and May of 2017 used in hydrologic model calibration and validation from the Sicamous weather station (ID 882, 2004 to present) (Ministry of Forests, Lands and Natural Resources Operations Wildfire Management Branch, n.d.) and the Malakwa weather station (ID 22096, 1999 to present) (Ministry of Transportation and Infrastructure, n.d.).
- Archival photos of Sicamous and Hummingbird Creeks from the Enderby and District Museum and Archives.
- Archival photos of Sicamous and Hummingbird Creeks from the Sicamous Museum.
- Photographs of Swansea Point taken in June 2012 provided by the CSRD.
- Photographs of Sicamous Creek taken in June 2012 provided by FLNRORD.
- Aerial photographs dated from 1930 to 2016 from the National Air Photo Library and the Province of British Columbia (Table B-1)
- Google Earth™ imagery dated from 2003 to 2020.
- Media articles about Sicamous and Hummingbird Creek from Black Press (Labere, 2010), CBC News (Canadian Press, 2012a, b), Enderby Commoner (McKnight-Yeates, 1997; Eke, 1997), Global News (Potenteau, 2021; Turcato, 2022), Globe and Mail (Canadian Press, 2012c), Eagle Valley Views (Hazzan, 1997; Graham, 1997; Labere, 2012; Lebere, 2013; Keely, 2013; Brouwer, 2017), Huffington Post (Brugmann, 2012), InfoNews (Bulmer, 2019), Penticton Western News (Labere, 2017; Roman, 2022; Labere, 2021; Labere, 2022), National Post (Canadian Press, 2012d), Revelstoke Review (Elliot, 2019), Revelstoke Review (Labere, 2021; Roman, 2022); Salmon Arm Observer (anon, 2012; Polak, 2013; Labere, 2013a, b; Wickett, 2018; Elliot, 2019a, b; Labere, 2020; Labere, 2021; Roman, 2021; Labere, 2022a, b, c), Shuswap Sun (Onedbach, 1997); Summerland Review (Elliot, 2021); Today in BC (Labere, 2012; anon, 2013), and Vernon Morning Star (Brouwer, 2017; Elliot, 2019; Labere, 2021).

Table B-1. Air photo imagery used in hazard assessment.

Roll	Photo Numbers	Imagery Date	Scale	Notes
A294	16-18	July 16, 1928	1:10,000	Lower fan-delta only
A11095	91-92	September 21, 1947	1:40,000	
A11090	124-125	September 21, 1947	1:40,000	
A13246	109-112	1951	1: 65,000	
BC2616	74-75	1959	1:15,840	Lower fan-delta only
BC5246	157-159, 152-155	June 15, 1967	1:32,000	Sicamous partially covered
BC5253	204-208, 224-229	August 2, 1969	1:32,000	Lower Hummingbird Creek not covered
BC7267	14-27, 28-38, 62-74, 77-85	July 14, 1970	1:16,000	
BC5378	15-16, 39-41	July 14, 1970	1:80,000	
BC5638	154-166	October 18, 1974	1:9,600	
BC7647	48-56, 60-68, 137-142, 143-151	August 28, 1974	1:16,000	Upper Sicamous Creek partially covered
BC5717	232-235	June 18, 1976	1:40,000	Hummingbird Creek partially covered
BC7892	22-28	September 19, 1976	1:20,000	Lower fan-delta only
BC77034	84-95	June 25, 1977	1:20,000	Upper watersheds partially covered
BC78061	98-104, 109-116, 156-162	June 5, 1978	1:20,000	
BCC317	96-105, 106-116,	September 23, 1982	1:3,000	Hummingbird Creek fan-delta
BC84015	18-25, 87-93, 50-58, 10-17	June 14, 1984	1:5,000	Lower Sicamous Creek
BC85046	95-105, 121-123, 36-42	July 14, 1985	1:25,000	Upper Sicamous Creek partially covered
BCC90092	38-48, 101-11	September 11, 1990	1:15,000	
BCB92001	44-53, 54-59	April 2, 1992	1:10,000	Fan-deltas
BCC94042	6-12	July 8, 1994	1:15,000	Sicamous Creek
BCB94003	11-22, 26-36	March 29, 1994	1:10,000	Sicamous Creek
BCC94041	118-126, 203-206	July 8, 1994	1:15,000	Hummingbird Creek
BCC94042	5-11	July 8, 1994	1:15,000	Sicamous Creek
BCC94047	36-41	July 10, 1994	1:15,000	Sicamous Creek
BCC94161	33-117	September 19, 1994	1:5,000	Hummingbird Creek
BCC951111 / BCC95106	1-14, 30-43, 60-73, 88-95, 145-156, 100-113	July 15, 1995	1:5,000	Upper Sicamous Creek
BCC96051	91-142	September 19, 1996	1:5,000	Upper Sicamous Creek
BCB97082	167-168	September 8, 1997	1:40,000	Sicamous lower 3 km
BCB97069 / BCB97070	30-36	August 11, 1997	1:40,000	
BCB97082	166-168	September 8, 1997	1:40,000	Hummingbird Creek
BCC97079 / BCC97067	1-292	July 27, 1997	1:5,000	Upper Sicamous Creek
BCC01026	47-52	September 9, 2001	1:30,000	

Roll	Photo Numbers	Imagery Date	Scale	Notes
BCC01024	144-150	September 16, 2001	1:30,000	
BCC04022	19-23	July 18, 2004	1:30,000	
BCC04021 / BCC04021	201-204	July 18, 2004	1:30,000	
BCC04054	151-154	August 10, 2004	1:30,000	
BCC07009 / BCC07014	11-20, 37-45, 199-219, 21-24	July 6, 2007	1:20,000	Hummingbird Creek
BCC07003	225-231	August 15, 2007	1:20,000	Sicamous Creek

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APPENDIX C FREQUENCY-MAGNITUDE METHODS

C.1. INTRODUCTION

This appendix describes the development of the frequency-magnitude (F-M) relationship for Hummingbird Creek. An F-M relationship answers the question “how often (frequency) and how big (magnitude) can steep creek hazards events become?”. Based on field evidence and remote sensing data, Hummingbird Creek is considered prone to clearwater floods, debris floods and debris flows at different recurrence intervals.

Debris- flow- and debris-flood return periods are expressed as a range of years describing their average recurrence intervals. The annual exceedance probability expresses the chance of a specific debris flow magnitude (volume and discharge) be exceeded in any given year. For example, an AEP of 5% means that there is a 5% chance that a debris flow or debris flood with a volume corresponding to the 20-year return period will be exceeded in any given year.

Table C-1 outlines the AEPs chosen by BGC for this hazard assessment that represent the potential spectrum of estimated event magnitudes. These AEPs correspond to those listed in the EGBC Guidelines for Legislated Flood Assessments in a Changing Climate (2018) and Guidelines for Landslide Assessments in BC (EGBC, September 29, 2022). Event “magnitude” is expressed as peak discharge and sediment volume, except for clearwater floods where only peak discharge is reported.

Table C-1. AEPs used for the hazard assessment on Hummingbird Creek.

Return Period Range (years)	Representative Return Period (years)	AEP (%)
1 to 3	2	50
3 to 10	5	20
10 to 30	20	5
30 to 100	50	2
100 to 300	200	0.5
300 to 1000	500	0.2
>1000	2000	0.05

Note: The 5-, 50- and 500-year return periods do not precisely fall at the mean of the return period ranges but were chosen because these return periods have a long tradition of use in BC.

This appendix is organized as follows:

- Methods – An overview of the methods for the data compilation and its interpretation.
- Desktop Study Results – A summary of the results of the desktop data compilation. This includes air photo interpretation, lidar review, and a review of historical records.
- Field Study Results – A summary of the results from the BGC field visit conducted October 5 to 8, 2021. Key results are the confirmation of hazard process identification, calculation of recharge rates within the channel, and characterization of bed material.
- Clearwater Floods – A summary of the calculated peak discharges from clearwater floods, their estimated frequency of occurrence, and the climate change adjustment.

- Debris Floods – A summary of the peak discharges and sediment volumes and their estimated frequency of occurrence at Hummingbird Creek.
- Debris Flows – A summary of the peak discharges and sediment volumes and their estimated frequency of occurrence. Included is an estimate of the maximum credible debris avalanche for Hummingbird Creek and discussion of climate change impacts.
- F-M relationship – This section combines the three hydrogeomorphic processes identified to occur at Hummingbird Creek into a single F-M relationship used as an input to the hydraulic modelling and hazard mapping (Appendix D).

Uncertainty and limitations on the development of F-M relationships is outlined in Appendix E.

C.2. METHODS

The flowchart shown in Figure C-1 outlines the workflow for the development of the F-M model. The key points of the workflow are outlined below.

- The desktop study and field investigation form part of the basis of the hazard process identification (i.e., clearwater flood, debris flood, and/or debris flow) and compiles events captured in the historical record.
- Two F-M models were developed: one for peak discharge and for sediment volumes. The final models are developed through combining an ensemble of process-based and empirical methods paired with experience-based judgment.

The F-M model in the form of sediment volume and peak discharge is the key input to the numerical modelling which results in hazard maps. Ultimately, hazard maps are input to risk assessments (not in current scope of work) and inform the design of potential mitigation measures. The accuracy of the F-M model is therefore crucial as otherwise both the risk assessment is inaccurate and mitigation measures may be either under- or over-designed.

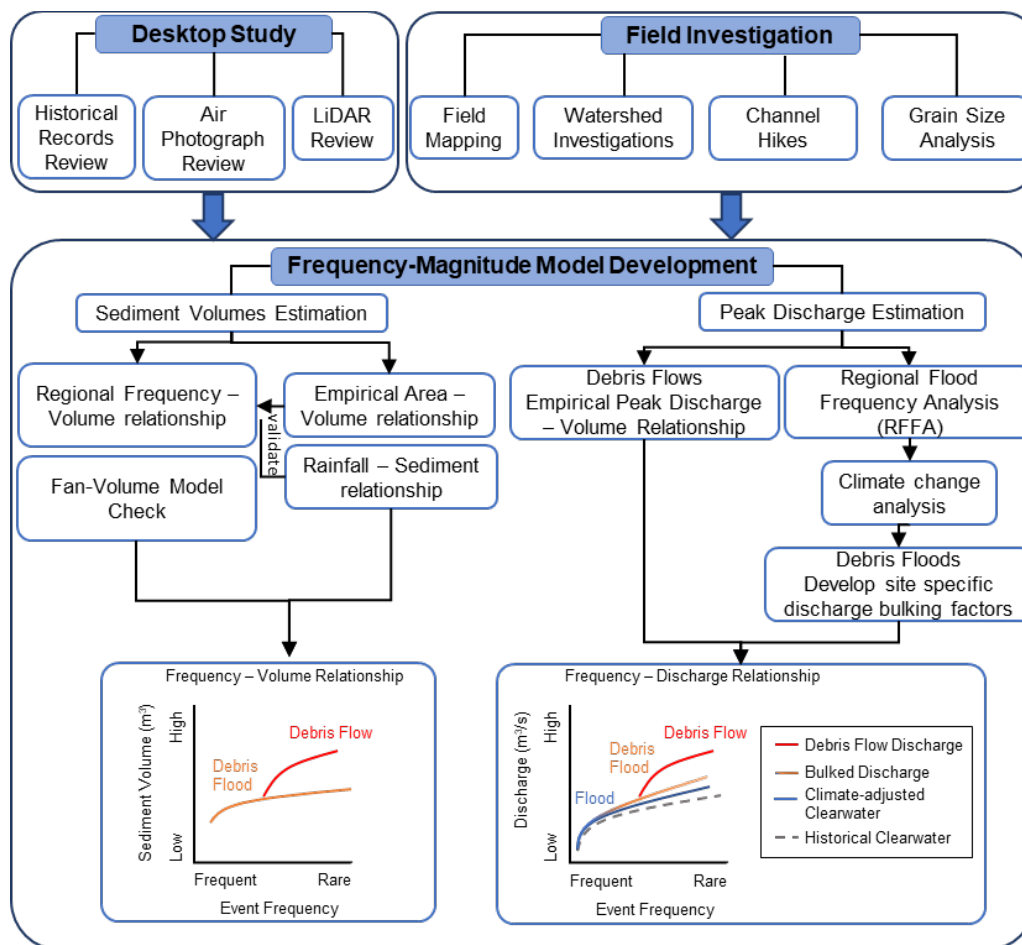


Figure C-1. Workflow applied for flood, debris flood and debris flow prone steep creeks for developing frequency-magnitude relationships.

C.2.1. Desktop Study

C.2.1.1. Historical Records Review

BGC reviewed engineering reports, scientific literature, local historical records, social media posts, and Ministry of Transportation and Infrastructure (MOTI) reports to identify past debris flow, debris flood, and/or flood events at Hummingbird Creek and nearby streams. Appendix B summarizes the data reviewed for this project. Historical records from the various sources described above were compiled by BGC and integrated into the F-M relationship.

C.2.1.2. Air Photo Review

Air photos were reviewed to:

- Map historical locations of the creek channel

- Estimate the frequency and deposit area of past hydrogeomorphic¹ events
- Map historical avulsion hazards
- Estimate bank erosion.

Debris flows or debris floods can obliterate or damage vegetation in the channel and on the alluvial fan. If such events are sufficiently large, a cover of debris deposits can be identified as light grey or white areas on air photographs. Where trees are only damaged by debris flows or debris floods, dense tree canopies can obscure such deposits, biasing a review of air photos toward larger magnitude events. This bias is corrected for by detailed ground investigations (e.g., dendrochronology, trenching, stratigraphic analysis of natural exposures) (see Section C.2.2).

A series of historical air photos was obtained from government sources at varying scales (Appendix B). The air photos were georeferenced using a geographic information system (GIS). A higher density of control points near alluvial fans is used to minimize distortion during the georeferencing process. BGC estimated the spatial accuracy afforded by application of these methods to be about +/- 10 m.

Where sediment deposition was interpreted to have occurred, areas were delineated with polygons. Other changes such as land use, road construction, logging and fire history were also noted.

Volumes of past debris flows and debris floods were estimated from the aerial extents mapped from the air photos using empirical relationships. We developed a relationship between mapped planimetric area (A) and sediment volume (V) based on case studies of 44 and 9 debris flows and debris floods in BC and AB (Figure C-2). Equations C-1 and C-2 are the resultant equations:

$$V = 0.182A^{1.15} \quad [\text{Eq. C-1}]$$

$$V = 0.241 A^{1.1} \quad [\text{Eq. C-2}]$$

¹ In this context, hydrogeomorphic events are debris floods and debris flows, as well as bank erosion and sediment inundation.

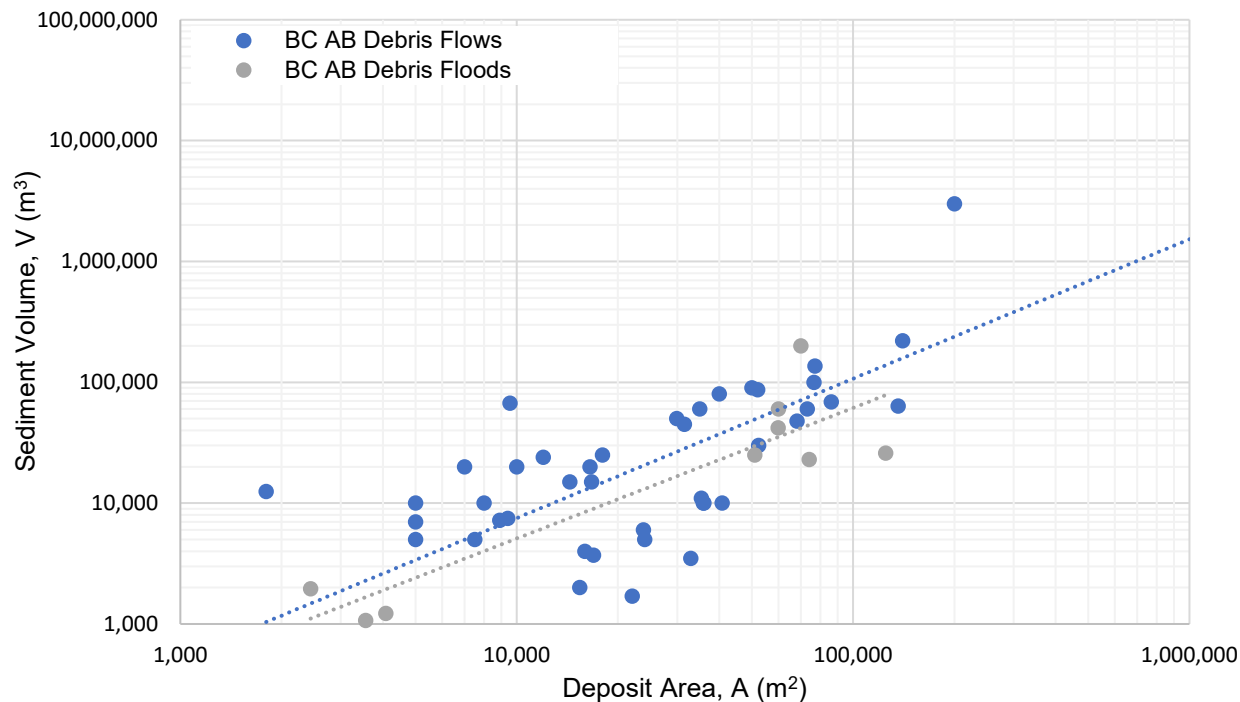


Figure C-2. Empirical area-volume relationships for debris flows and debris floods in BC and AB from documented case studies in the literature and other BGC studies.

C.2.1.3. Topographic Review

Lidar bare earth digital elevation models (DEMs) were used to identify historical channels or deposits on the fan, and geomorphic features (landslides, sediment sources, glacial deposits) in the watershed (Drawing 04 and 05). Lidar data used in this study is listed in Appendix B.

Bathymetric data for Mara Lake was obtained from navigational charts and fishing maps derived from Canadian Hydrographic Service (CHS) data (GPS Nautical Charts, n.d.). The bathymetric data and lidar of the fan were combined into a single DEM used as input to the Sloping Local Base Level (SLBL) tool to estimate fan volume. The SLBL tool is used to create a “no fan” topography surface meaning that it approximates what the DEM would have been prior to the existence of the fan shortly after de-glaciation. The difference the post-glaciation surface and the combined lidar and bathymetry present day surface allow for an estimation of the fan volume. The fan volume is used in Sections C.2.4.3 and C.2.5.2 in estimating sediment volumes from debris floods and debris flows. It is also used to validate the F-M relationship (Section C.2.6)

C.2.1.4. Climate and Climate Change

Climate change is expected to impact steep creek processes both directly and indirectly through complex feedback mechanisms (Jakob, 2021). Climate change was assessed by BGC for Hummingbird Creek at the monthly and annual timescale to capture general trends in the watershed. Climate change was assessed at the daily time scale to provide precipitation inputs for the detailed climate change assessment in Section C.2.3.3.

