



# Regional Geohazard Risk Assessment

Prepared by BGC Engineering Inc. for:



April 24, 2023

Project 1358008



April 24, 2023

Project 1358008

Squamish Lillooet Regional District  
Box 219  
Pemberton, BC V0N 2L0

Attention: Mike Fusca, Emergency Program Coordinator

**Squamish Lillooet Regional District (SLRD) Regional Geohazard Risk Assessment**

Please find BGC's report attached, which provides a regional scale assessment of flood, steep creek (debris flood and debris flow), and non-eruptive volcanic (lahar) risk for the Squamish Lillooet Regional District. We appreciate the opportunity to collaborate with you on this challenging and interesting project and look forward to your input on the deliverable.

The web application accompanying this report (Cambio) can be accessed at **[www.cambiocommunities.ca](http://www.cambiocommunities.ca)**.

Should you have any questions, please do not hesitate to contact the undersigned.

Yours sincerely,

**BGC Engineering Inc.**

**per:**

A handwritten signature in blue ink, appearing to read 'Kris Holm', is written over a light blue horizontal line.

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

## SUMMARY

From 2018 to 2020, Squamish Lillooet Regional District (SLRD, the District) undertook a regional district-wide geohazard risk assessment that assessed flood, steep creek (debris flood and debris flow), and non-eruptive volcanic hazards (lahars). The SLRD subsequently engaged BGC to update the original study to address two key recommendations: understanding how wildfires could affect steep creek risk compared to existing conditions (i.e., a baseline risk assessment scenario) and resolving under-reported hazard exposure on First Nations reserves caused by gaps in asset data. This assessment incorporates revised methods and expands on the initial steep creek hazard inventory. This assessment supersedes both the report and the results of the previous study.

The goal of this geohazard risk assessment is to support decisions that prevent or reduce injury or loss of life, environmental damage, and economic loss due to geohazard events. Completion of this study is a step towards this goal. The study encompasses four electoral areas, eleven First Nations, and four municipal governments.

The regional geohazard risk assessment provides the following outcomes across the SLRD:

- Identification and rating of geohazard areas based on the principles of risk assessment (i.e., consideration of both hazards and consequences). Risk ratings reflect the scale of the entire District.
- Geospatial information management for both geohazard areas and elements at risk
- Web communication tool to view geohazard areas and supporting information
- Information gap identification and recommendations for further study.

These outcomes support SLRD to:

- Continue operating under existing flood-related policies and bylaws using improved geohazard information and information management tools
- Review and potentially develop Official Community Plans (OCPs) and related policies, bylaws, and land use and emergency management plans
- Undertake flood resiliency planning, which speaks to the ability of an area “to prepare and plan for, resist, recover from, and more successfully adapt to adverse events” (NRC, 2012)
- Develop a framework for geohazard risk management that includes detailed hazard mapping, risk assessment, and mitigation planning
- Prepare provincial and federal funding applications to undertake additional work related to geohazard risk management within the SLRD.

This study provides the following:

- A report summarizing methods and results, with additional details in appendices.
- Access to the Cambio web application displaying geohazard areas and supporting information. This application represents the easiest way to interact with study results and is summarized in Appendix I.
- A geodatabase with geohazard areas.

- A Risk Assessment Information Template (RAIT) form as required by the National Disaster Mitigation Program (NDMP) (Appendix J).
- An Excel spreadsheet with attributes of geohazard areas (Appendix K).

In total, BGC rated 2328 geohazard areas encompassing about 1668 km<sup>2</sup> of the SLRD (Table E-1-1). Table E-1-1 lists the results worksheets provided in Appendix K.

**Table E-1-1 Number of risks rated areas in the SLRD, by geohazard type.**

Geohazard Type		Risk Rating					Grand Total
		Very High	High	Moderate	Low	Very Low	
Clear-Water Floods Waterbody (subtotal)		0	12	7	19	0	38
Clear-Water Floods Watercourse (subtotal)		0	83	70	1654	0	1807
Steep Creeks (Fans)	Baseline Rating	21	107	98	220	25	471
	Wildfire-adjusted Rating	23	148	115	220	10	
Volcanic Geohazards		0	12	0	0	0	12
<b>Baseline Risk Ratings Total (Count)<sup>1</sup></b>		<b>21</b>	<b>214</b>	<b>175</b>	<b>1893</b>	<b>25</b>	<b>2328</b>
<b>Grand Total (%)<sup>1</sup></b>		<b>1</b>	<b>9</b>	<b>8</b>	<b>81</b>	<b>1</b>	<b>100</b>

Notes:

1. The totals (count and %) consist of the clear-water floods, steep creeks-baseline rating and volcanic geohazards.

Table E-1-2 lists the Excel Worksheets that are provided in Appendix K. These worksheets can be filtered and sorted according to risk ratings or any other fields in the worksheet. When reviewing results, local authorities may wish to consider other factors outside the scope of this assessment but that also affect risk management decision making. For example, additional factors include the level of risk reduction already achieved by existing structural mitigation (dikes), the level of flood resiliency in different areas, and comparison of the risk reduction benefit to the cost of new or upgraded flood risk reduction measures.

**Table E-1-2. Results worksheets provided in Appendix I**

Appendix I (Excel Worksheet Name)	Contents
Study Area Metrics	Summary statistics of select elements at risk (count of presence in geohazard areas).
Study Area Hazard Summary	Summary statistics of elements at risk, according to their presence in geohazard areas.
Study Area Hazard Type Summary	Summary statistics of geohazard areas, according to the presence of elements at risk.
Priority by Jurisdiction Baseline	Summary statistics of risk rating results by jurisdiction for the baseline risk scenario (digital version of Table E-1-1).
Priority by Jurisdiction Fire-Adjusted	Summary statistics of risk rating results by jurisdiction for the wildfire-adjusted (steep creek) risk scenario (digital version of Table E-1-1).
Priority by First Nation Baseline	Summary statistics of risk rating results by First Nation Reserve for the baseline risk scenario
Priority by First Nation Fire-Adjusted	Summary statistics of risk rating results by First Nation Reserve for the wildfire-adjusted (steep creek) risk scenario
Steep Creek Hazard Baseline	Attributes displayed in the information sidebar on <i>Cambio</i> for all steep creek geohazard areas for the baseline risk scenario
Steep Creek Hazard Fire-Adjusted	Attributes displayed in the information sidebar on <i>Cambio</i> for all steep creek geohazard areas for the wildfire-adjusted (steep creek) risk scenario
Clear-water Flood Hazard Attributes	Attributes displayed in the information sidebar on <i>Cambio</i> for all clear-water flood geohazard areas.
Volcanic Geohazards Attributes	Attributes displayed in the information sidebar on <i>Cambio</i> for all volcanic geohazard areas.
Hazard Metrics Baseline	Summary of rating, hazard, consequence, exposure scores for each hazard for the baseline risk scenario
Hazard Metrics Fire-Adjusted	Summary of rating, hazard, consequence, exposure scores for each hazard for the wildfire-adjusted (steep creek) risk scenario

Table E-1-3 lists recommendations for consideration by SLRD and local, regional, and provincial authorities. These recommendations are based on rationale described in more detail in the report. BGC encourages SLRD and stakeholders to review this assessment and web tools from the perspective of supporting long-term geohazard risk and information management. Long-term provincial support could facilitate cooperation and efficiency between different regional districts using common web tools for geohazard risk and information management.

**Table E-1-3. List of recommendations.**

Type	Description
Data Gaps	<ul style="list-style-type: none"> <li>Continue work to resolve gaps and manage changes related to baseline data; geohazard sources, controls, and triggers; geohazard frequency-magnitude relationships, flood protection measures and flood conveyance infrastructure, and hazard exposure (elements at risk).</li> </ul>
Further Geohazards Assessments	<ul style="list-style-type: none"> <li>Geohazard areas: review prioritized geohazard areas and develop a plan to implement next steps in a framework of geohazard risk management</li> <li>If a wildfire occurs in one of the watersheds associated with a hazard area assessed in this study, complete more detailed assessment to refine the estimates provided in this study based on actual wildfire severity conditions in the watershed area.</li> </ul>
Long-term Geohazard Risk Management	<ul style="list-style-type: none"> <li>Consider long-term geohazard risk management programs that would build on the results of this study.</li> </ul>
Geohazards Monitoring	<ul style="list-style-type: none"> <li>Develop criteria for hydroclimatic monitoring and alert systems informing emergency management.</li> </ul>
Policy Integration	<ul style="list-style-type: none"> <li>Review Development Permit Areas (DPAs) following review of geohazard areas defined by this study.</li> <li>Review plans, policies and bylaws related to geohazards management, following review of the results of this study.</li> <li>Develop risk evaluation criteria that allow consistent risk reduction decisions (i.e., that define the term “safe for the use intended” in geohazards assessments for development approval applications).</li> </ul>
Information Management	<ul style="list-style-type: none"> <li>Review approaches to integrate and share asset data and geohazard information across functional groups in government, stakeholders, data providers and risk management specialists. Such an effort would assist long-term geohazard risk management, asset management, and emergency response planning.</li> <li>Develop a maintenance plan to keep study results up to date as part of ongoing support for bylaw enforcement, asset management, and emergency management.</li> </ul>
Engagement	<ul style="list-style-type: none"> <li>Provide training to SLRD staff who may rely on study results, tools and data services.</li> <li>Work with communities in the prioritized hazard areas to develop flood resiliency plans informed by stakeholder engagement.</li> </ul>
Indigenous Knowledge Gathering	<ul style="list-style-type: none"> <li>Complete further work to resolve remaining gaps about culturally significant areas and risk considerations beyond primarily economic values considered in the current approaches. Indigenous-led projects should be explored as a process through which First Nations perspectives can be most directly incorporated.</li> </ul>

## TABLE OF REVISIONS

Date	Revision	Remarks
March 17, 2023	Original	Issued in Draft
April 24, 2023	Original	Issued in Final

## CREDITS AND ACKNOWLEDGEMENTS

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BGC recognises that this report and the Phase I assessment were guided by expertise and mentorship of Dr. Matthias Jakob, P.Geo. (Principal Geoscientist), who tragically died during the course of this project. Many of the concepts and ideas for assessing steep creek geohazards were developed during fruitful and engaging conversations with Matthias. We miss his sage wisdom and humor.

## **LIMITATIONS**

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

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## 1.0 INTRODUCTION

### 1.1 Overview

From 2018 to 2020, Squamish Lillooet Regional District (SLRD) retained BGC Engineering Inc. (BGC) to complete a regional scale assessment of flood, steep creek (debris flood and debris flow) and non-eruptive volcanic (lahar) risk. All these processes were referred to as “geohazards”. The results of the study were provided to SLRD by BGC (April 10, 2020) and are herein referred to as the Phase I study.

The Phase I study recommended further work to resolve gaps in the completeness of geohazards and exposure data, as well as work to incorporate results into decision making. SLRD subsequently retained BGC to undertake this second phase of study (Phase II) to improve completeness of hazard exposure data on First Nations reserves and improve the ability of the SLRD to pro-actively consider effects of wildfires on steep creek<sup>1</sup> hazards. The updated study also provided the opportunity to refine and add to the steep creek hazard characterization.

This study and its associated deliverables supersede the Phase I study. This study provides the following:

- Identification and ratings of geohazard areas based on the principles of risk assessment (i.e., consideration of both hazards and consequences)
- Geospatial information management for both geohazard areas and elements at risk
- Web communication tool to view geohazard risk ratings and supporting information
- Evaluation of the relative sensitivity of geohazard ratings to climate change
- Information gap identification and recommendations for further study.

These outcomes support SLRD to:

- Continue operating under existing flood-related policies and bylaws based on improved geohazard information and information management tools
- Review and potentially develop Official Community Plans (OCPs) and related policies, bylaws, and land use and emergency management plans
- Undertake flood resiliency planning, which speaks to the ability of an area “to prepare and plan for, [resist], recover from, and more successfully adapt to adverse events” (NRC, 2012)
- Develop a framework for geohazard risk management, including detailed hazard mapping, risk assessment, and mitigation planning
- Prepare funding applications to undertake additional work related to geohazard risk management within the SLRD.

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<sup>1</sup> Rapid flow of water and debris in a steep channel, often associated with avulsions and strong bank erosion. Most stream channels within the SLRD are tributary creeks subject to steep creek processes that carry larger volumetric concentrations of debris than clear-water floods. Steep creek processes is used in this report as a collective term for debris flows and debris floods.

BGC's work considered the Engineers and Geoscientists BC (EGBC) Professional Practice guidelines for Legislated Flood Assessments in a Changing Climate in BC (EGBC, 2018), Flood Mapping in BC Professional Practice Guidelines (EGBC, 2017), and EGBC Professional Practice Guidelines for Landslide Assessments in BC (EGBC, 2023). The study framework also considered the United Nations International Strategy for Disaster Reduction (UNISDR) Sendai Framework (UNISDR, 2015). Specifically, it focuses on the first UNISDR priority for action, understanding disaster risk, and is a starting point for the remaining priorities, which focus on strengthening disaster risk governance, improving resilience, and enhancing disaster preparedness.

A list of key terminology used in this report is provided in Appendix A.

## 1.2 Scope of Work

BGC's scope of work was described in a proposal dated June 11, 2021 (BGC, 2021). Work was completed under the terms of the SLRD contract originally dated August 11, 2021, on a schedule extended to April 30, 2023 via a contract amendment between BGC and SLRD dated April 30, 2022.

The work was based on review and analysis of background information (Section 2.0 and Appendix B), a review of previous assessments (Appendix C), a geohazard event inventory (Appendix D), and a study of desktop-based hazard information. No field work was undertaken as part of this work.

Areas of the SLRD included for regional risk assessment contained both First Nations reserves and cadastral parcels of interest<sup>2</sup>, which were subject to clear-water flood (Section 3.1 and Appendix E), steep creek (Section 3.2 and Appendix F), or non-eruptive volcanic hazard processes (Section 3.3 and Appendix G). BGC identified elements at risk in geohazard areas and assigned exposure ratings (Section 4.0 and Appendix H).

The following updates to the Phase I study were completed as part of this scope of work:

- *Updated and substantially expanded* inventory of steep creek hazard areas (fans).
- *Updated* baseline steep creek hazard characterization methodology.
- *New*, systematic consideration of wildfires in steep creek hazard characterization.
- *New* wildfire-adjusted risk ratings for steep creek hazard areas for comparison to baseline risk ratings.
- *Updated* physical hazard exposure inventory to include data supporting estimates of building values on First Nations reserves.
- *New* inclusion of an index of social vulnerability as weighting factor for relative hazard exposure across all hazard areas.
- *Updated* record of geohazard events.

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<sup>2</sup> Cadastral parcels of interest were defined as those parcels identified in the BC Assessment dataset for 2019 as having a gross general improvement value greater than \$0, and a land use code not equal to 428 (Managed Forest (Improved)).

The clear-water flood and non-eruptive volcanic hazard characterizations completed for Phase I remain unchanged in this report. Recommendations provided in Phase I that were not addressed by this study have been carried forward.

The risk rating basis used in this study remains the same as the Phase I study, namely:

- The study does not make any assumption about the effects of structural mitigation on hazard characteristics or level of risk (i.e., the study does not estimate residual hazard or risk).
- The risk ratings are relative and consequently should not be considered equivalent to an absolute level of risk, and SLRD will likely need to consider additional factors outside this scope of work when making decisions about next steps (i.e., consideration of the existing levels of flood management).
- More than one hazard type can potentially be present at a given location. BGC displays hazards on the Cambio web application such that a user can identify overlapping hazards if present at a given location. However, hazard ratings are completed separately for each hazard type.
- In the case of steep creek geohazards, geohazard area identification and ratings entirely focuses on fans, as these are the landforms most commonly occupied by elements at risk. Areas upstream of the fan apex were assessed as part of hazard characterization but were not mapped or rated. As such, steep creek geohazard risk exists within the SLRD that was not included in this study because the elements exposed to geohazards did not intersect a mapped fan.
- The boundary between settled areas and wilderness is not always defined. Geohazard areas typically include buildings improvement and adjacent development (i.e., transportation infrastructure, utilities, and agriculture). Although infrastructure in otherwise undeveloped areas (e.g., roads, pipelines, transmission lines, and highways) could be impacted by geohazards, these were not included. Elements where loss can be intangible, such as objects of cultural value, were not included in the inventory. Hazards were also not mapped in areas that were undeveloped except for minor dwellings (i.e., backcountry cabins).

Geohazards existing within the SLRD but that are excluded from this assessment include:

- Channel encroachment due to bank erosion during high or low flows
- Shoreline erosion
- Wind-generated or landslide-generated waves in lakes/reservoirs
- Dam and dike/levee failure<sup>3</sup>

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<sup>3</sup> A dynamic and rapid release of stored water due to the full or partial failure of a dam, dike, levee or other water retaining or diversion structure. The resulting floodwave may generate peak flows and velocities many orders of magnitude greater than typical design values. Consideration of these hazards requires detailed hazard scenario modelling. Under BC's Dam Safety Regulation, owners of select classes of dams are required to conduct dam failure hazard scenario modelling.

- Overland urban flooding<sup>4</sup>
- Sewer-related flooding<sup>5</sup>
- Ice jam flooding
- Detailed assessment of floods associated with reservoir regulation.
- Landslides other than those considered as part of steep creek assessments
- Volcanic eruptions
- Natural hazards other than those listed as being assessed (e.g., wildfire, seismic, volcanic eruptions).
- Surface rupture or liquefaction from earthquakes

### 1.3 Deliverables/Web Map

Outcomes of this study include both documentation (this report) and digital deliverables. Digital deliverables include geospatial information provided in a geodatabase (geohazard risk ratings). The results are presented on a secure web application called *Cambio*. The web application will be provided until March 31, 2024 and thereafter hosted for a license fee if requested by SLRD or on behalf of SLRD by other agencies (e.g., Province of BC).

*Cambio* is the most convenient way to view study results. The application shows the following information:

- Geohazard areas and information (see Section 3.0).
- Elements at risk (i.e., community assets).
- Additional information provided for visual reference, including geohazard, hydrologic and topographic features.
- Access to data from near-real time stream flow monitoring stations where existing.

Note that the application should be viewed using Chrome or Firefox and is not designed for Internet Explorer. Appendix I provides a more detailed description of *Cambio* functionality.

In addition to the digital deliverables the following are provided:

- A Risk Assessment Information Template (RAIT) form, as required by the National Disaster Mitigation Program (NDMP) (Appendix J)
- An Excel spreadsheet with attributes of geohazard areas (Appendix K).

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<sup>4</sup> Due to drainage infrastructure such as storm sewers, catch basins, and stormwater management ponds being overwhelmed by a volume and rate of natural runoff that is greater than the infrastructure's capacity. Natural runoff can be triggered by hydro meteorological events such as rainfall, snowmelt, freezing rain, etc.

<sup>5</sup> Flooding within buildings due to sewer backups, issues related to sump pumps, sewer capacity reductions (tree roots, infiltration/inflow, etc.)

## 2.0 BACKGROUND

Figure 2-1 shows the extent of the Phase II project area, which is the administrative boundary of the SLRD. The SLRD covers approximately 17,000 km<sup>2</sup> in southwestern British Columbia. The SLRD encompasses many First Nation and local governments, who maintain jurisdiction over geohazard risk management decisions. These governments include:

- Lil'wat Nation
- N'Quatqua First Nation
- Sekw'el'was (Cayoose Creek Band)
- Squamish Nation
- T'it'q'et First Nation
- Lytton First Nation
- Ts'kw'aylaxw First Nation
- Tsal'alh (Seton Lake Band)
- Whispering Pines/Clinton Indian Band
- Xaxli'p First Nation (Fountain First Nation)
- Xwisten (Bridge River Indian Band)
- District of Squamish
- Resort Municipality of Whistler
- Village of Pemberton
- District of Lillooet.

The reader is referred to Appendix B for a description of the following background information:

- Topography
- Physiography and ecoregions
- Geological history
- Climate and project climate change
- Hydrology
- Historical geohazard event inventory.

During this study, BGC reviewed accounts of flood, debris flood, and debris flows that occurred after the Phase I study and incorporated observations of these events into the attributes of the hazard areas. These events are listed in Appendix D and a snapshot of major events is shown in Figure 2-2.



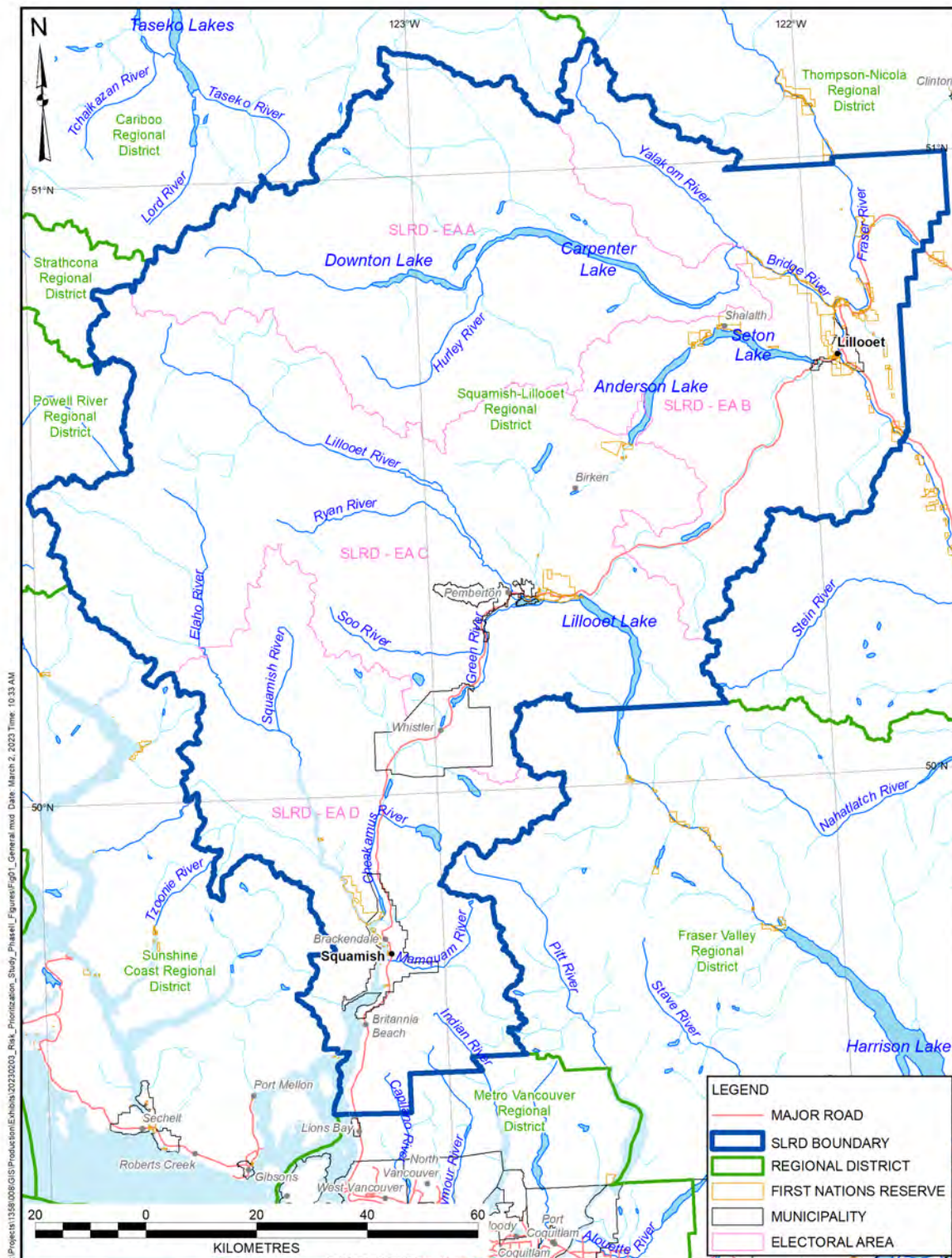


Figure 2-1. The SLRD boundary is shown in blue.

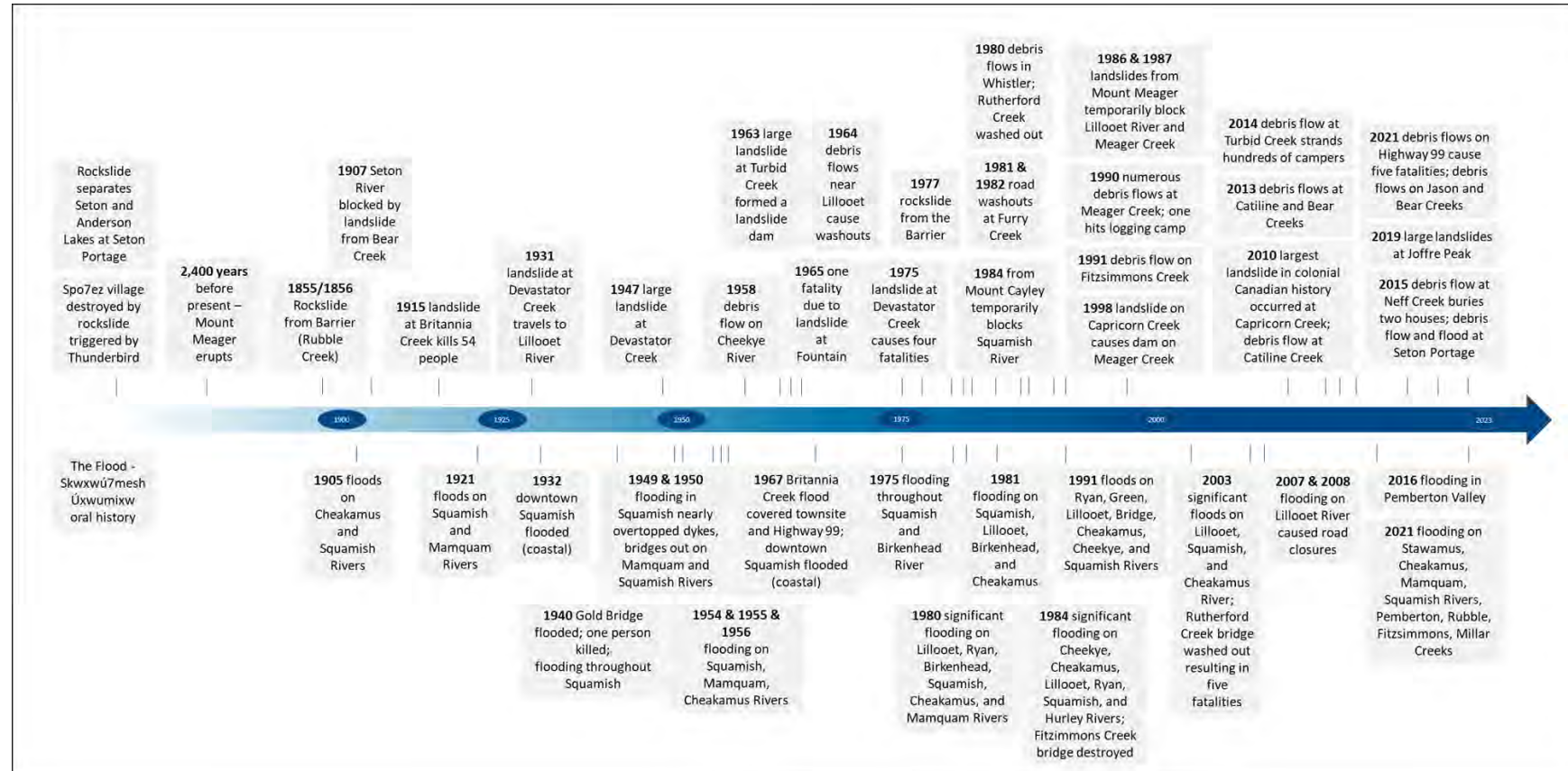


Figure 2-2. Timeline of major historical geohazard events in the SLRD. Detailed timeline of historical geohazard events provided in Appendix D.

### 3.0 GEOHAZARD ASSESSMENT METHODS

This section summarizes geohazard assessment methods, which are unchanged compared to the Phase I study for clearwater floods and non-eruptive volcanic hazards, and substantially updated for steep creeks. Appendix D, Appendix E and Appendix F provide detailed descriptions of geohazards assessment methods for each process type.

#### 3.1 Clear-Water Flood Geohazards

Clear-water flood hazards focused on waterbody and watercourse hazard areas. Hazard areas were generated from the methods shown in Table 3-1 and amalgamated<sup>6</sup> into geohazard areas for rating.

The clear-water flood hazard assessment consists of the following, as summarized below and detailed in Appendix D:

- Characterization of flood hazard areas
- Hazard likelihood
- Consequence rating.

Table 3-1 summarizes the approaches used to identify and characterize different types of clear-water flood hazard areas, including watercourses, lakes, and regulated reservoirs. The resulting geohazard areas are shown on the web application accompanying this report. Also shown on the web application are all mapped stream segments and their associated geohazard process type, as well as historical mapped floodplains and flood depth results from the screening-level hydraulic models.

Frequency analysis estimates how often geohazard events occur, on average. Historical floodplain maps are typically based on the designated flood as represented by the 0.5% annual exceedance probability (AEP) (200-year return period) event. Therefore, the 200-year flood event likelihood was used to rate clear-water flood sites across the SLRD.

Hazard intensity describes the destructive potential of uncontrolled flows that could impact elements at risk (as defined by cadastral parcels of interest). Hazard intensity ratings were used to define a consequence rating for each hazard area, as described in Section 5.

In a detailed hazard assessment, hazard intensity is quantified by parameters such as flow depth and velocity. At regional scale, these parameters are difficult to estimate, because they are site-specific. To address this limitation, at the scale of the SLRD, and in the context of the current prioritization study, BGC used the estimated maximum flood depth derived from the screening-level flood hazard mapping which is a terrain-based flood hazard identification approach using the Height Above Nearest Drainage (HAND) approach.

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<sup>6</sup> Amalgamation was based on the concept of “consultation zones”, which define a geographic area considered for geohazard safety assessment (Geotechnical Engineering Office, 1998; Porter, Jakob, and Holm, 2009). Geographic areas were selected on the basis of hazard type and characteristics, jurisdiction/community continuity, future detailed study funding considerations and study efficiencies.



**Table 3-1. Summary of clear-water flood identification approaches.**

Approach	Area of SLRD Assessed	Application
Historical flood event inventory	All mapped watercourses and waterbodies prone to clear-water flooding.	Identification of creeks and rivers with historical precedent for flooding. The historical flooding locations are approximate locations where known landmarks adjacent to a watercourse were flooded, or specific impact to structures (roads, houses) was reported in media.
Existing floodplain mapping	All watercourses and waterbodies prone to clear-water flooding where existing information was available.	Identification of floodplain extents from publicly available historical mapping (MFLRNO, 2016; MFLRNO, 2017) and third-party data sources.
Coastal flood hazard extents	All mapped watercourses subject to sea level rise and coastal flooding.	Identification of low-lying areas below the projected future 1 m sea level rise 200-year coastal flood level of 3.99 m based on the Squamish Integrated Flood Hazard Management Plan (KWL, October 2017).
Identification of low-lying areas to predict floodplain extents	All mapped watercourses and waterbodies without existing floodplain mapping.	Identification of low-lying areas adjacent to streams and lakes using a terrain-based flood hazard identification approach referred to as the Height Above Nearest Drainage (HAND) applied to mapped stream segments. Method provides screening level identification of flood inundation extents and depths based on a digital elevation model.

### 3.2 Steep Creek Geohazards

Steep creek geohazard areas in this study focused on alluvial fans occupied by elements at risk. The boundaries of alluvial fans define the steep creek geohazard areas. Upstream watersheds were analyzed to identify geohazard processes and estimate geohazard ratings.

Throughout the District, 473 fans were mapped, which included an additional 272 new alluvial fans mapped since the Phase I study. Existing fan boundaries were also reviewed in areas with new lidar. In some cases, coalesced fans from more than one drainage were split into individual fans to be linked to individual catchments.

The new alluvial fans were identified with the help of newly available lidar data. Lidar data improves the accuracy of delineated fan boundaries and also helps to characterize the frequency and magnitude of debris flows and debris floods. Without lidar data, BGC relied on air photo interpretation to estimate hazard likelihood and magnitude. Lidar data also provides clearly identifiable features to use in the hazard assessment (e.g., debris flow deposits, channel scour, landslide source material). Lidar data is still not readily available across the entire SLRD.

The steep creek geohazard assessment methods followed the following approach:

- Alluvial fan inventory
- Process type identification
- Hazard likelihood estimation
- Impact likelihood estimation
- Hazard intensity (destructive potential) estimation.

Appendix F provides the details of the approach to assess steep creek geohazards. The steep creek geohazard characterization methods from the Phase I study were updated to account for the following factors:

- **Alluvial fan inventory:** As discussed above, improvements were made to the inventory based on First Nation reserve boundaries and newly available lidar data.
- **Process type identification:** Recognition of “mixed-type” watersheds (e.g., debris flow and debris flood processes occurring in the same watersheds), in line with emerging understanding of the continuum of steep creek processes (Church and Jakob, 2020).
- **Impact likelihood estimation:** The impact likelihood ratings, based on terrain characteristics, have been updated to reflect evidence of “mixed type” processes occurring within a watershed. The potential for Landslide Dam Outburst Floods (LDOFs) in some watersheds was accounted for in Phase I Risk Prioritization Study using a factor that can increase the potential for avulsion, in the impact likelihood rating. This application of this factor serves to flag fans where there is a possibility of major flooding events associated with potential LDOF events. The conditions for the use of the LDOF factor have been updated in Phase II to avoid overestimating the impact likelihood rating.
- **Hazard intensity (destructive potential):** (a) Phase I study results used Flood Frequency Analyses (FFA) to estimate “clear-water” peak discharge in steep creeks. It was recognized that the regionalization of hydrometric gauge records used in FFA tends to underestimate peak flows for small watersheds and overestimate peak flows for larger watersheds. To address this limitation in Phase II, hydrological rainfall-runoff models were used to estimate peak discharge in steep creek catchments, where possible. (b) Improvements to predicted debris flow peak discharge were made by applying updates to empirically derived discharge-volume correlations, which better fit observations of BC debris flows. (c) In the Phase I study, the 200-year (0.5% AEP) was used in the analyses. In Phase II, the 100-year (1% AEP) was used for steep creek processes (i.e., debris flow, debris flood and clear-water flood on fans) instead to simplify comparisons to post-wildfire debris-flow magnitude estimates. Because the analyses are relative, the choice of return period does not affect results. (d) In the Phase I Risk Prioritization Study, the classes of the hazard intensity rating were defined based on percentiles. In Phase II, the classes have been updated to correspond to peak discharge categories based on Jakob (2005).
- **Wildfire-adjusted geohazard likelihood and intensity:** Wildfires in steep mountainous terrain are often followed by a temporary period of increased geohazard activity. For steep creeks, changes in hydrologic response can increase the likelihood or peak discharge of debris floods or debris flows compared to the baseline conditions. More details are provided in Section 5.5.

### 3.3 Volcanic Geohazards

This assessment considers non-eruptive lahars (volcanic debris flows) and LDOFs originating from volcanic complexes within the SLRD that have the potential to reach presently developed areas. Representative rock avalanches scenarios are also considered. This section summarizes the assessment approach, which was unchanged from the Phase I study. Details are provided in Appendix G.

There are three notable volcanic complexes (VC) located within the SLRD: Mount Meager VC in the upper Lillooet River watershed, Mount Cayley VC in the upper Squamish River watershed and the Mount Garibaldi VC towering above Squamish (Figure 3-1). These volcanic complexes contain unstable slopes due to the relative youth of their edifices and the poor quality of volcanic rock often associated with some hydrothermal alteration, and the strong magmatic seismicity associated with previous eruptions.

The volcanic hazard assessment was completed based on the following, as outlined in Appendix G:

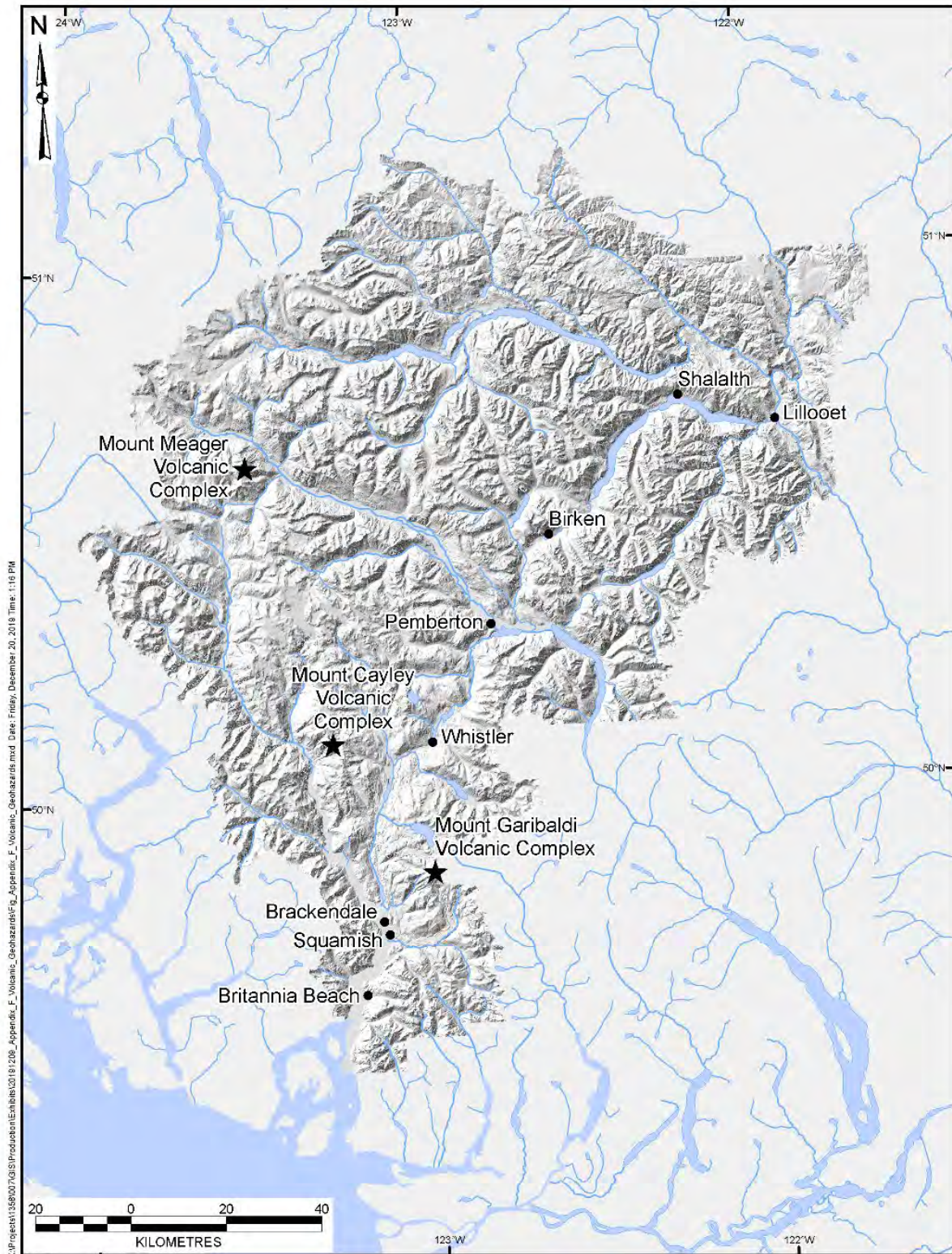
- Geohazard identification and mapping
- Geohazard likelihood rating
- Relative consequence rating.

A total of 12 volcanic geohazard areas were mapped in the District. BGC notes that the volcanic hazard assessment is subject to higher uncertainty than the other hazard types considered in this study (clear-water floods and steep creek geohazards). The hazard scenarios considered in this assessment are not exhaustive, and the hazard areas delineated should not be considered precise. They are intended to be used in the following way:

- To provide a regional scale overview of areas potentially subject to volcanic geohazards
- To identify the level of potential exposure of elements at risk
- To inform decisions to complete more detailed volcanic hazard assessments in future.

Volcanic hazard likelihood was estimated for geohazard areas based on judgement with reference to the data sources listed in Appendix G. BGC notes that several scenarios have an estimated annual probability of less than 0.33% (less than 1:300). Those were all binned into the lowest Geohazard Likelihood category (Very Low).





**Figure 3-1. Major volcanic complexes within the SLRD. Town locations shown for geographical reference. Grayscale basemap is the 20-m Digital Elevation Model (DEM) slope map clipped to the SLRD boundary.**

## 4.0 EXPOSURE ASSESSMENT

This section summarizes how BGC identified elements at risk in geohazard areas. The objective of assigning exposure ratings to compare the overall exposure of diverse elements at risk to the geohazards considered in this study. In the absence of detailed consequence or risk estimation, higher exposure ratings imply a greater potential for losses due to geohazards. Table 4-1 lists the elements at risk considered in this study, and weightings used to compare the types and value of elements in different hazard areas. Two groups of elements at risk have been defined: Community and Lifeline. Appendix H describes methods to compile and organize these data. Section 5.0 describes how exposure ratings were used as inputs for risk ratings.

The exposure weightings are consistent with comparable studies completed by BGC across British Columbia (e.g., Holm et al., 2019) and weigh the relative importance of elements at risk from a regional perspective with reference to the response goals of the BC Emergency Management System (BCEMS) (Government of BC, 2016). BCEMS goals are ordered by priority as follows:

1. Ensure the health and safety of responders.
2. Save lives.
3. Reduce suffering.
4. Protect public health.
5. Protect infrastructure.
6. Protect property.
7. Protect the environment.
8. Protect economic and social losses.

Weightings also considered loss indicators cited by the United Nations in the areas of public safety, economic loss, services disruption, environmental loss, or social loss (culture, loss of security) (United Nations, 2016; UNISDR, 2015).

BGC used the following steps to assign a hazard exposure rating to each area:

1. Identify the presence of elements at risk.
2. Calculate their value and weight according to the categories listed in Table 4-1.
3. Sum the weightings to achieve a total exposure score for each geohazard area.
4. Assign relative exposure ratings to geohazard areas based on their percentile rank of the total exposure scores compared to other areas.

BGC notes that different weightings contribute to the total exposure rating assigned to a given geohazard area. The results provided in spreadsheet format (see Appendix K) list each element at risk contributing to the exposure rating for a given geohazard area and can be used to clarify why one area might be ranked differently than another. Table 4-2 provides a more detailed breakdown of how weightings were assigned to critical facilities based on the BCEMS response goals (Government of BC, 2016).

To improve understanding of additional aspects of geohazard risk exposure, BGC added the following new information since the Phase I study:

Building improvements values in First Nation reserves:



- BC Assessment data does not provide building improvement values on First Nation Reserves. Therefore, BGC used the estimated building asset value from a 2020 Physical Exposure dataset compiled nationally in GIS format by Natural Resources Canada (NRCan) (2020a) to resolve data gaps on-reserve. Journeay et al. (2022a) describes methods to compile these data.

Social vulnerability values for both on and off reserve for all hazards:

- Social Vulnerability Score indicates a community's level of ability to withstand impacts of a disaster based on their demographics and other social characteristics. Journeay et al. (2022b) describes how communities with racially marginalized populations (among other groups) are most often more vulnerable to the impacts of unexpected disaster events. Therefore, the social vulnerability score helps increase priority for these populations that may be otherwise underprioritized based on other exposure factors.

Quality Control of data:

- Various data sources were used in this analysis. To estimate the accuracy in its use for this report, BGC conducted a Quality Control of the data by comparing to other data sources. This was done specifically for the population and building cost for NRCan Physical Exposure data (2020a). The building footprint displayed in Cambio was also checked against aerial imagery.

**Table 4-1. Weightings applied to elements at risk within a hazard area.**

Hazard Exposure Group	Element at Risk	Description	Value	Weight
Community	Population	Total Census (2016) Population (Census Dissemination Block) <sup>1</sup>	0	0
			1-10	5
			11 – 100	10
			101 – 1,000	20
			1,001 – 10,000	40
			>10,000	80
	Buildings	Building Improvement Value <sup>2</sup> (summed by parcel)	\$0	0
			<\$100k	1
			\$100k - \$1M	5
			\$1M - \$10M	10
			\$10M - \$50M	20
			>\$50M	40
	Critical Facilities	Critical Facilities (point locations)	Emergency Response Services	36
			Emergency Response Resources	10
			Utilities	30

Hazard Exposure Group	Element at Risk	Description	Value	Weight
			Communication	18
			Medical Facilities	36
			Transportation	22
			Environmental	18
			Community	36
	Businesses	Business annual revenue (summed) (point locations)	0\$ Annual Revenue or 0 Businesses	0
			<\$100k Annual Revenue or 1 Business	1
			\$100k - \$1M Annual Revenue or 2-5 Businesses	5
			\$1M - \$10M Annual Revenue or 6-10 Businesses	10
			\$10M - \$50M Annual Revenue or 11-25 Businesses	20
			\$50M - \$100M Annual Revenue or 26-100 Businesses	40
			>\$100M annual revenue or >100 businesses	80
	Environmental Values	Active Agricultural Area	Presence of	15
		Fisheries	Presence of	15
		Species and Ecosystems at risk	Presence of	15
	Social Vulnerability	Applied as a regional proxy for a community's level of ability to withstand impacts of a disaster based on their demographics and other social characteristics.	Null or 0	0
			1-2	5
			3-5	10
			6-8	15
			>9	20
Lifelines	Lifelines	Roads (centerline)	Road present; no traffic data	1
			Highway present; no traffic data	5
			No Traffic Level	0
			No Summer Maintenance	1
			0-10 vehicles/day (Class 7)	1

Hazard Exposure Group	Element at Risk	Description	Value	Weight
			10-100 vehicles/day (Class 6)	5
			100-500 vehicles/day (Class 5)	10
			500-1,000 vehicles/day (Class 4)	20
			1,000-5,000 vehicles/day	40
			5,000-10,000 vehicles/day	40
			> 10,000 vehicles/day	40
		Railway	Presence of	10
		Petroleum Infrastructure	Presence of	15
		Electrical Infrastructure	Presence of	10
		Communication Infrastructure	Presence of	10
		Water Infrastructure	Presence of	10
		Drainage Infrastructure	Presence of	10
		Sanitary Infrastructure	Presence of	10

Notes:

1. Census population was scaled according to the proportion of census block area intersecting a hazard area. For example, if the hazard area intersected half the census block, then half the population was assigned. The estimate does not account for spatial variation of population density within the census block.
2. Large parcels with only minor outbuildings or cabins, typically in remote areas, were not included in the assessment.
3. Critical facilities and lifelines were assigned a weighting based on the presence of at least one of a given type within the hazard area. For example, if a geohazard area contained two critical facility elements classed as "utilities", the weighting was applied once (not multiplied by the number of elements). Where more than one is present, the maximum weighting is applied. This approach reflects how some elements are represented as geospatial features, to avoid accidental double counting where a single facility is spatially represented by multiple parts.

**Table 4-2 Basis for weightings applied to critical facilities.**

Category	BC Assessment Actual Use Value Description	Category Code	Risk to Life	Impacts Suffering	Impacts Public Health	Impacts infrastruc- ture (supports recovery)	Impacts Property	Causes Economic and Social Loss	Total Weights
Emergency Response Services	Emergency Operations Center, Government Buildings (Offices, Fire Stations, Ambulance Stations, Police Stations)	1	14	12	10				<b>36</b>
Emergency Response Resources	Asphalt Plants, Concrete Mixing, Oil & Gas Pumping & Compressor Station, Oil & Gas Transportation Pipelines, Petroleum Bulk Plants, Works Yards	2				8		2	<b>10</b>
Utilities	Electrical Power Systems, Gas Distribution Systems, Water Distribution Systems	3		12	10	8			<b>30</b>
Communication	Telecommunications	4			10	8			<b>18</b>
Medical Facilities	Hospitals, Group Home, Seniors Independent & Assisted Living, Seniors Licenses Care	5	14	12	10				<b>36</b>
Transportation	Airports, Heliports, Marine & Navigational Facilities, Marine Facilities (Marina), Service Station	6		12		8		2	<b>22</b>
Environmental	Garbage Dumps, Sanitary Fills, Sewer Lagoons, Liquid Gas Storage Plants, Pulp & Paper Mills	7			10	8			<b>18</b>
Community	Government Buildings, Hall (Community, Lodge, Club, Etc.), Recreational & Cultural Buildings, Schools & Universities, College or Technical Schools.	8	14	12		8		2	<b>36</b>

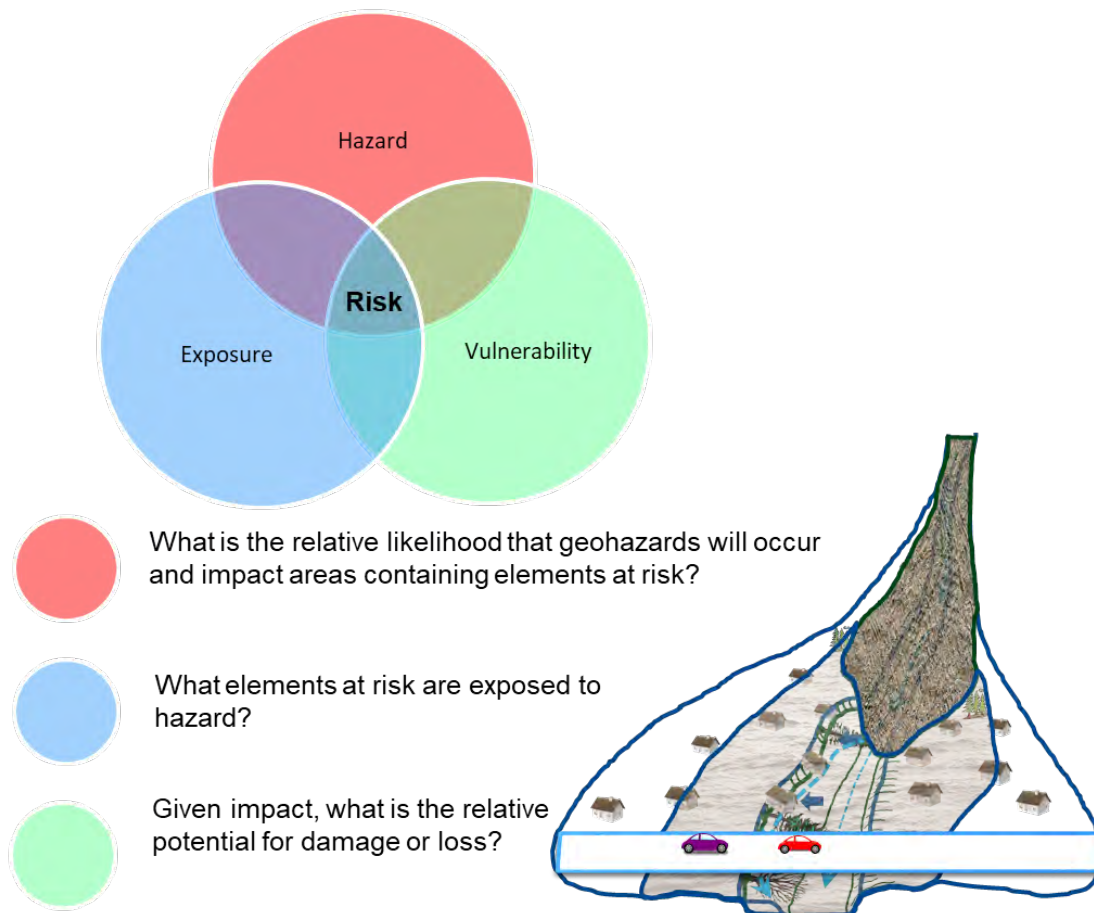
## 5.0 GEOHAZARD RISK RATINGS

### 5.1 Introduction

Figure 5-1 illustrates the three components of the risk rating framework used in this study: hazard, exposure, and vulnerability. The combination of exposure and vulnerability represents consequences, and all three components together represent risk. Each of these components is estimated separately and combined to form a priority rating for a given site.

The risk rating framework used in this study reflects the following principles:

- Support decision making, but with the recognition that additional factors for risk management and policy making exist that are outside the scope of this assessment
- Provide results to incorporate into steep creek and river risk management policy
- Provide a framework that can be expanded to other types of geohazards (i.e., landslides)
- Apply an approach that can be refined and improved in the future without duplicating effort.



**Figure 5-1 Elements of the prioritization approach.**

The approach uses matrices to arrive at separate ratings for hazard and consequence, which are then combined to provide a risk priority rating for each hazard area. This three-part

approach facilitates risk management planning and policy implementation in that it is relatively simple while still identifying each factor contributing to risk.

The results are aggregate ratings that support, but do not replace, more detailed risk management and resiliency planning. Inputs used to generate each rating are provided on the web map and via data services and downloads. These original data can be used to include additional or different combinations of factors in risk management plans.

Sections 5.2 to 5.4 summarize steps to assign geohazard, consequence, and risk ratings for each geohazard area. Section 5.5 provides details about wildfire-adjusted risk ratings.

## 5.2 Geohazard Rating

Table 5-1 presents the categorical geohazard rating system used in this study. It combines hazard and impact likelihood ratings to rate the potential for events to occur and – if they occur – impact elements at risk. The ratings assume that elements at risk are present within the hazard zone at the time of impact, as would be expected for buildings, lifelines, critical facilities, and other immobile features that are the subject of this study.

**Table 5-1. Geohazard rating.**

Hazard Likelihood	Geohazard Rating				
Very High	M	H	H	VH	VH
High	L	M	H	H	VH
Moderate	L	L	M	H	H
Low	VL	L	L	M	H
Very Low	VL	VL	L	L	M
<b>Impact Likelihood</b>	Very Low	Low	Moderate	High	Very High

Table 5-2 describes how hazard and impact likelihood were defined for each hazard type. Table 5-3 defines approximate frequency and return period ranges for hazard likelihood categories<sup>7</sup>.

**Table 5-2. Definitions of hazard likelihood and impact likelihood for the geohazard types assessed.**

Factor	Geohazard Type	Definition
Hazard Likelihood	Steep creeks and volcanic geohazards.	Likelihood of a geohazard event of enough magnitude to potentially impact elements at risk.
	Clear-water floods	0.5% AEP (200-year) flood

<sup>7</sup> Note that geohazard events outside the ranges shown are possible, such as the occurrence of extremely rare events. The categories included reflect the objectives of this study and types of geohazards assessed.

Factor	Geohazard Type	Definition
Impact Likelihood	Steep creeks and volcanic geohazards.	Estimated likelihood of an uncontrolled flow reaching elements at risk, given that a geohazard event occurs.
	Clear-water floods	Assumed impact likelihood of High (Table 5-1) within the flood extent, given occurrence of the 0.5% AEP (200-year) flood.

**Table 5-3. Annual Exceedance Probability (AEP) ranges and representative categories.**

Geohazard Likelihood	AEP Range (%) <sup>(1)</sup>	Representative AEP	Representative Return Period (years)
Very High	>10%	20%	5
High	>10% - <3.3%	5%	20
Moderate	>3.3% - 1%	2%	50
Low	>1% - <0.33%	0.5%	200
Very Low	<0.33% - 0.1%	0.2%	500

Note:

1. AEP ranges are consistent with those identified in EGBC (2018).

### 5.3 Consequence Rating

Consequence combines the value of the element at risk with its vulnerability to damage or loss, given impact by that hazard. Formally, it is the conditional probability that elements at risk will suffer some severity of damage or loss, given geohazard impact with a certain severity. In detailed studies, consequences can be measured qualitatively or quantitatively for areas such as public safety (i.e., probability of loss of life), economic loss, services disruption, environmental loss, or social loss (culture, loss of security) (United Nations, 2016; UNISDR, 2015).

The same principles apply to this study, but with some simplification that reflects the level of detail of assessment. Consequence ratings were assigned that compare the relative *potential* for loss between hazard areas, given hazard impact. They consider the presence and value of elements at risk within the hazard area, and the intensity of flows that could impact elements at risk. Higher value or greater number of elements at risk, combined with the potential for more highly destructive flows, results in a higher consequence rating for a given area.

Table 5-4 displays the matrix used to assign consequence ratings, based on two factors rating the exposure of elements at risk (exposure rating) to destructive flows (vulnerability rating). Appendix E, Appendix F, Appendix G and Appendix H describe methods used to assign values to each rating, for each process type. The two axes help clarify the source of consequence for mitigation planning. For example, land use and emergency response planning can manage hazard exposure (vertical access), whereas risk control measures (i.e., increased flood storage) can control hazard intensity (horizontal axis).

**Table 5-4. Relative consequence rating.**

Hazard Exposure	Relative Consequence Rating				
Very High	M	H	H	VH	VH
High	L	M	H	H	VH
Moderate	L	L	M	H	H
Low	VL	L	L	M	H
Very Low	VL	VL	L	L	M
<b>Hazard Intensity</b>	Very Low	Low	Moderate	High	Very High

## 5.4 Risk Rating

Table 5-5 displays a matrix used to rate each geohazard area based on geohazard (Table 5-1) and consequence (Table 5-4).