Note that these analyses do not reflect the expected substantial increases in the frequency of extreme short-duration precipitation as postulated by Prein et al. (2017) and others. Regional climate models are still at too coarse of a spatial scale to simulate convective storms and predict the changes in sub-daily precipitation extremes (Martel et al. 2021). These short duration (a few hours) are important for the triggering of debris flows when the antecedent moisture condition is high. Engineering judgement was used to adjust the F-M relation to reflect the anticipated increase in the frequency of debris-flow triggering rainfall.

Monthly and annual historical climate was derived from reanalysis PRISM (Daly et al., 2008) and ERA5 (C3S, 2017) datasets. Changes to these historical conditions were determined from an ensemble of downscaled Global Climate Models (GCM) data obtained from the Climate-BC tool (Wang et al., 2016), the Canadian Centre for Climate Modelling and Analysis (CCCma), and Pacific Climate Impact Consortium (PCIC). These data come from model runs applying the SSP5 global emissions scenario. This is a high carbon emissions scenario in which socioeconomic reliance on fossil fuels is perpetuated and assumes a tripling of CO₂ emissions by 2075 (IPCC, 2021). It is widely considered a “worst case” scenario.

From these models, the following variables were extracted for the watershed for the project climate in 2041 to 2100 and the results are summarized in the main report.

- Mean annual air temperature
- Mean annual precipitation
- Precipitation as snow (measured as snow water equivalent, SWE)
- Minimum and maximum daily temperature
- Maximum daily precipitation
- Number of days per year exceeding 20 mm precipitation
- Number of dry days per year (<1 mm precipitation).

Daily climate projections were downloaded from an ensemble of downscaled GCMs from PCIC for the period from 1950 to 2100. At the daily time step, the variables available included minimum and maximum daily temperature, and daily precipitation at a gridded resolution of roughly 10 km². The daily data are derived from model runs applying Representative Concentration Pathway (RCP) 8.5² often described as the “business as usual” carbon emissions scenario and a “worst case” scenario (i.e., similar to the SSP5 global emissions scenario for the monthly and annual datasets). The change in daily precipitation data from a historical baseline period to future projected periods was used to estimate the change in peak discharges (Section C.2.3.3).

² RCP 8.5 is an emission scenario from the previous release of GCMs from the Coupled Model Intercomparison Project (CMIP) 5. BGC is in the process of downloading the updated GCM data from CMIP 6 at the daily time step which now uses updated emissions scenarios (e.g., SSP5) that reflect differing climate policies that could be enacted to curtail climate change. SSP5 and RCP 8.5 are both considered “worst case” scenarios, and their results are comparable.

C.2.2. Field Investigation

Field work was conducted by BGC personnel October 5 to 8, 2021, and included:

- Field mapping of past hydrogeomorphic events and human-made features (roads, trails, etc.)
- Cross section measurements of the channel above the fan-delta apex for the estimation of channel yield rates and channel recharge rates
- Coring of trees for dendrogeomorphic analysis
- Collecting measurements and photographs for grainsize distributions.
- While test pits could not be excavated on the fan-delta due to landowner restrictions, two radiocarbon samples were collected from an existing foundation excavation at the edge of the fan-delta with kind permission by the owner who was present at the time.

C.2.2.1. Field Mapping

Field observations were recorded with an iPad using ArcCollector (developed by ESRI). Collected information included: general observations, photographs, oral accounts by residents, channel characteristics and dimensions, dimensions of bridge and culvert openings, high water marks, deposits, potential avulsion points, dendrogeomorphological observations, and grainsize distribution.

C.2.2.2. Yield Rates

Yield rates are an estimate of the volume of erodible material available per meter of channel length and that is potentially mobilized by future debris-flow events. Field observations were used to estimate the amount of erodible channel material available along the channel. Cross-section measurements were collected over a channel length of 750 m upstream of the fan-delta apex until the channel became steeper and more difficult to navigate on foot. Measurements included station location, bankfull channel width, thickness of erodible debris, and channel slope. The amount of erodible channel material available was then translated into an approximate yield rate.

The yield rate of Hummingbird Creek was previously estimated by Jakob et al. (2000) following the 1997 debris flow event. The updated 2021 yield rate was compared to the previous yield rate to estimate the length of time it takes for the channel to accumulate a similar amount of debris as was entrained during the 1997 debris flow, i.e., the channel recharge rate.

C.2.2.3. Dendrogeomorphology

Dendrogeomorphology is a subdiscipline of dendrochronology, in which tree rings and tree growth are used to analyze historic landslide activity. Where possible, results of the dendrogeomorphologic analysis are used to confirm ages of deposits or supplement F-M relationships as established from other methods.

Tree cores were extracted from living trees using a 5 mm increment borer. In the office, the samples were glued onto wooden mounting boards and sanded to facilitate ring and feature identification. Analysis was completed using a specialized scanner and WinDENDRO software

(Regent Instruments Inc., 2012). WinDENDRO is a semi-automatic image analysis program, which identifies tree rings and measures the width of the yearly growth. Once the tree ages were confirmed, the growth rings were analyzed to identify anomalies that may be associated with debris flood, debris flow or avalanche events impacting the trees.

C.2.2.4. Grain Size Distribution

Grain size distributions were collected to support sediment transport and flow resistance estimates. Sampling was conducted on the fan at 2 to 3 locations along the fan-delta channel to characterize variability.

Grain size distributions were estimated from photographic samples of the bed material along the channel and riprap placed on the channel banks. The photographic samples were obtained by placing a scale object on the stream bed (soccer ball with a diameter of approximately 220 mm) and collecting oblique photos (Figure C-3). The photographic samples were processed by Split Engineering using Split-Desktop™ to calculate grain size distributions.



Figure C-3. Oblique photo of the channel bed material in the lower reaches of Hummingbird Creek.

C.2.2.5. Radiocarbon Dating of Organic Materials

Test trenching or collection of organic materials from natural exposures or building foundation excavations allows estimation of the thickness of past debris flows/debris floods, which are typically distinct from overlying and underlying deposits. It also permits sampling of datable organic materials found in paleosols (old soil layers) and embedded within the event deposits. An approximate age can then be assigned to the deposit.

Radiocarbon dating involves measuring the amount of the radioisotope ^{14}C preserved in organic materials and using the rate of radioactive decay to calculate the age of a sample. This method requires the deposition and preservation of organic materials within the sedimentary stratigraphy of the fan. The age range of this method is from approximately 45,000 years to several decades before present. As such, the method is applicable to the time scale of post-glacial fan formation in western Canada.

Radiocarbon samples were collected in plastic bags, air-dried, and then sent to Beta Analytics in Florida for age determination by Accelerator Mass Spectrometry (AMS). Results from radiocarbon dating and exposure documentation were used to inform the frequency assessment of hydrogeomorphic events on the fan, sediment deposit thickness for modelling, as well as to cross-check sediment volume estimates.

C.2.3. Clearwater Peak Flow

Hummingbird and Mara Creeks (Water Survey of Canada gauges 08LC023 and 08LC024) have limited stream gauge flow records (1946 to 1949) that are insufficient in length for estimating the peak flows for the flood quantiles (i.e., 2-, 5-, 10-year floods). Therefore, peak flows for clearwater floods were estimated using two methods:

- Regional flood frequency analysis (FFA) using the index-flood method.
- Pro-rated FFA estimated from a calibrated hydrologic model for Sicamous Creek located 7 km north of Hummingbird Creek.

The clearwater peak flows were then adjusted to account for climate change (Section C.2.3.3) and bulked to estimate debris-flood discharges (sediment and water) as described in Section C.2.4.2. Peak discharges for debris flows were calculated independently from the clearwater peak flow (Section C.2.5).

C.2.3.1. Index-Flood Method

A regional FFA approach transfers hydrologic information from gauged watercourses with similar watershed characteristics to the ungauged site. Several methods have been developed to conduct a regional FFA and among these methods, the index-flood is considered superior to other models (Ouarda et al., 2008).

The index-flood method involves the development of a dimensionless regional growth curve assumed to be constant within a homogeneous region³. The probability distribution of flood events at hydrometric stations in a homogeneous region are identical apart from a site-specific scaling factor, the index-flood⁴. The parameters of the probability distribution are estimated at each hydrometric station. These at-site estimates are combined using a weighted average to generate

³ A homogeneous region is defined as a region that is in a similar geographic region (< 150 km radius), is in a similar hydroclimatic zone, and follows a similar hydrologic regime (e.g., peak streamflow is snowmelt driven)

⁴ The index-flood can be the mean annual flood, median annual flood, or another flood quantile of choice that is calculated for each hydrometric station within the homogeneous region. At Hummingbird Creek, the index-flood used was the mean annual flood.

a regional estimate. The regional growth curve is a dimensionless quantile function common to every hydrometric station in the region as per Equation C-3:

$$X_T = Q_T / Q_m \quad [\text{Eq. C-3}]$$

where X_T is the growth factor for return period T, Q_T is the flood magnitude at return period T, and Q_m is the index-flood magnitude. The flood magnitude at any return period is calculated using this relationship given the index-flood estimate.

The index-flood method can be applied to an ungauged catchment by developing a regional relationship between the index-flood and the catchment characteristics at hydrometric stations in the region. Once the catchment characteristics are extracted at the ungauged site, the index-flood can be estimated, and the flood magnitude of any AEP can be estimated using the index-flood estimate and the regional growth curve by re-organizing Equation C-3. Regional flood records from Water Survey of Canada hydrometric stations including the annual maximum peak instantaneous stream, the maximum average daily streamflow, date and time of event, catchment area, and number of years on record were extracted from the HYDAT database (Government of Canada, n.d.). A list of selected catchment characteristics generated for this analysis and the source datasets are listed in Table C-2.

Table C-2. List of selected catchment characteristics.

Type	No.	Acronym	Characteristic	Units	Dataset
Catchment	1	Centroid_Lat	Latitude at the centroid location in the catchment polygon	degrees	STRM (Farr et al., 2007)
	2	Centroid_Long	Longitude at the centroid location in the catchment polygon	degrees	
	3	Centroid_Elev	Elevation at the centroid location in the catchment polygon	m	
	4	Area	Area of the catchment polygon	km ²	
	5	Relief	Maximum minus minimum catchment elevation	m	
	6	Length	Area divided by perimeter	km	
	7	Slope	Catchment length divided by relief times 100	%	
Climate	8	MAP	Mean annual precipitation	mm	Climate NA (Wang et al., 2016)
	9	MAT	Mean annual temperature	°C	
	10	PAS	Precipitation as snow	mm	
	11	PPT_wt	Winter precipitation (Dec, Jan, Feb)	mm	
	12	PPT_sp	Spring precipitation (Mar, Apr, May)	mm	
	13	PPT_sm	Summer precipitation (Jun, Jul, Aug)	mm	
	14	PPT_fl	Fall precipitation (Sep, Oct, Nov)	mm	
Physiographic	15	Forest	Forest cover in the catchment	%	NALCMS (Latifovic et al., 2017)
	16	Water_Wetland	Wetland and open water cover in the catchment	%	
	17	Urban	Urban cover in the catchment	%	
	18	CN	Inferred based on integrating land cover and soils cover	unitless	NALCMS and HYSOGs250m (Ross et al., 2018)

C.2.3.2. Pro-rated Flood Quantiles

The second method used to estimate the clearwater flood quantiles for Hummingbird Creek was through pro-ration of clearwater flood quantiles estimated from a calibrated hydrologic model developed for Sicamous Creek (BGC, 2022 – In Progress).

The flood quantiles can be transferred between two watersheds using a relationship between the flood quantiles and the catchment area (Equation C-4):

$$Q_{Hummingbird,T} = Q_{Sicamous,T} \left(\frac{A_{Hummingbird}}{A_{Sicamous}} \right)^n \quad [\text{Eq. C-4}]$$

where Q_T is the peak flow for the T^{th} quantile for Hummingbird and Sicamous, A is the catchment area of Hummingbird Creek and Sicamous Creeks at the fan apex and n is an exponent to be

selected. Three overlapping years of Water Survey of Canada historical streamflow data (1946 to 1948) were available for comparison between Sicamous Creek (08LC027) and Mara/Hummingbird Creeks (08LC023 and 08LC024), from which an exponent of 1 was estimated.

C.2.3.3. Climate Change Analysis

A climate change adjustment was applied to the flood quantiles. The climate change impact on peak flows was assessed using daily temperature and precipitation data from the PCIC statistically downscaled GCMs from 1950-2100 to estimate an increase or decrease in precipitation from a historical baseline period. The climate-adjusted precipitation was then applied to the calibrated hydrologic model for Sicamous Creek to estimate the changes in watershed precipitation on runoff and peak streamflow. It is assumed that changes in surface runoff at Sicamous Creek are transferrable to Hummingbird Creek given the proximity of the two watersheds and the similarity in hydrologic regime.

The daily precipitation data from 27 PCIC GCMs was partitioned into daily rainfall and daily potential snowmelt using a simple temperature model⁵ for snowmelt. The daily potential runoff was then calculated as the sum of daily rainfall and potential snowmelt. A precipitation frequency analysis was completed for both the daily potential runoff and daily precipitation for the historical period and projected time periods. The time periods considered were:

- Modeled historical baseline matching the period of record of the relevant climate station (1964 to 2016 for Salmon Arm Airport Station).
- 2011 to 2040 (Approximating current conditions)
- 2041 to 2071
- 2071 to 2100.

The ratio of the 200-year daily potential runoff depths for the period of 2071 to 2100 over the modeled historical baseline period was taken for all 27 GCMs. The median of these ratios was used as a scaling factor representing the expected change in potential runoff depth for that grid cell. A scaling factor was also calculated for the change in the 200-year daily precipitation.

The median scaling factor estimated at adjacent grid cells was variable, likely due to the differences in the median elevation of the terrain in each cell. The range of scaling factors for the 200-year daily potential runoff depths and 200-year daily precipitation are provided in Table C-3. Given the uncertainty inherent in each GCM and the variability in median scaling factors observed for adjacent grid cells, the chosen scaling factor was the more conservative value of 1.3.

⁵ The workflow of the snowmelt model is the following: The daily precipitation is divided into rainfall and snowfall accumulation assuming that precipitation falls as snow when the temperature is less than 1°C. The potential daily snowmelt is calculated using a rain-on-snow equation assuming a forested catchment and negligible wind conditions from Coulson (1991). The actual daily snowmelt is dependent on the snowpack available for melt. The accumulated snowfall is what is available for melt and was used to determine how much of the estimated potential daily snowmelt from the previous step actually melts and can contribute to runoff.

Table C-3. Scaling factor for change in the 200-year daily precipitation and 200-year daily potential runoff depth from the historical period to the 2080s (2071 to 2100).

	Change in Daily Potential Runoff Depth	Change in Daily Precipitation
Range of scaling factors	1.1 to 1.3	1.3 to 1.4
Weighted average scaling factor	1.1	1.3
Chosen scaling factor	1.3	

The 30% increase in precipitation was applied to the Sicamous Creek hydrologic model with the assumption that the watershed snowpack remains similar in the future. This is a conservative, yet reasonable assumption for watersheds with a significant portion of the watershed at or above 1600 m elevation such as for Sicamous Creek and Hummingbird Creek (Schnorbus et al. 2012).

C.2.4. Debris-Flood Assessment

This section outlines methods to estimate debris flood F-M relationships, which includes the debris-flood initiation thresholds, the peak discharge of the debris flood, and the sediment volumes that a debris flood may carry. Methods are consistent with those outlined in Jakob et al. (2022).

C.2.4.1. Debris Flood Initiation Threshold

The stage of bedload transport in a river (i.e., how much of the bed is mobilized) can be estimated from the ratio of the Shields stress⁶ (τ_*) of the streamflow acting on the channel bed over the critical Shields stress ($\tau_{*,c}$) for movement of the channel bed grain sizes. For shear stress ratios greater than 2 and up to 4, the channel is thought to be dynamically unstable and likely to change its shape to restabilize which is often done through bank erosion and channel aggradation (i.e., becoming shallower and wider). Debris flood onset and full bed mobilization is estimated to begin at shear stress ratios of 2 or more (Church & Jakob, 2020).

The debris flood onset discharge was estimated by first calculating the critical shields value ($\tau_{*,c}$) for mobilization of the grain size diameter for which 84% of the grain sizes are finer (D_{84}) using a relationship developed by Bunte et al. (2013) (Equation C-5). The critical shields value is assumed to be dependent on the channel slope, S .

$$\tau_{*,c} = 0.021 + 0.71S \quad [\text{Eq. C-5}]$$

From the critical shields value, a depth of flow, d_{DFlood} , for onset of debris floods can be estimated from Equation C-6:

$$d_{DFlood} = \frac{2\tau_{*,c}(\rho_s - \rho_f)D_{84}}{\rho_f S} \quad [\text{Eq. C-6}]$$

⁶ The Shields stress is also known as the dimensionless shear stress and is calculated as the shear force applied to the channel bed over the weight of the submerged grains.

where ρ_s and ρ_f are the density of the sediments (2650 kg/m^3) and the density of the fluid (assumed to be 1000 kg/m^3) respectively.

A discharge, Q_{DFlood} , for the onset of debris floods can then be estimated using Manning's equation and assuming a trapezoidal channel approximated by cross sections taken from the lidar. Eight cross sections were extracted from the 2019 lidar from the fan apex downstream to Mara Lake.

The calculation of the shear stress ratio is highly dependent on the representative grain size used. The D_{84} was selected as the representative grain size diameter because the coarser grains typically control the bed turbulence and hydraulics, and therefore influence the initiation of transport and overall channel stability (Mackenzie et al., 2018; Recking et al., 2015).

C.2.4.2. Discharge Bulking Method

It is very difficult to measure sediment concentrations during a flood, debris flood, or debris flow event. The sediment concentration of the flow is approximated using a bulking factor which can be specified based on geomorphological indicators in the watershed. These bulking factors should not be interpreted as precise. Jakob et al. (2022) introduce the concept and logic inherent in determining the bulking coefficient of debris floods for small ($<100 \text{ km}^2$) watersheds.

Using the classifications described in Jakob et al. (2022), Hummingbird Creek is subject to Type 1 and Type 2 debris floods at different return periods. Bulking factors were estimated for each debris flood return period based on its debris flood type and channel characteristics.

C.2.4.3. Debris Flood Sediment Volumes

BGC employed two methods to estimate debris-flood sediment volumes for variable return periods after methods described in Jakob et al. (2022):

- Regional debris flood F-M relationship: A relationship relating fan area or fan volume to debris flood sediment volumes based on data from detailed frequency-magnitude studies within the region of Southwestern BC and Southern Alberta near the Rocky Mountains compiled in Jakob et al. (2020).
- Empirical rainfall-sediment volume relationship: An empirical relationship developed from case studies of known sediment and rainfall volumes from widespread sediment transport events during floods and debris floods in Europe and Canada.