The original data used to generate each rating are provided on the web map, as geospatial data provided with the study, and as part of the results spreadsheets provided in Appendix K. These inputs can be used to consider additional or different combinations of factors in risk management plans, beyond the aggregate risk rating.

**Table 5-5. Prioritization matrix (assets).**

Geohazard Rating	Risk Rating				
Very High	M	H	H	VH	VH
High	L	M	H	H	VH
Moderate	L	L	M	H	H
Low	VL	L	L	M	H
Very Low	VL	VL	L	L	M
<b>Consequence Rating</b>	Very Low	Low	Moderate	High	Very High

BGC notes that risk ratings are intended to be used by the SLRD as a regional planning tool where some ratings, such as hazard exposure, are ranked relative to district-wide data (e.g., where “high” means relatively high in relation to other hazard areas). When viewing results, it is helpful to view the supporting inputs to understand why a hazard area received a particular rating.

BGC also notes that the geohazard areas are not identical in areal extent. This means that – all else being equal – larger areas rank higher where they contain more elements at risk. The approach reflects the notion of “consultation zones”, which define a geographic area considered for geohazard safety assessment (GEO, 1998; Porter et al., 2009). In landslide safety



assessments, a consultation zone “includes all proposed and existing development in a zone defined by an approving authority that contains the largest credible area affected by landslides, and where fatalities arising from one or more concurrent landslides would be viewed as a single catastrophic loss” (Porter et al., 2009). This definition can be generalized across geohazard types (i.e., not only landslides) and consequences (i.e., not only fatalities). The chosen approach reflects societal perception of risk, where higher priority areas are those where there is a greater chance of more significant consequences. For steep creeks, the consultation zone is the prioritized fan. For clear-water floods, geographic areas were selected based on geohazard characteristics, specifically sub-catchment areas and consideration for community boundaries.

## 5.5 Wildfire-Adjusted Risk Ratings

Wildfires in steep mountainous terrain are often followed by a temporary period of increased geohazard activity. For steep creeks, changes in hydrologic response can increase the likelihood or peak discharge of debris floods or debris flows compared to baseline conditions.

To measure how wildfires could affect steep creek risk compared to baseline (existing) conditions, BGC defined a “wildfire-adjusted risk” rating for steep creek geohazard areas in the District.

The framework for the wildfire-adjusted risk ratings was to:

1. Modify the basin activity rating to reflect the likelihood of a wildfire-related hydrogeomorphic process to be initiated in the steep creek watershed. The modified basin activity rating affects the geohazard likelihood and also the geohazard rating.
2. Modify the baseline hazard intensity to reflect a wildfire-related hydrogeomorphic process, based on an assumed burn scenario. The modified intensity adjusts the consequence rating.

Appendix F provides a detailed methodology for estimating wildfire-adjusted geohazard likelihood, intensity, and associated risk ratings. A brief description of the methodology is provided in the following sections.

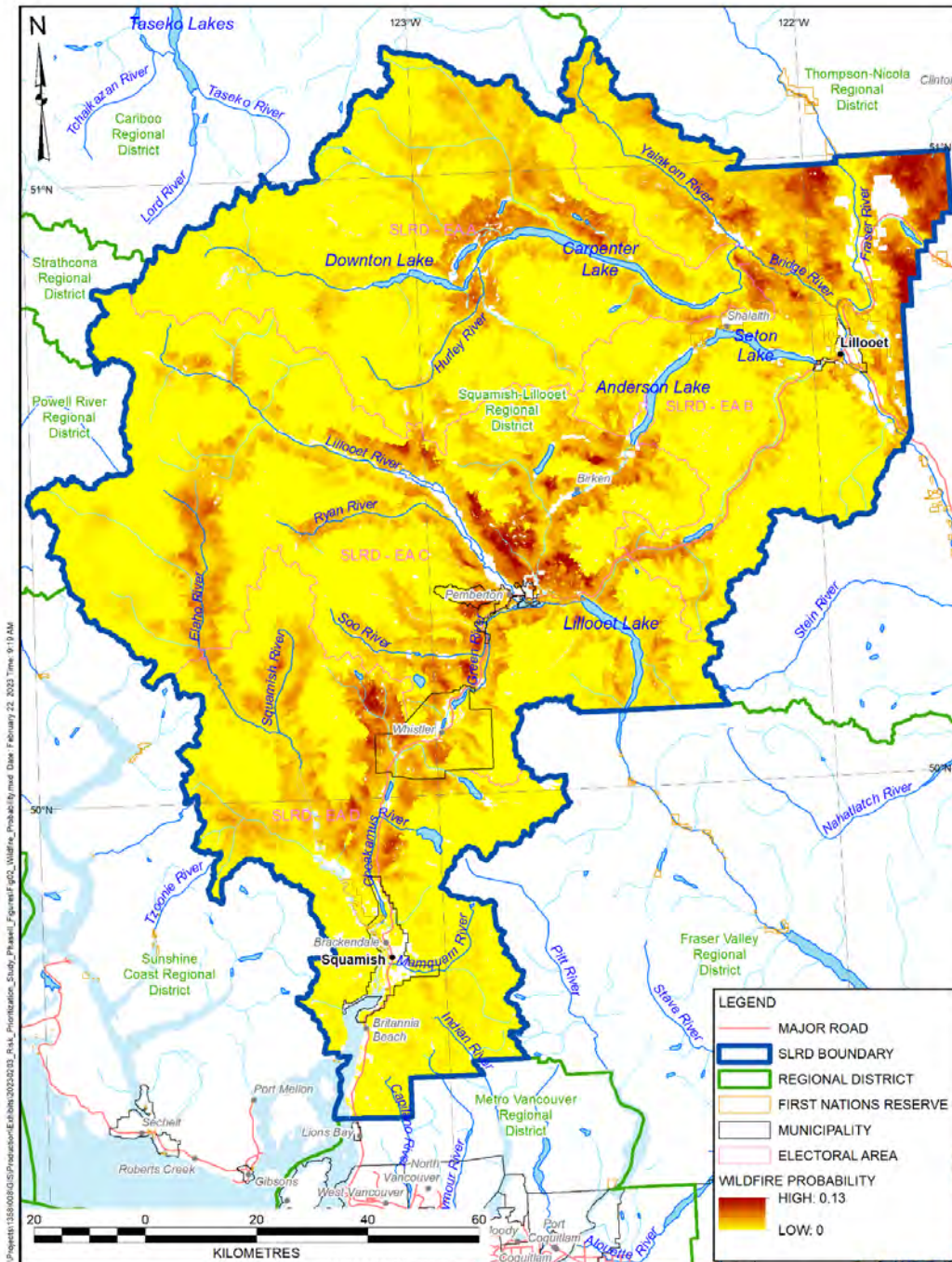
### 5.5.1 Wildfire-adjusted geohazard likelihood rating

To estimate the likelihood of a wildfire related hydrogeomorphic process in a steep creek watershed, burn probability modeling provided by the B.C. Wildfire Service were incorporated into the basin activity rating (see Appendix F). The burn probability map was provided by the BC wildfire service (on December 01, 2021) and created using the Burn-P3 software. The Burn-P3 software uses inputs characterizing fuels (e.g., vegetation), topography, weather and patterns of fire ignitions throughout BC. Burn probabilities in BC range from 0 to 0.45. Within the SLRD, burn probabilities range from 0 to 0.13 (Figure 5-2).

The weighted average of the burn probability in each watershed was used as a proxy for the likelihood of post-wildfire hydrogeomorphic event (i.e., a debris flow, debris flood or flood)

occurring in that watershed. This likelihood of post-wildfire hydrogeomorphic event was linked to the basin activity rating to arrive at a wildfire-adjusted geohazard likelihood rating.

Figure 5-3 provides an example of how a watershed with a moderate wildfire probability (between 0.005 and 0.2) would increase the geohazard likelihood rating by two classes and consequently the geohazard rating from Low to Moderate.



**Figure 5-2. Wildfire probability map for the SLRD. Burn probabilities were estimated by the BC Wildfire Service using the Burn P3 software. BC Wildfire Service provided these data and redacted data in private property parcels.**

Geohazard Likelihood	Geohazard Rating <span>?</span>				
Very High	Moderate	High	High	Very High	Very High
High	Low	Moderate	High	High	Very High
Moderate	Low	Low	Moderate	High	High
Low	Very Low	Low	Low	Moderate	High
Very Low	Very Low	Very Low	Low	Low	Moderate
Impact Likelihood	Very Low	Low	Moderate	High	Very High

**Figure 5-3.** Example of how the geohazard likelihood rating would increase for watershed with a high average burn probability (between 0.05 and 0.2) and result in a geohazard rating increasing from Low to Moderate.

### 5.5.2 Wildfire-adjusted Hazard Intensity Rating

Following wildfire, flow magnitudes can increase because the decreased infiltration capacity of the burned watershed can increase runoff during rainfall. An empirical model for estimating post-wildfire debris-flow volume was used to estimate debris-flow volumes for the debris-flow prone creeks in the SLRD (Gartner et al., 2014). The volumes were converted to peak discharges using the empirical volume-peak discharge relationships (presented in Appendix F) and used as input for estimating the wildfire-adjusted hazard intensity ratings.

Figure 5-4 demonstrates how a wildfire-related increase in hazard intensity rating would contribute to increasing the consequence rating.

Hazard Exposure	Relative Consequence Rating <span>?</span>				
Very High	Moderate	High	High	Very High	Very High
High	Low	Moderate	High	High	Very High
Moderate	Low	Low	Moderate	High	High
Low	Very Low	Low	Low	Moderate	High
Very Low	Very Low	Very Low	Low	Low	Moderate
Hazard Intensity	Very Low	Low	Moderate	High	Very High

Figure 5-4. Example of how the relative consequence rating would be affected by a change in the estimates of hazard intensity rating that consider wildfire potential.



## 6.0 RESULTS

### 6.1 Overview

This study provides results in several ways:

- This report section provides a summary overview of results.
- Cambio ([www.cambiocommunities.ca](http://www.cambiocommunities.ca)) displays all geohazard areas and is the easiest way to interact with study results. Users can see large areas at a glance or view results for a single site. Appendix I provides a guide to navigate Cambio.
- Appendix J provides the example RAIT form required by the National Disaster Mitigation Program (NDMP).
- Appendix K provides an Excel spreadsheet with tabulated results.
- Data download of attributed geohazard areas in geodatabase format.

In total, BGC rated 2328 geohazard areas encompassing about 1668 km<sup>2</sup> of the SLRD (Table 6-1). Table 6-2 lists the results worksheets provided in Appendix K, and Figure 6-1 provides summary statistics by jurisdiction.

**Table 6-1. Number of risk-rated areas in the SLRD, by geohazard type.**

Geohazard Type		Risk Level					Grand Total
		Very High	High	Moderate	Low	Very Low	
Clear-Water Floods Waterbody (subtotal)		0	12	7	19	0	38
Clear-Water Floods Watercourse (subtotal)		0	83	70	1654	0	1807
Steep Creeks (Fans)	Baseline rating	21	107	98	220	25	471
	Wildfire-adjusted rating	23	148	115	220	10	
Volcanic Geohazards		0	12	0	0	0	12
<b>Baseline Risk Ratings Total (Count)<sup>1</sup></b>		<b>21</b>	<b>214</b>	<b>175</b>	<b>1893</b>	<b>25</b>	<b>2328</b>
<b>Grand Total (%)<sup>1</sup></b>		<b>1</b>	<b>9</b>	<b>8</b>	<b>81</b>	<b>1</b>	<b>100</b>

Note:

1. The totals (count and %) consist of the clear-water floods, steep creeks-baseline rating and volcanic geohazards.

**Table 6-2. Results worksheets provided in Appendix K.**

Appendix K (Excel Worksheet Name)	Contents
Study Area Metrics	Summary statistics of select elements at risk (count of presence in geohazard areas).
Study Area Hazard Summary	Summary statistics of elements at risk, according to their presence in geohazard areas.
Study Area Hazard Type Summary	Summary statistics of geohazard areas, according to the presence of elements at risk.
Priority by Jurisdiction Baseline	Summary statistics of risk rating results by jurisdiction for the baseline risk scenario (digital version of Table 6-1).
Priority by Jurisdiction Fire-Adjusted	Summary statistics of risk rating results by jurisdiction for the wildfire-adjusted (steep creek) risk scenario (digital version of Table 6-1).
Priority by First Nation Baseline	Summary statistics of risk rating results by First Nation Reserve for the baseline risk scenario
Priority by First Nation Fire-Adjusted	Summary statistics of risk rating results by First Nation Reserve for the wildfire-adjusted (steep creek) risk scenario
Steep Creek Hazard Baseline	Attributes displayed in the information sidebar on <i>Cambio</i> for all steep creek geohazard areas for the baseline risk scenario
Steep Creek Hazard Fire-Adjusted	Attributes displayed in the information sidebar on <i>Cambio</i> for all steep creek geohazard areas for the wildfire-adjusted (steep creek) risk scenario
Clear-water Flood Hazard Attributes	Attributes displayed in the information sidebar on <i>Cambio</i> for all clear-water flood geohazard areas.
Volcanic Geohazards Attributes	Attributes displayed in the information sidebar on <i>Cambio</i> for all volcanic geohazard areas.
Hazard Metrics Baseline	Summary of rating, hazard, consequence, exposure scores for each hazard for the baseline risk scenario
Hazard Metrics Fire-Adjusted	Summary of rating, hazard, consequence, exposure scores for each hazard for the wildfire-adjusted (steep creek) risk scenario



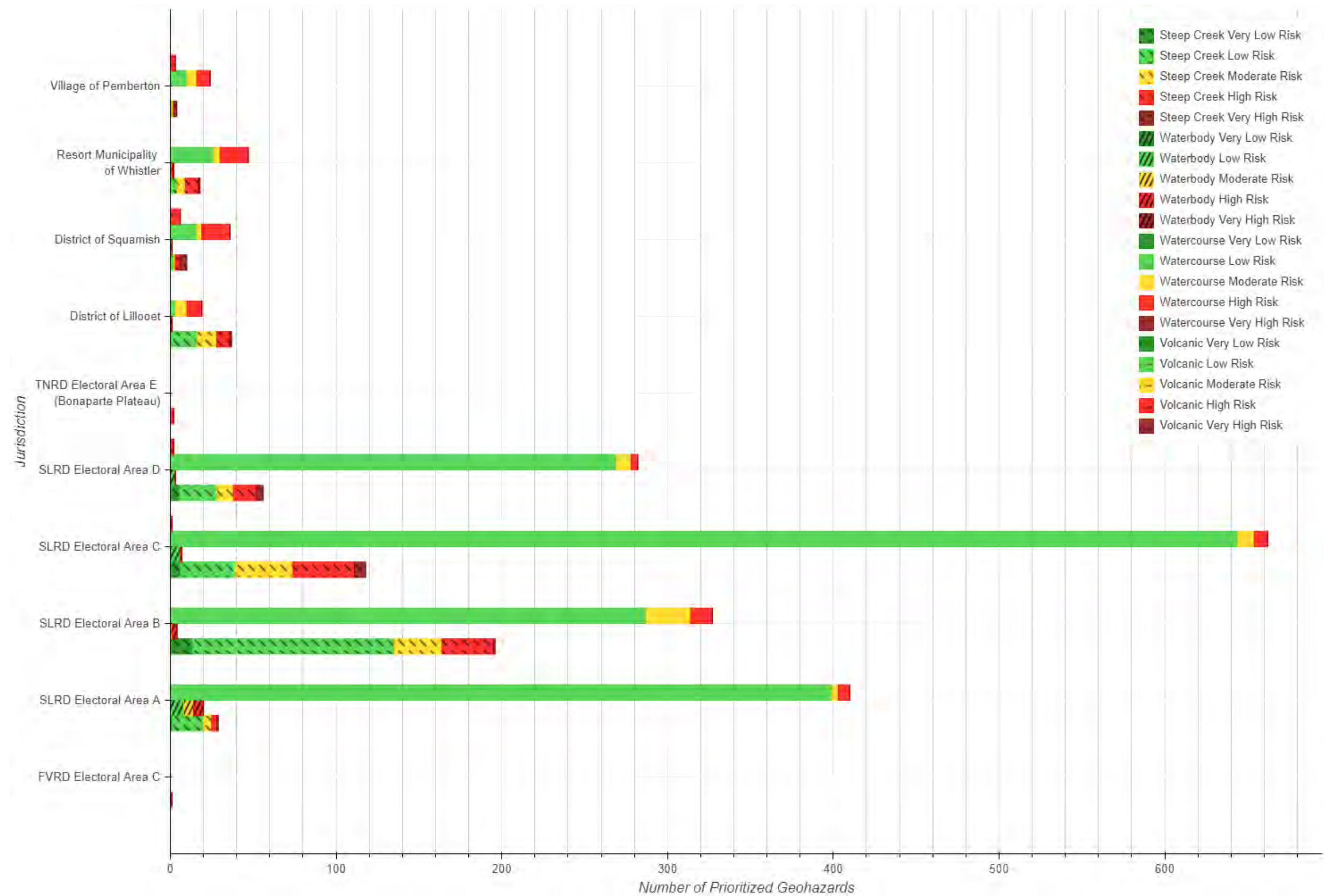
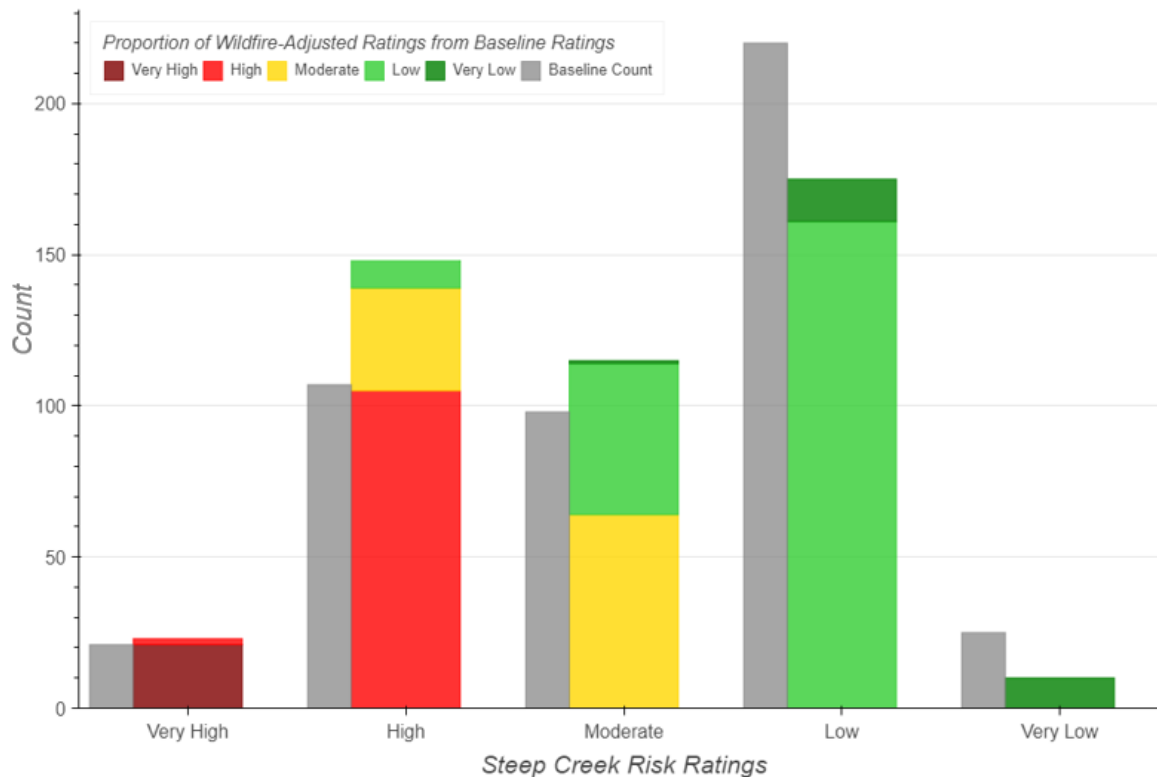


Figure 6-1. Number of risk rated geohazards in each jurisdiction within the SLRD.

## 6.2 Wildfire-adjusted (Steep Creek) Ratings

The results spreadsheet provided in Appendix K identifies steep creek hazard areas where ratings have changed once wildfires were considered as a risk factor. In summary, wildfires can increase the frequency and/or magnitude of steep creek hazards (Section 5.5). Areas with greater change generally correspond to geographic areas with higher wildfire probability, such as valley bottoms and the northeastern portion of the district (Figure 5-2).

Figure 6-2 compares baseline and wildfire-adjusted Combined Priority Ratings<sup>8</sup>. Wildfire-adjusted Combined Priority Ratings were higher for 110 sites compared to baseline conditions, of which 10 sites increased by 2 categories (e.g., from Low to High). Wildfire-adjusted Community Priority Ratings<sup>9</sup> were higher for 115 sites compared to baseline conditions, of which 9 sites increased by 2 categories. Table 6-3 highlights hazard areas that see the greatest increase (2 categories) in Community Priority Ratings when adjusted to consider wildfires as a risk factor.



**Figure 6-2. Wildfire-adjusted ratings compared to baseline ratings for steep creeks.**

<sup>8</sup> “Combined” priority ratings consider all inventoried elements at risk (Section 4.0).

<sup>9</sup> “Community” priority ratings consider the Community asset group and exclude Lifelines (Section 4.0)

**Table 6-3. Steep Creek Hazard Areas where Community Priority Rating increases by two levels from Baseline to Wildfire-Adjusted conditions.**

Hazard Name	Hazard Code	Geohazard Process	Community Priority Rating (Baseline)	Community Priority Rating (Wildfire-Adjusted)
Sumner Creek	10247	Debris Flow	Low	High
Birkenhead River Tributary 11	10255	Debris Flow	Low	High
Gates River Tributary 7	10264	Debris Flow	Low	High
Blackwater Creek	10266	Debris Flood	Low	High
Fred Creek	10282	Debris Flow	Low	High
Birkenhead River Tributary 6	65937	Debris Flow	Low	High
Birkenhead River	66147	Flood	Low	High

1. Garibaldi Creek (#10188) and Fountain Creek Tributary 11 (#66010) also increased by two levels, but are not included in Table 6-3 due to the limited assets present on these fans.

The Priority Ratings shown in Figure 6-2 and Table 6-3 combine changes related to frequency and magnitude. Considered separately, wildfire-adjusted geohazard likelihood ratings were higher than the baseline scenario at 184 steep creeks. Wildfire-adjusted geohazard intensity ratings were higher than the baseline scenario at 67 steep creeks. Wildfire-adjusted Community Priority Risk increased at 115 sites due to increases to only the geohazard likelihood rating (78 sites), increases to only the intensity rating (18 sites), or increases to both the geohazard likelihood and intensity ratings (19 sites).

Figure 6-3 provides an example of Brandywine Creek, where the wildfire-adjusted risk rating was higher than the baseline risk rating due to an increase in hazard intensity (approximated by the peak discharge). Figure 6-4 provides an example of Felix Creek, where the wildfire-adjusted risk rating was higher than the baseline risk rating due to an increase in the geohazard likelihood rating.



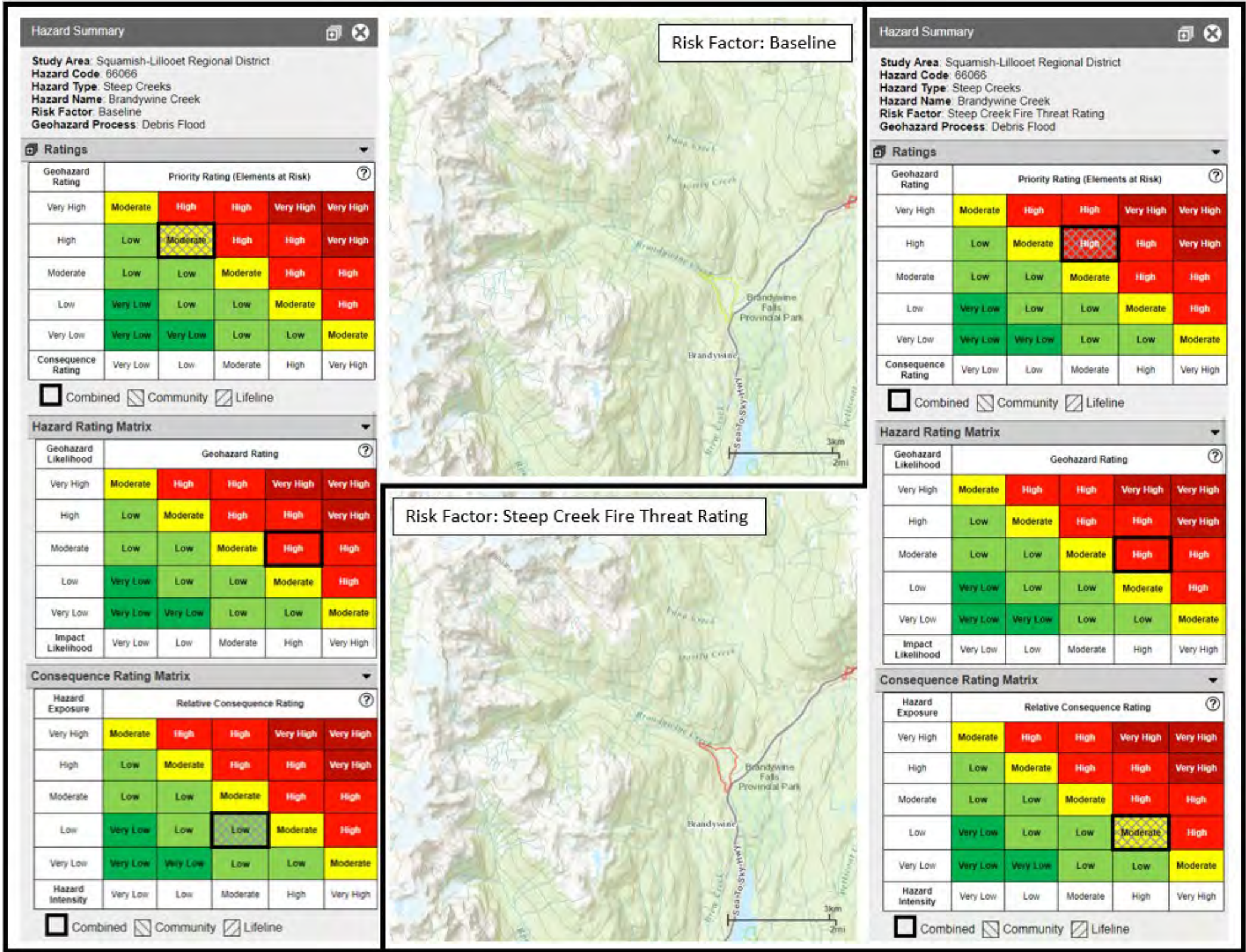


Figure 6-3. Baseline (left panel) and wildfire-adjusted (right panel) risk [priority] ratings for Brandywine creek. For this creek, the increase in risk was caused by an increase in estimated post-wildfire hazard intensity, from “low” to “moderate.”



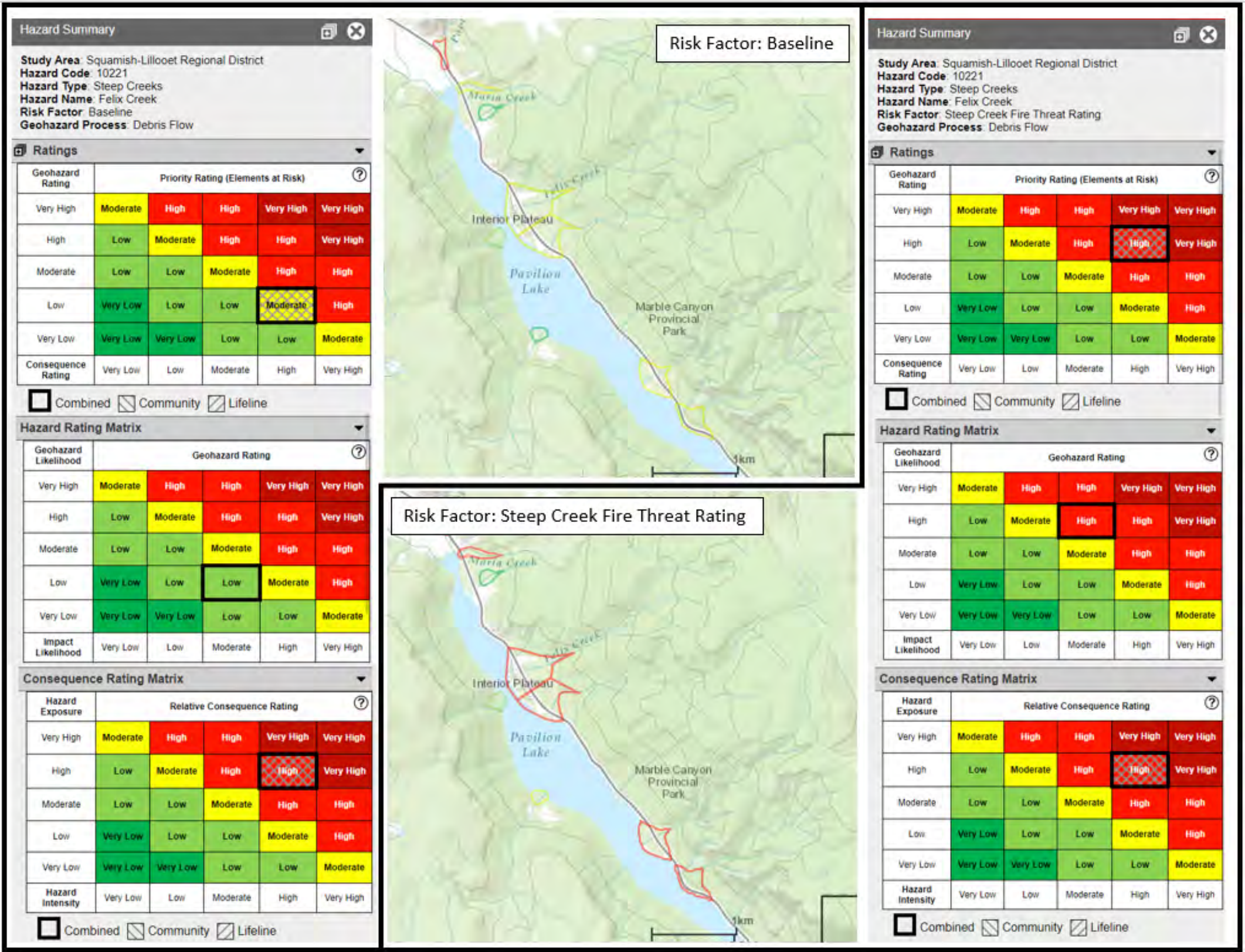


Figure 6-4. Baseline (left panel) and wildfire-adjusted (right panel) risk [priority] ratings for Felix creek. For this creek, the increase in risk was caused by an increase in estimated post-wildfire hazard likelihood, from “low” to “high.”

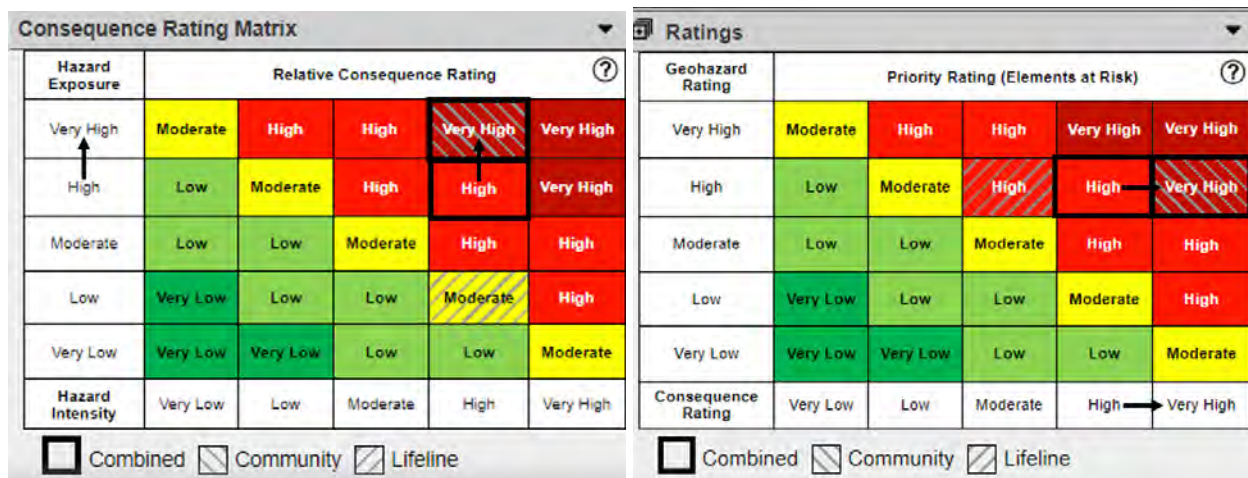
### 6.3 Hazard Exposure: First Nations Reserves

As explained in Section 4.0, the hazard exposure assessment in the current risk study updates integrated building improvement values on First Nation reserves, and social vulnerability values for the entire study area (both on and off reserve). Appendix K provides the complete list of results for all geohazard areas, organized by hazard type and jurisdiction.

Including Total Improvement Value (building costs) data on First Nation reserves added approximately \$95M to the total estimated value of buildings in inventoried geohazard areas.

First Nations reserves intersecting at least 50% of a steep creek hazard area had an average social vulnerability score 65% higher than other areas in the SLRD (off reserve) (score of 4.8 vs. 2.9). After providing the social vulnerability score weightings, this increased the hazard exposure scores by an average of 5 points. This relatively small shift resulted in ratings adjustments where scores were close to category thresholds and experienced relatively higher change than other areas.

Figure 6-5 shows how an adjustment to the Hazard Exposure Score can change the Priority Rating.



**Figure 6-5. Consequence Rating and Priority Rating Matrix showing an increase in their ratings due to an increase in the Hazard Exposure Score (black arrows).**



## 7.0 RECOMMENDATIONS

Table 7-1 lists the types of recommendations for consideration by SLRD and local, regional, and provincial authorities. Appendix L expands on each recommendation type listed in Table 7-1. BGC encourages SLRD and stakeholders to review this assessment and web tools from the perspective of supporting long-term geohazard risk and information management. Long-term provincial support could facilitate cooperation and efficiency between different regional districts using common web tools for geohazard risk and information management.

**Table 7-1. List of recommendations.**

Type	Description
Data Gaps	<ul style="list-style-type: none"> <li>Continue work to resolve gaps and manage changes related to baseline data; geohazard sources, controls, and triggers; geohazard frequency-magnitude relationships, flood protection measures and flood conveyance infrastructure, and hazard exposure (elements at risk).</li> <li>Incorporate traditional and local knowledge into hazard assessments.</li> </ul>
Further Geohazards Assessments	<ul style="list-style-type: none"> <li>Geohazard areas: review prioritized geohazard areas and develop a plan to implement next steps in a geohazard risk management framework.</li> <li>Areas that would benefit from improved hazard and risk assessments include: <ul style="list-style-type: none"> <li>Birken-D'Arcy corridor (e.g., Gates River, Neff, Poole, Landsborough, and Young John Creeks,).</li> <li>Resort Municipality of Whittier (e.g., Alta Creek and Lake, Nineteen Mile Creek)</li> <li>Village of Lillooet (Seton and Fraser River)</li> <li>Lil'wat Nation (steep creeks draining Lil'wat Mountain).</li> </ul> </li> <li>If a wildfire occurs in one of the watersheds associated with a hazard area assessed in this study, complete more detailed assessment to refine the estimates provided in this study based on actual wildfire severity conditions in the watershed area.</li> </ul>
Post-wildfire Geohazards Assessments	<ul style="list-style-type: none"> <li>Following a wildfire, detailed post-wildfire geohazard assessment can be performed to provide more specific information on geohazard likelihood, magnitude, inundation area and intensity.</li> <li>Post-wildfire geohazard assessment following wildfire can reflect the actual burn severity conditions in the steep hillslopes and watersheds where geohazards can initiate.</li> </ul>
Long-term Geohazard Risk Management	<ul style="list-style-type: none"> <li>Consider long-term geohazard risk management programs that would build on the results of this study.</li> </ul>
Geohazards Monitoring	<ul style="list-style-type: none"> <li>Develop criteria for hydroclimatic monitoring and alert systems informing emergency management.</li> </ul>
Policy Integration	<ul style="list-style-type: none"> <li>Review Development Permit Areas (DPAs) following review of geohazard areas defined by this study.</li> <li>Review plans, policies and bylaws related to geohazards management, following review of the results of this study.</li> <li>Develop risk evaluation criteria that allow consistent risk reduction decisions (i.e., that define the term "safe for the use intended" in geohazards assessments for development approval applications).</li> </ul>

Type	Description
Information Management	<ul style="list-style-type: none"><li>• Review approaches to integrate and share asset data and geohazard information across functional groups in government, stakeholders, data providers and risk management specialists. Such an effort would assist long-term geohazard risk management, asset management, and emergency response planning.</li><li>• Develop a maintenance plan to keep study results up to date as part of ongoing support for bylaw enforcement, asset management, and emergency management.</li></ul>
Engagement	<ul style="list-style-type: none"><li>• Provide training to SLRD staff who may rely on study results, tools and data services.</li><li>• Work with communities in the prioritized hazard areas to develop flood resiliency plans informed by stakeholder engagement.</li></ul>
Indigenous Knowledge Gathering	<ul style="list-style-type: none"><li>• Complete further work to resolve remaining gaps about culturally significant areas and risk considerations beyond primarily economic values considered in the current approaches. Indigenous-led projects should be explored as a process through which First Nations perspectives can be most directly incorporated.</li></ul>

## 8.0 CLOSURE

This report contains sections under the supervision of different individuals. Joseph Gartner and Carie-Ann Lau are the responsible authors for the geohazard assessment portions of the geohazard risk ratings for baseline and wildfire-adjusted steep creek ratings (Sections 3.0, 5.2 and 5.5. Kris Holm is the responsible author for the exposure assessment, geohazard risk ratings, results, and recommendations (Sections 4.0, 5.3, 5.4 6.0, and 7.0).

Should you have any questions or comments, please do not hesitate to contact us.

Yours sincerely,

**BGC Engineering Inc.**  
per:

A circular professional seal for a geoscientist in the Province of British Columbia. The seal contains the text "PROFESSIONAL GEOSCIENTIST", "PROVINCE OF BRITISH COLUMBIA", and "K. W. HOLM". A handwritten signature is written over the seal, and the date "Apr 24, 2023" is written to the right.

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

A circular professional seal for an engineer in the Province of British Columbia. The seal contains the text "PROFESSIONAL ENGINEER", "PROVINCE OF BRITISH COLUMBIA", and "DR. J. E. GARTNER # 163308". A handwritten signature is written over the seal, and the date "Apr 24, 2023" is written to the right.

Joseph Gartner, Ph.D., P.Eng.  
Senior Geological Engineer

Carie-Ann Lau, M.Sc., P.Geo.  
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Reviewed by:

Matthieu Sturzenegger, Ph.D. P.Geo.  
Senior Engineering Geologist

EGBC Permit to Practice, BGC Engineering Inc. 1000944

KH/MS/sf/mm

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# APPENDIX A

## TERMINOLOGY





## A-1 TERMINOLOGY

This report refers to the following key definitions<sup>1</sup>:

- **Asset:** anything of value, including both anthropogenic and natural assets<sup>2</sup>, and items of economic or intangible value.
- **Annual Exceedance Probability (AEP):** chance that a flood magnitude is exceeded in any year. For example, a flood with a 0.5% AEP has a one in two hundred chance (i.e., 200-year return period) of being exceeded in any year. While AEP is increasingly replacing the use of the term 'return period' to describe flood recurrence intervals, both terms are used in this document.
- **Clear-Water Floods:** 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. While called "clear-water floods", such floods still transport sediment. This term serves to differentiate from other flood forms such as landslide dam outburst floods, floods on alluvial fans or debris floods. Appendix E provides a comprehensive description of clear-water floods.
- **Steep-Creek Processes:** rapid flow of water and debris in a steep channel, often associated with avulsions and strong bank erosion. Most stream channels within the SLRD are tributary creeks subject to steep creek processes that carry larger volumetric concentrations of debris than clear-water floods. Steep creek processes are used in this report as a collective term for floods on alluvial fans, debris flows, and debris floods. Appendix F provides a comprehensive description of steep creek processes.
- **Consequence:** formally, the conditional probability that elements at risk will suffer some severity of damage or loss, given geohazard impact with a certain intensity (destructive potential). In this study, the term was simplified to reflect the level of detail of assessment. Consequence refers to the relative potential for loss between hazard areas. Consequence ratings consider both the value of elements at risk and the intensity (destructive potential) of a geohazard, but do not provide an absolute estimate of loss.
- **Elements at Risk:** assets exposed to potential consequences of geohazard events.
- **Exposure Model:** organized geospatial data about the location and characteristics of elements at risk.
- **Burn Severity:** A measure of amount of heat experienced by the soil during a wildfire. Burn severity is approximated by the amount of combustion in the tree canopy, forest litter and duff, and soil. Burn severity can be used to approximate the amount of change to the hydrology of a watershed caused by a fire (see Appendix F).
- **Burn Probability:** A measure of the annual probability of a wildfire at a specific location. Burn probability can be estimated based on forest type, climatic conditions, and number of potential ignition sources (see Appendix F).

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<sup>1</sup> CSA (1997), EGBC (2017; 2018).

<sup>2</sup> Assets of the natural environment: these consist of biological assets (produced or wild), land and water areas with their ecosystems, subsoil assets and air (UNSD, 1997).

- **Flood Mapping:** delineation of 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.
- **Geohazard:** all geophysical processes with the potential to result in some undesirable outcome, including floods and other types of geohazards.
- **Hazardous Flood:** a flood that is a source of potential harm.
- **Resilience:** the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to, and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions.
- **Risk:** a measure of the probability of a specific geohazard event occurring and the consequence of that event.
- **Strahler Stream Order:** a classification of stream segments by their branching complexity within a drainage system. Strahler stream order is an indication of the significance in size and water conveying capacity at points along a river (Figure A-1).
- **Waterbody:** ponds, lakes and reservoirs.
- **Watercourse:** creeks, streams and rivers.

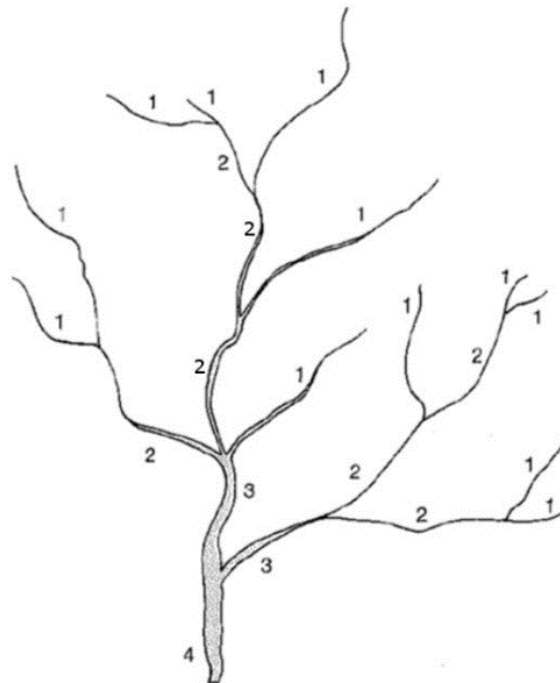


Figure A-1. Illustration showing Strahler stream order (Montgomery, 1990).

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# APPENDIX B

## BACKGROUND INFORMATION



## **B-1 OVERVIEW**

This appendix provides background information on topography, geology, climate and hydrology in the SLRD. The information provided herein was incorporated into the site analyses to estimate regional geohazard risk.

## **B-2 TOPOGRAPHY**

The resolution of topographic data is a dominant control on the precision and accuracy of geohazard location, extent, likelihoods, and intensity estimates. Low resolution (approximately 25 m) Canadian Digital Elevation Model (CDEM)<sup>1</sup> data were used for this study in areas without Lidar coverage.

### **B-2.1 Physiography and Ecoregions**

The SLRD is located mostly within the Coast Mountain physiographic region<sup>2</sup> with a small portion of the northeastern corner transitioning into the Interior Plateau physiographic region (Holland, 1976). As defined by DeMarchi (2011), the SLRD encompasses three ecoregions, which are areas of major physiographic and minor climatic variation (Figure B-1). Table B-1 outlines the characteristics of each ecoregion and associated ecosection.

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<sup>1</sup> CDEM resolution varies according to geographic location. The base resolution is 0.75 arc second along a profile in the south-north direction and varies from 0.75 to 3 arc seconds in the east-west direction, depending on location. In the SLRD, this corresponds to approximately 25 m grid cell resolution (Government of Canada, 2016).

<sup>2</sup> Referring to landforms and geology.

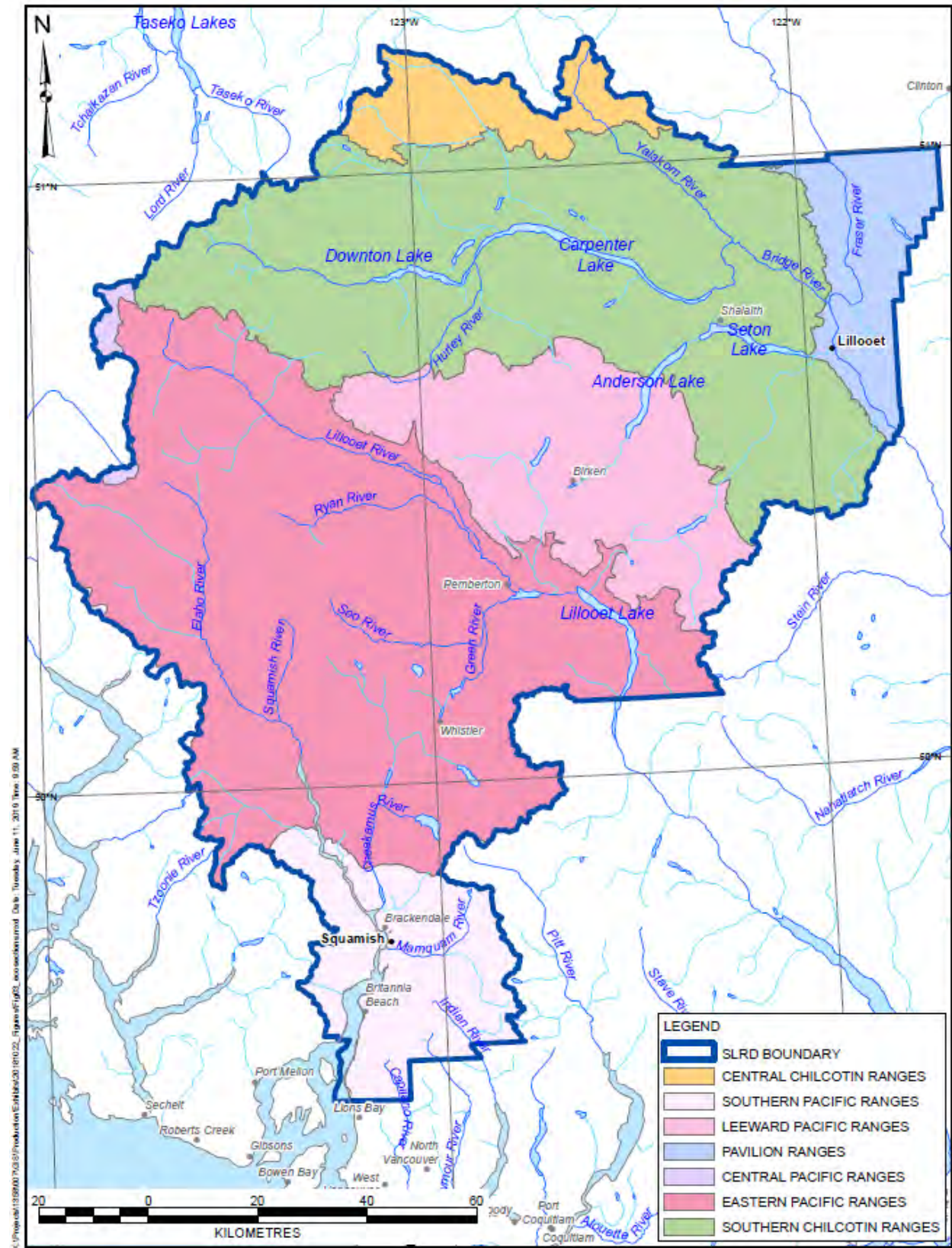


Figure B-1. Ecosections within the SLRD (DeMarchi, 2011).



**Table B-1. Ecoregions and ecosections of the SLRD (as defined by Demarchi, 2011 and shown on Figure B-1).**

Ecoregion	Ecosection	Area Within SLRD (km <sup>2</sup> )	Physiography	Climate	Major Watersheds	Vegetation
Pacific Ranges	Eastern Pacific Ranges	6,500	High, rugged mountains with large icefields, some narrow valleys and canyons. Granitic rocks. Some of the most recent volcanoes in BC.	Transitional wet mild coast and dry cold interior climates including some strong rain shadows.	Lillooet River, Squamish, Cheakamus, Coquihalla.	Valleys Coastal Western Hemlock, sub-alpine Mountain Hemlock.
	Southern Pacific Ranges	1,300	Bold, rugged mountains with fjords and fjord-lakes. Granitic rocks.	Summer – dry and warm, occasional rainy periods Winter – heavy rain and snow	Howe Sound, Squamish, Pitt River.	Valleys Coastal Western Hemlock, sub-alpine Mountain Hemlock.
	Central Pacific Ranges	100	High, rugged mountains with large icefields. Granitic rocks.	Rising air hits cold air to precipitate heavy rains or snows. Can experience cold temperatures and strong winds from interior for short periods of time.	Smokehouse, Klinaklini, Homathko, Southgate, Toba.	Valleys Coastal Western Hemlock, sub-alpine Mountain Hemlock
Interior Transition Ranges	Leeward Pacific Ranges	2,000	Very rugged mountains with deep narrow valleys. Rounded landscape with cirque-basins that contain small glaciers and snowfields.	Under influence of moist Pacific air but interior systems cause dry summer and early fall.	Nahatlatch, Kwoiek, upper Stein, upper Joffre, Gates, Birkenhead, upper Donnelly, Birkenhead Lake, Duffy Lake, Nahatlatch Lake and lower Anderson Lake.	Moist coast forests in valleys, interior-type forests in sub-alpine.
	Southern Chilcotin Ranges	5,200	Foothills mountain area with high rounded mountains and deep narrow valleys. Plutonic rocks in Pacific Ranges and sedimentary and volcanic rocks in Chilcotin Ranges. Extensive ice fields.	Under rain shadow effect from coast but greatly affected by interior weather systems, especially in winters with dense Arctic air.	Bridge, Lockie, Hurley, lower Relay, lower Yalakom, Seton, Cayoosh, Texas.	Valleys Interior Douglas Fir and Montane Spruce.
	Pavilion Ranges	800	Mountainous uplands that is the transitional area between the Coast Ranges and the Interior Plateau. Limestone, basalt, chert and serpentine.	In rain shadow of Coast Mountains but hot tropical air in summer and cold Arctic air from north in winter and early spring.	Fraser River, Pavilion Creek, Kelly Creek.	Valleys of Sagebrush and Ponderosa Pine, sub-alpine Interior Douglas Fir and Montane Spruce.
Chilcotin Ranges	Central Chilcotin Ranges	700	Rounded mountains. Volcanic and sedimentary rocks. Granitic rocks along western boundary.	Dry due to Rain shadow effect from high Pacific range. Hot summers and winters experience outbreaks of Arctic air.	Upper Yalakom, Tyaughton Creek, Watson Bar Creek, Fraser River.	Dry grasslands, valleys Douglas-fir, Engelmann Spruce-Subalpine Fir, Montane Spruce, Lodgepole Pine.

Mountain ranges within the Coast Mountains region typically exhibit a northwest-southeast trend and are dissected by narrow valleys and large trenches. In the base of these trenches lie large rivers and lakes such as the Fraser River, Lillooet River, Anderson Lake, Seton Lake, Carpenter Lake, Downton Lake and Lillooet Lake. These lakes and rivers predominantly drain into the Fraser River to flow south to the Lower Mainland. The rivers in the south of the region drain to Howe Sound. Some of the lakes are regulated by dams and hydroelectric facilities (Section B-5.3).

The highest mountain ranges occur in the western part of the SLRD (Eastern Pacific Ranges Ecoregion), where the peaks contain glaciers and icefields. The mountains transition to more rounded peaks in the eastern part of the SLRD, and into the Interior Transition Ranges Ecoregion. The shift in terrain parallels a shift in precipitation patterns, from heavy rain and snow controlled by Pacific weather in the west, to a drier climate controlled by the Interior physiography in the east (DeMarchi, 2011).

The topography of the region influences both the population distribution and hydrology within the SLRD. Owing to the rugged terrain, settled areas are restricted to flatter topography, primarily floodplains and alluvial fans, in the valleys and along lakeshores. Mountainous streams can cause steep creek processes on alluvial fans, such as debris flows and debris floods. These events can be triggered by rainfall as well as rain-on-snow events. As the streams transition from the mountains to the valleys, steep creek processes transition into clear-water floods, which are typically controlled by heavy rainfall and snowmelt.

### **B-3 GEOLOGICAL HISTORY**

This section summarizes bedrock and surficial geology in the SLRD to provide context on the fundamental earth processes that built the landscape assessed in this study.

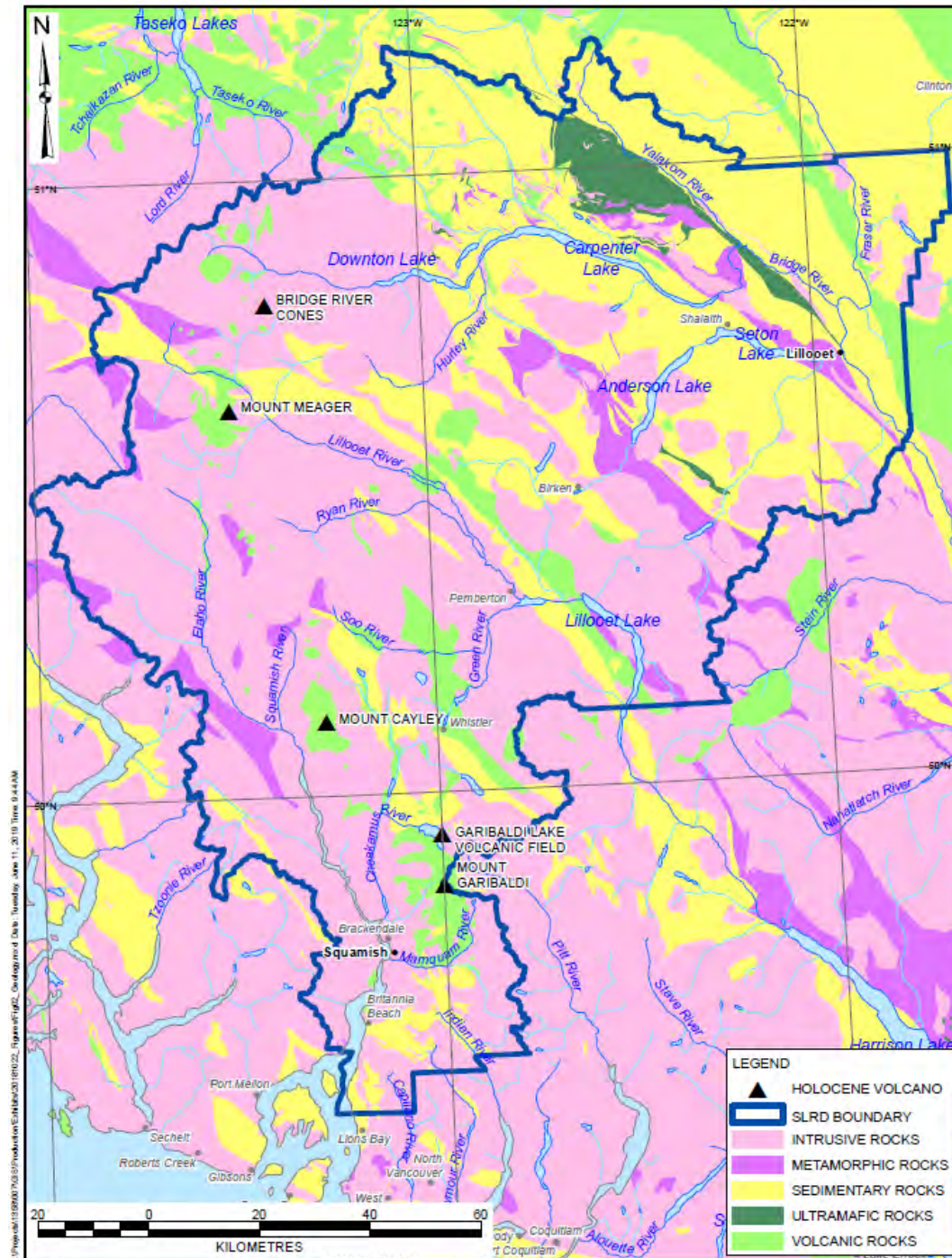
#### **B-3.1 Bedrock Geology**

The SLRD is located in the Coast Belt of the Canadian Cordillera, which contains distinct regions of different rock types. Much of what is now present as rock in the SLRD was formed when small continents began colliding with the western margin of North America nearly 200 million years ago, causing ocean sediments and older rocks to be pushed eastward and folded and faulted as they deformed (Monger & Price, 2002; Eyles & Miall, 2007; Bustin et al., 2013). Much of the SLRD has been intruded by magma that was created by the continental collision process to form what is called the Coast Mountains Batholith, a tract of granitic and gneissic rocks. Due to the magmatic activity at the continental margins, the SLRD also contains some volcanic complexes such as Mount Meager, Mount Cayley and Garibaldi Mountain.