Regional Debris Flood F-M Analysis

For the regional debris flood F-M relationship, we used an equation that predicts sediment volume normalized to fan volume (V_{NV}) at given return periods (T) based on detailed F-M studies in southwestern BC in Jakob et al. (2020) (Equation C-7):

$$V_{NV} = V_f [354 \ln(T) + 218] \quad [\text{Eq. C-7}]$$

where V_f is the fan volume of Hummingbird Creek estimated to be approximately 18 Mm^3 (Section C.2.6).

Rainfall-Sediment Relationship

For the empirical rainfall-sediment volume relationship, we used the equation relating total sediment volume displaced (V_S) from observed rainfall volume (V_R) from Jakob et al. (2022) (Equation C-8):

$$\log V_S = 0.7382 \log V_R - 0.4371, R^2 = 0.79 \quad [\text{Eq. C-8}]$$

We estimated the total rainfall volume from each return period using the following workflow:

1. The 24-hour rainfall volumes were obtained from both from the Salmon Arm Airport climate station (ID 1166R45) Depth-Duration-Frequency (DDF) data and from the MetPortal web-interface point precipitation frequency data (DTN and MGS Engineering, 2020). The 24-hour duration is considered a reasonable proxy for a major storm.
2. The 24-hour precipitation values were then multiplied by the watershed areas of Hummingbird Creek and Mara Creek (approximately 38 km²) to arrive at an estimated total volume of rain falling onto the two watersheds in a 24-hour period.
3. To account for climate change effects, the total rainfall volume was increased by 30% based on the results of the climate change analysis in Section C.2.3.3.
4. To allow for snowmelt contribution, BGC added 30% water equivalent over half of the watershed. This value can vary depending on the timing of a given storm (i.e., how much snow is available at difference elevation bands) and the snow water equivalent (i.e., how wet the snow is at the time of the rainstorm).
5. Equation C-8 was then applied to estimate the debris-flood sediment volume for each return period class.

C.2.5. Debris Flow Assessment

This section outlines methods to estimate debris flow F-M relationships, which includes debris-flow frequency based on the historical record, debris-flow sediment volumes and peak discharges for select return periods of future events, and a discussion on the impacts of climate and land use changes on debris-flow- magnitude and frequency.

C.2.5.1. Debris-Flow Frequency

The frequency of debris flows and their magnitude can be supported from the historical record review, air photo interpretation, dendrogeomorphology, and test trenching. The frequencies of past events were mainly estimated from the air photo, historical record, and radiocarbon samples (Section C.2.1).

C.2.5.2. Debris-Flow Volume

BGC employed several methods to estimate debris-flow volumes for variable return periods:

- A regional debris flow F-M relating fan volume or fan area to debris flow sediment volumes similar to the one for debris floods described in Section C.2.4.3.
- Empirical relationship relating rainfall volumes to sediment volumes similar to the one for debris floods described in Section C.2.4.3.

- A “maximum credible” approach in which the largest credible debris avalanche triggers a debris flow and entrains additional material.

Regional Debris Flow F-M Analysis

For the regional debris flow F-M relationship, we used an equation that predicts sediment volume normalized to fan area (V_{NA}) at given return periods (T) based on a selection of sites with detailed F-M studies within Southwestern BC that share similar geomorphic characteristics (Equation C-9):

$$V_{NA} = A_f(47984 \ln(T) - 124030) , R^2 = 0.83 \quad [\text{Eq. C-9}]$$

where A_f is the area of the Hummingbird Creek fan-delta of approximately 1.0 km².

Rainfall-Sediment Relationship

The empirical rainfall-sediment relationship was developed from case studies of known sediment and rainfall volumes from widespread sediment transport events during debris flows in Europe and Canada similar to the empirical rainfall-sediment relation for debris floods described in Jakob et al. (2022). The equation used to relate total sediment volume displaced (V_S) from observed rainfall volume (V_R) was Equation C-10:

$$\log V_S = 0.7967 \log V_R - 0.4811, R^2 = 0.51 \quad [\text{Eq. C-10}]$$

The total event rainfall was estimated using the same methods described in Section C.2.4.3.

Maximum Credible Event

The maximum credible single landslide event involved a review of the lidar for the Hummingbird and Mara watersheds for the largest initiating landslide that is either natural or from a logging road failure that would be anticipated to either i) block the channel and impound flow behind it creating the potential for a landslide dam outbreak flood (LDOF), or ii) remain mobilized as the landslide impacts the channel and continue to entrain more sediment until it reaches the fan apex. The potential for an LDOF was considered unlikely in both Hummingbird and Mara Creek. Scenario ii was considered possible in Hummingbird Creek.

A landslide initiating a debris flow that reaches the fan apex was considered more likely in Hummingbird Creek because of its event history (e.g., the 1997 debris flow) and because the channel gradient in Hummingbird creek immediately above the fan apex is steeper (approximately 24%), which allows the sediment to maintain its momentum and debris-flow characteristics as it flows down the channel. The maximum credible single landslide event is a combination of the maximum credible landslide that can occur in Hummingbird Creek and the length of channel from the landslide initiation to the fan apex that can entrain sediment. For example, a very large landslide occurring at the fan apex will likely carry less sediment than a smaller one that occurs 2 km upstream of the fan apex and can bulk its volume with channel material.

The maximum credible single landslide sediment volume is approximated by the estimated volume of the initial landslide plus the channel yield rate multiplied by the channel length. The hypothesized largest credible single landslide within the steeper section of Hummingbird channel

is located 500 m downstream of the landslide initiated during the 1997 event (Figure C-4) and 1600 m upstream of the fan apex. The volume of initiating landslide was estimated by separating the landslide into 3 zones of differing thickness based on the underlying terrain material estimated from the lidar. A best estimate of the volume was made along with a lower and upper bound. The channel yield rate was estimated from field measurements and described in Section C.2.2.2. It is consistent with the yield rate reported in Jakob et al. (2000) during the 1997 event.

The maximum credible event that can be deposited onto the fan-delta is the sum of events that occur quasi-simultaneously within the Hummingbird and Mara creek watersheds. The maximum credible single landslide event applies to Hummingbird Creek, however, it is anticipated that the rainfall event triggering the maximum credible single landslide in Hummingbird Creek would likely also cause some event (though estimated to be smaller magnitude) in Mara Creek. The maximum credible event is therefore estimated to carry a larger sediment volume. The maximum credible event volume was estimated using geoscientific judgement.

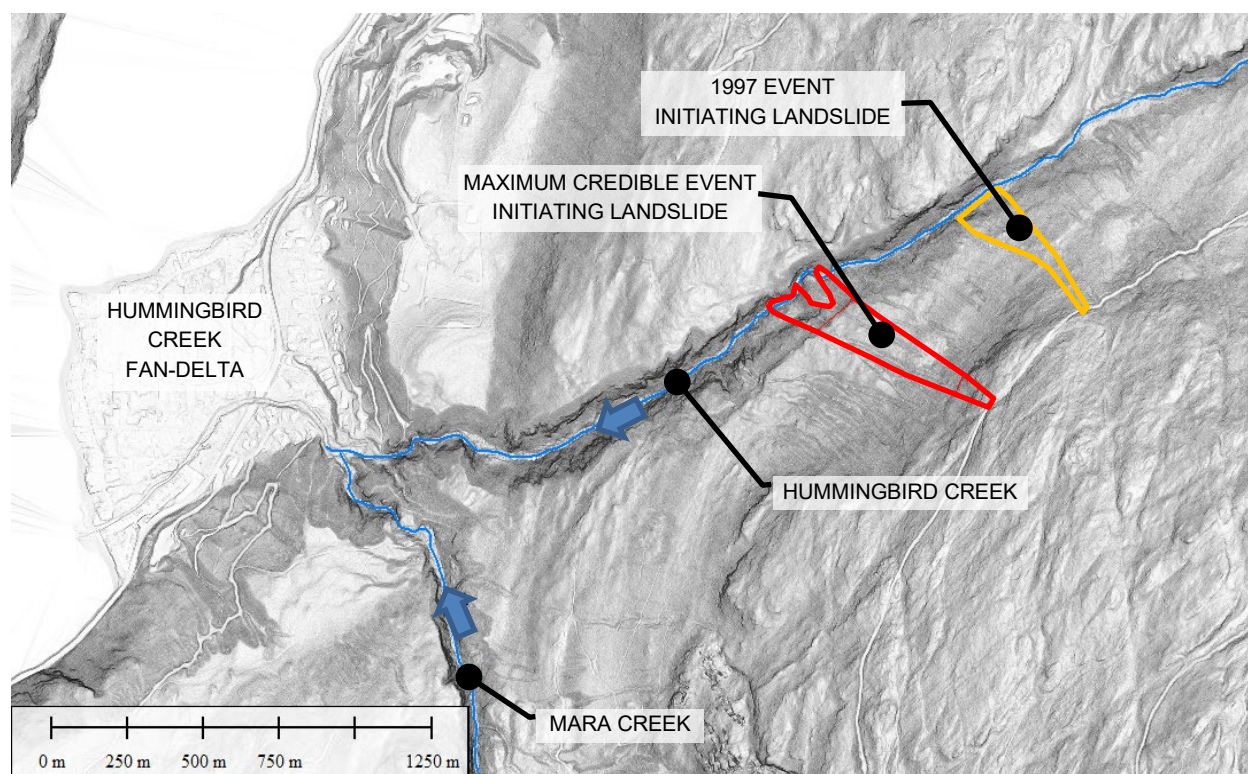


Figure C-4. Estimation of the maximum credible event initiating landslide on Hummingbird Creek.

C.2.5.3. Peak Discharge Estimates

Debris flow peak discharge was estimated from empirical correlations from debris flow volume developed from field observations at 66 debris flow fans in Southwestern BC and AB from case studies reported in literature and other BGC studies (Figure C-5). These equations are similar to those reported in Bovis and Jakob (1999) and Jakob (2005) but are specific to debris flows in BC

and Alberta because of the unique geological and rheological properties of these flows compared to global debris flows reported elsewhere.

Equation C-11 shows the developed relationship between sediment volume (V) and peak discharge (Q).

$$Q = 0.154V^{0.73} \quad [\text{Eq. C-11}]$$

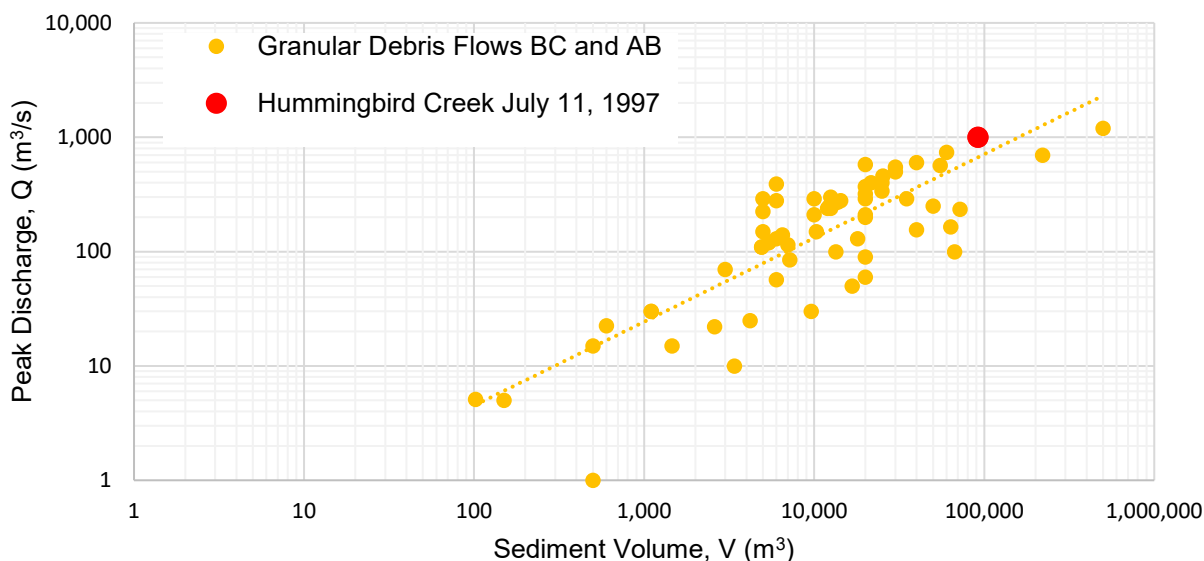


Figure C-5. Relation between peak discharge, Q and sediment volumes, V for reported debris flow events in Southwestern BC and AB.

C.2.5.4. Climate Change Effects

Climate change is expected to affect future debris flows both directly and indirectly through complex feedback mechanisms (Jakob, 2021):

- Change in clearwater peak discharge
- Increased landslides and greater sediment supply
- Wildfires – increase in runoff and sediment supply.

With regards to changes in clearwater peak discharge, regional climate change projections indicate that there will be an increase in winter rainfall (Section 2.4 in main report) and an increase in the hourly intensity of extreme rainfall and increase in frequency of events (Prein et al., 2017). These two factors increase the likelihood of landslides and debris flows being triggered in the watershed.

When considering potential changes to sediment supply due to precipitation changes, steep creek channels can be generally categorized as being either:

- Supply-limited: meaning that available debris for transport is a limiting factor on the magnitude and frequency of steep creek events. In other words, once debris in the source zone and transport zone has been depleted by a debris flow or debris flood, another event even with the same hydro-climatic trigger will be of lesser magnitude until the sediment supply is replenished; or,
- Supply-unlimited: meaning that available debris for transport is not a limiting factor on the magnitude and frequency of steep creek events, and another factor (such as precipitation frequency/magnitude) is the limiting factor. In other words, there is always an abundance of debris along a channel and in source areas so that whenever a critical hydro-climatic threshold is exceeded, an event will occur. The more severe the hydro-climatic event, the higher the resulting magnitude of the debris flow or debris flood.

The sensitivity of the two basic types of basins to increases in rainfall (intensity and frequency increases) differ (Figure C-6):

- Supply-limited basins would likely see a decrease in individual geohazard event magnitude, but an increase in their frequency as smaller amounts of debris that remains in the channel are easily mobilized (i.e., more, but smaller events).
- Supply-unlimited basins would likely see an increase in hazard magnitude and a greater increase in frequency (i.e., significantly more, and larger events).

Given the observations of abundant landslides in the upper watersheds of Hummingbird and Mara Creeks, Hummingbird Creek is considered a supply-unlimited watershed. Therefore, projected increases in the frequency and intensity of rainfall events are likely to cause more frequent debris flows.

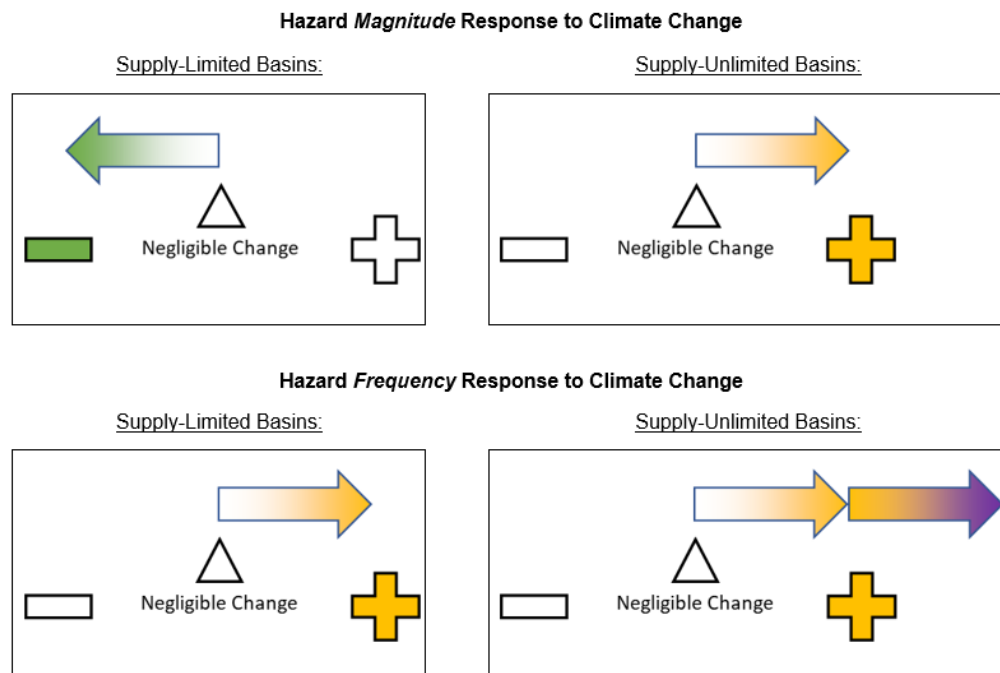


Figure C-6. Steep creek hazard sensitivity to climate change – supply-limited and supply unlimited basins.

Wildfires are expected to increase in frequency and intensity across British Columbia due to the increase in fire season length, drought conditions, and fire severity (Nitschke & Innes, 2008). Wildfires increase available sediment supply and lower the precipitation threshold for debris flow initiation. This effect is most pronounced within the first three to five years after the fire (Cannon & Gartner, 2005; DeGraff et al., 2015). After about three to five years, vegetation can re-establish on hillslopes and loose, unconsolidated sediment mantling hillslopes and channels may have been eroded and deposited downstream. A second period of post-fire debris-flow activity is possible about ten years following a fire, when long duration storms with high rainfall totals or rain-on-snow events cause landslides that more easily mobilize due to a loss of cohesion caused by tree root decay (Degraff et al., 2015; Klock & Helvey, 1976; Sidle, 1991). This second period of heightened debris-flow activity is rare.

Detailed post-wildfire geohazard assessment is outside the present scope of work. Information on the occurrence of past wildfires in the watershed is shown on Drawing 04 for informational purposes. Future wildfire activity could impact the potential debris flow activity and should be evaluated if future wildfires occur in the watershed.

C.2.6. Frequency-Magnitude Relationship

To check the validity of the F-M model, BGC compared the integrated F-M curve against the estimated fan-delta volume. Summing all events over the past 9,000 years should approximate the fan-delta volume given that debris floods and debris flows deposited their loads on the fan-delta.

BGC estimated the fan volume via the SLBL tool. The SLBL is a geometrical approach to define a quadratic surface above which earth materials are erodible within a short period of time (i.e., 9,000 years; Jaboyedoff & Tacher, 2005). The approach was designed for landslide volume estimation and assumes that erosion by landsliding can affect only a limited thickness of a slope defined by the quadratic surface.