Figure B-2 shows the distribution of the following rock types:

- Sedimentary rocks which are primarily in the northeastern part of the SLRD, including the Bridge River Complex and Jackass Mountain Group rocks (Schiarizza, 1996; Massey et al., 2005).
- Intrusive rocks that underlie most of the SLRD as large batholiths.

- Metamorphic rocks, which are scattered across the region, primarily near Anderson Lake, Seton Lake, and in the lower Elaho River valley.
- Ultramafic rocks near Yalakom River in the Shulaps Ultramafic Complex.
- Volcanic rocks, common within the intrusive rocks, and major, recent volcanic complexes are also noted.



**Figure B-2. Bedrock geology of the SLRD. Digital mapping and bedrock classes from Cui et al. (2015).**

### B-3.2 Surficial Geology

While the geological history of the region is the basis for the landscape observed in the SLRD, the present-day surficial material and topography is mainly a result of glacial activity during the late Pleistocene and Holocene, and post glacial processes since deglaciation. Surficial material and topography are summarized here as they strongly influence the geohazard processes assessed in this study.

The Late Pleistocene (approximately 126,000 to 11,700 years before present) represents a time of repeated advances and retreats of glaciers across North America. During the most recent glaciation, which began approximately 25,000 years ago and ended approximately 10,000 years ago, thick glaciers covered the SLRD. As these glaciers flowed across the landscape, they sculpted the bedrock and deposited sediment, creating many of the landforms that are seen today. Remnant glacial features include “U”-shaped valleys, steep mountains with sharp peaks, and angular rock faces caused by cirque glaciers (Holland, 1976). Reduced glaciers and ice fields are still present in ranges in the northeastern part of the SLRD. At lower elevations, evidence of glaciers is in the form of sediment, such as elevated glaciofluvial terraces and till deposits.

Post-glacial processes since deglaciation have transported sediment from mountain peaks to gullies and valleys throughout the SLRD. Most gullies and small valleys have colluvium deposited in the lower elevations. In the larger “U”-shaped valleys the deposits are primarily fluvial, such as in the lower Squamish valley and the Lillooet River valley.

Due to the steep nature of the mountains in this region, bedrock is exposed at most high elevations where glaciers and ice fields are no longer present. Volcanic materials, such as volcanic rock, ash, or volcanic debris can be found scattered at surface throughout the SLRD. Glacio-fluvial and glacio-lacustrine materials are found adjacent to the Fraser River, as well as eolian deposits derived from glaciolacustrine materials remobilized by wind processes post-glacially. Till deposits are most dominant in locations where materials have not been re-mobilized or overlain by fluvial, colluvial or lacustrine materials, such as gentler lower slopes and in pockets of irregular topography.

## B-4 CLIMATE

Climate is defined as typical weather in an area averaged over multiple decades and is often characterized by average temperature, precipitation and seasonal changes<sup>3</sup>. Climate change is a significant systematic shift in the long-term statistics of climate variables over several decades or longer due to natural or human induced forces<sup>4</sup>. An important distinction between climate

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<sup>3</sup> [http://www.wmo.int/pages/prog/wcp/ccl/faq/faq\\_doc\\_en.html](http://www.wmo.int/pages/prog/wcp/ccl/faq/faq_doc_en.html). Accessed June 18, 2018.

<sup>4</sup> According to the World Meteorological Organization, The United Nations Framework Convention on Climate Change (UNFCCC) defines climate change in more specific terms as: “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods”.



variability and climate change is the persistence of unusual conditions, such as previously rare events occurring more frequently. For the SLRD, climate change can result in extreme events such as snow and ice storms, heavy rains, heat waves, thunder, lightning and wind storms. These events can contribute to a shift in the magnitude, rate and timing of rainfall and snowmelt, which can impact flood hazards.

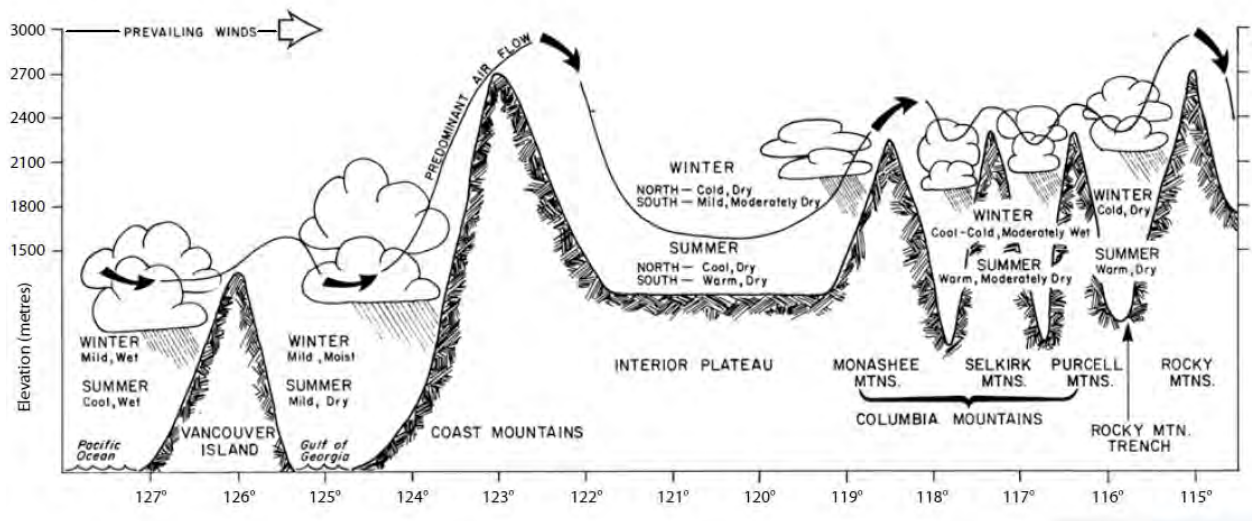
The following sections describes the regional-scale climatic conditions for SLRD, climate normal and projected climate impacts due to climate change.

#### B-4.1 Regional-Scale Climate Factors

The distinct climate patterns found across BC reflect the interaction between regional-scale weather systems with topography that varies with elevation, distance from the Pacific Ocean, prevailing winds and season. Large-scale airflows moving in from the coast bring moist, marine air from west to east. Mountain ranges that lie perpendicular to the prevailing winds largely determine the distribution of precipitation and temperatures within the distinct climatic regions found across BC (Figure B-3).

The approximate northwest-southeast orientation of the Coast Mountains in the SLRD strongly controls the westerly movement of air from the Pacific Ocean. The mountains force air to rise, where it cools and condenses, resulting in more frequent and higher volumes of precipitation on the west side than on the lee side (orographic effect), which leads to a much drier climate towards the interior. Valleys and other low-lying areas can allow cold air to enter, creating higher occurrences of frost and fog, as the cold air becomes trapped with moisture following arctic outflows. This arctic air can result in short winter storms with strong, cold winds that move through the Squamish valley, which are known locally as the “Squamish Winds” (DeMarchi, 2011).

The Coast Mountains experiences frontal storms which brings rain to lower elevations and snow to higher elevations. Atmospheric river storms bringing extreme rainfall, high winds and warm temperatures can results in large scale rain-on-snow flooding across western North America (Neiman et al., 2008). Generally, the climate of the SLRD is characteristic of the Coast Mountains with warmer, drier summers and cooler, wetter winters.



**Figure B-3. Latitudinal cross-section through southern BC depicting physiographic diversity and resulting climatic regimes. The SLRD is associated with the Coast Mountains and a portion of the Interior Plateau. (From Moore et al., 2008).**

#### B-4.2 Temperature and Precipitation Normals

Regional-scale factors affect temperature and precipitation patterns, as do local factors such as altitude, aspect, wind direction, proximity to water bodies and the degree of glaciation. An extreme elevation difference between the mountain peaks and valley troughs contributes to large differences in temperature and precipitation across the SLRD.

Table B-2 provides a summary of the climate normals as averaged from four Environment and Climate Change Canada (ECCC) stations shown in Figure B-4 for the period of 1981 to 2010.

Table B-3 summarizes monthly variations from climate stations located in Squamish, Whistler and Lillooet and reflects the range of valley-bottom conditions observed across the SLRD.

Figure B-5 and Figure B-6 show the average monthly precipitation and temperature normals for summer and winter for the region using data from the years 1976 to 2018. Precipitation is typically highest in the winter months (October to December), and lowest in the summer months (July to August). Total precipitation is highest in the Squamish region, reflecting a mix of rainfall and snowfall (Figure B-7). The highest temperatures occur in June and July in the Lillooet region with a mean of approximately 20°C, while temperatures in Whistler average between 14°C and 16°C during the same month. The lowest mean temperatures occur in December, with a mean of -0.7°C and a range of -3 to 3°C (Table B-2).



**Table B-2. Summary of 1981 to 2010 climate normals for the SLRD.**

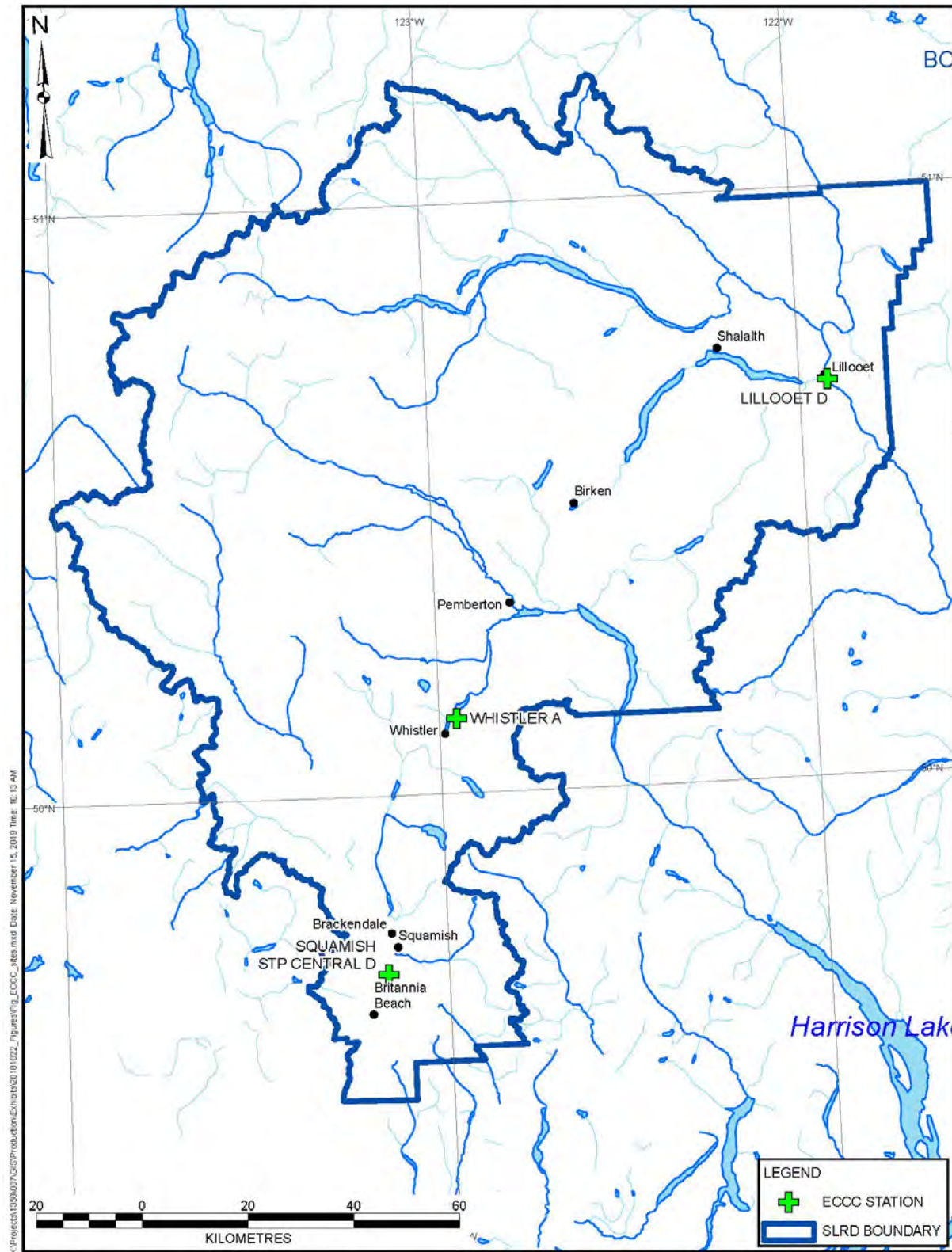
Variable	Units	Average	Range	
			Minimum	Maximum
Mean Annual Precipitation	mm	1,537	349	2,342
Mean Summer Precipitation (May to September)	mm	299	135	406
Total Snowfall	cm	191	26.5	419
Mean Annual Temperature	°C	8.9	6.7	10.1
Mean Coldest Month Temperature (December)	°C	-0.7	-2.8	2.5
Mean Warmest Month Temperature (July/August)	°C	18.5	16.5	21.6
Extreme Minimum Temperature	°C	-23.1	-29.2	-14.5
Frost-free Period	days	166	130	199

**Table B-3. 1981 to 2010 climate normals at the ECCC Whistler A, Lillooet D and Squamish STP Central D stations.**

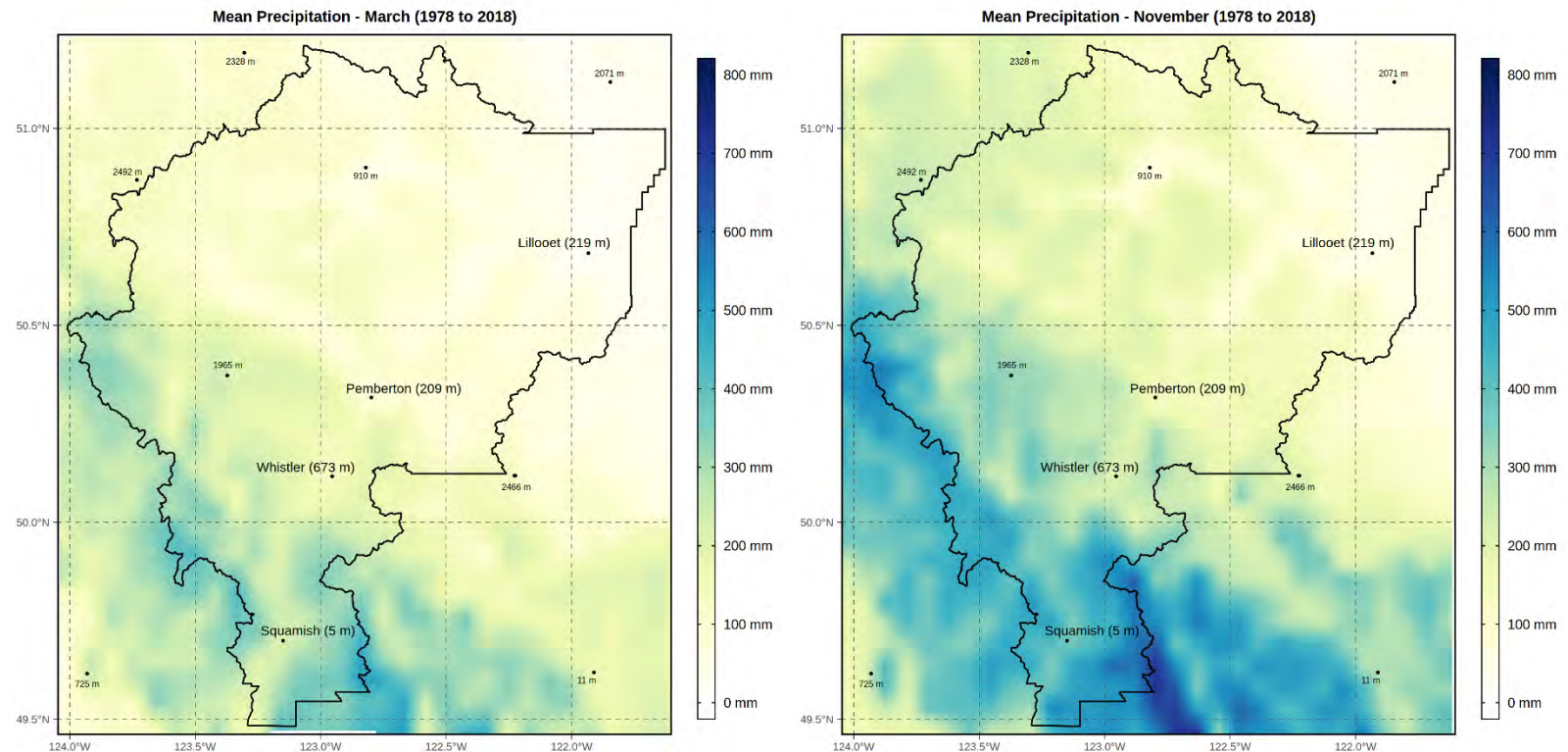
Variable	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
<i>Whistler A<sup>1</sup> (ID 1048898)</i>												
Temperature (°C)	-2	-1	2	6	10	14	16	17	13	7	1	-3
Rainfall (mm)	85	50	55	61	66	59	45	48	55	147	131	55
Snowfall (mm)	91	54	42	15	1	0	0	0	0	8	61	99
Precipitation <sup>2</sup> (mm)	176	105	98	76	67	59	45	48	55	155	192	154
<i>Lillooet D<sup>3</sup> (ID 1114627)</i>												
Temperature (°C)	-2	0	5	10	15	19	22	21	16	9	2	-2
Rainfall (mm)	31	17	15	19	26	24	36	26	24	33	41	32
Snowfall (mm)	7	3	2	0	0	0	0	0	0	1	4	10
Precipitation (mm)	38	20	17	19	26	24	36	26	24	34	44	42
<i>Squamish STP Central D<sup>3</sup> (ID 1047671)</i>												
Temperature (°C)	3	5	7	10	13	16	18	18	15	10	6	3
Rainfall (mm)	300	180	198	153	116	83	59	66	83	256	382	268
Snowfall (mm)	26	13	8	0	0	0	0	0	0	0	9	31
Precipitation <sup>2</sup> (mm)	326	193	207	153	116	83	59	66	83	256	391	299

Notes:

1. Climate station meets the World Meteorological Organization (WMO) standards for temperature and precipitation and the "A" stands for the WMO "3 and 5 rule" (i.e., no more than 3 consecutive and no more than 5 total missing for either temperature or precipitation).
2. Precipitation is a combination of rainfall and snowfall amounts.
3. "D" represents that there is 15 years of data.

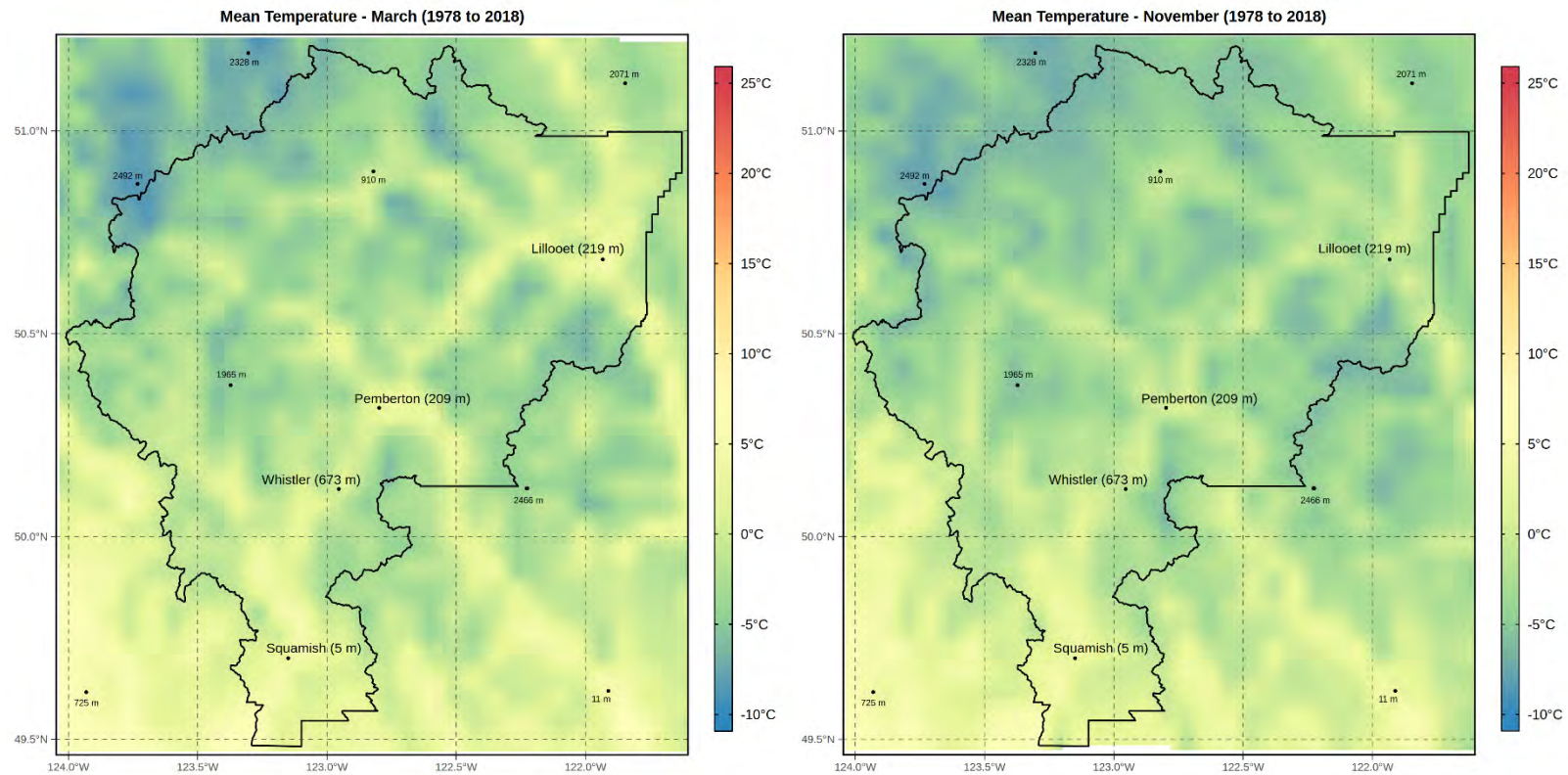


**Figure B-4. Environment and Climate Change Canada (ECCC) stations in the SLRD and referenced in this document.**

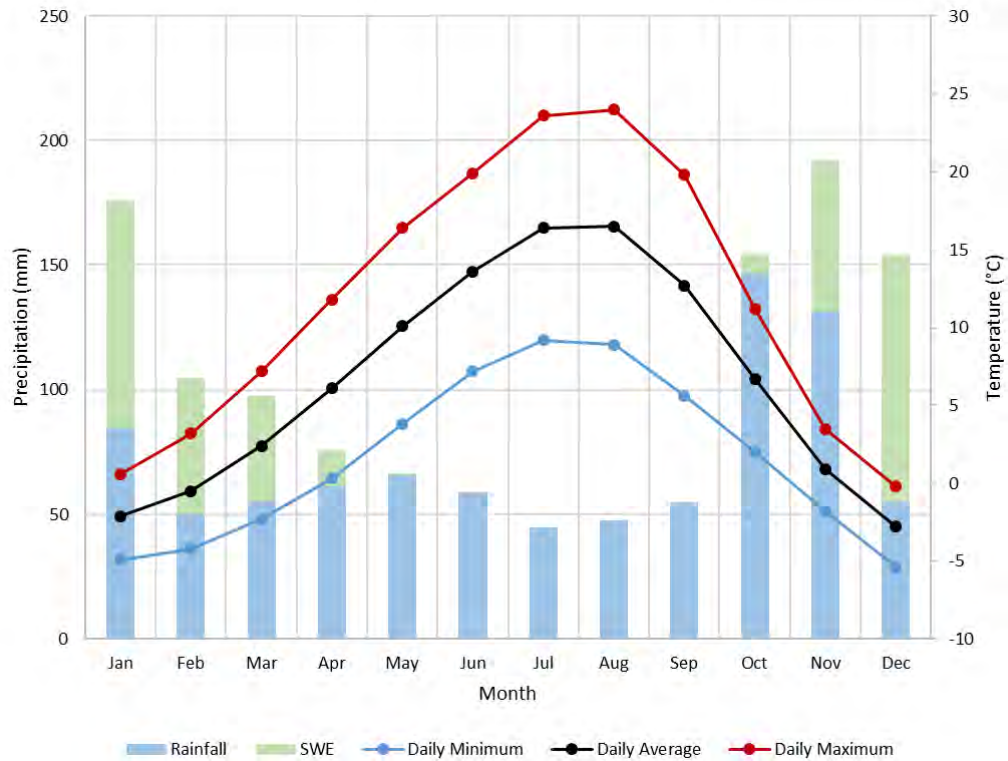


**Figure B-5.** Mean precipitation normals for March and November from 1976 to 2018 for the SLRD (outlined in black). Data compiled and presented by BGC. Source data: ClimateBC (Wang et al., 2016).

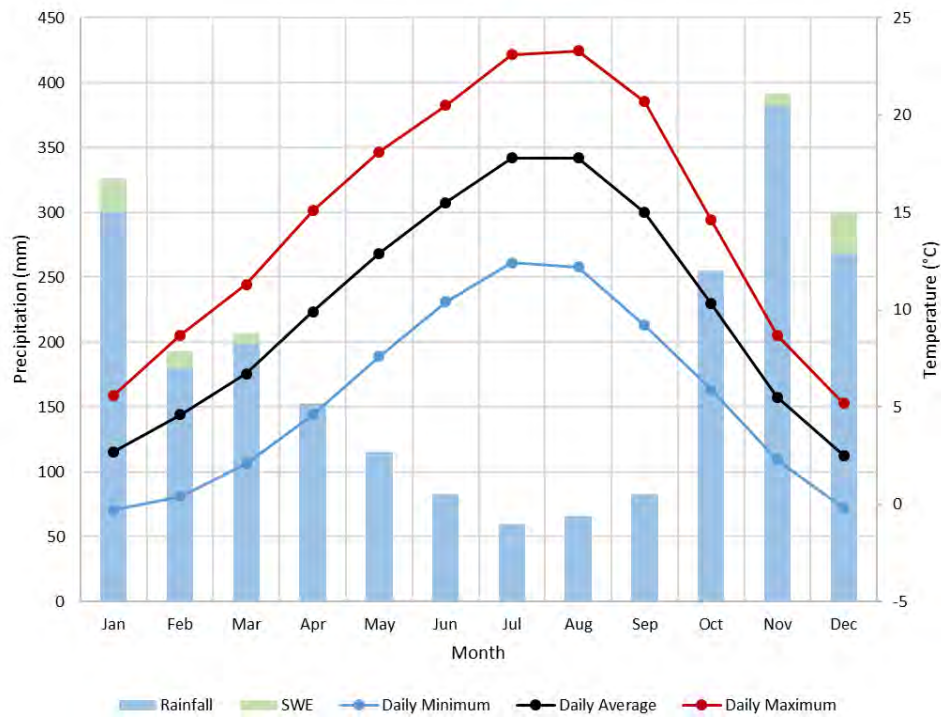




**Figure B-6.** Mean temperature normal for March and November from 1976 to 2018 for the SLRD (outlined in black). Data compiled and presented by BGC. Source data: ClimateBC (Wang et al., 2016).