The SLBL method was adapted to estimate the volume of Hummingbird Creek fan-delta. The surface was generated by the software to generate a “no-fan” topography, corresponding to the topography prior to the fan’s development. This approach assumes that the contours on the “no-fan” topography are approximately straight lines connecting the present-day contours outside of the fan boundaries (the topography outside of the fan boundaries having not been modified with the SLBL computation). The fan volume was calculated as part of the SLBL computation by taking the difference between the “no-fan” topography and the present-day topography (Figure C-7).

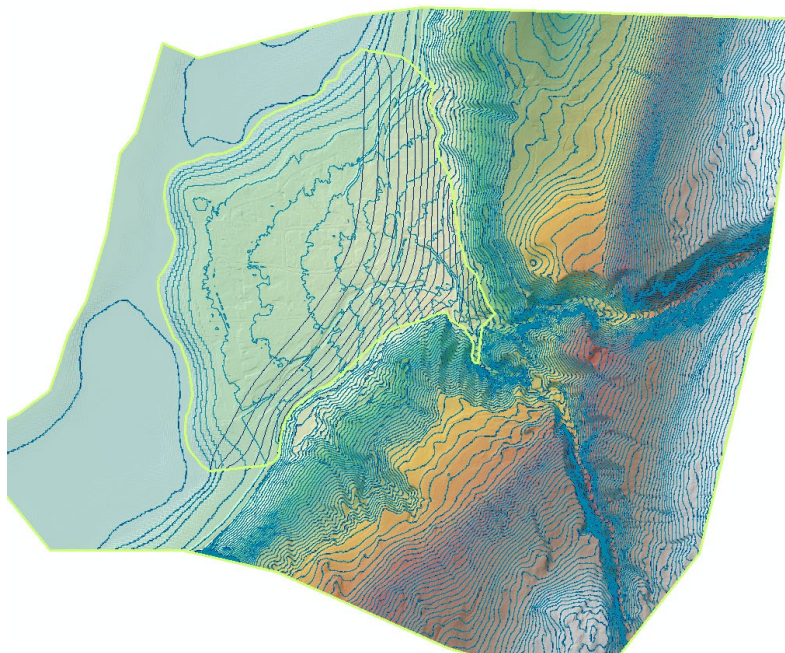


Figure C-7. Best estimate of the “no fan” topography reconstruction using the SLBL method (black 5 m contours) against the present-day topography (blue 5 m contours).

C.3. DESKTOP STUDY RESULTS

Section 4.2 in the main report summarizes the records of floods, debris floods, and debris flows at Hummingbird Creek from historical records, air photos, dendrochronology, and test trenches. Interpretations from these events and the lidar DEMs are provided on the fan-delta geomorphic map (Drawing 05) and the air photo comparison (Drawing 06).

Section 2.4 in the main report summarizes the historical and projected climate at Hummingbird Creek, which was used to inform the climate change analysis for clearwater and debris floods (Section C.2.3.3) and debris flows (Section C.2.5.4).

C.4. FIELD STUDY RESULTS

Drawings 02A, 02B, 04, and 05 present BGC’s field observations and selected photographs are provided in the Photo Appendix.

The location of the dendrogeomorphic sample is shown in Drawing 04. The results of the dendrogeomorphic assessment at Hummingbird Creek were inconclusive and could not definitively identify past debris flow or debris flood events. Dendrogeomorphic results from previous reports (EBA and KWL, 1998), which had more successful results due to logging sampling techniques, were incorporated into the observations of past events (Section 4.2 of the main report).

Grain size distributions were analysed by BGC at three locations within the Hummingbird Creek channel downstream of the Highway 97A bridge. A previous estimate on grain sizes was reported by NHC (2020) based on photos of the channel bed material immediately upstream of the

Highway 97A bridge. The D_{50} and D_{84} of each grain size sample, their channel station as measured from Mara Lake, and the average D_{50} and D_{84} of the channel bed material are shown in Table C-4.

Table C-4. Grain size distribution results from photographic samples.

Sample Type / Source	Channel Station (m)	D_{50} (mm)	D_{84} (mm)	D_{max} (mm)
Photo Sample / BGC	10	50	90	140
Photo Sample / BGC	34	70	120	240
Photo Sample / BGC	201	170	320	490
Photo Sample / NHC	705	130	N/A	570
Average all samples		100	200	330

Two radiocarbon samples were obtained from an existing foundation excavation at 8905 Swanshore Road (Photo 27 and 28 in Photo Appendix). Table C-5 summarizes the results of the lab testing and information about the sample location in relation to observed deposits. Given that BGC only collected two samples, the inferences that can be made are minimal: that is, debris flows or debris floods have occurred in the past and they have reached the edge of the fan-delta boundary in a single event.

Table C-5. Radiocarbon dates from a test pit on the fan.

Event Date (years BP)	Sample	Depth (m)	# of units above	Minimum Event Return Period (rounded) (years)
580	HUM-PT-02 SA-01	1.0	2	330
150	HUM-PT-02 SA-01	0.7	1	220

C.5. FREQUENCY-MAGNITUDE RESULTS

C.5.1. Clearwater Floods

Table C-6 summarizes the clearwater flood quantiles estimated for Hummingbird Creek. Clearwater peak flows were previously estimated for Hummingbird Creek using a regional FFA method (EBA and KWL, 1998) and are provided in Table C-6 for comparison. BGC's updated flood quantiles are higher than the previous report. This is attributable to the ensemble of methods described in the Section C.2.3 and the additional 20+ years of streamflow discharge data since the EBA and KWL (1998) report.

Table C-6. Summary of historical clearwater flood quantile estimates for Hummingbird Creek from previous studies and BGC's regional analyses.

Return Period (years)	Peak Flow (m ³ /s)			
	EBA and KWL (1998)	Index Flood RFFA	Pro-rated FFA	Chosen Flood Quantiles
2	N/A	16	18	16
5	N/A	23	25	23
20	N/A	31	33	31
50	17.8	38	40	38
200	20.1	46	47	46

Precipitation was projected to have an estimated increase of 30% due to climate change. When this value was run through a hydrologic model for Sicamous Creek, it increased the estimated clearwater peak flows by approximately 35%. Applying the same adjustment factor, the climate-adjusted clearwater flood quantiles for Hummingbird Creek at the fan-delta apex are summarized in Table C-7.

Table C-7 Historical and climate-adjusted clearwater flood quantiles for Hummingbird Creek.

Return Period Class (years)	Representative Return Period (years)	Historical Clearwater Peak Instantaneous Flows (m ³ /s)	Climate-Adjusted Clearwater Peak Instantaneous Flows (m ³ /s)
1 to 3	2	16	21
3 to 10	5	23	31
10 to 30	20	31	42
30 to 100	50	38	52
100 to 300	200	46	62

C.5.2. Debris Floods

The estimated critical shear stress to mobilize the D_{84} of the channel bed material of Hummingbird Creek occurs at an average flow depth of 1 m. This corresponds to an approximate discharge range of 30 and 40 m³/s, which falls within the 10- to 30-year return period class. At higher return periods, debris floods are unlikely to occur as debris flows will likely replace debris floods as the dominating hydrogeomorphic event type. At lower return periods, clearwater floods with limited amounts of sediment transport are more likely given that full-bed sediment mobilization is unlikely to occur. Therefore, debris floods are only expected to occur within a relatively narrow return period range.

Table C-8 summarizes the debris-flood sediment volumes that were estimated using each of the empirical methods described in Section C.2.4.3. Table C-9 summarizes the return period and associated peak discharges and total debris volumes for debris floods at Hummingbird Creek that were incorporated into the F-M relationship (Section C.5.4).

Table C-8. Debris-flood sediment volumes estimated through an ensemble of empirical methods.

Return Period Class (years)	Method	Debris Volume (m ³)
10 to 30	Regional F-M	22,000
	Rainfall-sediment (Climate-adjusted)	23,000

Table C-9. Debris-flood frequency-magnitude analysis results adjusted for climate change.

Return Period Class (years)	Debris Flood Type (Church & Jakob, 2020)	Debris Volume (m ³)	Peak Discharge (m ³ /s)
10 to 30	Type 1 Debris Flood	23,000	42

C.5.3. Debris Flows

The available evidence suggests that debris flows have historically occurred on average every 50 to 100 years at Hummingbird Creek.

Table C-10 summarizes the results of the methods used to estimate debris-flow volumes from the regional F-M analysis, rainfall-sediment relationship, and maximum credible event. Break points in the F-M curve exist in the final F-M relationship around the 50-year and 500-year return periods as process types change from debris floods to debris flows and from debris flows likely in a single channel to debris flows likely in both channels. These so-called knickpoints are based on geoscientific judgement accounting for the observations in historical record, and direct and indirect effects of climate change and land use in the future. Table C-11 summarizes the sediment volumes incorporated into the F-M relationship, the debris flow process type, and the estimated peak discharge for each of these volumes.

Table C-10. Debris-flow sediment volume results adjusted for climate change from an ensemble of methods.

Return Period Class (years)	Method	Total Debris Volume (m ³)
30 to 100	Regional F-M	66,000
	Rainfall-sediment	57,000
100 to 300	Regional F-M	120,000
	Rainfall-sediment	63,000
300 to 1000	Regional F-M	170,000
	Rainfall-sediment	70,000
1000 to 3000	Regional F-M	227,000
	Rainfall-sediment	76,000
3000 to 10,000	Regional F-M	280,000
	Rainfall-sediment	83,000
Maximum credible single landslide		121,000
Maximum credible event		200,000

Table C-11. Debris-flow frequency-magnitude analysis results adjusted for climate change.

Return Period Class (years)	Debris flow process type	Total Debris Volume (m ³)	Debris-Flow Peak Discharge (m ³ /s)
30 to 100	Assume debris flow occurs in Hummingbird OR Mara Creek	36,000	340
100 to 300	Assume debris flow occurs in Hummingbird OR Mara Creek	75,000	600
300 to 1000	Assume debris flows occur quasi-simultaneously in both creeks	170,000	1000
1000 to 3000	Assume debris flows occur quasi-simultaneously in both creeks reaching magnitude of the maximum credible event	200,000	1200
3000 to 10,000	Maximum credible event	200,000	1200

C.5.4. Frequency-Magnitude Relationship

BGC made the following assumptions in developing the final F-M model:

- Post-wildfire debris flows following the Two Mile Road Fire are possible, but unlikely due to the relatively small portion of the watershed burnt (2%) at moderate to high intensity (Hope et al., 2015; Westrek Geotechnical, March 15, 2022). This, however, may change in future wildfires.
- The re-occurrence of a debris flow originating below a forest road may be less likely in the future due to changes to forestry road management made after the 1997 debris flow

(Forest Practices Board, August 2001). However, BGC still observed recent debris slides originating below forestry roads (Photo 6, Drawing 05). Therefore, BGC included the potential for logging road related debris flows in the estimate of debris-flow return periods.

Table C-12 summarizes the results of the F-M model integration. When summed, the total volume of debris having been transported onto the Hummingbird Creek fan-delta from the watershed is approximately 31 million m³. The annualized sediment volume is approximately 3450 m³. In comparison, the reconstructed fan volume using the SLBL tool provided a total estimate between 15 Mm³ and 20 Mm³ with a best estimate of 18 Mm³. However, the F-M relationship developed by BGC is a forward-looking curve that was adjusted to account for the direct and indirect effects of climate change and landuse, which is why the total integrated volume of the F-M curve is higher than the reconstructed fan volume from historical events. The F-M analysis, while imperfect, is a close representation of the total fan volume and thus supports the validity of the F-M model (Figure C-8).

Table C-12. Total volume of fan sediments as the integral of the frequency-magnitude curve.

Event Type	Volume Class	Return Period Class (years)	Event Sediment Volume (m ³)	Annualized Volume (m ³)
Flood	1	3 to 10	N/A	N/A
Debris Flood	2	10 to 30	23,000	1530
Debris Flood / Debris Flow	3	30 to 100	36,000	840
Debris Flow	4	100 to 300	75,000	500
Debris Flow	5	300 to 1000	170,000	390
Debris Flow – both channels	6	1000 to 3000	200,000	130
Debris Flow – both channels	7	3000 to 10,000	200,000	50

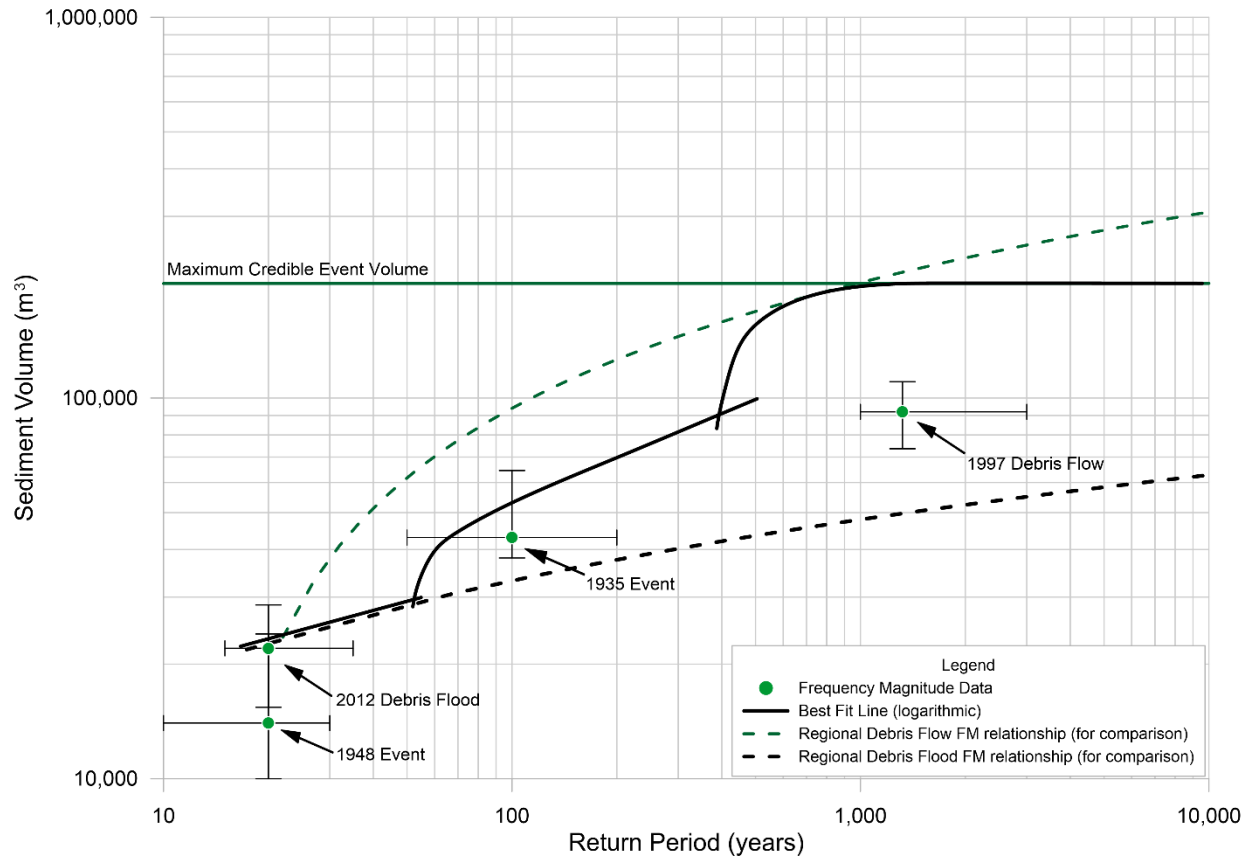


Figure C-8. The frequency-volume curve methods considered reasonable for Hummingbird Creek. Error bars are based on judgement.

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APPENDIX D COMPOSITE HAZARD MAP METHODS

D.1. INTRODUCTION

This appendix describes the numerical modelling of steep creek hazards, bank erosion modelling, and the development of the composite hazard map for Hummingbird Creek. The modelling answers the following questions:

- When steep creek hazards occur, how far do they spread across the fan-delta?
- How deep, fast, and dense is the flow during a steep creek event?
- What impact forces (the product of the flow depth, velocity, and density) are produced during these events?
- How much bank erosion is expected to occur during these events?

The composite hazard map then amalgamates the likely recurrence and intensity of flows for any location on the fan. It does not allow interpretation of either variable separately for which the individual scenario modeling maps are intended. The map informs policy and land use development planning.

This appendix is organized as follows:

- **Methods** – An overview of the methods for the numerical modelling of debris floods and debris flows on Hummingbird Creek, bank erosion modelling, and the development of the composite hazard map.
- **Numerical Modelling Results** – A summary of the individual maps developed for each hazard scenario and the modelled impact forces.
- **Bank Erosion Modelling Results** – A summary of the interpreted modelled results in the form of likely and potential bank erosion lines.
- **Composite Hazard Map** – A summary of the composite hazard map incorporating both numerical modelling results and bank erosion modelling results.

Uncertainty and limitations are outlined in Appendix F.

D.2. METHODS

The flowchart shown in Figure D-1 outlines the workflow for the numerical modelling, bank erosion modelling, and how the modelling contributes to the generation of a composite hazard map.

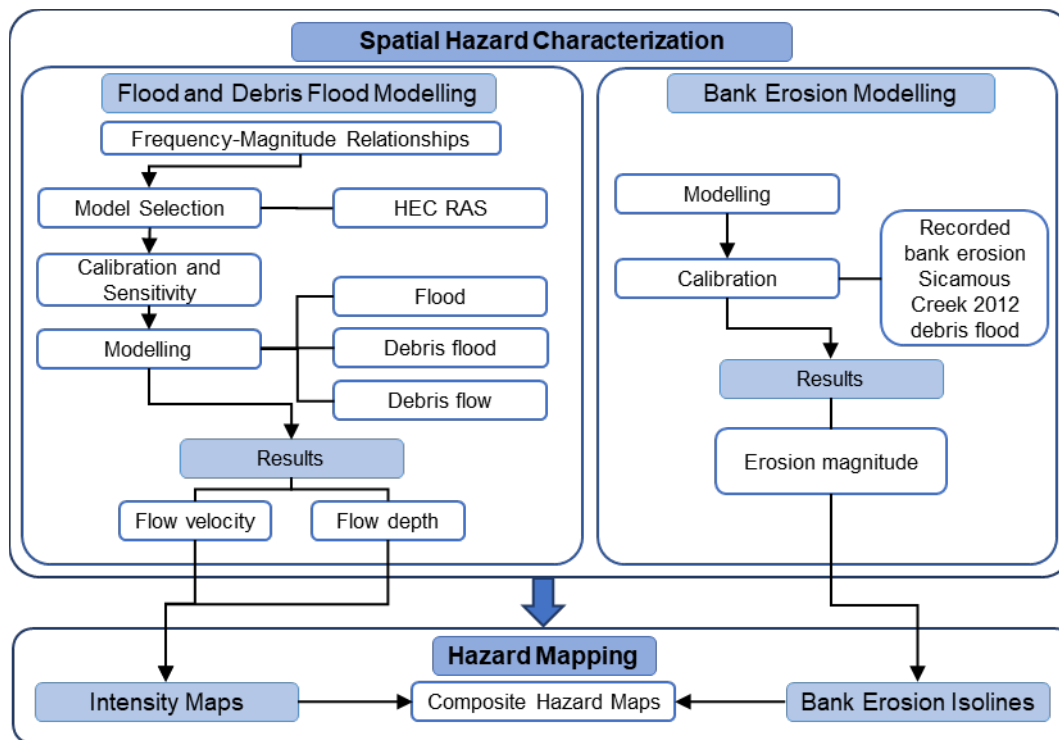


Figure D-1. Workflow applied to characterize the spatial hazard from debris floods and debris flows at Hummingbird Creek resulting in a composite hazard map.