(a)



(b)

**Figure B-7. Climate normals at the ECCC Whistler A (a) and Squamish STP Central D (b) climate stations for 1981 to 2010.**

### B-4.3 Projected Climate Change

Climate change is expected to impact flood hazards both directly and indirectly through complex feedback mechanisms. This makes it challenging to reliably estimate future flood hazards for the entire spectrum of flood processes across the range of spatial and temporal scales. At this time, climate change science for the SLRD can provide general trends on average values at regional scales, and limited information (with higher uncertainty) on the extremes<sup>5</sup> that are of interest for flood hazards on specific watercourses.

Projected changes in average climate variables across the SLRD (Table B-4; (PCIC, 2012)) show that there is likely to be:

- A net increase in mean temperatures on an annual basis.
- A net increase in precipitation with drier summers and wetter winters.
- A net decrease in snowfall, including a smaller decrease in winter and a larger decrease in spring snowfall (due to a projected increase in temperature).
- On average, there is likely to be a reduction in snowpack depth, an increase in winter rainfall, and higher freezing levels.

**Table B-4. Projected changes in average climate variables in SLRD (2050s, A2 and B1 scenarios, PCIC 2012).**

Variable	Unit	Season	Projected Change from 1961 – 1990 Baseline <sup>1</sup>	
			Median	Range (10th to 90th Percentile)
Temperature	°C	Annual	+1.7°C	+1.1°C to +2.6°C
Precipitation <sup>2</sup>	%	Annual	+6%	-1% to +11%
		Summer	-12%	-21% to 5%
		Winter	+6%	-4% to +14%
Snowfall	%	Winter	-15%	-25% to -2%
		Spring	-51%	-72% to -12%

Notes:

1. Source: Pacific Climate Impacts Consortium (2012). Values provided reflect results from 30 Global Climate Model (GCM) projections from 15 different models each with a high (A2) and a low (B1) greenhouse gas emission scenario. The range of values represents the median, 10<sup>th</sup> and 90<sup>th</sup> percentiles of these results. The range in model output values reflects uncertainties in projections of future greenhouse gas levels (in this case represented by the A2 and the B1 scenarios) as well as uncertainties due to simplifications of complex natural process in the models themselves. For more information on how these number, rain and/or snow), including a decrease in summer precipitation and an increase in winter precipitation were obtained, the reader is directed to [www.plan2adapt.ca/tools/planners](http://www.plan2adapt.ca/tools/planners)
2. Precipitation includes both rain and snow.

Historical data from the region shows that average annual temperatures and total annual precipitation increased 0.8°C and 14%, respectively between 1900 and 2013 (MOE, 2016). In addition, snow depths have decreased 6% in the region during the period 1950 to 2014 and

<sup>5</sup> “Extremes” can refer to both extreme highs and extreme lows. Flooding inherently refers to high flows. Climate change also has the potential to impact low flows/base flows/drought conditions, and sensitivity analyses could also be conducted for these conditions; however, these were not the hazards of interest for this study.



there has been a 34% change in glacier area, corresponding to a 3 km<sup>2</sup> reduction in glaciated area, during the period 1985 to 2005 (MOE, 2016). One important climate change impact is the potential for sea level rise due to warmer ocean temperature and melting sea ice. A sea level rise of 1 m by 2100 and 2 m by 2200 is used for planning purposes by the Province of BC<sup>6</sup>. Coastal flood hazards in Howe Sound are anticipated to increase due to sea level rise and climate change (KWL, October 2017).

General trends suggest that the coastal and interior regions of BC are getting warmer and wetter, with increasing minimum temperatures and number of frost-free days. Rivers within the SLRD may be particularly sensitive to climate change due to a flow regime shift away from a glacier or nival (snow-dominated) regime towards a more hybrid or pluvial (rain-dominated) regime due to decreased snowfall and increasing annual temperatures. This shift is expected to have an impact on the frequency and magnitude of peak flows such that a shift in timing of the annual peak may increase the magnitude of flood events in the future. NHC (August 31, 2018) examined trends in the observed flow records for gauge stations located around the Lillooet area and found an increasing trend in flows for some long-term hydrometric stations (e.g., *Lillooet River at Pemberton*), while other stations showed a statistically decreasing trend; suggesting that it is difficult to tease out potential climate change impacts from the historical record.

To account for uncertainties, EBGC (2018) recommends that design flows be increased with a 20% factor to account for climate change when an increasing trend is found in an observed flood record and a 10% factor when no trend is detected. Appendix F describes how adjustments were made to peak flow estimates for steep creeks to account for climate change. The floodplain mapping techniques conducted by BGC for the clear-water hazard areas produced flood depths that are conservatively high but provide a relative ranking of hazard areas as described in Appendix E. As a result, an additional factor was not added to account for climate change for clear-water hazards.

## B-5 HYDROLOGY

The hydrology within the SLRD is characterized by flooding triggered from autumn rainfall, rain-on-snow events in the winter, and spring snowmelt within a mixed-precipitation hydrologic regime.

### B-5.1 Physiographic Characterization of Watercourses

This report defines three general categories of watercourses that are differentiated by scale and physiography as per Table B-5.

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<sup>6</sup> BC Climate Action Toolkit Sea Level Rise Adaption Primer (<https://www.toolkit.bc.ca/>).

**Table B-5. Physiographic characterization of watercourses.**

Category	Watershed Area Range	Strahler Order <sup>1</sup>	Example Watersheds
Major Valley Systems	>3,000 km <sup>2</sup>	6+	Squamish River, Lillooet River, Bridge River, Fraser River, Cheakamus River
Minor Valley Systems	500 – 3,000 km <sup>2</sup>	4 - 6	Alta Creek, Brandywine Creek, Ryan River, Birkenhead River
Tributary Creeks	<500 km <sup>2</sup>	1 - 3	Millar Creek, Fitzsimmons Creek, Whistler Creek

Note:

1. Strahler stream order classification system (Strahler, 1952) was applied to all the stream reaches within the SLRD. Strahler order is a classification of stream segments by its branching complexity within a drainage system. It is an indication of the significance in size and water conveying capacity at points along a river. A first order stream corresponds to the headwaters, while a higher order stream indicates a larger channel.

### Major Valley Systems (Rivers and Lakes)

Major valley bottoms are characterized by wide, U-shaped valley bottoms, which feature large rivers and lakes that are the backbone of the region's physical and human geographies. Catchment areas are in excess of 3,000 km<sup>2</sup>. These areas are where most people live and work, and where transportation and linear infrastructure is generally located.

### Minor Valley Systems (Rivers and Lakes)

Minor valley bottoms are characterized by U-shaped valley bottoms that form major tributaries to the major valleys. They typically bisect mountain ranges and have catchment areas around 500-3,000 km<sup>2</sup>. These areas contain farms and lower density residential development and provide access to forestry operations. Transportation and linear infrastructure follow some of the larger valleys as they connect major valley bottoms. Where minor valleys terminate in a fan, these fans are typically more densely populated with urban development.

### Tributary Creeks

Tributary creeks are typically mountain streams that have headwaters at high elevation and follow a less circuitous path down the mountainside. Valleys are typically V-shaped. Catchment areas are typically less than 500 km<sup>2</sup> with many of the tributary creeks terminating at fans where they enter larger and lower-gradient valley bottoms. Many tributary creeks (typically < 10 km<sup>2</sup>) are subject to steep creek processes (debris floods and debris flows). Methods to identify creeks subject to steep creek processes are provided in Appendix F.

### Major Lakes

Within the District there are several large lakes, the largest three being Downton Lake, Carpenter Lake and Lillooet Lake. Both Downton Lake and Carpenter Lake are regulated as part of the Bridge River Hydroelectric Complex operated by BC Hydro. A list of the major lakes in the district is shown in Table B-6.

**Table B-6. Major lakes and reservoirs within the SLRD.**

Name	Description	Surface Area (km <sup>2</sup> )	Regulation
Downton Lake	Downton Lake is a reservoir in the Bridge River Country, formed by Lajoie Dam, the uppermost of the series of dams and diversions of the Bridge River Power Project.	58.2	Regulated (Lajoie Dam)
Carpenter Lake	Carpenter Lake, officially Carpenter Lake Reservoir, is the largest of the three reservoirs of the Bridge River Power Project, which is located in the mountains west of Lillooet, BC.	50.0	Regulated (Terzaghi Dam)
Lillooet Lake	Lillooet Lake is about 95 km downstream from the source of the Lillooet River.	33.5	Unregulated
Anderson Lake	Anderson Lake is located north of the town of Pemberton, BC and is drained by the Seton River, which feeds Seton Lake and eventually the Fraser River.	28.5	Unregulated
Garibaldi Lake	Garibaldi Lake is an alpine lake, located 37 km north of Squamish and 19 km south of Whistler.	27.4	Unregulated
Seton Lake	Seton Lake is a freshwater fjord draining east via the Seton River into the Fraser River at the town of Lillooet, BC.	26.2	Regulated (Seton Dam)
Gun Lake	Gun Lake is an unincorporated community in the Bridge River Country of the West-Central Interior of BC, Canada, located northwest of the community of Gold Bridge.	14.6	Unregulated
Daisy Lake	Daisy Lake, is a reservoir on the Cheakamus River in the Sea to Sky Corridor, just south of Whistler, BC.	9.9	Regulated (Cheakamus Dam)
Cheakamus Lake	Cheakamus Lake is a lake in Garibaldi Provincial Park on the southeastern outskirts of Whistler, BC. It is an expansion of the upper Cheakamus River, with the river entering it at its east end and exiting at the west end.	5.7	Unregulated

## B-5.2 Hydrology

Annual river flow distribution in BC can be classified into one of five streamflow regimes (Ministry of Forests and Range, 2010):

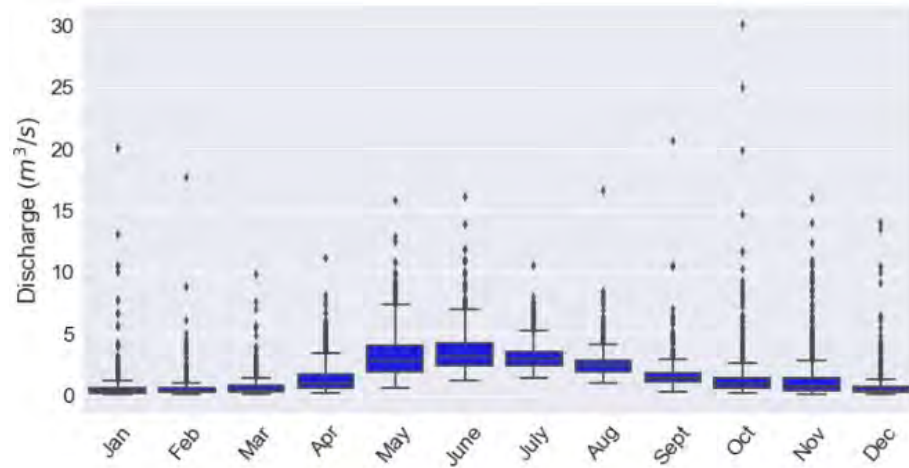
- Pluvial (rain driven)
- Pluvial-dominant hybrid (rain dominant)
- Nival-dominant hybrid (snowmelt driven)
- Nival (snowmelt dominant)
- Glacial-supported nival (snowmelt driven in spring and glacial melt driven in summer).

The SLRD displays a mix of regimes with different flood timings due to the precipitation and elevation changes within the District boundaries. Rain-driven and -dominant regimes can be found at lower elevations and in western portions of the District, where enhanced rain from the orographic effect falls during the winter months. Snowmelt-driven and -dominant regimes occur at both higher elevations and in the eastern portions of the District with their maximum annual flows occurring with the spring freshet; the eastern portions of the district experience much less winter precipitation and rain where the orographic effect is most prevalent, so snowmelt-dominant regimes tend to emerge. In the snowmelt-driven or nival-dominant hybrid regimes, a secondary, smaller peak flow typically occurs in the autumn and is often associated with a snowfall event(s), typically with low freezing elevations, followed by rising freezing levels and rain-on-snow. Rain-on-snow is especially common where winter precipitation levels are higher.

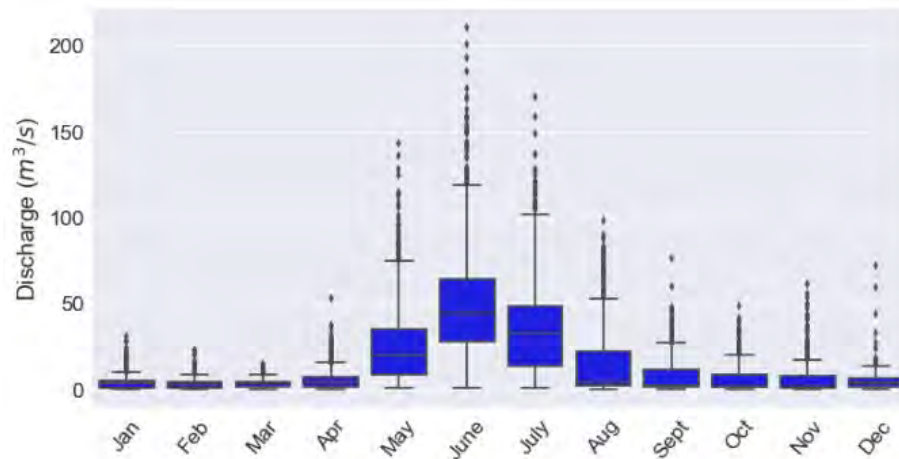
There are several glacier-supported nival streamflow regimes due to the number of glaciers which occur across the SLRD where the mountains are higher and where winter precipitation is greatest. For example, meltwater during the summer from the Bridge Glacier supplies water to the Bridge River hydroelectric complex which generates 6 to 8% of BC's electrical supply.

Examples of pluvial-dominant hybrid, nival and glacial supported flow regimes are shown in the figures below.

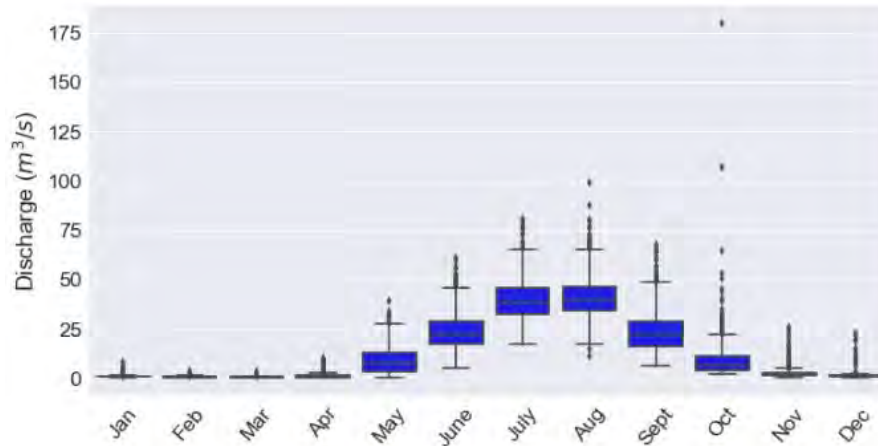
- Figure B-8 shows a boxplot of monthly discharges for Water Survey of Canada (WSC) hydrometric station 08MG025 (*Pemberton Creek near Pemberton*), which is located near the center of the District at approximately 210 m elevation and drains 32.4 km<sup>2</sup>. Pemberton Creek represents a pluvial-dominant hybrid flow regime with peak flows occurring throughout the year and in particular during the rainy fall and winter period.
- Figure B-9 shows a boxplot of monthly discharges for WSC station 08ME002 (*Cayoosh Creek near Lillooet*), which is located in the northeast portion of the District at approximately 230 m elevation and drains 885 km<sup>2</sup>. Cayoosh Creek represents a nival-dominant regime with the peak flows occurring during the spring freshet (May, June and July).
- Figure B-10 shows the monthly flows for WSC gauge 08ME023 (*Bridge River (South Branch) below Bridge Glacier*), which is located near the outlet of Bridge Glacier in the northwestern portion of the District at approximately 1,380 m elevation and drains 144 km<sup>2</sup>. Bridge River is an example of a glacial-supported nival flow regime with snowmelt driven in spring and glacial melt driven in summer.



**Figure B-8.** Boxplots of the monthly discharge data for WSC gauge 08MG025, *Pemberton Creek near Pemberton*. Pemberton Creek represents a pluvial-dominant hybrid regime.



**Figure B-9.** Boxplots of the monthly discharge for WSC gauge 08ME002, *Cayoosh Creek near Lillooet*. Cayoosh Creek represents a nival-dominant hybrid regime.



**Figure B-10. Boxplot of the monthly discharge for WSC gauge 08ME023, Bridge River (South Branch) below Bridge Glacier. Bridge River represents a glacial-supported nival regime.**

### B-5.3 Flow Regulation

Within the District there are a number of rivers and waterbodies for which the flows are regulated by various dams. Major regulated rivers within the District are the Bridge River, Seton River and the Cheakamus River. Regulation provides services such as energy generation and flood protection and alters the natural flows and water levels in the rivers and lakes respectively. A list of the major dams with the owner, type height and consequence classification is presented in Appendix E. Although the occurrence of dams has an impact on peak flows, the degree of flow regulation was not considered in estimates of peak flows for hazard study areas.

### B-5.4 Coastal Flooding

Results of an inundation study completed as part of an Integrated Flood Hazard Management Plan (IFHMP) for Squamish indicate that downtown Squamish is at risk of coastal flooding in a less than 200-year return period event with 1 m of projected sea level rise (KWL, October 2017). The IFHMP defines a 200-year return period “still-water” coast flood elevation of 3.99 m for coastal flooding in Squamish that does not account for wave or wind allowances.

## B-6 HISTORICAL EVENT INVENTORY

BGC reviewed historical accounts of flood, debris flood and debris flow events across the SLRD. Appendix D lists event information related to point locations at the at the location of the event (or general vicinity, in the case of geohazard events with large extent). All data contains a hazard type, date, location, and location confidence level. Depending on the completeness of data sources, additional attributes may include event trigger and qualitative description of consequences. For consistency at Provincial scale, the data taxonomy applied in Appendix D has been standardized by BGC across similar risk prioritization studies for other Regional Districts in BC.



Data bias is typically inherent in historical accounts of past events due to gaps in recorded storms or geohazard events, because media reports tend to generalize effects of large region-wide events (e.g., 1940 region-wide floods) rather than smaller and more localized impacts.

Large region-wide data sources of historical events include:

- A text compilation of media reports of flooding, landslide, and avalanche events from 1808 to 2006 (Septer, 2007).
- The Canadian Disaster Database (Public Safety Canada, n.d.).
- DriveBC data for mud slides and washouts across the major highways of the study area, compiled by BGC from 2006 to 2018.
- Historical media reports of floods and geohazard events in the region compiled by BGC.
- Geotechnical reports where available.

The historical event inventory is not exhaustive, but the information contained within it can be used to identify the location of past geohazards events and associated consequences of these events. These locations were referenced during geohazard identification. Recorded events at steep creek fans are listed in supporting information for a given site on *Cambio*.

The SLRD has a long history of damaging flood and volcanic debris-flow events, with recorded history dating as far back as 1855. The most notable findings from review of historical and anecdotal data indicate that most large floods occur in the fall and early winter as large rain-on-snow events in the District of Squamish and Village of Pemberton areas (Squamish, Mamquam, Cheakamus, Cheekeye, Lillooet, Ryan, and Green rivers). The years with the largest interpreted flood inundation occurred in 1940, 1954, 1955, 1975, 1980, 1981, 1984, 1991, 2003 and 2010.

The District is also susceptible to large volcanic debris-flows that initiate from many of the volcanic mountains present in the study area. Most notably, large-scale events have been reported on Mount Meager and Mount Cayley.

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# APPENDIX C

## DATA COMPILATION



Location				Project		Hazard Type			Reference
Name	River Basin	District	NTS ID	Project Title	Report? (Y/N)	Flooding?	Landslide?	Steep Creek?	Citation
Lillooet River	Lillooet River	SLRD	092J07	Engineering study for Lillooet River corridor	Y	Y			Kerr Wood Liedel Associated Ltd. (2002, December 23). <i>Engineering study for Lillooet River corridor</i> . Prepared for British Columbia Ministry of Water, Land and Air Protection.
Capricorn Creek	Lillooet River	SLRD	092J11	The July 29, 1998, debris flow and landslide dam at Capricorn Creek, Mount Meager Volcanic Complex, southern Coast Mountains, British Columbia	N		Y	Y	Bovis, J.M., and Jakob, M. (2000). The July 29, 1998, debris flow and landslide dam at Capricorn Creek, Mount Meager Volcanic Complex, southern Coast Mountains, British Columbia. <i>Canadian Journal of Earth Science</i> , 37, 1321-1334.
Capricorn Creek	Lillooet River	SLRD	092J11	The 6 August 2010 Mount Meager rock slide-debris flow, Coast Mountains, British Columbia: characteristics, dynamics, and implications for hazard and risk assessment	N		Y	Y	Guthrie, R.H., Friele, P., Allstadt, K., Roberts, N., Evans, S.G., Delaney, K.B., Roche, D., Clague, J.J., and Jakob, M. (2012). The 6 August 2010 Mount Meager rock slide-debris flow, Coast Mountains, British Columbia: characteristics, dynamics, and implications for hazard and risk assessment. <i>Natural Hazards and Earth System Sciences</i> , 12(5), 1277-1294.
Lillooet River	Lillooet River	SLRD	092J07	A review of the floodplain mapping for the Lillooet River near Pemberton, B.C.	Y	Y			Ministry of Environment, Lands and Parks Water Management Division. (1995). A review of the floodplain mapping for the Lillooet River near Pemberton, B.C. (File: 35100-30/119-0000) [Report]. Victoria, British Columbia: Author.
Fitzsimmons Creek	Green River	SLRD	092J02	An overview of the study undertaken to produce floodplain mapping in the Resort Municipality of Whistler	Y	Y		Y	Ministry of Environment, Lands and Parks Water Management Division. (1992). An overview of the study undertaken to produce floodplain mapping in the Resort Municipality of Whistler (File: 35100-30/119-4671) [Report]. Victoria, British Columbia: Author.
Cheakamus River	Squamish River	SLRD	092G14	Report on the floodplain mapping study Cheakamus River	Y	Y			Ministry of Environment, Lands and Parks Water Management Division. (1986). Report on the floodplain mapping study Cheakamus River (File: 90-1300-S.1) [Report]. Victoria, British Columbia: Author.
Town Creek	Fraser River	SLRD	092I12	Post-wildfire natural hazards risk analysis in British Columbia	Y		Y	Y	Hope, G., Jordan, P., Winkler, R., Giles, T., Curran, M., Soneff, K., & Chapman, B. (2015). Post-wildfire natural hazards risk analysis in British Columbia (Land Management Handbook 69). Victoria, BC: British Columbia Ministry of Forests, Lands and Natural Resource Operations.
Rubble Creek	Cheakamus River	SLRD	092G14	The Rubble Creek landslide, southwestern British Columbia	N		Y	Y	Moore, D.P., & Mathews, W.H. (1978). The Rubble Creek landslide, southwestern British Columbia. <i>Canadian Journal of Earth Sciences</i> , 15(7), 1039-1052.
Turbid Creek	Squamish River	SLRD	092J03	Dynamics of the 1984 rock avalanche and associated distal debris flow on Mount Cayley, British Columbia, Canada; implications for landslide hazard assessment on dissected volcanoes	N		Y	Y	Evans, S.G., Hungr, O., & Clague, J.J. (2001). Dynamics of the 1984 rock avalanche and associated distal debris flow on Mount Caley, British Columbia, Canada; implications for landslide hazard assessment on dissected volcanoes.
Debris flows in gullies	All	SLRD	N/A	Debris flow initiation and sediment recharge in gullies	N		Y	Y	Brayshaw, D., & Hassan, M.A. (2009). Debris flow initiation and sediment recharge in gullies. <i>Geomorphology</i> , 109, 122-131.
M Creek	Howe Sound	SLRD	092G06	Debris flow triggering by impulsive loading: mechanical modelling and case studies	N		Y	Y	Bovis, J.M., and Dagg, B.R. (1992). Debris flow triggering by impulsive loading: mechanical modelling and case studies. <i>Canadian Geotechnical Journal</i> , 29, 345-352.
M Creek	Howe Sound	SLRD	092G06	Meteorological antecedents to debris flow in southwestern British Columbia; some case studies	N		Y	Y	Church, M., & Miles, M.J. (1987). Meteorological antecedents to debris flow in southwestern British Columbia; some case studies. In J.E. Costa & G.F. Wieczorek (Eds), <i>Debris flows/avalanches: process, recognitions and mitigation</i> (pp. 63-79). Boulder, Colorado: Geological Society of America.

Location				Project		Hazard Type			Reference
Name	River Basin	District	NTS ID	Project Title	Report? (Y/N)	Flooding?	Landslide?	Steep Creek?	Citation
Britannia Creek, Cheekeye River, Culliton Creek, Nineteen Mile Creek, Twenty-one Creek, Fitzsimmons Creek, Rutherford Creek, Furry Creek	Howe Sound, Squamish River	SLRD	092G11	Slope stability and mountain torrents, Fraser lowlands and southern Coast Mountains, British Columbia	N	Y	Y	Y	Eisbacher, G.H. (1983). Slope stability and mountain torrents, Fraser lowland and southern Coast Mountains, British Columbia (Field trip guidebook, Trip 15). Victoria, BC: Geological Association of Canada.
Culliton Creek	Cheakamus River	SLRD	092G14	Debris flows and debris torrents in the southern Canadian Cordillera	N	Y		Y	VanDine, D.F. (1984). Debris flows and debris torrents in the southern Canadian Cordillera. Canadian Geotechnical Journal, 22, 44-68.
Cheekeye River	Cheakamus River	SLRD	092G14	Chronology and hazards of large debris flows in the Cheekeye River basin, British Columbia, Canada	N		Y	Y	Clague, J.J., Friele, P.A., & Hutchinson, I. (2003). Chronology and hazards of large debris flows in the Cheekeye River basin, British Columbia, Canada. Environmental & Engineering Geoscience, 9(2), 99-115.
Cheekeye River	Cheakamus River	SLRD	092G14	Cheekeye River mudflows	Y		Y	Y	Jones, W.C. (1959). Cheekeye River mudflows. Victoria, BC: British Columbia Department of Mines.
Dusty Creek, Turbid Creek	Squamish River	SLRD	092J03	The Dusty Creek landslide on Mount Cayley, British Columbia	Y	Y	Y	Y	Clague, J.J., & Souther, J.G. (1982). The Dusty Creek landslide on Mount Cayley, British Columbia. Canadian Journal of Earth Science, 19, 524-539.
Avalanche Creek, Turbid Creek	Squamish River	SLRD	092J03	The rockslide and debris flow from Mount Cayley, B.C., in June 1984	Y	Y	Y	Y	Cruden, D.M., & Lu, Z.Y. (1992). The rockslide and debris flow from Mount Cayley, B.C., in June 1984. Canadian Geotechnical Journal, 29, 614-626.
Cheakamus River	Squamish River	SLRD	092G14	Record of recent river channel instability, Cheakamus Valley, British Columbia	N	Y			Clague, J.J., Turner, R.J.W., & Reyes, A.V. (2002). Record of recent river channel instability, Cheakamus Valley, British Columbia. Geomorphology, 53, 317-332.
Tommy Creek	Bridge River	SLRD	092J15	Landslide Risk Case Studies in Forest Development Planning and Operations	N		Y	Y	Wise, M.P., Moore, G., & VanDine, D.F. (2004). Landslide risk case studies in forest development planning and operations (Land management handbook No. 56). Victoria, BC: Ministry of Forests.
Lillooet River	Lillooet River	SLRD	092J07	The record of an extreme flood in the sediments of montane Lillooet Lake, British Columbia: implications for paleoenvironmental assessment	N	Y			Gilbert, R., Crookshanks, S., Hodder, K.R., Spagnol, J. and Stull, R.B. (2006). The record of an extreme flood in the sediments of montane Lillooet Lake, British Columbia: implications for paleoenvironmental assessment. Journal of Paleolimnology, 35, 737-745.
Cheakamus River, Green River, Lillooet River		SLRD	092G11, 092G14, 092J03, 092J02, 092J07, 092J08, 092J09, 092I12	Magnitude and frequency of rock falls and rock slides along the main transportation corridors in southwestern British Columbia	N		Y	Y	Hungr, O., Evans, S.G., and Hazzard, J. (1999). Magnitude and frequency of rock falls and rock slides along the main transportation corridors of southwestern British Columbia. Canadian Geotechnical Journal, 36, 224-238.
Jane Creek	Howe Sound	SLRD	092G11	Landslide hazards and their mitigation along the Sea to Sky corridor, British Columbia	N		Y	Y	Blais-Stevens, A. & Hungr, O. (2008). Landslide hazards and their mitigation along the Sea to Sky corridor, British Columbia. In J. Locat, D. Perret, D. Turmel, D. Demers, and S. Lerouel (Eds.), Proceedings of the 4th Canadian Conference on Geohazards: From cause to management (pp. 594). Quebec City, QC: Laval University Press.
				Seismic design guidelines for dikes	N	Y			Atukorala, U., Hawson, H., Mylleville, B., & Williams, R. (2014, June). Seismic design guidelines for dikes (2nd Edition) [Report]. Prepared for Ministry of Forests, Lands and Natural Resource Operations Flood Safety Section.
Lillooet River	Lillooet River	SLRD	092J07	Geomorphic response of Lillooet River, British Columbia, to meander cutoffs and base level lowering	N	Y			Weatherly, H. & Jakob, M. (2014). Geomorphic response of Lillooet River, British Columbia, to meander cutoffs and base level lowering. Geomorphology, 217, 48-60.