D.2.1. Numerical Modelling

The following section includes a description of the model selection, model geometry, model development and calibration, model sensitivity analysis, and the model scenarios. The July 11, 1997, debris flow on Hummingbird Creek was used for model calibration, and the calibration parameters were then applied to modelling debris flood and debris flow scenarios.

D.2.1.1. Model Selection

BGC used the two-dimensional (2D) numerical modelling software Hydrologic Engineering Center’s River Analysis System (HEC-RAS) Version 6.1 for modelling both debris floods and debris flows on Hummingbird Creek. HEC-RAS is a public domain hydraulic modeling program developed and supported by the United States Army Corps of Engineers (USACE) (Brunner & CEIWR-HEC, 2021). In 2020, HEC-RAS 2D added a mud- and debris-flow module that supports hydrodynamic modelling of tailings, mud, and debris flows (Gibson & Sánchez, 2020).

The debris floods were modelled as clear water flows in HEC-RAS using bulked discharges, as described in Appendix C. The debris flows were modelled using the “Bingham” rheological model,

which is parameterized by the dynamic viscosity¹ of the flow and the yield stress². A material’s rheology defines how it behaves under stress. Clear water, which is classified as a “Newtonian” fluid has a linear stress-strain relationship and deforms under any stress that is applied. A “Bingham” fluid also has a linear stress-strain relationship but requires that a certain threshold of stress is applied before the fluid deforms. In other words, it behaves more like ketchup than water when flowing downhill.

D.2.1.2. Model Geometry

The model geometry includes the underlying model terrain, flood conveyance infrastructure, the model domain (the area included in the model run), and the model mesh. Table D-1 outlines the assumptions made in the model geometry for Hummingbird Creek.

Table D-1. Model geometry development.

Model Geometry Inputs	Description
Model Terrain	Lidar acquired by Terra Remote Sensing between October 6 to 26, 2019 was used to generate a 1.0 m resolution bare earth Digital Elevation Model (DEM) for the model terrain. The vertical datum of all reported elevations is the Canadian Geodetic Vertical Datum (CGVD) 2013. It is assumed that water depths in the channels were low, or the channel was dry at the time the lidar was flown and the channel topography was reasonably well-represented without requiring additional survey. Terrain modifications were made to properly present the bridge abutments within the channel and the bridge opening for the Highway 97A bridge (Bridge no. 8515) at Hummingbird Creek. Terrain modifications were also made to represent the terrain during different phases of a debris flood and debris flow (Section D.2.1.4).
Flood Conveyance Infrastructure	The bridge opening dimensions were estimated from the Record Drawing (Government of British Columbia, 2014) with a channel bottom width of 14 m and 1.5H:1V side slopes. The bridge low chord elevation was estimated from the drawings to be 372.05 m.
Model Domain	The model domain was selected to include the entire fan-delta extent and a fringe of Mara Lake to limit boundary effects ³ on model results.
Model Mesh	The model mesh cell size was 10 m x 10 m on the fan itself with refined areas within the channel (3 m x 3 m) and along the roads and other flow pathways (5 m x 5 m). Breaklines were used to align the cell faces along topographic high points (e.g., banks, roads) and to align the cell faces along the direction of flow.

¹ Dynamic viscosity is the resistance to movement of one layer of a fluid over another.

² A fluid yield stress is a characteristic whereby the material does not flow unless the applied stress exceeds a certain value greater than zero. The yield stress is therefore defined as the stress that must be applied to the sample before it starts to flow.

³ Boundary effects as described here are reference to the impact a boundary condition can have on model results. It is preferable to have boundary conditions a few hundred meters or further from areas of interest to minimize the influence of said boundary condition on the modelling results.

D.2.1.3. Model Sensitivity

Model calibration consists of identifying the model input parameters that are uncertain (i.e., cannot be directly measured or calculated) to which the model is most sensitive and then fine-tuning these parameters to best match the observed event. A sensitivity study was conducted on the 200-year debris flow event (described further in Section D.2.1.5) to evaluate which input parameters have the greatest impact on the modelled depositional area, depths, and velocities. The input parameters with minimal impact on modelled results (i.e., lowest sensitivity) can be fixed and were not adjusted during model calibration.

The input parameters evaluated were:

- Roughness coefficient – Manning’s n was varied by -10%, -20%, and +20% from a baseline value.
- Mesh size – the mesh size was halved.
- Impact of the Highway 97A bridge being blocked.
- Rheological parameters – Dynamic viscosity and yield stress were varied by +/- one order of magnitude and +/- 50%.

The results of the sensitivity analysis are summarized in Table D-2. The principal takeaways were:

- The roughness coefficient can be fixed.
- The model mesh can remain at a 10 m grid over most of the fan-delta, but within channel and along flow paths, the mesh was refined by reducing the grid size and including breaklines along the cell faces, as described in Table D-1.
- Blocking the Highway 97A bridge increased inundation areas and modelled impact intensities on the fan-delta. For modelled scenarios, the bridge would be assumed blocked if the modelled water surface elevation (WSE) was near to or greater than the low chord bridge elevation.
- Of the rheological parameters, the dynamic viscosity had very little impact on the impact intensities and modelled inundation area. The yield stress was the most sensitive input parameter needing to be fine-tuned in model calibration.

Table D-2. Results of model sensitivity analysis.

Input Parameter	Adjustment	Impact on Modelled Results
Manning's n	-10%	Decrease in inundation area by 2%. Minimal difference to modelled depths, velocities, and impact force.
	-20%	Decrease in inundation area by 6%. Minimal difference to modelled depths, velocities, and impact force.
	+20%	Increase in inundation area by 3%. Minimal difference to modelled depths, velocities, and impact force.
Mesh size	From 10 m to 5 m on average	Decrease in inundation area by 4%. Minimal difference to modelled depths, velocities, and impact force.
Bridge	Blocked versus unblocked	Assuming the bridge is blocked results in an increase in inundation area by 7% with greater impact intensities along Highway 97A and Swansea point Road in particular.
Dynamic viscosity	+ order of magnitude	No impact
	+ order of magnitude	No impact
Yield stress	+50%	Decrease in inundation area by 16%. Decrease in velocities and increase in depths resulted in lower impact intensities.
	-50%	Increase in inundation area by 28%. Increase in velocities resulted in an increase in impact intensities.

D.2.1.4. Model Calibration

The debris flow model parameters were calibrated to the depositional area and depth of the July 11, 1997 debris flow at Hummingbird Creek, as shown in Figure D-2 (Jakob et al., 2000). This calibration exercise was undertaken to evaluate the fixed and adjusted parameters. Barnhart et al. (2021) demonstrated that once a numerical model is well calibrated, the main variable explaining differences between different numerical models is the correct volume estimate.

During the sensitivity analysis, it was noted that the single-flow phase debris flow models using a constant rheology were not showing similar runout characteristics to the July 11, 1997 debris flow. No viscous deposit appeared in the modelled output, rather, the debris flow was more spread evenly on the fan-delta. BGC interpreted that this is due to a common characteristic of multi-phase debris flows, which are characterized by a more viscous portion and a more liquid afterflow. The more rigid portion consists of large boulders and often trees that slow the flow through frictional resistance. Once that load has been deposited, the more liquid, and often faster liquid afterflow overshoots or bypasses the freshly deposited rigid plug. This phenomenon is not included in a single rheology model such as HEC-RAS and multi-rheological models are not yet readily available to simulate this process. Therefore, BGC split the model into a more viscous and less viscous flow phases to model debris flows as realistically as possible.

Fig. 6. Distribution of debris deposits on Hummingbird Creek fan.

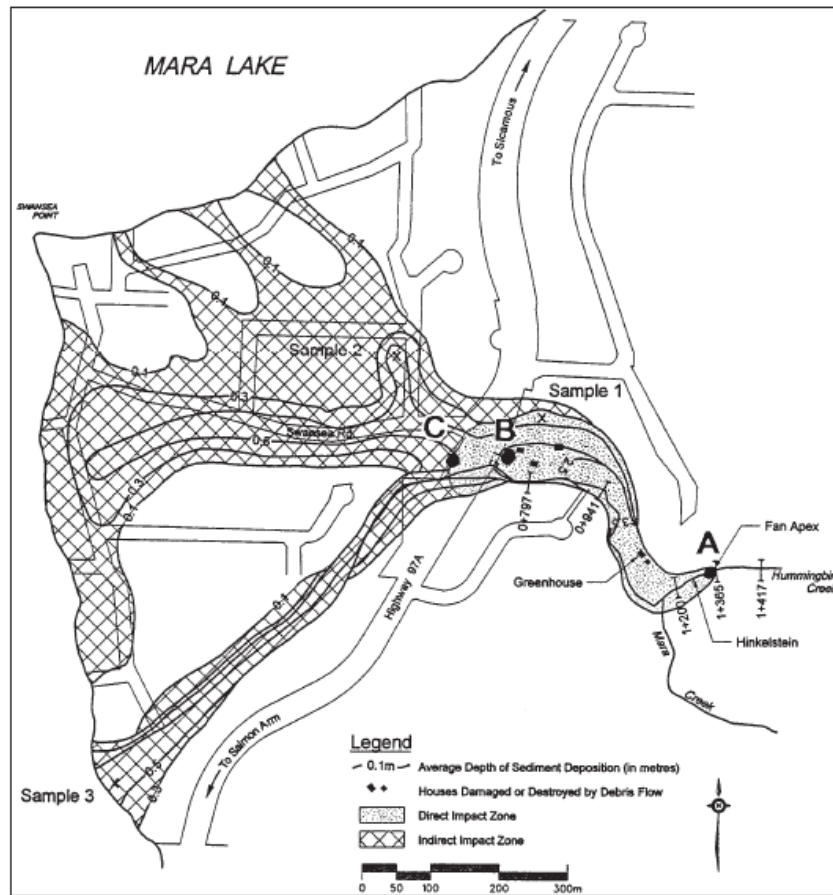


Figure D-2. Reconstructed distribution of debris flow deposits on Hummingbird Creek in 1997 (Jakob et al., 1999). The dotted area at and upstream of the highway crossing can be characterized as the coarse debris deposits. Those indicated in cross-hatching are associated with hyperconcentrated afterflow.

Overall, the model parameters calibrated were as follows:

- Fixed parameters
 - Manning's n
 - Dynamic viscosity
- Adjusted parameters
 - Inflow hydrograph (e.g., multiple surges) and division of sediment volume between the viscous plug phase and the hyperconcentrated afterflow phase.
 - Yield stress.

The yield strength and dynamic viscosity were calculated assuming an exponential relationship with volumetric concentration, C_v , which was assumed constant at 50%. Processes to calibrate selected parameters are detailed below.

Manning's n

The roughness coefficient defines the frictional resistance of the terrain to flow. Channels, fan surfaces, and roads should be assigned unique Manning's n values. Across the fan-delta outside of the channel, values were selected based on guidance in Chow (1959). For the channel, Manning's n values were estimated using the empirical equations of Jarrett (1984) developed for steep creeks of varying slopes. Resultant Froude numbers were cross checked to ensure they did not exceed 1, except for short distances or for short periods of time (Piton and Recking, 2019; Jarrett, 1984). If they exceeded 1, the initially estimated Manning's n value was adjusted to maintain predominantly subcritical flow within the channel.

The floodplain values were estimated through associating different land cover types with different values of Manning's n as summarized in Table D-3.

Table D-3. Assumed Manning's n-values for Hummingbird Creek debris-flood and debris-flow modeling.

Land Cover Layer	Manning's n
Roads	0.02
Dirt / Grass	0.04
Channel	0.12
Residential / Forest	0.1

Inflow Hydrograph

An approximately triangular shaped hydrograph was set as the upstream boundary condition, with the rising limb of the hydrograph being 1/6 of the total flow hydrograph duration (e.g., Figure D-3). This assumed hydrograph shape is a simplified assumption of the actual shape of the 1997 peak discharge, as there is no gauge data for similar watersheds in the region to use as a template. The simplified flow hydrographs are bulked and thus include sediment in the flow assuming a constant sediment volumetric concentration (C_v) of 50% for debris flows, and a bulking factor for debris floods. Therefore, the integrated area of the hydrograph shape and duration approximates the estimated volume of sediment/debris associated with each modelled return period peak flow.

To simulate the two-phase flow that was interpreted to occur during the 1997 debris flow, the inflow hydrograph was split into two separate hydrographs: a viscous first surge, followed by a less viscous second surge (hyperconcentrated afterflow) (Figure D-3). The model was run with the first viscous surge and the modelled deposit was then added to the model terrain (i.e., the terrain was modified to include the deposit of the viscous flow). The hyperconcentrated afterflow was then modelled over the modified terrain.

The split hydrograph was based on the rigid plug volume interpreted from the 1997 event and the flow volume difference to achieve the total reported volume of 92,000 m³ (Figure D-3). The peak discharge of the rigid plug volume was interpreted to be the peak discharge of 1,000 m³/s reported in Jakob et al. (2000). The peak discharge, Q_p , of the hyperconcentrated afterflow was estimated

using the empirical peak discharge – sediment volume (V) relationship developed by Bovis and Jakob (1999) for muddy debris flows (Equation D-1).

$$Q_p = 0.0059V^{0.94} \quad [\text{Eq. D-1}]$$

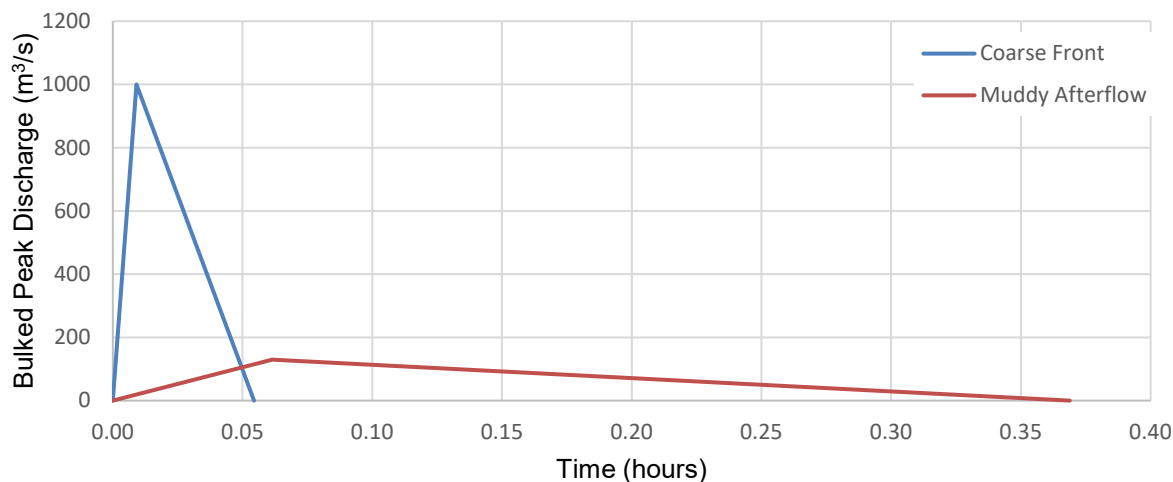


Figure D-3. 1997 flow hydrograph split for the initial surge and the hyperconcentrated afterflow. The initial surge is assumed to be associated with the peak discharge.

D.2.1.5. Model Scenarios

Once the model was calibrated, scenarios were modelled based on the frequency-magnitude volume and peak discharge inputs. All debris flows were modelled as a two-phase flow as described in Section D.2.1.4, with the first viscous surge modelled to completion, then the deposit added to the existing terrain, and the less viscous afterflow modelled overtop of the modified terrain. Highway 97A bridge blockage was assumed during debris flow scenarios, as the modelled WSEs exceeded the bridge low chord elevation (Section D.2.1.4.).

The modelled outputs include the depth and velocity of flow, and extent of debris-flow inundation for both surges (single surge for the debris flood scenario). The impact intensity, I , of each surge was then calculated as the depth, d , multiplied by the velocity, v , squared. The impact intensity has been used as a metric in previous studies in predicting the vulnerability of buildings to debris flow impact (Jakob et al, 2012). The maximum impact intensity from each modelled scenario is the maximum modelled impact intensity from either surge at all points on the fan (Drawing 07).

The planimetric area of the modelled debris flow deposits and their corresponding debris volume were consistent with empirical relationships between these values described by Griswold and Iverson (2008). This comparison was used to validate the model results and calibration parameters applied.

D.2.2. Bank Erosion Modelling

Debris floods are associated with high shear stresses that destabilize the channel bed and banks, resulting in bank erosion. Because bank erosion along steep creeks is not considered in standard hydraulic models, it needs to be assessed separately. BGC applied the probabilistic physically

based bank erosion model outlined in Jakob et al. (2022) for streams like Hummingbird Creek with banks made of non-cohesive material, such as sands and gravels.

Figure D-4 shows a conceptual representation of the bank erosion model. The reach-averaged shear stress is directly proportional to the average channel depth, therefore the threshold for widening can be expressed in terms of a critical depth, d_c (see Equation D-2 for calculation of d_c). The river remains stable until the critical depth is reached at a shear stress ratio of 2. Once the critical depth has been exceeded, the river widens until the depth reduces back to the critical depth and the bed re-stabilizes, preventing further erosion.

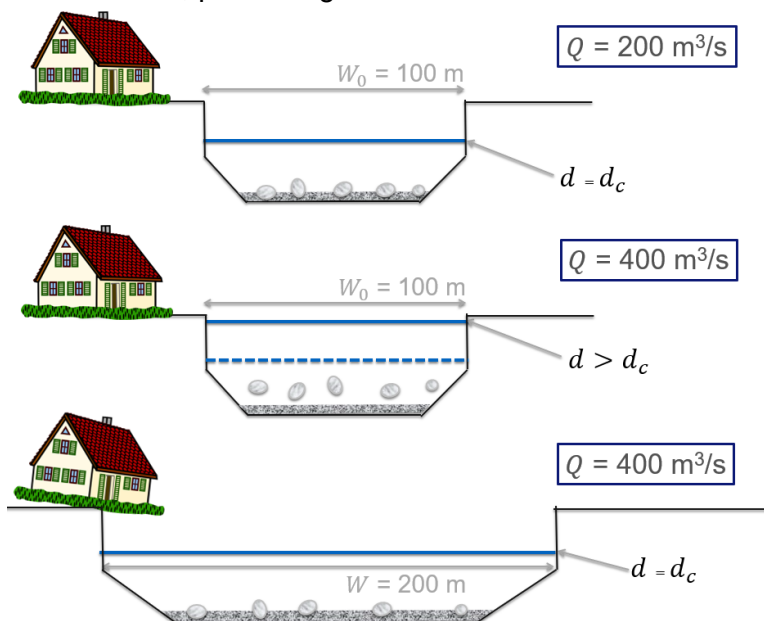


Figure D-4. Schematic showing channel widening to maintain a flow depth equal to the critical value during a flood or debris-flood event.

The critical depth, d_c , was calculated using Equation D-2:

$$d_c = \frac{2\tau^*_{c84}(\rho_S - \rho_f)D_{84}}{\rho_f S} \quad [\text{Eq. D-2}]$$

where τ^*_{c84} represents the Shields Number for the D_{84} , ρ_S represents the sediment density (2,650 kg/m³), ρ_f represents the density of the flow (1000 kg/m³), and S represents the channel slope of the river.

The critical discharge, Q_c , was then estimated using Manning's equation (Equation D-3):

$$Q_c = \frac{1}{n} d_c^{1.67} S^{0.5} W_0 \quad [\text{Eq. D-3}]$$

where W_0 is the pre-flood channel width and n is Manning's roughness coefficient. The amount of bank erosion E_{total} required for the river to re-stabilize can then be estimated based on the ratio of the flood discharge (Q_i) to the critical discharge (Eaton et al., 2017) (Equation D-4):

$$E_{total} = W_0 \left(\frac{Q_i}{Q_c} - 1 \right) \quad [\text{Eq. D-4}]$$

The magnitude of erosion is governed in part by the elevation of the surrounding topography relative to the channel (Bufe et al., 2019). Assuming the same volumetric rate of bank erosion occurs, a river surrounded by higher elevation topography will experience a lower total erosion distance than one with lower elevation topography during the same flood event. Therefore, a topographical adjustment was applied. The total modelled erosion (E_{total}) was adjusted based on the ratio of the height of the eroded topography on either side of the channel (floodplain/terrace height above the channel bed, H_{FP}) relative to the height of the creek bank (H_{bank}). The likely erosion distance (E_L) was then calculated with Equation D-5 as:

$$E_L = E_{total} \left(\frac{H_{FP}}{H_{bank}} \right) \quad [\text{Eq. D-5}]$$

The median bank erosion output was considered the “likely” bank erosion corridor and the 95th percentile bank erosion output was considered the “potential” bank erosion corridor.

Wherever possible, the model should be calibrated by iteratively adjusting the Shields Number and Manning’s n to match erosion measurements from previous observed events. At Hummingbird Creek, the bank erosion model was calibrated to the observed bank erosion from a debris flood on the adjacent Sicamous Creek on June 23 to 25, 2012. The calibrated Shields number and Manning’s n value used were 0.04 and 0.1. The model was run using the calibrated coefficients at a selection of 8 cross sections, simplified to rectangles, spanning the length of the creek between the fan apex and the distal edge at multiple return periods on Hummingbird Creek.

D.2.3. Composite Hazard Mapping

Hazard quantification combines the intensity of potential events and their respective frequency. Areas with a low likelihood of being impacted and low intensity of flow (for example, slow flowing, ankle-deep, muddy water) should be designated differently from areas that are impacted frequently and/or at high intensities (such as water and rocks flowing at running speed). In the latter case, the resulting geohazard risk is substantially higher and development must be more restricted than in the former.

A composite hazard map combines the frequency and intensity of individual modelled scenarios and is meant as a tool for land-use decision making. The following sections outline the methods used to generate the composite hazard map.

D.2.3.1. Hazard Intensity Mapping

Two-dimensional model outputs are grid cells showing the velocity, depth, and extent of debris-flow inundation. Each of these variables describe the intensity of an event but provide no information to correlate to potential damages incurred by the event. The model outputs can be combined to show impact force (F_I), which is defined as the combination of velocity (v), impact area (A) and fluid bulk density (ρ_f), or alternatively, the impact intensity (I) multiplied by the fluid bulk density (Equation D-6).

$$F_I = \rho_f Av = I\rho_f = v^2 d_f \rho_f \quad [\text{Eq. D-6}]$$

Using impact force to quantify geohazard intensity, rather than intensity defined as a momentum flux (e.g., Jakob et al. 2011), better represents denser processes such as debris floods, debris flows, or landslides. This, in turn, allows for intensities between geohazard processes to be directly compared instead of requiring different binning and descriptions for different processes.

We used the maximum impact force value at each cell location. The impact force results are binned to illustrate what their impacts may be (Table D-4). The ranges were chosen to encompass reasonably representative consequences for the corresponding impact forces.

Table D-4. Impact force binning and descriptions.

Unit Impact Force (kN/m)	Description
< 1	Slow flowing shallow or deep water carrying little or no debris. High likelihood of water damage. Potentially dangerous to people in buildings, in areas with greater water depths.
1 to 10	Mostly slow but potentially fast flowing shallow or deep flow with some debris. High likelihood of sedimentation and water damage. Potentially dangerous to people in the basement or first floor of buildings without elevated concrete foundations.
10 to 100	Fast flowing water 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 building destruction. Very dangerous to people in buildings irrespective of floor.

It is challenging to assign an intensity value for bank erosion because only the hazard extent is estimated. Instead, bank erosion corridors (as described in Section 5.2.2) are displayed for each return period scenario.

D.2.3.2. Interpreted Composite Hazard Maps

We have created an impact force-probability (P_{Fi}) geohazard mapping procedure that consists of two principal components: the intensity expressed by an impact force per metre flow width and the frequency of the respective events (Equation D-7).

$$P_{Fi} = v^2 \times \rho_f \times d_f \times P(H) \quad [\text{Eq. D-7}]$$

where v is flow velocity (m/s), d_f is the fluid's flow depth (m) (proxy for area), ρ_f is the fluid density (kg/m^3) to obtain a unit of force per metre flow width as explained in Section D.2.3.1, and $P(H)$ is the annual probability of the geohazard. The unit of P_{Fi} is then Newton per metre per year (N/m per yr).

The P_{Fi} values for each scenario model output are then considered weighted averages (i.e., weighted by the hazard probability) and summed at each location to produce a raw composite hazard map. This raw, uninterpreted result is then binned by P_{Fi} values and interpreted to homogenize zones of inundation. The maximum return period likely bank erosion corridor and interpreted maximum sediment inundation area are also included on the composite hazard map.

Equation D-7 can be translated into a matrix in which the impact force 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 light yellow (very low hazard) to black (extreme hazard) (Table D-5). The numbers in each cell symbolize the impact force in N/m/yr.

Table D-5. Geohazard impact force-frequency matrix.

Return Period Range (years)	Incremental Probability	Impact Force [$v^2 \cdot d_f \cdot p_f$] in N/m				
		< 10	10 to 100	100 to 1000	1000 to 10,000	>10,000
		6	55	550	5500	55,000
1 - 3	0.7	4	39	385	3,850	38,500
3 - 10	0.2	1	11	110	1,100	11,000
10 - 30	0.07	0.4	4	39	385	3,850
30 - 100	0.02	0.1	1	11	110	1,100
100 - 300	0.007	0.04	0.04	4	39	385
300 - 1000	0.002	0.01	0.1	1	11	110
1000 – 3000	0.0005	0.003	0.03	0.3	3	28

The above matrix includes the range of impact forces in N/m per year for each cell. The matrix can be simplified for public use as per Table D-6. Here, the geohazard intensity has been replaced by adjectives describing the intensity of the event from “low” to “extreme” and the different cells have been united into zones. In general terms, the active channel will have the warmest colours because the active channel is occupied by the hazard most often and impact forces in a confined channel are the highest.

Table D-6. Simplified geohazard impact force-frequency matrix.

Return Period Range (years)	Geohazard Intensity					
	Very Low	Low	Moderate	High	Very High	
10 to 30		Very Low Hazard	Low Hazard	Moderate Hazard	High Hazard	Very High Hazard
30 to 100						
100 to 300						
300 to 1000						
1000 to 3000						
3000 to 10,000						

D.3. NUMERICAL MODELLING RESULTS

D.3.1. Model Calibration Results

The resulting calibrated rheological input parameters used for modelled debris flows in this assessment are listed in Table D-4. Ideally models are calibrated to an observed event and then validated with another known event to evaluate the robustness of the model calibration. However, no additional data were available to validate the model and engineering/geoscientific judgement was used to evaluate the reasonability of the model calibration and its application to other watersheds.

Table D-7. Final model rheological parameters following model calibration.

Model Phase	Rheological Parameter	Equation	Value
Viscous Plug	Yield Stress, τ_y	$\tau_y = \alpha e^{bC_v}$	5000 Pa
	Dynamic Viscosity, μ_m	$\mu_m = \mu_w e^{BC_v}$	1.0 Pa*s
Low Viscosity Afterflow	Yield Stress, τ_y	$\tau_y = \alpha e^{bC_v}$	100 Pa
	Dynamic Viscosity, μ_m	$\mu_m = \mu_w e^{BC_v}$	1.0 Pa*s

Figure D-5 shows the calibrated modelled debris-flow runout compared to the observed 1997 debris flow deposit. BGC interprets that some of the deposited volume of the event was lost into Mara Lake, but that this volume is insignificant with respect to the total debris volumes involved in the 1997 debris flow. Figure D-5 also shows a plot of the maximum velocities modelled during the event for the viscous plug and low viscosity afterflow. These velocities range from 1 to 7 m/s within the confined reaches of the upper fan, which corresponds to back-calculated values from

Jakob et al. (2000). Based on the results of this calibration exercise, the debris flow rheological parameters were used in the modelled scenarios.

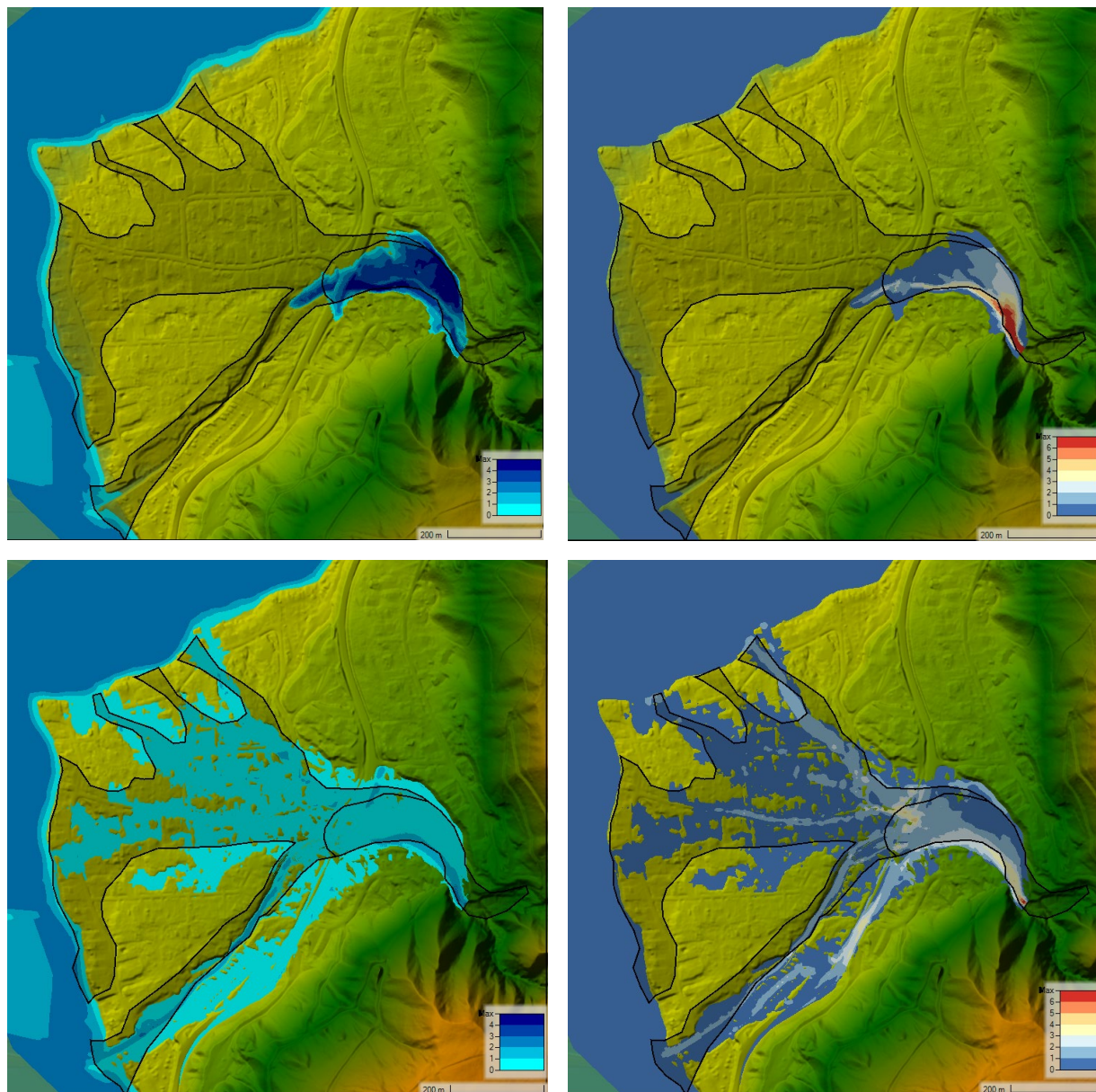


Figure D-5. Hummingbird Creek model calibration results for the debris flow on July 11, 1997 for the viscous plug (top) and low viscosity afterflow (bottom). Simulated deposit depths are on the left and maximum simulation velocities are shown on the right. Outlined in black is the 1997 debris flow deposit.

D.3.2. Modelled Scenarios

BGC modelled five scenarios based on the frequency-magnitude model for Hummingbird Creek (Appendix C):

- 10 to 30-year return period (AEP = 3 to 10%) debris flood

- 30 to 100-year return period (AEP = 1 to 3%) debris flow
- 100 to 300-year return period (AEP = 0.3 to 1%) debris flow
- 300 to 1000-year return period (AEP = 0.1 to 0.3%) debris flow
- 1000 to 3000-year return period (AEP = 0.03 to 0.01%) debris flow
- 3000 to 10,000-year return period (AEP = 0.01 to 0.03%) debris flow.

The modelled maximum impact intensities for each model scenario are provided in Drawing 07. The raw modelled depths and velocities from each model scenario are on file at BGC and can be made available.

D.4. BANK EROSION MODELLING RESULTS

Drawing 07 displays the modelled bank erosion for debris flood processes. Erosion may be concentrated preferentially along one bank due to differences in bank material (i.e., erosion resistance), topography, or channel curvature. As a result, the modelled erosion cannot be simply divided between the two banks; it is physically possible for the modelled erosion to occur entirely along one bank or the other. To account for the uncertainty in the erosion distribution, the mapped erosion in the modelled scenarios and composite hazard map shows the full modelled erosion amount as if 100% were to occur on either bank. It is a conservative estimate of erosion as it displays the maximum likely (50th percentile) and maximum potential (95th percentile) bank erosion on both sides of the channel.

D.5. COMPOSITE HAZARD MAP

Drawing 08 displays the composite hazard map with the highest return period bank erosion corridor. The bank erosion corridor is colour coded according to Table D-6 to reflect the frequency of the displayed bank erosion on the map assuming the geohazard intensity of bank erosion is “moderate”.

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APPENDIX E DISCUSSION OF UNCERTAINTY

E.1. INTRODUCTION

The importance of consistent and transparent treatment of uncertainties is important to the understanding of this report. This appendix discusses four sources of uncertainty in the defined hazards for Hummingbird Creek.

1. Discussion on past and future land use change and forest harvesting within Hummingbird Creek and the impact it may have on the Frequency-Magnitude (F-M) model.
2. Discussion on wildfires and the impact they may have on the F-M model.
3. Discussion on uncertainties and limitations in the development of the F-M model.
4. Discussion on uncertainties and limitations with hydrodynamic modelling of debris floods and debris flows, and the development of a composite hazard map.

The uncertainty discussion and classification are based on those used by the United Nations Intergovernmental Panel on Climate Change (2010).

Estimating uncertainties is intrinsically about describing the limits to knowledge and for this reason involves expert judgment about the state of that knowledge. Uncertainty also arises in systems that are either chaotic or not fully deterministic in nature, and this limits our ability to project all aspects of climate change. It also includes our inability to predict when a wildfire may occur, how large it will be and at what intensity it will burn, as well as the success or lack thereof fighting the fire. Similarly beetle infestations or other reasons for tree mortality and subsequent salvage logging operations cannot be predicted.

The scientific literature uses a variety of other generic ways of categorizing uncertainties. Uncertainties associated with ‘random errors’ have the characteristic of decreasing as additional measurements are accumulated (for example, should it eventually be possible to test trench Hummingbird Creek fan and obtain data on debris-flow frequency and thickness), whereas those associated with ‘systematic errors’ do not. For example, in dealing with climate records, considerable attention can be given to the identification of systematic errors or unintended biases arising from data sampling issues and methods of analyzing and combining data.

The uncertainty guidance provided in this report distinguishes between levels of confidence in scientific understanding and the likelihoods of specific results (definitions provided in Appendix A). This allows authors to express high confidence that an event is extremely unlikely (e.g., rolling a dice twice and getting a six both times), as well as high confidence that an event is about as likely as not (e.g., a tossed coin coming up heads). Confidence and likelihood as used here are distinct concepts but are often linked in practice.

E.2. DISCUSSION ON PAST AND FUTURE FOREST HARVESTING

The impact of forest harvesting and land use changes within a watershed on runoff is very complex. Calder et al. (2007) summarized the state of knowledge in the study of forest hydrology reports and stated “Forest hydrologists generally agree that, although forests mitigate floods at the local scale and for small to medium-sized flood events, there is no evidence of significant

benefit at larger scales and for larger events.” This concept has since been criticized by Green and Alila (2012), and Yu and Alila (2019). Specifically, these authors critique the reliance on paired watershed studies for analyzing flood frequency analyses and have shown that forest harvesting can substantially increase the frequency of the largest floods in logged watersheds. The quantification of future forest harvesting effects on runoff was not completed by BGC as it was not within the current scope of work and there is no current standard of practice.