Location				Project		Hazard Type			Reference
Name	River Basin	District	NTS ID	Project Title	Report? (Y/N)	Flooding?	Landslide?	Steep Creek?	Citation
Squamish River	Squamish River	SLRD	092G14	Radar architecture and evolution of channel bars in wandering gravel-bed rivers: Fraser and Squamish rivers, British Columbia, Canada	N				Woolridge, C.L. & Hickin, E.J. (2005). Radar architecture and evolution of channel bars in wandering gravel-bed rivers: Fraser and Squamish rivers, British Columbia, Canada. Journal of Sedimentary Research, 75, 844-860.
Capricorn Creek	Lillooet River	SLRD	092J11	Stability assessment of the Capricorn Creek Valley, British Columbia	N		Y	Y	Croft, S.A.S. (1983). Stability assessment of the Capricorn Creek Valley, British Columbia. B.Sc. thesis, University of British Columbia, Vancouver, BC.
Unnamed Creek	Lillooet River	SLRD	092J11	A rock avalanche from the peak of Mount Meager, British Columbia	N		Y	Y	Evans, S.G. (1987). A rock avalanche from the peak of Mount Meager, British Columbia; In, Current Research, Part A, Geological Survey of Canada, Paper 87-JA, (pp. 929-934). Ottawa, Ontario: Geological Survey of Canada.
Unnamed Creek	Green River	SLRD	092J07, 092J	Surface displacement and massive toppling on the northeast ridge of Mount Currie, British Columbia	N		Y	Y	Evans, S.G. (1987). Surface displacement and massive toppling on the northeast ridge of Mount Currie, British Columbia; In, Current Research, Part A, Geological Survey of Canada, Paper 87-IA (pp. 181-189). Ottawa, ON: Geological Survey of Canada.
Meager Creek	Lillooet River	SLRD	092J11	Hazard and risk from large landslides from Mount Meager volcano, British Columbia, Canada	N		Y	Y	Friele, P., Jakob, M. & Clague, J. (2008) Hazard and risk from large landslides from Mount Meager volcano, British Columbia, Canada. Georisk, 2(1), 48-64.
Lillooet River	Lillooet River	SLRD	092J11	Evidence for catastrophic volcanic debris flows in Pemberton Valley, British Columbia	N		Y	Y	Simpson, K.A., Stasiuk, M., Shimamura, K., Clague, J.J., & Friele, P. (2006). Evidence of catastrophic volcanic debris flows in Pemberton Valley, British Columbia. Canadian Journal of Earth Sciences, 43(6), 679-684, 686-689.
Lillooet River	Lillooet River	SLRD	092J11	Flood hazard and risk in Lillooet River Valley, British Columbia, Canada	N	Y			Heideman, M. (2013). Flood hazard and risk in Lillooet River Valley, British Columbia, Canada (Doctoral dissertation). Simon Fraser University, Burnaby, BC.
	Lillooet River, Squamish River	SLRD		Morphometric and geotechnical controls of debris flow frequency and magnitude in southwestern British Columbia	N		Y	Y	Jakob, M. (1996). Morphometric and geotechnical controls of debris flow frequency and magnitude in southwestern British Columbia [Doctoral dissertation]. University of British Columbia, Vancouver, BC.
Turbid Creek	Squamish River	SLRD	092J03	Debris avalanche impoundment of Squamish River, Mount Cayley area, southwestern British Columbia	N		Y	Y	Brooks, G.R. & Hickin, E.J. (1991). Debris avalanche impoundment of Squamish River, Mount Cayley area, southwestern British Columbia. Canadian Journal of Earth Sciences, 28, 1375-1385.
Loggers Creek	Howe Sound	SLRD	092G06	Mechanisms of debris supply to steep channels along Howe Sound, southwest British Columbia	N		Y	Y	Bovis, M.J. & Dagg, B.R. (1987). Mechanisms of debris supply to steep channels along Howe Sound, southwest British Columbia (IAHS Publication no. 165).
Meager Creek	Lillooet River	SLRD	092J11	The Meager and Pebble Creek Hotsprings near Pemberton, British Columbia: Guidance towards a landslide risk management plan	N		Y	Y	Cordilleran Geoscience. (2017, March 17). The Meager and Pebble Creek Hotsprings near Pemberton, British Columbia: Guidance towards a landslide risk management plan [Report]. Prepared for Ministry of Forests, Lands and Natural Resource Operations.
Gillon Creek, Gibbs Creek	Fraser River	SLRD	092I13	Earthflows in the Interior Plateau, southwest British Columbia	N		Y		Bovis, M.J. (1985). Earthflows in the Interior Plateau, southwest British Columbia. Canadian Geotechnical Journal, 22, 313-334.
Devastator Creek	Lillooet River	SLRD	092J12	Glacier-caused slide near Pylon Peak, British Columbia	N		Y	Y	Mokievsky-Zubok, O. (1977). Glacier-caused slide near Pylon Peak, British Columbia. Canadian Journal of Earth Sciences, 14, 2657-2662.
	Lillooet River	SLRD	092J12, 092J	Debris flows in the southern Coast Mountains, British Columbia: Dynamic behaviour and physical properties	N		Y	Y	Jordan, R.P. (1994). Debris flows in the southern Coast Mountains, British Columbia: Dynamic behaviour and physical properties [Doctoral dissertation]. University of British Columbia, Vancouver, BC.
Meager Creek	Lillooet River	SLRD	092J12, 092J	Mount Meager, a glaciated volcano in a changing cryosphere: hazard and risk challenges	N		Y	Y	Roberti, G. (2018). Mount Meager, a glaciated volcano in a changing cryosphere: hazard and risk challenges [Doctoral dissertation]. Simon Fraser University, Burnaby, BC.
				Risk assessments for debris flows	N		Y	Y	Jakob, M. & Holm, K. (2012). Risk assessments for debris flows. In J.J. Clague and D. Stead (Eds.), Landslides: Types, mechanisms and modeling. Cambridge, UK: Cambridge University Press.

Location				Project		Hazard Type			Reference
Name	River Basin	District	NTS ID	Project Title	Report? (Y/N)	Flooding?	Landslide?	Steep Creek?	Citation
Squamish River	Squamish River	SLRD	092G14	The geomorphic impact of the catastrophic October 1984 flood on the planform of Squamish River, southwestern British Columbia	N	Y			Hickins, E.J. & Sickingabula, H.M. (1988). The geomorphic impact of the catastrophic October 1984 flood on the planform of Squamish River, southwestern British Columbia. Canadian Journal of Earth Science, 25, 1078-1087.
Dusty Creek, Avalanche Creek	Squamish River	SLRD	092J03	Two debris flow modes on Mount Cayley, British Columbia	N		Y	Y	Lu, Z.Y. & Cruden, D.M. (1996). Two debris flow modes on Mount Cayley, British Columbia. Canadian Geotechnical Journal, 33, 123-139.
Turbid Creek	Squamish River	SLRD		Emergency response incidence summaries	N		Y	Y	Government of British Columbia (2015, August 10-16), Emergency response incident summaries. Retrieved from <a href="https://www2.gov.bc.ca/gov/content/safety/emergency-management/emergency-management/incident-summaries">https://www2.gov.bc.ca/gov/content/safety/emergency-management/emergency-management/incident-summaries</a>
Squamish River	Squamish River	SLRD	092J03, 092J04	Squamish-Lillooet Regional District flood hazard mapping and risk assessment upper Squamish	N	Y			Northwest Hydraulic Consultants (NHC). (2018, November 26). Squamish-Lillooet Regional District flood hazard mapping and risk assessment upper Squamish [Report, R4]. Prepared for Squamish-Lillooet Regional District.
Squamish River	Squamish River	SLRD	092J03, 092J04	Squamish-Lillooet Regional District flood hazard mapping and risk assessment upper Squamish	N	Y			Northwest Hydraulic Consultants (NHC). (2019, April 10). Squamish-Lillooet Regional District flood hazard mapping and risk assessment upper Squamish [Report, R6]. Prepared for Squamish-Lillooet Regional District.
Lillooet River	Lillooet River	SLRD	092J11, 092J12	Lillooet River floodplain mapping	Y	Y			Northwest Hydraulic Consultants (NHC). (2018, November 22). Lillooet River floodplain mapping [Report]. Prepared for Pemberton Valley Dyking District Office.
Green River	Lillooet River	SLRD	092J07	2016 Mount Currie rock fall and local instabilities	Y		Y		Ministry of Forests, Lands and Natural Resource Operations. (2016, October 24). 2016 Mount Currie rock fall and local instabilities [Report]. Prepared for Squamish-Lillooet Regional District.
Cheakamus River, Mamquam River, Cheekeye River	Squamish River	SLRD	092G11, 092G12	Squamish flood timeline 14 October 2014.	N	Y			District of Squamish (DoS). (2014). Squamish flood timeline 14th October 2014. Retrieved from <a href="https://squamish.ca/assets/Squamish-Flood-Timeline-14-Oct-2014.pdf">https://squamish.ca/assets/Squamish-Flood-Timeline-14-Oct-2014.pdf</a>
Cheakamus River, Mamquam River, Cheekeye River	Squamish River	SLRD	092G11, 092G12	Integrated flood hazard management plan	Y	Y			Kerr Wood Liedel Associated Ltd. (2017, October). Integrated flood hazard management plan [Report]. Prepared for District of Squamish.
Cheakamus River, Fitzsimmons Creek, Crabapple Creek, Rutherford Creek, Nineteen Mile Creek, Twenty-one Mile Creek	Cheakamus River, Green River	SLRD	092J02	Flood hazard specific guide	N	Y		Y	Resort Municipality of Whistler (RMOW). (2016). Flood Hazard Specific Guide. Retrieved from <a href="https://www.whistler.ca/sites/default/files/2016/Dec/related/21022/rmowfloodhazard-specificguide.pdf">https://www.whistler.ca/sites/default/files/2016/Dec/related/21022/rmowfloodhazard-specificguide.pdf</a>
Howe Sound	Howe Sound	SLRD	092G11	Potential impact areas of sea level rise by the year 2100 in British Columbia	N	Y			Kerr Wood Leidal Associated Ltd. (2012, April). Potential impact areas of sea level rise by the year 2100 in British Columbia [Map]. Scale 1:250,000. Victoria, BC: FLNRO.
Turbid Creek	Squamish River	SLRD	092J03	Weather thresholds and operational safety planning, Turbid Creek, Mount Cayley, Squamish River Valley, BC.	N		Y	Y	Cordilleran Geoscience. (2013, March 19). Weather thresholds and operational safety planning, Turbid Creek, Mount Cayley, Squamish River Valley, BC [Report]. Prepared for FLNRO.
				Debris flow control structures for forest engineering	Y			Y	VanDine, D.F. (1996). Debris flow control structures for forest engineering (Working Paper 22 1996). Victoria, BC: Ministry of Forests Research Program.
Meager Creek	Lillooet River	SLRD	092J11	Volcanic landslide risk management, Lillooet River Valley, BC: Start of north and south FSRs to Meager confluence, Meager Creek and Upper Lillooet River	Y		Y	Y	Cordilleran Geoscience. (2012, March 10). Volcanic landslide risk management, Lillooet River Valley, BC: Start of north and south FSRs to Meager confluence, Meager Creek and Upper Lillooet River [Report]. Prepared for FLNRO.

Location				Project		Hazard Type			Reference
Name	River Basin	District	NTS ID	Project Title	Report? (Y/N)	Flooding?	Landslide?	Steep Creek?	Citation
				Landslides in the Vancouver-Fraser Valley-Whistler region	N		Y	Y	Evans, S.G. & Savigny, K.W. (1994). Landslides in the Vancouver-Fraser Valley-Whistler region. In J.W.H. Monger (Ed.), Geology and Geological Hazards of the Vancouver Region, Southwestern British Columbia (Geological Survey of Canada, Bulletin 481, pp. 251-286). Ottawa, ON: Geological Survey of Canada.
Britannia Creek	Howe Sound	SLRD	092G11	The 1915 and 1921 disasters at the Britannia Mine complex, Howe Sound, British Columbia; geotechnical implications for intensive resource development in steep mountain watersheds in the Coast Mountains	N		Y	Y	Evans, S.G. (2000). The 1915 and 1921 disasters at the Britannia Mine complex, Howe Sound, British Columbia: Geotechnical implications for intensive resource development in steep mountain watersheds in the Coast Mountains. In Canadian Society of Engineering Geologists, Annual Meeting 2000, Abstract 896.
Catiline Creek	Lillooet River	SLRD	092J07	Catiline Creek debris-flow hazard and risk assessment	Y			Y	BGC Engineering Ltd. (2015, January 22). Catiline Creek debris-flow hazard and risk assessment [Report]. Prepared for Squamish-Lillooet Regional District.
Bear Creek	Fraser River	SLRD	092J09	Bear Creek Fan preliminary debris-flow hazard assessment, Whitecap development	Y			Y	BGC Engineering Ltd. (2017, January 31). Bear Creek Fan preliminary debris-flow hazard assessment, Whitecap development [Report]. Prepared for Squamish-Lillooet Regional District.
Mount Currie	Green River	SLRD	092J07	Mount Currie landslide risk assessment	Y		Y		BGC Engineering Ltd. (2018, January 16). Mount Currie landslide risk assessment [Report]. Prepared for Squamish-Lillooet Regional District.
Bear Creek, Whitecap Creek	Portage River	SLRD	092J09	Seton Portage area integrated hydrogeomorphic risk assessment	Y			Y	BGC Engineering Ltd. (2018, April 6). Seton Portage area integrated hydrogeomorphic risk assessment [Report]. Prepared for Squamish-Lillooet Regional District.
Boulder Creek	Lillooet River	SLRD	092J11	Post-wildfire geohazard risk assessment: Boulder Creek Fire, BC	Y			Y	BGC Engineering Ltd. (2016, September 28). Post-wildfire geohazard assessment: Boulder Creek Fire, BC [Report]. Prepared for FLNRO.
Downton Lake, Carpenter Lake	Bridge River	SLRD	092J14, 092J	Geo-referenced landslide information system for characterization of landslide hazards at the reservoir scale, Bridge River watershed, southwestern BC	N		Y		Vera, G.A.B. (2014). Geo-referenced landslide information system for characterization of landslide hazards at the reservoir scale, Bridge River watershed, southwestern BC [Master's thesis]. University of British Columbia, Vancouver, BC.
Lillooet River	Lillooet River	SLRD	092J11, 092J	2011 Lillooet River survey, cross section and bathymetric survey	Y	Y			Kerr Wood Leidal Associated Ltd. (2011, December 21). 2011 Lillooet River survey, cross section and bathymetric survey [Report]. Prepared for Pemberton Valley Dyking District.
Lillooet River	Lillooet River	SLRD	092J11, 092J	Lillooet River survey, interpretation of 2011 river survey	Y	Y			Kerr Wood Leidal Associated Ltd. (2011, December 22). Lillooet River survey, interpretation of 2011 river survey [Memo]. Prepared for Pemberton Valley Dyking District.
Lillooet River	Lillooet River	SLRD	092J11, 092J	Large woody debris assessment and mitigation plan	Y	Y			Kerr Wood Leidal Associated Ltd. (2011, June 16). Large woody debris assessment and mitigation plan [Report]. Prepared for Pemberton Valley Dyking District.
Lillooet River	Lillooet River	SLRD	092J07, 092J	Lillooet Lake lowering analysis, summary of hydraulic modelling	Y	Y			Kerr Wood Leidal Associated Ltd. (2010, December 3). Lillooet Lake lowering analysis, summary of hydraulic modelling [Memo]. Prepared for Pemberton Valley Dyking District.
Ryan River	Lillooet River	SLRD	092J07, 092J	Ryan River hydraulic model and dyking assessment	Y	Y			Kerr Wood Leidal Associated Ltd. (2009, February). Ryan River model and dyking assessment [Report]. Prepared for Pemberton Valley Dyking District.
				High magnitude-low frequency landslides in British Columbia	N		Y		Evans, S.G. (1992). High magnitude-low frequency catastrophic landslides in British Columbia. In P. Bobrowsky (Ed.), Geologic Hazards in British Columbia, Proceedings of Geologic Hazards '91 Workshop February 20-21, 1992, Victoria, BC (pp. 71-98). Victoria, BC: BC Geological Survey Branch.
				Risk analysis of landslides affecting major transportation corridors in southwestern British Columbia	N		Y		Hazzard, J. (1998). Risk analysis of landslides affecting major transportation corridors in southwestern British Columbia [Master's thesis]. University of British Columbia, Vancouver, BC.

Location				Project		Hazard Type			Reference
Name	River Basin	District	NTS ID	Project Title	Report? (Y/N)	Flooding?	Landslide?	Steep Creek?	Citation
				Landslides along the Sea to Sky corridor	N		Y	Y	Blais-Stevens, A. & Septer, D. (2006). Landslides along the Sea to Sky corridor. In Sea to Sky Geotechnique 2006, Technical Paper M4-C (pp. 448-455).
Whistler Creek	Cheakamus River	SLRD	092J02	Flood and debris flow mitigation for the proposed Whistler Creek redevelopment	N	Y		Y	Hungr, O. (1993). Flood and debris flow mitigation for the proposed Whistler Creek redevelopment. In Proceedings, Canadian Water Resource Association, BC Chapter, Vancouver, BC (pp. 97-103).
Whistler, Squamish Howe Sound	Green River, Cheakamus River, Squamish River	SLRD		Slope hazards in the southern Coast Mountains of British Columbia	N	Y	Y	Y	Jackson, L.E., Church, M., Clague, J.J. & Eisbacher, G.H. (1985). Slope hazards in the southern Coast Mountains of British Columbia (Field Trip 4 Guidebook). Geological Society of America Cordilleran Section Annual Meeting, Vancouver, British Columbia, May 6-10. Vancouver, BC: Geological Society of America.
				Effects of climate change on the frequency of slope instabilities in the Georgis Basin, BC	Y		Y	Y	M. Miles & Associates Ltd. (2001, September). Effects of climate change on the frequency of slope instabilities in the Georgia Basin, BC [Report]. Prepared for Canadian Climate Action Fund, Natural Resources Canada.
Fitzsimmons Creek	Green River	SLRD	092J02	The 50-year flood on Fitzsimmons Creek, Whistler, British Columbia	N	Y		Y	Ward, P.R.B., Skermer, N.A. & LaCas, B.D. (1991). The 50-year flood in Fitzsimmons Creek, Whistler, British Columbia. The BC Professional Engineer, December 1991, 5-6.
Britannia Creek	Howe Sound	SLRD	092G11	Britannia Creek report on channel restoration design and construction	Y	Y		Y	Bland, C.R. (1992). Britannia Creek report on channel restoration design and construction [Report]. Prepared for BC Environment Water Management Division.
Britannia Creek	Howe Sound	SLRD	092G11	Britannia Creek landslide dam outbreak flood assessment	Y	Y	Y	Y	BGC Engineering Ltd. (2017, February 9). Britannia Creek landslide dam outbreak flood assessment [Report]. Prepared for Britannia Oceanfront Development Corporation.

# APPENDIX D

## GEOHAZARD EVENT INVENTORY





Year	Month	Type of Hazard	Location	Source	Description of Event
		Flood	Squamish	Skwxwú7mesh Úxwumixw oral history	Refer to description provided by Skwxwú7mesh Úxwumixw
1900	June	Watercourse Flood	Squamish, Squamish River	Septer (2007)	After heavy rain, the Squamish River flooded it's banks by 1.5 to 1.8 m, washing away some homes and confining residents to upper stories of the rest. Damage estimated at \$50,000.
1906	September	Watercourse Flood	Squamish, Cheakamus River	Septer (2007), District of Squamish (2014)	Bridge over the Cheakamus River washed away in flooding
1906	September	Watercourse Flood	Squamish, Squamish River	Septer (2007), District of Squamish (2014)	After heavy rain, the bridge over the east mouth of the Squamish River washed away in floodwaters of at least 3 m high.
1906	September	Watercourse Flood	Squamish, Squamish River	Septer (2007), District of Squamish	After heavy rain, hop farms in the Squamish Valley were flooded from the rising Squamish River.
1921	October	Watercourse Flood	Squamish, Mamquam River	District of Squamish (2014)	Flooding covered the Squamish valley floor
1921	October	Watercourse Flood	Squamish, Squamish River	District of Squamish (2014)	Flooding covered the Squamish valley floor
1924	September	Watercourse Flood	Squamish, Mamquam River	Septer (2007)	Squamish Railway bridge was washed away by the flooding Mamquam river. Traffic was rerouted by stage through Ashcroft. Damage was in the thousands of dollars and expected to be repaired in 2-3 days.
1924	September	Watercourse Flood	Squamish, Squamish River	Septer (2007)	The government bridge at Squamish was washed away by the Squamish River.
1932	December	Watercourse Flood	Squamish, Howe Sound	District of Squamish (2014)	The ocean topped the sea dike and flooded downtown Squamish
1937	October	Watercourse Flood	Squamish, Mamquam River, Cheeky River	Septer (2007)	A railway bridge was pushed out of alignment and flooded by the Mamquam river, isolating Brackendale between 2 lost bridges.
1940	October	Watercourse Flood	Squamish, Squamish River	Septer (2007), District of Squamish (2014)	Flooding of the Squamish River caused evacuations from Brackendale to downtown Squamish.
1940	October	Watercourse Flood	Squamish, Squamish River	Septer (2007)	Flooding on the Squamish River caused evacuations from Brackendale to downtown Squamish, Dynamite was used to blast the main sea dikes and some small dikes blocking water.
1940	October	Watercourse Flood	Squamish, Mamquam River	Septer (2007)	Flooding of the Mamquam flooded Squamish streets with 1.5 m of water, overturning cars with a strong current.
1940	October	Watercourse Flood	Squamish, Mamquam River	Septer (2007)	Flooding of the Mamquam weakened the PGE railbridge and several other smaller railway bridges were also lost.
1949	November	Watercourse Flood	Squamish, Squamish River	Septer (2007)	A violent winter storm caused flooding at Squamish. In the vicinity of the PGE railway shops, 10-12 families had to be evacuated. At one stage the water was within 5 cm of the top of the dykes ringing the settlement. In Squamish itself, lower level homes were surrounded by water and basements flooded in the school area. The overflowing log-jammed Squamish and Mamquam rivers wiped out three bridges (two railway bridges and the highway bridge). Some 300 homes were temporarily isolated by 2 m of water, which flooded the valley.
1950	October	Watercourse Flood	Squamish, Mamquam River, Squamish River	District of Squamish (2014), Septer (2007)	Flooding on the Squamish River caused damage to roads and rail bridges. Flash floods hit the shop area of Squamish. Road and railway crews worked all night clearing logs and debris away from bridges. The Mamquam River bridge had a curve as water started to recede and floating logs had torn the decking and railings. The high tide backed up the water from the swollen Squamish River to several outlying areas but did not affect the town itself. As the tide receded, the rivers gradually went down and by the next day were well inside their banks. There were accounts of extensive bank erosion caused by the Squamish River during the flood.
1951	December	Watercourse Flood	Squamish, Howe Sound	District of Squamish (2014), Septer (2007)	On December 1, wind-backed tides breached the sea dike in two places. Water poured into the area on the east side of Cleveland Avenue. Within a short time, water was running over the sidewalks and the main street of Squamish was flooded with 0.6 m of water. Just south of Squamish, Highway 99 washed out.
1953	January	Watercourse Flood	Squamish, Howe Sound	Septer (2007)	High tides backed by a strong south wind drove water over River Road and flooded low-lying areas near Squamish. The road washed out and was badly rutted for 100 m. One residence flooded, and water came within inches of coming into several others. In the lower end of Squamish, the water was almost level with the dyke.
1954	November	Watercourse Flood	Squamish, Mamquam River	Septer (2007)	Heavy warm rain melted snow on the mountains along Howe Sound and brought the river levels up. The Squamish River came over the road in several places and the Mamquam River was running bank full. Crews dynamited logs which jammed against the railway bridge and city crews kept close watch over road bridges.

Year	Month	Type of Hazard	Location	Source	Description of Event
1954	November	Watercourse Flood	Squamish, Stawamus River, Mamquam River, Shannon Creek	Septer (2007)	In the middle of November, heavy rains and subsequent flooding caused considerable damage to the road and bridge system in the Squamish Valley. It was the second time in two weeks that the heavy rains brought the rivers in the area to dangerous levels. A culvert north of Shannon Creek washed out, cutting traffic on Highway 99. High water undermined a small bridge south of Shannon Creek. Water flooded across the road above the Mamquam bridge. Logs and debris coming down with the high water damaged the Mamquam River bridge. Squamish lost its municipal water supply for over 24 hours as heavy rains caused the Stawamus River to rise and wash out a bent between the intake and the forebay. Gravel and debris washed in front of the intake at the dam, reducing the amount of water coming through the pipe.
1955	June	Watercourse Flood	Squamish, Cheakamus River, Squamish River, Mamquam River	Septer (2007)	A sudden hot spell caused the Squamish and Cheakamus rivers to rise. The Squamish River crested when it was 0.6 m below the road at Alvie Andrews'. The Cheakamus River threatened BC Hydro's bridge across the Cheakamus. Rock fills were placed around the bents, but further work was required as soon as the river dropped. The southern approach to the Mamquam River collapsed when a logging truck passed over it. The approach was filled, and a breakwater built alongside it. The bridge, which since the previous fall's high water had been anchored by cables, required extensive repairs or replacement.
1955	October	Watercourse Flood	Squamish, Mamquam River, Squamish River	District of Squamish (2014), Septer (2007)	After 75 mm or rain the Squamish and Mamquam rivers rose 2.5 m in 24 hours. Many acres of the north end of Squamish were flooded. Flooding on the Mamquam River washed out the Mamquam Bridge for the 10th time in 28 years. After debris piled against it, both ends gave way and hurled against the railroad bridge. After water levels subsided, the bridge was a twisted mass of wreckage with a portion of the bridge draped over a huge logjam in the middle of the river. Railway crews managed to save their bridge by blasting away the logs and debris which lodged against it. Until the completion of a new road bridge, the railway bridge was planked and temporary road built to the highway.
1955	November	Watercourse Flood	Cheakamus River Valley, Evans Creek, Cheakamus River, Mamquam River, Squamish River	Septer (2007)	Heavy rain on snow brought local rivers over their banks. The Highway 99 Bridge across Stoney Creek was in precarious condition and bus transport between Squamish and Britannia Beach was cancelled. The Mamquam and Squamish rivers flooded the valley from the former Joyce ranch to below the shops. About 100 people were evacuated. The Cheakamus River washed out a small portion of the road to Paradise Valley. Evans Creek washed holes in the upper valley road.
1956	June	Watercourse Flood	Squamish, Mamquam River, Cheakamus River	Septer (2007)	The Mamquam, Squamish and Cheakamus rivers rose 0.3 m per hour. Near Squamish, the Squamish and Mamquam rivers threatened three bridges. On June 7, a sudden rise sent logs and debris into a railway bridge and two highway spans about 5 km north of Squamish. The Mamquam River flooded a road about 3 km from Squamish and was washing away the approaches of a vehicular bridge. Logging companies in the area were blasting logs and debris away from all bridges and moving equipment to higher ground.
1956	September	Watercourse Flood	Squamish, Mamquam River	Septer (2007)	Rain caused the Mamquam River to rise 1.8 m at its mouth at Squamish. The floodwater piled up debris against a railway bridge. The river knocked out an 18 m section of the rail line including the bridge.
1957	September	Watercourse Flood	Squamish, Cheakamus River, Squamish River	Septer (2007)	Torrential rains caused flooding in the Squamish Valley. The swollen Squamish River burst its banks, flooding to a depth of 4 m in places and blocking the only road. Dozens of cars and trucks were trapped. The BC Hydro powerhouse under construction at Cheakamus was flooded; it cut off 40 workers for two night.
1958	October	Watercourse Flood	Squamish, Squamish River	District of Squamish (2014)	Flooding on the Squamish River caused four feet of water over the main road in Brackendale.
1963	July	Debris Flow	Squamish River Valley, Dusty Creek, Turbid Creek	Clague and Souther (1982); Jakob (1996)	A large landslide occurred on the west flank of Mount Cayley, the failure commenced when a large block of poorly consolidated tuff breccia detached and slid into the valley of Dusty Creek. The block fragmented and moved about 1 km down Dusty Creek. The debris mass thinned as it spread across the broader, flatter valley of Turbid Creek, and was deposited as an irregular blanket with a maximum thickness of 65 m. Because of the landslide Turbid and Dusty creeks were blocked, and lakes formed behind the debris. These debris dams were soon overtopped and rapidly breached, causing floods and probably debris flows to sweep down Turbid Creek valley far beyond the terminus of the landslide.
1967	December	Outburst Flood - Manmade Structure	Squamish, Howe Sound	District of Squamish (2014)	The sea dike was overtopped and flooded downtown Squamish.
1968	September	Watercourse Flood	Squamish, Stoney Creek	Septer (2007)	Rains washed out a temporary road and culvert built around the bridge during construction of Stoney Creek bridge.
1968	October	Watercourse Flood	Squamish, Stoney Creek	Septer (2007)	Stoney Creek spilled its banks, flooding and washing out a section of Highway 99 and railroad track 4 km south of Squamish, closing both for a day.
1968	November	Watercourse Flood	Squamish, Mamquam	District of Squamish (2014)	Flooding on the Mamquam River damaged a trailer park, highways and the railway.