Forest harvesting and land use change necessitates the construction of resource roads (commonly called “forest roads”). Improperly maintained roads can affect the frequency and magnitude of debris flood and debris flow occurrence. For example, the July 11, 1997 debris avalanche and debris flow on Hummingbird Creek occurred because of drainage concentration through a logging road culvert (Government of British Columbia, October 1997; Jakob et al.; 2000). No other debris flow was found in the 70-year air photograph record which suggests that forest road operation is a human-caused forcing mechanism in debris flow frequency and magnitude for Hummingbird Creek.

Forest road management practices may have improved since 1997. However, a recent audit (Forest Practices Board, 2017) found some major issues when examining examples of recent forest road practices in BC:

“While forestry roads on steep slopes were constructed in compliance with most of the legislative requirements, nearly one-quarter were not considered structurally safe for industrial users. Five of the road segments assessed had no specialist involvement and did not ensure the safety of the road builders or other road users, as required by legislation. In addition, most of the road segments examined had some qualified professional input on road construction techniques for roads located on “complex” terrain, but only 10 of 26 steep slope road segments fully followed the professional practice guidelines and met legal requirements. With respect to protecting the environment, 5 of the steep slope road segments assessed had no terrain specialist involvement and in each case, conventional construction techniques were used, which increased the potential for road failure and consequent environmental damage.”

BGC realizes that some forest licensees have better standards or employ more skilled professionals than others. However, BGC cannot predict what standards will be employed and enforced in the future. Thus, BGC has assumed that human-caused debris avalanches and debris flows will remain a hazard into the future.

E.3. DISCUSSION ON WILDFIRES

Future wildfires are expected to occur in Hummingbird and Mara creeks. The size and extent of burn severity and intensity of rainfall in the years following the fire will determine future susceptibility to post-wildfire debris floods and debris flows. None of the above variables can be predicted with any degree of certainty, neither is the response by fire fighters which will depend, to some extent, on the number of other fires to be fought in the area.

Sensitivity studies could be carried out assuming certain proportion of the watershed burnt and at specific intensities. This work would result in numerous potential outcomes, neither of which could be attributed to specific return periods given that area burnt, and its intensity cannot be forecasted.

In BGC's opinion, the empirical methods employed in addition with consideration of a worst-possible case from a large debris avalanche likely covers post-wildfire debris flow scenarios, which were therefore not studied separately.

E.4. DISCUSSION ON THE FREQUENCY-MAGNITUDE MODEL

The F-M relationship for the two creeks includes floods and debris floods at lower return periods and debris flows at higher return periods.

For lower return period events, BGC employed two methods to estimate the clearwater flood quantiles to reduce the uncertainty in the estimates. However, there are several limitations associated with hydrologic analyses:

- A model is only as reliable as the data that is used to support it. There is inherent measurement error in the recording of flood events, especially for the larger (and rarer) flood events.
- Hydrometric records in regional watersheds (i.e., watersheds in similar geographic region and under a similar hydrologic regime) are often limited for smaller watersheds, the records are often too short to support a robust statistical analysis, and the records may not have captured any large events.
- Finally, the impacts of climate change, land use change, wildfires, insect infestations, or urban development on the hydrology of a watershed are not easily quantified. Hydrometric records offer a snapshot of the flood history for a given location and trends associated with change are often not identifiable at a significant statistical level.

For higher return periods that can impact a significant proportion of the fan, BGC was not able to collect numerous samples for radiocarbon dating from test pits and soil exposures across the fan. This lack of data challenged the debris-flow hazard assessment and required a higher reliance on empirical methods to decipher F-M relationships. The only location where BGC was able to obtain radiocarbon dates was a foundation excavation on the distal fan-delta (Drawing 06). Given that this is only one location on a very large fan-delta, the only inference that can be made is a debris flood or debris flow reached the shores of Mara Lake as recently as 150 years ago.

None of the individual methods used to generate the F-M model by themselves can produce precise results. This is analogous to weather forecasting where a single meteorological model only produces one possible outcome. Weather forecasts often compile, compare, and evaluate several models to increase confidence and credibility. Given uncertainty associated with climate change effects on flood volumes and forestry operations in the watersheds potentially initiating debris avalanches and debris flows, selecting reasonably conservative estimates was warranted due to the potential for life loss and major infrastructure damage. However, what is known is that climate change will increase landslide activity in this and other watersheds and create conditions for debris floods and debris flows not seen in the historic record (i.e., Jakob & Owen, 2021; Jakob, 2022).

E.5. DISCUSSION ON THE COMPOSITE HAZARD MAP

The hydrodynamic modelling results are the main inputs to the composite hazard map and have the following limitations:

- The modelling did not explicitly account for various auxiliary hazards (e.g., timing of debris flows with respect to lake levels, subsequent debris-flow surges or afterflow incision). Such scenarios could cause additional avulsions and transport sediment and debris onto portions of the developed fan-delta.
- Existing hydrodynamic models are limited to modelling a single flow rheology. Debris flows may have multiple flow rheologies within a flow surge and often occur in multiple surges. The model was calibrated to the 1997 debris flow event on Hummingbird Creek lending high confidence in the results; however, the flow rheology was necessarily simplified to fit within this modelling limitation. The simplified rheology is the author's best estimation of a representative rheology for future debris flows on Hummingbird Creek.
- The numerical model used does not allow for entrainment of channel material along its flow path, nor other terrain modifications that may occur during a debris flood or debris flow (i.e., channel avulsions, bank erosion). It is unknown how much material, if any, could be entrained and how flow may be redirected due to topographical changes. This implies some uncertainty with respect to the modelled inundation areas for the results of individual modelling scenarios.

The modelling and composite hazard map also do not account for the following:

- Future mitigation measures designed to deflect or stop debris or provide additional bank armouring.
- Major alterations to the fan-delta topography and infrastructure from natural events (which deposit debris, scour, or erode banks) and human modification (through construction, bridge replacements, addition of culverts or buildings).
- The presence of homes on the fan-delta and the effects it may have on a debris flow. It is unknown which buildings will survive a debris flow and how the flow may be diverted.

The composite hazard map is a snapshot in time that relies on the topography and infrastructure present at the time it was developed. Any future global mitigation measures will, depending on their scale, location and effectiveness, reduce the hazard. This requires re-modeling of debris floods and debris flows to estimate the effect of hazard reduction cartographically.

The most significant limitation of the composite hazard map lies in the manual homogenization of the various model outputs into hazard zones. The hazard zones are not precise and should not be interpreted as such, as debris flows and debris floods are to some extent chaotic processes and their exact behaviour cannot be predicted with precision. In extreme cases, a hazard map may be obsolete after major events or human fan surface alterations. Hazard maps should be re-drawn in such cases. It is essential to redraw hazard maps after completion of mitigation works to demonstrate their effectiveness.

While the authors believe that the composite hazard map is the best representation of true hazard (i.e., intensity and probability), this method may not be applicable in every jurisdiction and policy

makers may also choose to rely on specific return period maps. However, a selected truncation based on selected return periods (e.g., 300 years) may underestimate hazard and risk (Strouth & McDougall, 2022). Most life loss and economic risk is concentrated at the highest return periods and this risk may not be reflected in other return periods. Hydroclimatic events are also anticipated to increase in frequency in a changing climate which may necessitate an upward adjustment in the return period range considered for hazard and risk assessments (i.e., Jakob, 2022).

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APPENDIX F CAMBIO COMMUNITIES USER GUIDE

F.1. INTRODUCTION

This appendix describes the purpose and use of Cambio web application to deliver maps and supporting information for the Stream 1 and subsequent flood hazard mapping studies.

F.1.1. Purpose

Cambio is an ecosystem of web applications that support regional scale, geohazard risk-informed decision making by government and stakeholders. It is intended to support community planning, policy, and bylaw implementation, and provides a way to maintain an organized, accessible knowledge base of information about geohazards and elements at risk.

The version of Cambio used to provide study results is called Cambio Communities. Other versions exist to support operational geohazard risk and information management programs for pipelines, roads, railways and the mining sector. Cambio also provides access to dynamic and real-time information sources (e.g., streamflow monitoring).

The application combines map-based information about geohazard areas and elements at risk with evaluation tools based on the principles of risk assessment. Cambio can be used to address questions such as:

- Where are geohazards located and what are their characteristics?
- What community assets (elements at risk) are in these areas?
- What areas might require further assessment for a development approval application?
- What geohazard information is available in an area to support further assessment?

These questions are addressed by bringing together three major components of the application:

Hazard Information:

- Geohazard maps at three levels of detail: hazard identification, “base level”, and detailed¹.
- Supporting information, e.g., hazard characteristics, hydrologic information and imagery.

Exposure information:

- Type, location, and characteristics of community assets, including elements at risk and risk management infrastructure.

Analysis tools:

- Identification of assets in geohazard identification areas (elements at risk).
- Prioritization of geohazard identification areas based on geohazard and consequences ratings.
- Access to data downloads and reports for geohazard areas if available².

¹ See the main document of this report for further description of mapping levels of detail and use.

² The ability to download available reports at a given geohazard area is only available for study areas where government has worked with BGC to define report location metadata.

This user guide describes how users can navigate map controls, view site features, and obtain additional information about geohazard identification areas and maps. It should be read with the main report, which describes methodologies, limitations, and gaps in the data presented on the application.

F.1.2. Site Access

Cambio can be viewed at www.cambiocommunities.ca. Username and password information is available on request. The application should be viewed using Chrome or Firefox web browsers and is not designed for Internet Explorer or Edge.

Cambio study areas are organized by Regional District. Local government users and contractors may have access to a single district; provincial or federal users may have access to multiple Regional District study areas.

The remainder of this guide is best read after the user has logged into Cambio. This guide describes information displayed across multiple administrative areas within British Columbia. Footnotes indicate cases where information is specific to certain study areas.

F.1.3. Navigation

Figure A-1 provides a screen shot of Cambio following user login and acceptance of terms and conditions. Section A.2 describes map controls and tools. On login, the map opens with all layers turned off. Section A.2 describes how to access information in the layer list.



Figure A-1. Online map overview.

F.1.4. Overview of Map Controls

Figure A-1 showed the map controls icons on the top left side of the page. Map controls can be listed by clicking on the Compass Rose, then opened by clicking on each icon (Figure A-2). Section A.3 describes the tools in more detail.

Clicking on an icon displays a new window with the tool. The tool can be dragged to a convenient location on the page or popped out in a new browser window.

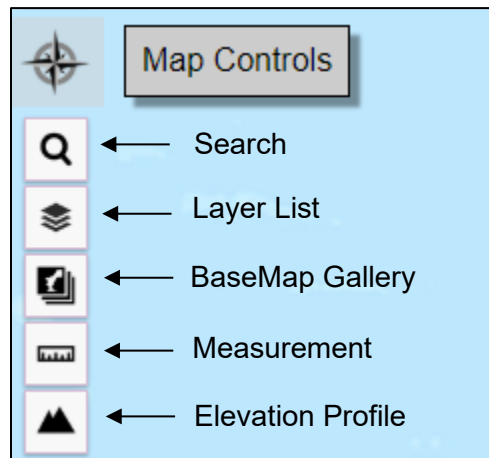


Figure A-2. Map controls.

F.2. LAYER LIST

F.2.1. Introduction

The layer list control (Figure A-3) allows the user to select which data types and layers to display on the map. It will typically be the first map control accessed on login.

Note that not all layers are visible at all zoom levels, to avoid clutter and permit faster display. Labels change from grey to black font color when viewable, and if the layer cannot be turned on, use map zoom to view at a larger (more detailed) scale. Additionally, the user can adjust the transparency of individual basemap and map layers using the slider located below each layer in the layer list. Complex layers and information will take longer to display the first time they are turned on and cached in the browser.

Each layer list drop-downs is described further below.

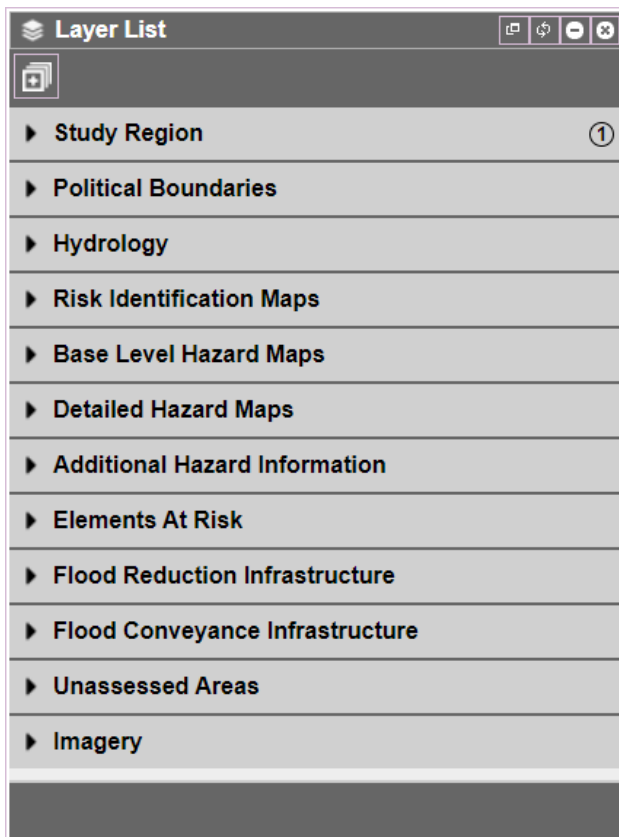


Figure A-3. Layers list.

F.2.2. Study Region

This section allows the user to display the boundaries of the study areas available to the user.

F.2.3. Political Boundaries

This section allows the user to display administrative boundaries of local governments, parks, and First Nations reserves.

F.2.4. Hydrology

F.2.4.1. River Network

The river network displayed on the map (when set to viewable) is sourced from the National Hydro Network and published from BGC's hydrological analysis application, River Network Tools™ (RNT). Clicking any stream segment will open a popup window indicating characteristics of that segment including Strahler stream order, approximate average gradient, and cumulative upstream catchment area (Figure A-4). Streams are colored by Strahler order. Clicking on the Google Maps icon in the popup will open Google Maps in the same location. All statistics are provided for preliminary analysis and contain uncertainties. They should be independently verified before use in detailed assessment and design.

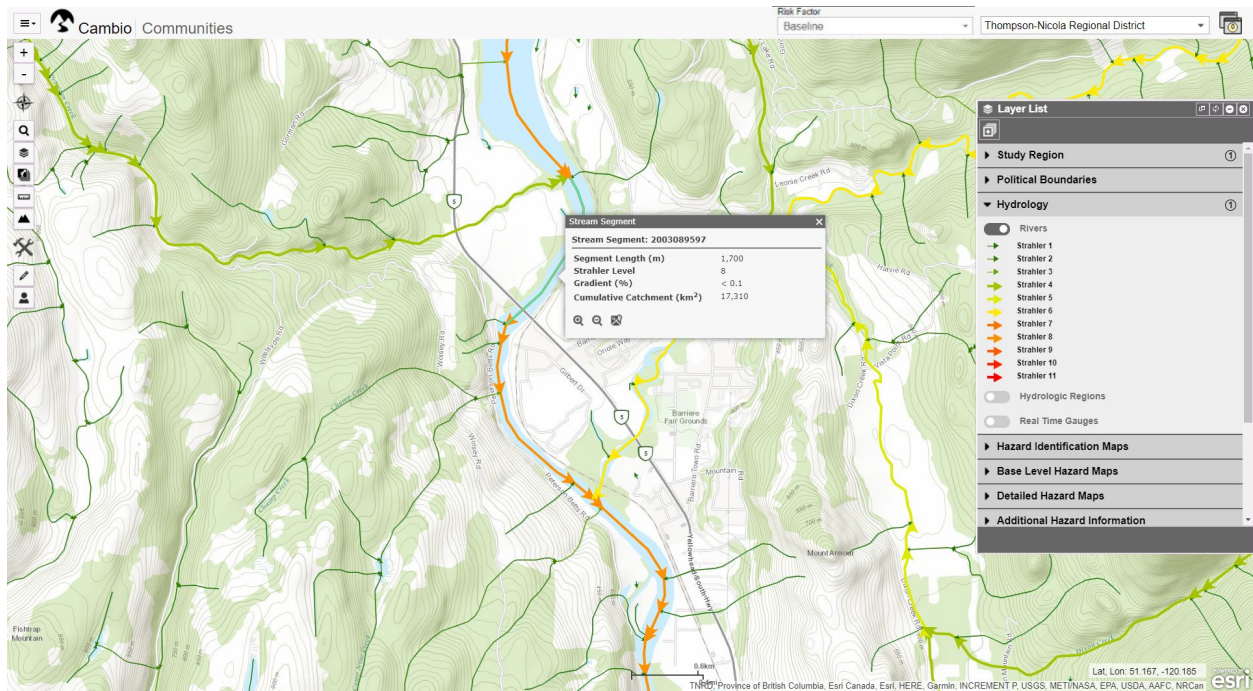


Figure A-4. Interactive Stream Network. The popup shows information for the highlighted orange stream segment.

F.2.4.2. Real-time Flow Gauges

Cambio also provides access to real-time³ stream flow and lake level monitoring stations where existing. The data are sourced from the Water Survey of Canada (WSC) and published from RNT. Clicking any gauge will open a popup window with gauge data including measured discharge and flow return period for the current reading date (Figure A-5). The real time gauges are also colored on the map by their respective flow return period for the current reading date.

³ i.e., information-refresh each time flow monitoring data is updated and provided by third parties.

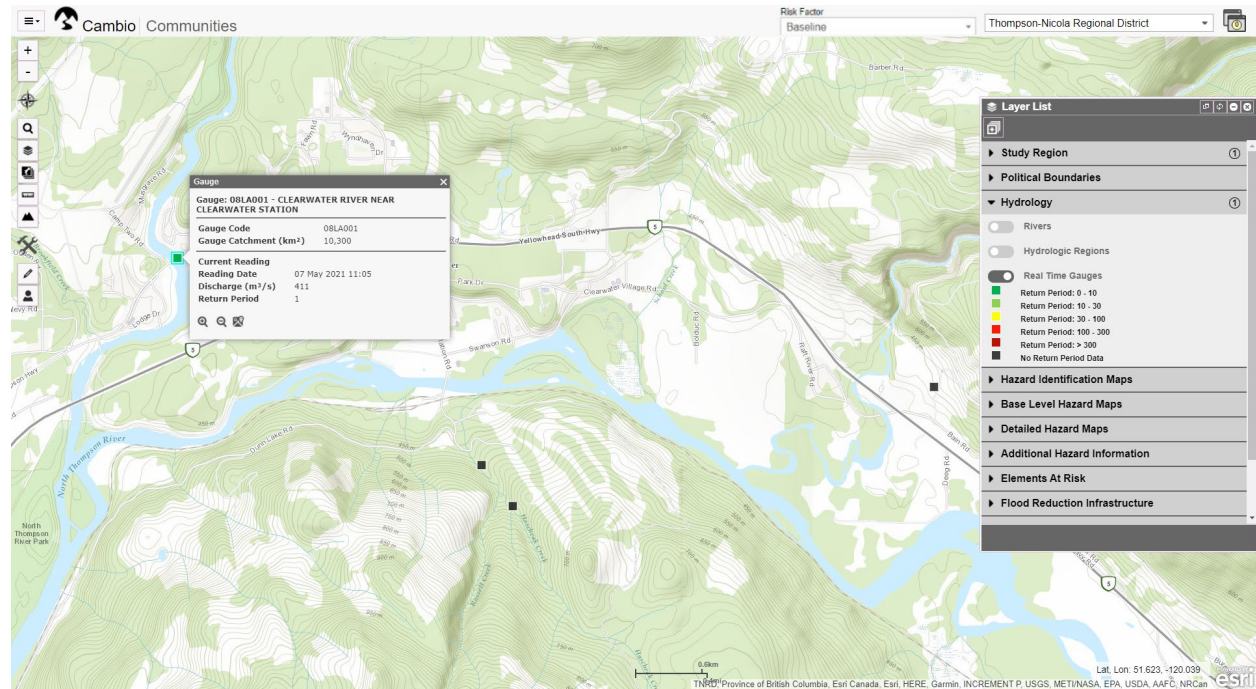


Figure A-5. Near real-time flow gauge. The popup shows gauge information including measured discharge and return period for a given reading date and time.

F.2.5. Risk Identification Maps (including Risk Prioritization)

Hazard identification areas can be added to the map by selecting a given geohazard type under “Hazard Identification Maps” in the layer list. Once selected, the hazard areas can be colored coded by hazard type, hazard rating, priority rating, or consequence rating.

Clicking on an individual hazard feature reveals a popup window indicating the study area, hazard code (unique identifier), and hazard name (Figure A-6). The geohazard process is also listed for Steep Creek Hazards. Below this identifying information, the Hazard Rating as well as the community, lifeline, and combined Consequence and Priority Ratings are displayed for specific site.

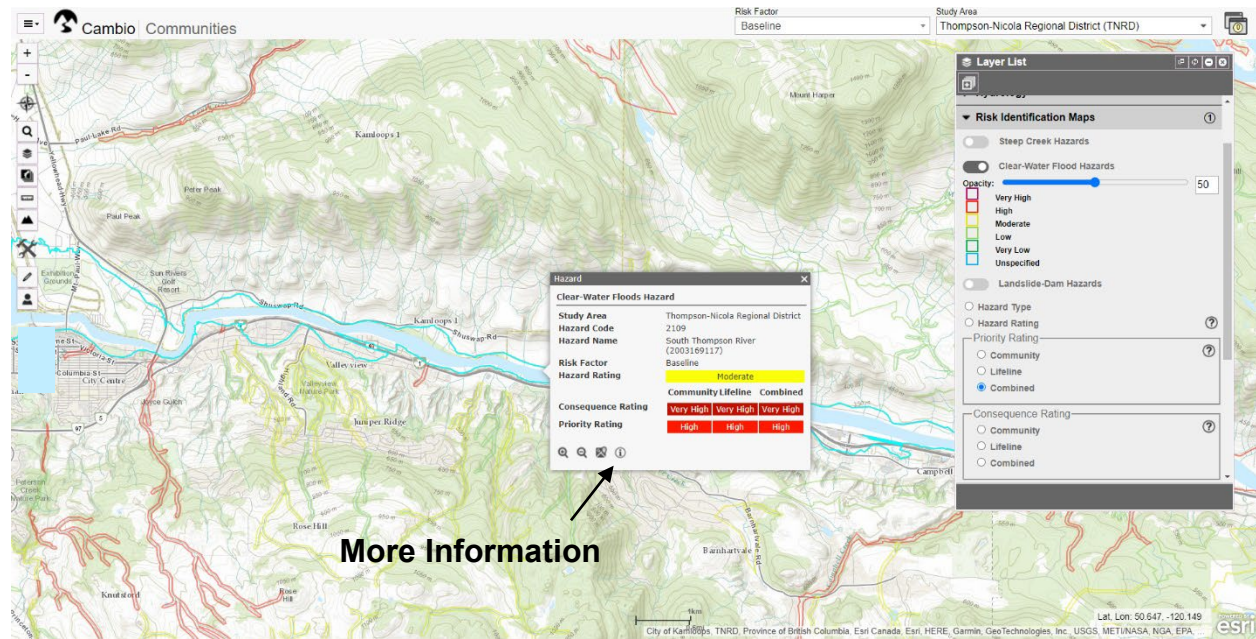


Figure A-6. Hazard summary popup.

At the bottom of the popup window, there are several options (Figure A-6). Clicking the Google Maps icon opens Google Maps in a new browser window at the hazard site. This feature can be used to quickly access Google Street View to view ground level imagery where available. Clicking the “i” icon opens a sidebar on the right side of the screen with detailed information about the individual feature (Figure A-7). Drop-down menus allow the user to view as much detail as required.

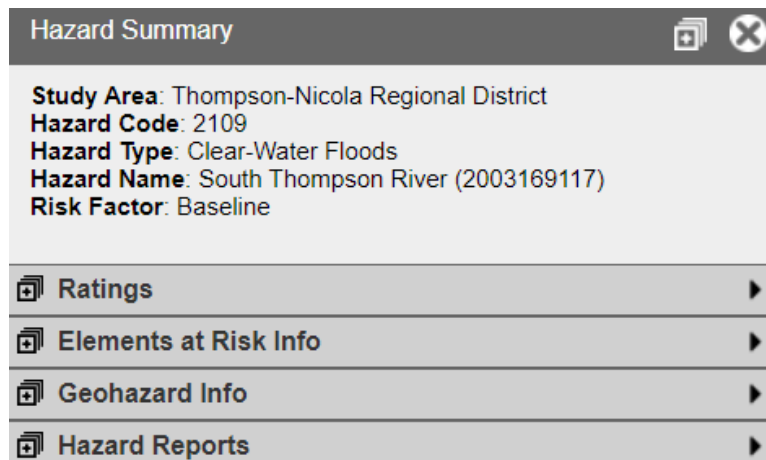


Figure A-7. Hazard summary sidebar.

Table A-1 summarizes the information displayed within the sidebar drop-down menu. In summary, clicking Ratings reveals the site Priority, Consequence, and Hazard Ratings within their respective matrices. See Chapter 5.0 of the Stream 1 study (BGC, March 31, 2019) for further description of these ratings. The geohazard, elements at risk, and hazard reports drop-downs display site specific data and supporting information. Hover the mouse over the “i” icon in each row to gain

a more detailed definition, the assumptions made, and/or the limitations for the information displayed.


Click the “” icon at the bottom right of the sidebar to download all sidebar information in either comma-separated values (CSV) or JavaScript Object Notation (JSON) format.

Table A-1. Geohazard information sidebar contents summary.

Drop-down Menu	Contents Summary
Ratings	Provides Geohazard, Consequence and Priority Ratings for an area, displayed graphically as matrices. The community, lifeline, and combined ratings are plotted separately within the Priority and Consequence Rating matrices. The Geohazard and Consequence Ratings combine to provide the Priority Rating. For more information on ratings methodology, see the main report.
Elements at Risk Info	Summary of the elements at risk and/or values within the geohazard area. This includes data on population, land and improvements, businesses, lifelines, and environmentally sensitive habitat. These inputs form the basis for the consequence rating for a given area.
Geohazards Info	Summary of the geohazard characteristics and/or values for the specific geohazard feature. This includes data on fan parameters, watershed parameters, hydrology, event history, basin characterization, and comments. There is also metadata provided for the inspection entry date and the inspection author. These inputs form the basis of the geohazard rating and intensity (destructive potential) component for the consequence rating of a given area.
Hazard Reports	Links to download previous reports associated with the area (if any) in pdf format.

F.2.6. Base Level Hazard Maps

Geohazard maps are provided in Cambio for Base Level flood assessment areas (this study). These maps show spatial information about hazards within a geohazard identification area. Selecting “Base Level Hazard Maps” under the layer list will display the available geohazard identification areas (Figure A-8). There is the option to view a 200-year event flood depth map and/or a flood velocity map for each area. The maps can be added to the web display by selecting a given hazard layer within the geohazard identification area drop-down menu.

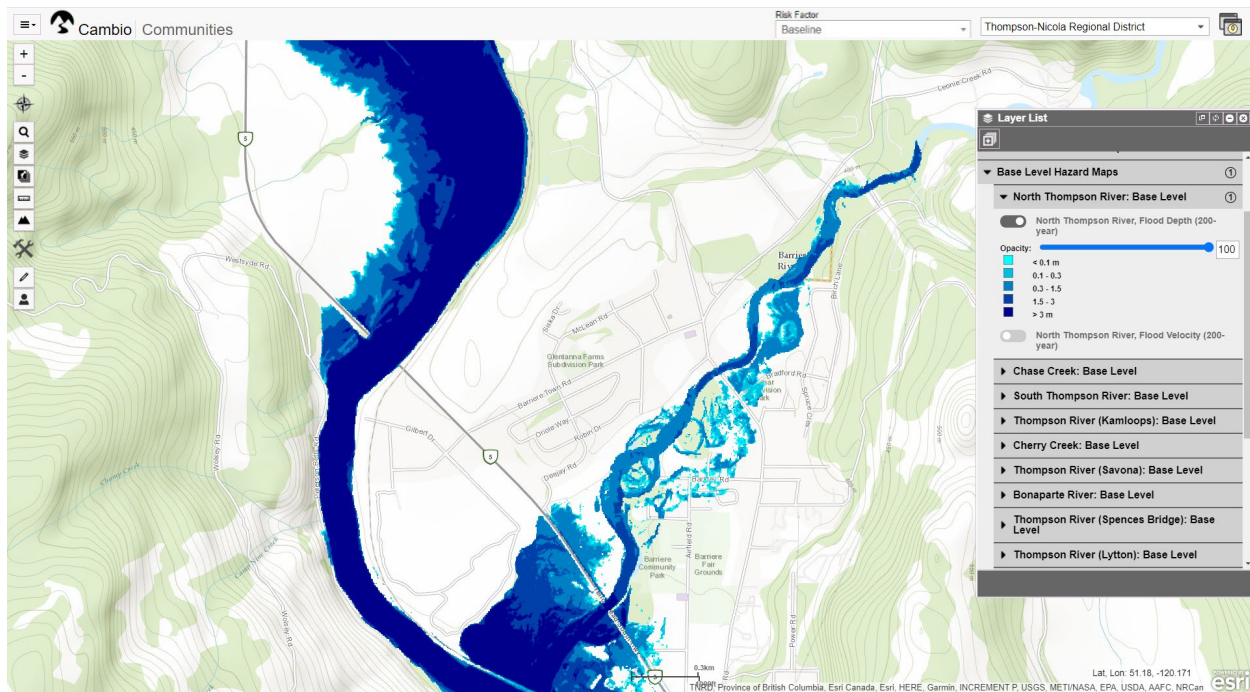


Figure A-8. Example base level hazard map layers.

F.2.7. Detailed Hazard Maps

Detailed hazard maps are provided in Cambio for select assessment areas. These maps show spatial information about hazards within a geohazard identification area.

Once selected, a drop-down list of each geohazard identification area where geohazard maps are available is displayed (Figure A-9). The geospatial data includes multiple maps at the range of return periods assessed as well as maps which include climate change (CC) consideration. Hazard map layers can be viewed by selecting the toggle-switch icon located left of the layer name (Figure A-9). Hazard map layers can also be accessed through the “Hazard Identification Maps” sidebar under “Hazard Detailed Layers” (Figure A-7).

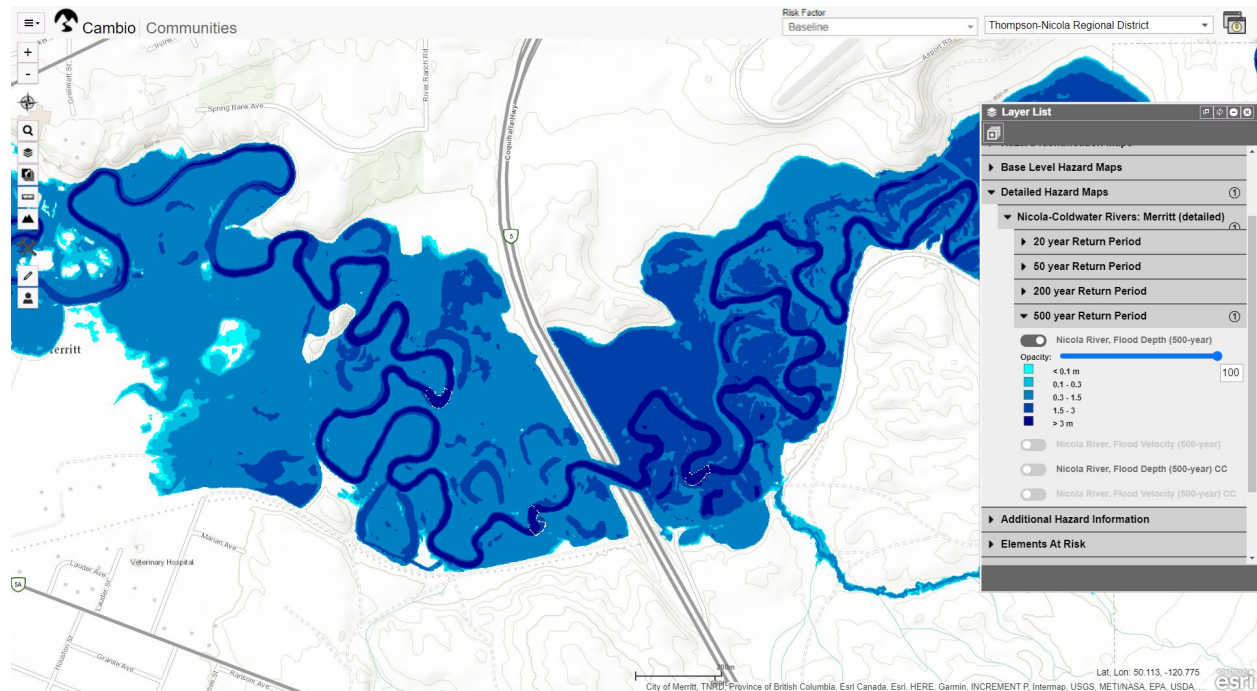


Figure A-9. Example detailed hazard map layers.

F.2.8. Additional Hazard Information

Additional geohazard-related layers are found under “Additional Hazard Information” in the layer list. Available layers include historical floodplains, historical wildfire events, debris flow susceptibility regions, flood plain identification modelling results, and flood advisory and warning notifications. These should be reviewed with reference to the main report document for context and limitations.

F.2.9. Elements at Risk

Elements at risk can be displayed on the map by selecting a given asset type in the layer list. The available elements at risk include community assets (land and improvements, business, critical facilities, environmental values) and lifelines. Infrastructure labels will show up for select features at a higher zoom level. BGC notes that the asset data displayed on the map is not necessarily complete.

F.2.10. Flood Reduction Infrastructure

Flood reduction infrastructure can be displayed on the map by selecting a given infrastructure type in the layer list. The available flood reduction structures include dikes, appurtenant structures, and dams. BGC notes that the infrastructure data displayed on the map is not necessarily complete.

F.2.11. Flood Conveyance Infrastructure

Flood conveyance infrastructure can be displayed on the map by selecting a given infrastructure type in the layer list. The available flood conveyance structures include culverts and bridges. BGC notes that the infrastructure data displayed on the map is not necessarily complete.

F.2.12. Unassessed Areas

This section identifies parcels within the study area that intersect areas modelled as potentially susceptible to steep creek hazards, but not alluvial fans that were mapped and prioritized by BGC (2019). Further information about steep creek hazard susceptibility modelling and unassessed steep creek parcels is provided in the Stream 1 study report (BGC, March 31, 2019).

F.2.13. Imagery

The imagery drop-down provides access to lidar hillshades and ortho-imagery as available.

F.3. ADDITIONAL MAP CONTROLS

F.3.1. Search

Search is currently available for hazard identification map names and street addresses. To search for hazards:

- a. Select the hazard type from the drop-down menu.
- b. Scroll through the drop-down list to select the feature of interest.

F.3.2. Basemap Gallery

The basemap gallery allows the user to switch between 14 different basemaps including street maps, a neutral canvas, and topographic hillshades. Map layers may display more clearly with some basemaps than others, depending on the color of the layer.

F.3.3. Measurements Tool

The measurements tool allows measurement of area and distance on the map, as well as location latitude and longitude. For example, a user may wish to describe the position of a development area in relation to a geohazard feature. To start a measurement, select the measurements tool icon from the options in the drop down.

F.3.4. Elevation Profile Tool

The elevation profile tool allows a profile to be displayed between points on the map. For example, a user may wish to determine the elevation of a development in relation to the floodplain. To start a profile, click "Draw a Profile Line". Click the starting point, central points, and double click the end-point to finish. Moving the mouse across the profile will display the respective location on the map. The "i" in the upper right corner of the profile viewer screen displays elevation gain and loss statistics. The precision of the profile tool corresponds to the resolution of the digital elevation model (approximately 25 m DEM). As such, the profile tool should not be relied upon for design of engineering works or to make land use decisions reliant on high vertical resolution.

F.4. RISK FACTOR

The Risk Factor drop down enables a user to toggle between risk associated with steep creek hazards before and after wildfire occurrences. If post-wildfire risk assessment has not been completed in a study area, no results will be shown when the *Steep Creek Fire Threat Rating* has been selected.

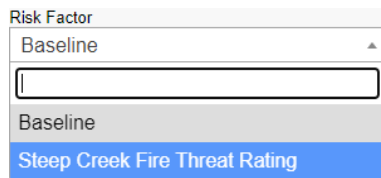


Figure A10. Risk Factor drop down.

F.5. FUTURE DEVELOPMENT

BGC is working to develop future versions of Cambio Communities, and the user interface and features may be updated from time to time. Site development may include:

- Further access to attributes of features displayed on the map.
- Administrative functions for data management via desktop and mobile applications.
- Real-time⁴ precipitation monitoring and forecasts, in addition to stream flow and lake level.
- Automated alerts for monitored data (i.e., stream flow or precipitation).
- Automated alerts for debris flow occurrence locations and characteristics.
- Inclusion of other types of geohazards (i.e., landslides and snow avalanches).
- Inclusion of functions implemented in other versions of Cambio, related to field inspections and reporting.

BGC welcomes feedback on Cambio. Please do not hesitate to contact the undersigned of this report with comments or questions.

⁴ i.e., information-refresh each time monitoring data are updated and provided by third parties.