Year	Month	Type of Hazard	Location	Source	Description of Event
1975	November	Watercourse Flood	Cheakamus River Valley, Cheakamus River, Daisy Lake, Mamquam River, Cheakamus River, Squamish River,	Septer (2007)	Continuous rain combined with a sudden rise in the freezing level caused the Cheakamus and Squamish rivers to flood. Dozens of residents were evacuated or commuted by rowboat. Many backroads were impassable, and homes were surrounded by 1 m of water. The Daisy Lake reservoir threatened to overflow its dam, BC Hydro was forced to open the gate, thus increasing river levels above its banks at some points. About 25-30 people left the Cheakamus area when minor flooding hit their homes. The Mamquam River caused bank erosion and the District of Squamish carried out emergency bank stabilization. Where Highway 99 follows the Squamish River it was flooded with 1 m of water. The heavy rain also washed out a temporary bridge at Stoney Creek, 5 km south of Squamish, closing Highway 99.
1975	November	Watercourse Flood	Squamish	Septer (2007)	On November 13, residents of a trailer park near Squamish were evacuated due to flooding caused by a week-long rain storm in the region.
1980	December	Watercourse Flood	Squamish, Stawamus River	Septer (2007)	Logjams on Squamish, Cheakamus and Mamquam rivers led to damages to 200 homes and closure of Highway 99. A partial jam on Mamquam River suddenly gave way, sending a wall of water down the river. The Squamish River jumped dykes flooding an area where the dyke was never completed as funding ran out. Overflow from Daisy Lake caused the Squamish River to backup. Government Road was under water. The Cheakamus River threatened several cottages between it and Highway 99. In the Squamish Valley, many of the mobile homes in the Spiral Trailer Court were flooded, forcing evacuation of the trailer park and other homes closest to the water's edge. Three helicopters and a hovercraft were used to evacuate more than 500 people in low-lying areas of Squamish and Brackendale. The Mamquam River flooded the Wagon Wheel Trailer Court and road. At the Valleycliffe subdivision, the Stawamus River, diverted some years earlier by city engineers to form a park, reverted to its old course and threatened to sweep away a house. The BC rail line was broken to permit water out. Floodwaters cut roads north of Squamish and three bridges on the road to Cheekeye washed out. After the Cheekeye bridge on the Cheakamus River washed out, the residents of the Upper Squamish Valley were flown out. Dykes prevented flooding in Squamish itself and the new highway but the unprotected area on the north shore of the Mamquam River and from the confluence of the Mamquam and Squamish rivers up to the Lions Easter seal camp suffered heavy flooding.
1981	January	Outburst Flood - Natural Impoundment	Squamish, Culliton Creek	Septer (2007)	A temporary log bridge on Highway 99 washed out. The structure at Culliton Creek had been installed only weeks prior as a replacement for the permanent bridge that had been washed out during the Boxing Day floods. The washout was caused by heavy rain developing a dam, which broke and released the floodwaters. Since the floods also washed out an old logging road bridge in the area, children going to school in Squamish and residents going to work, walked across a 47 m long railway bridge across Culliton Creek. BC Rail security posted a "No Trespassing" sign on the bridge as trains could not be stopped in time. The railway bridge was the only lifeline for the 25 families that lived in the Upper Cheakamus Valley.
1981	October	Watercourse Flood	Squamish, Squamish River	District of Squamish (2014)	177 mm of rain fell in Squamish in 48 hours. The Squamish River overflowed its left bank from the downstream end of the dyke completed in 1975 to the BC rail crossing at Government Road and then along the BC rail right of way, through the Spiral Mobile Park and then into the area of the confluence of the Mamquam and Squamish rivers. Hop Ranch Creek inundated the Easter Seals Camp area.
1981	November	Watercourse Flood	Squamish, Cheakamus River	Septer (2007)	The Cheakamus River overflowed its banks, breaching dykes and washing out a 300 m stretch of road at Paradise Valley. Eighteen students and three teachers from Brackendale Elementary School were left stranded in the Cheakamus subdivision and an area known locally as Upper Cheakamus.
1984	June	Debris Flow	Squamish River Valley, Avalanche Creek, Turbid Creek	Cruden and Lu (1992); Jakob (1996)	Approximately 3.2 million cubic meters of volcanics travelled 2 km down Avalanche Creek at velocities up to 35 m/s to dam the confluence of Avalanche and Turbid creeks. The breaching of the landslide dam caused an extremely fast debris flow. The debris flow removed the logging road bridge and road approaches to the mouth of Turbid Creek, blocked the Squamish River during surges, and introduced huge quantities of sediment to the Squamish River.
1984	October	Watercourse Flood	Squamish, Cheakamus River, Cheekeye River, Squamish River,	District of Squamish (2014); Ebbwater (2022)	A section of dyke along the Cheekeye River to the Cheakamus River started to give away behind the Black Bear Restaurant by Alice Lake, but temporary repairs were made. A log bridge across the Cheakamus River was destroyed, the flooding it caused damaged homes. In the Eagle Run Drive area, water was starting to collect behind the Petrocan station and in the nearby trailer court. A ditch was dug from the court to the nearby pumphouse, which relieved the problem.
1984	October	Watercourse Flood	Squamish, Squamish River	Hickin and Sickingabula (1988)	Three successive days of heavy rain from October 6 to October 8 caused bankfull or greater flows on Squamish River for three consecutive days during this flood. At least 10 homes near Squamish had to be evacuated due to the heavy flooding. In the braided reach the flood caused floodplain erosion and major reorganization of the channel to an extent previously unrecorded, apparently exceeding a threshold for channel stability.
1986	January	Watercourse Flood	Squamish, Squamish River	Septer (2007)	Heavy rains combined with frost in the ground resulted in minor flooding in a number of areas in the Squamish Valley. Problems were reported in Brackendale, Garibaldi Estates and Valleycliffe. A section of unprotected bank along the Mamquam River started to develop erosion threatening the dyke. By the middle of February, the river had already taken away up to 30 m of sandy bank.

Year	Month	Type of Hazard	Location	Source	Description of Event
1989	November	Watercourse Flood	Squamish, Cheakamus River, Squamish River	Septer (2007)	As water levels in the Upper Squamish and Cheakamus rivers rose rapidly due to heavy rains, RCMP warned about 75 Squamish residents to prepare to flee their homes.
1990	November	Watercourse Flood	Squamish, Mashiter Creek	Septer (2007)	High water caused the Mashiter Creek rock dam that diverts water to the cement intake structure to break. Adjacent to the new intake structure, a 15 m rock dam was ripped out. The hole in the dam allowed water to divert away from the intake and reopen the original creek bed. When the dam broke, a pulse of water, gravel and logs was sent down the creek. Damage was extensive, and the fisheries intake was estimated at \$15,000. Although a section of the diversion weir washed out and sediment was deposited, there was no apparent damage to the gates, screens or concrete of the diversion structures. It was rumoured that the dam had been designed to fail under such flooding conditions in order to reduce damage to the main intake.
1991	August	Outburst Flood - Manmade Structure	Squamish, Mashiter Creek	Septer (2007)	The Mashiter Creek dam was taken out after a debris jam formed in the Mashiter Creek water intake. On August 30, rocks and debris had filled the dam solid and rendered it inoperable. The original creek bed was ripped up, and the creek was redirected back to its original course.
1992	October	Watercourse Flood	Squamish River Valley, Squamish River	Septer (2007)	Resident at the Tantalus Acres subdivision, north of Brackendale near the Squamish River experienced flooding problems. Water was flowing along the Squamish Valley Road and on to the road to the subdivision. The water, 0.2-0.3 m deep, collected in some low-lying areas including front and backyards. Subdivision residents noted that at high water in the Squamish River, water backs up a creek channel that crosses Squamish Valley Road, where it flows down the road to Tantalus.
1993	July	Debris Flow	Squamish River Valley, Turbid Creek	Jakob (1996)	Debris flow observed by Jakob in the field. The debris flow discharged approximately 300,000 m <sup>3</sup> into the Squamish River over a 30-minute time period. The debris arrived in regular surge intervals spaced 25 to 35 seconds apart. Boulders up to 0.5 m diameter and up to 15 m long logs were transported in the flow. The site was visited two days after the event at which time the deposit had not drained, indicating a high clay content.
1995	October	Watercourse Flood	Squamish, Stawamus River	Septer (2007)	Heavy rain caused increased the level of sedimentation in the Squamish municipal drinking water, which turned noticeably discoloured. As well, some pine needles, moss and mucky material came through some resident's taps. The turbidity did not increase enough to require a boil water advisory.
1999	May	Watercourse Flood	Squamish River Valley, Squamish River	Septer (2007)	Rapid snowmelt resulted in high water flows, causing the loss of the existing riverbank along Squamish Valley Road, about 9.1 km from the Cheakamus River bridge. The cost to restore the riverbank and road protection along the full 15 m length was \$44,500. The next event would have the potential to wash out the road at this point and isolate the local first nations reserve.
2003	October	Watercourse Flood	Squamish, Cheakamus River, Squamish River	District of Squamish (2014), Septer (2007); Ebbwater (2022)	Largest flood in 50 years (369 mm in 4 days) caused District evacuations and damaged the BC rail line. Dikes were not overtopped.
2005	January	Watercourse Flood	Squamish, Mashiter Creek	Septer (2007)	After Mashiter Creek rose sharply, a boil water advisory was declared in the Garibaldi Heights area of Squamish. Officials were keeping close watch over the rising Cheakamus River. On January 21, heavy rain caused a rockfall to come down in the Cheakamus Canyon on Highway 99. An estimated 600-800 m <sup>3</sup> of rock ended up in the ditch along the highway.
2006	November	Watercourse Flood	Squamish, Squamish River	Septer (2007)	As the Squamish River was rising rapidly, evacuations were under way in Squamish. The river was expected to continue rising the next day, causing some flooding upriver from Brackendale.
2011	March	Watercourse Flood	Squamish	DriveBC	Flooding on highway 99, 1 km south of Alice Lake Road, closed a lane on the highway.
2012	November	Debris Flow	Squamish River Valley, Turbid Creek	Cordilleran (2013); Cordilleran (2022)	A debris flow on Turbid Creek washed out the Squamish River FSR and stranded two vehicles on the far side of the creek unable to reach Squamish.
2014	June	Watercourse Flood	Squamish River Valley, Turbid Creek	EMBC (June 9, 2014); Cordilleran (2022)	Turbid Creek (known locally as Mud Creek near Squamish) overflowed its banks causing the Squamish River FSR to wash out around 21 km. Several hundred people were attending a gathering and were stranded. A contractor opened a path to provide an exit for people to walk out before the road was opened the following day.
2019	September	Debris Flow	Squamish River Valley, Turbid Creek	Cordilleran (2022)	A debris flow damaged the Squamish River FSR. The repairs took approximately three days.
2019	September	Debris Flow	Squamish River Valley, Turbid Creek	n/a	Another debris flow, larger than the earlier September event, once again damaged the Squamish River FSR. The repairs took approximately six days to complete.
2021	November	Watercourse Flood	Pemberton Creek, Fitzsimmons Creek, Rubble Creek, Stawamus River; Cheakamus River; Mamquam River; Squamish River; Millar Creek	Lau et al (2022); Chua (2021); Lalonde (2021)	The mid-November to early December atmospheric rivers caused many rivers to drastically rise in SLRD. Overland flooding was reported on the Cheakamus I.R. 11 along Fergie's Landing Road. The Stawamus River reached the bottom of the CN rail bridge but did not sustain damage.

# APPENDIX E

## CLEAR-WATER HAZARD MASSESSMENT METHODS





## E-1 INTRODUCTION

### E-1.1 Objective

This appendix describes the approach used by BGC to identify and characterize clear-water flood geohazards within the Squamish-Lillooet Regional District (SLRD). The results form the basis to assign hazard and consequence ratings to prioritize flood-prone areas in proximity to developed areas within the study area.

This appendix is organized as follows:

- Section E.2 describes methods and data sources used to identify and characterize areas
- Section E.3 describes methods used to assign priority ratings.

This appendix entirely pertains to clear-water flood geohazards. The main report describes how geohazard and consequence ratings were combined to prioritize each geohazard area.

#### E.1.1. Context

Damaging floods are common in the SLRD. Areas susceptible to flood-related losses include settled valley bottoms such as the communities located along the Squamish, Mamquam, Cheakamus, Stawamus and Lillooet Rivers, and areas where lifeline infrastructure including regional transportation corridors traverse floodplains. While the SLRD has historical precedent for flooding, recent floods around the Pemberton area in 2016 (Figure E-1) and the post-wildfire flood events of 2015 such as the Terminal Creek mudslide have highlighted the need for a coordinated, approach to flood management in the SLRD. Identifying and prioritizing flood-prone areas is an important step towards improving flood management planning within the SLRD.



**Figure E-1. Damage from flooding of Lillooet River in Pemberton, BC (CBC, November 10, 2016).**

The largest community of Squamish is located with a hazard area that is subject to multiple flood-related hazards including clear-water, steep creek (debris flood and debris flow), avulsion

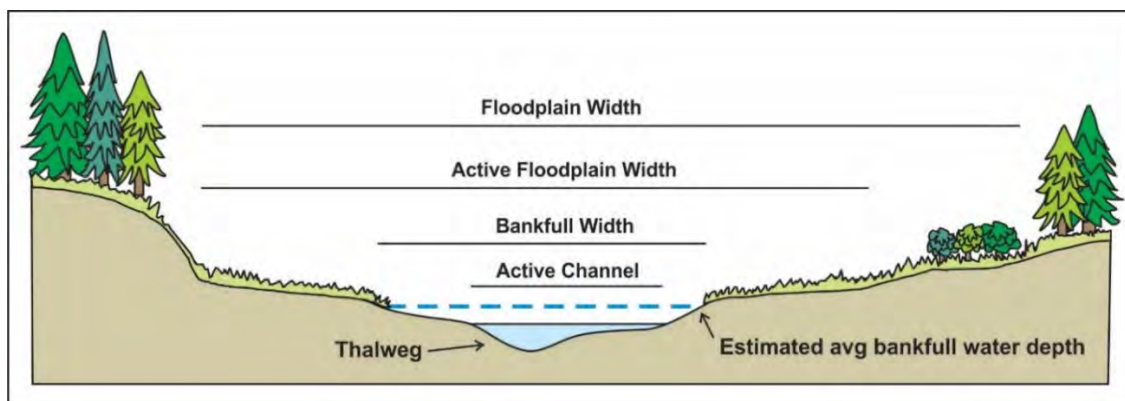
and erosion hazards and dike breaches along the five major rivers that converge within the District of Squamish in addition to coastal flood and tsunami hazards from Howe Sound. The District of Squamish recently completed a comprehensive Integrated Flood Hazard Management Plan (IFHMP) (Kerr Wood Leidal [KWL], October 2017) that provides an update to the 1994 Flood Hazard Management Plant (FHMP) (Klohn Leonoff, 1994), to develop an integrated approach to managing potential risks from the following flood hazards including:

- River floods from the Squamish, Mamquam, Cheakamus, and Stawamus Rivers
- Debris flows and floods on the Cheekeye River
- Coastal floods and tsunamis from Howe Sound.

A majority of the severe flooding in the SLRD occurs between October and December due to intense multi-day rainstorms, atmospheric rivers, or combined rain-on-snow events. In contrast to other areas in BC, the spring freshet typical of May to July is not a major cause of flooding. Major flooding has occurred in August. Flood severity can vary considerably depending on:

- The amount and duration of the precipitation (rain and snowmelt) event
- The antecedent moisture condition of the soils
- The size of the watershed
- The floodplain topography
- The effectiveness and stability of flood protection measures.

For example, excessive rainfall, rain-on-snow, or snowmelt can cause a stream or river to exceed its natural or engineered capacity. Overbank flooding occurs when the water in the stream or river exceeds the banks of the channel and inundates the adjacent floodplain in areas that are not normally submerged (Figure E-2). Climate change also has the potential to impact the probability and severity of flood events by augmenting the frequency and intensity of rainfall events, altering snowpack depth, distribution, timing, snow water equivalent (SWE), and freezing levels and causing changes in vegetation type, distribution and cover. Impacts are likely to be accentuated by increased wildfire activity and / or insect infestations (British Columbia Ministry of Environment [BC MOE], 2016). Sea level rise also poses a significant threat to areas subject to coastal flooding such as Howe Sound.



**Figure E-2. Conceptual channel cross-section in a typical river valley.**

In BC, the 200-year return period flood is used to define floodplain areas, with the exception of the Fraser River, where the 1894 flood of record is used, corresponding to an approximately 500-year return period (Engineers and Geoscientists BC [EGBC], 2017). The 200-year flood is the annual maximum river flood discharge (and associated flood elevation) that is exceeded with an annual exceedance probability (AEP) of 0.5% or 0.005. While flooding is typically associated with higher return events, such as the 200-year return period event, lower return period events (i.e., more frequent and smaller magnitude events) have the potential to cause flooding if the banks of the channel are exceeded.

### E.1.2. Approach Overview

Historical flood events that have occurred within the SLRD are generally due to riverine flooding from rainfall, snowmelt and glacial runoff processes. However, flooding can also be triggered from other mechanisms such as ice or large woody debris jams, undersized watercourse crossings, structural encroachments into flood-prone areas, channel encroachment due to bank erosion, wind- or landslide-generated waves, failure of engineered structures or, landslide, glacial, moraine or beaver dam outbreak floods.

The focus of the clear-water flood hazard assessment for the SLRD is on riverine and lake flooding from precipitation (rainfall or snowmelt driven melt) within natural watercourses and lakes and does not consider flooding due to other mechanisms such as failure of engineered structures (e.g., dams and dikes), or overland urban/sewer-related flooding. Historical floodplain maps have been developed for select areas of the SLRD based on the designated flood as represented by the 200-year return period event or AEP of 0.5% (British Columbia Ministry of Forests, Lands and Natural Resource Operations [BC MFLNRO], 2016). These floodplain maps are the basis for this prioritization study, along with a review of historical flood events and a prediction of floodplain extents for natural watercourses and lakes in the SLRD where historical floodplain mapping or more recent third-party mapping is unavailable. The floodplain maps and predicted floodplain extent are shown on the web application accompanying this report.

Table E-1 summarizes the approaches used to identify and characterize clear-water flood hazard areas. In this study, flood areas were identified from the following spatial sources (Figure E-3):

1. Inventory of historical flood event locations.
2. Existing historical and third-party floodplain mapping.
3. Prediction of coastal flooding extents.
4. Prediction of floodplain extents for streams, rivers and lakes using terrain analysis.

**Table E-1. Summary of clear-water flood identification approaches.**

Approach	Area of SLRD Assessed	Application
Historical flood event inventory	All mapped watercourses and waterbodies prone to clear-water flooding.	Identification of creeks and rivers with historical precedent for flooding. The historical flooding locations are approximate locations where known landmarks adjacent to a watercourse were flooded, or specific impact to structures (roads, houses) was reported in media.
Existing floodplain mapping	All watercourses and waterbodies prone to clear-water flooding where existing information was available.	Identification of floodplain extents from publicly available historical mapping and third-party data sources.
Coastal flood hazard extents	All mapped watercourses subject to sea level rise and coastal flooding.	Identification of low-lying areas below the projected future 1 m sea level rise 200-year coastal flood level of 3.99 m based on the Squamish Integrated Flood Hazard Management Plan (KWL, October 2017).
Identification of low-lying areas to predict floodplain extents	All mapped watercourses and waterbodies without existing floodplain mapping.	Identification of low-lying areas adjacent to streams and lakes using a terrain-based inundation mapping method called Height above Nearest Drainage (HAND) applied to mapped stream segments. Method provides screening level identification of flood inundation extents and depths based on a digital elevation model.





**Figure E-3.** Example spatial sources used to identify clear-water flood hazards in the SLRD including historical floodplain mapping (purple outlines) and predicted floodplain extents for streams and lakes without existing floodplain mapping (transparent orange areas). Locations of known flood protection structures (black line) were inventoried but not prioritized. Refer to Section D.2.4 for a description of the methods used for predicting floodplain extents.



## E.2. CLEAR-WATER FLOOD GEOHAZARD CHARACTERIZATION

The following sections describe methods and data sources used to identify and characterize clear-water flood geohazard areas as summarized in Table E-1. In addition to the clear-water flood hazard areas described below, BGC notes that flood hazard exists on steep creek fans that are also prone to debris floods or debris flows. Assessment methods for steep creek fans are described in Appendix F.

### E.2.1. Historical Flood Event Inventory

BGC compiled a historical flood and steep creek inventory across the SLRD and digitized the locations of historical events from Septer (2007), DriveBC (British Columbia Ministry of Transportation and Infrastructure [BC MoTI], April 2018), and recent freshet-related floods and landslides sources (e.g., media reports). Historical flood events such as the event shown in Figure E-4 were used to confirm flood-prone low-lying terrain outside of the historical floodplain maps. Clear-water flood hazard areas were intersected with the flood event inventory compiled by BGC to identify areas with greater potential susceptibility to flooding. However, geohazard ratings were not increased for clear-water hazard areas that intersected a past flood event location.

The historical flooding locations presented on the web application are approximate locations where known landmarks adjacent to a watercourse were flooded, or specific impact to structures (roads, houses) was reported in media. Flooding events are indicated as a point location and therefore do not represent the full extent of flooding on a watercourse (e.g., Figure E-3). Additional details on the historical flood event inventory are provided in geospatial (GIS) layers delivered with this study.



**Figure E-4.** Flood event of October 1940 when the Squamish River topped its banks and sent flood water into downtown Squamish, BC after five inches of rain fell within 24 hours. (The Squamish Chief, November 8, 2018).

## E.2.2. Existing Floodplain Mapping

### E.2.2.1. Historical Mapping Sources

The BC government provides publicly-available information on the location of floodplains, floodplain maps and supporting data (BC MFLNRO, 2016). A provincial floodplain mapping program began in BC in 1974, aimed at identifying flood risk areas. This was in part due to the large Fraser River flood of 1972, which resulted in damage in the BC Interior. From 1975 to 2003, the Province managed development in designated floodplain areas under the Floodplain Development Control Program. From 1987 to 1998, the rate of mapping increased through the Canada / British Columbia Agreement Respecting Floodplain Mapping. The agreement provided shared federal–provincial funding for the program and included provisions for termination of the agreement as of March 31, 2003. This mapping was generally focused on major rivers as summarized in Table E-2. While the maps are now outdated, their use is promoted by the MFLNRO as often representing the best floodplain mapping information available (EGBC, 2017).

The historical floodplain maps typically show both the extent of inundation and flood construction levels (FCLs) based on the 0.5% AEP or 200-year return period event and include a freeboard allowance. At select locations, the 5% AEP or 20-year return period flood elevation (including a freeboard allowance) was also provided for septic tank requirements under the Health Act at the time. Flood levels associated with the 0.5% AEP (including a freeboard allowance) have been used to establish design elevations for flood mitigation works and to inform local floodplain management policy and emergency preparedness. The historical flood maps do not consider the occurrence and location of flood protection measures in the map extents.

Historical floodplain mapping in the SLRD is approximately 35 years old and as a result does not:

- Reflect the full data record available for hydrometric stations within the watershed since the mapping was conducted. Estimates of the 200-year return period flood have likely changed since there are now an additional 20+ years of hydrometric records.
- Reflect potential changes in channel planform and bathymetry (e.g., aggradation and bank erosion as well as channel changes and avulsion paths formation), or development within the floodplain that could alter the extent of inundation.
- Accuracy is limited to the resolution of the input data. Mapping predates high resolution Lidar surveys and hydraulic analysis was limited to 1-dimensional (1D) analysis.
- Consider climate change impacts on flooding (directly by predicted changes in rainfall and/or snowmelt and indirectly by changes in vegetation cover through wildfires and/or insect infestations).
- Consider the presence of flood protection measures such as dikes or embankments, if applicable, and does not consider flood scenarios associated with failure of these structures (e.g., dike breaches, which would result in different flood inundation patterns, depths and velocities than if water levels rose in the absence of dikes).

The quality and accuracy of the historical floodplain mapping was not evaluated as part of this prioritization study. Further, freeboard and flood protection measures such as dike protections have not been evaluated or considered in the geohazard or consequence ratings applied.

Table E-2. Summary of historical floodplain mapping within the SLRD conducted by the BC Province.

Site No. <sup>1</sup>	Watercourse (Area)	District	Approximate Floodplain Area (km <sup>2</sup> )	Approximate Floodplain Length (km)	Floodplain Map Year	Flood Protection Measures?	Recorded Historical Flood Events	Comments
1	Lillooet River (Green, Ryan and Birkenhead Rivers, Miller and Pemberton Creeks)	PVDD <sup>2</sup>	71	40	1973, 1980, 1990, 1995	Yes	1940, 1981, 1984, 1991, 2003, 2016	Several floodplain mapping and hydraulic studies have since been completed for the Lillooet River with the latest mapping conducted in 2018 for a 50 km reach from Pemberton Meadows to Lillooet Lake (Northwest Hydraulic Consultants [NHC], August 31, 2018). Historical mapping includes alluvial fans on Ryan and Birkenhead Rivers and Pemberton and Wolverine Creeks.
2	Whistler Area (Millar and Fitzsimmons Creeks, Green, Nita and Alpha Lakes)	SLRD	9	18	1978, 1984, 1993	Yes	1940, 1981, 1984, 1991, 2003, 2016	Mapping efforts included several tributaries that occur on active alluvial fans and are prone to sediment deposition, avulsion and bank erosion including Whistler and Fitzsimmons Creeks. Floodplain mapping includes Millar, Alta and Nita Creeks and Alta and Green Lakes.
3	Squamish River (High Falls to Howe Sound)	SLRD	60	37	1983	Yes	1940, 1981, 1984, 1991, 2003, 2016	Mapping efforts included the confluence with the Mamquam and Cheakamus Rivers. Alluvial fans of the Cheakamus, Mamquam and Cheekeye River were also mapped. A detailed flood hazard mapping and risk assessment study was conducted for the Upper Squamish River in 2019 (NHC, April 10, 2019) along with flood hazard assessment conducted by KWL, October 2017.
4	Cheakamus River (Hut Creek to Squamish River)	SLRD	7	11	1986	Yes	1940, 1981, 1984, 1991, 2003, 2016	Mapping efforts cover a distance of Cheakamus River upstream from its confluence with the Squamish River. BC Hydro conducted a 1984 study on a hypothetical breach in Daisy Lake Dam in the upper Cheakamus River and produced inundation maps that show runoff for the probable maximum flood (PMF) to Howe Sound (BC Hydro, 1984). Peak flows in Cheakamus River were not attenuated by the reservoir during high flood events such as the October 1981 flood (BC MOE, 1986).

Notes:

- 1. Refer to Figure D-5 for floodplain location.
- 2. Pemberton Valley Dyking District (PVDD).

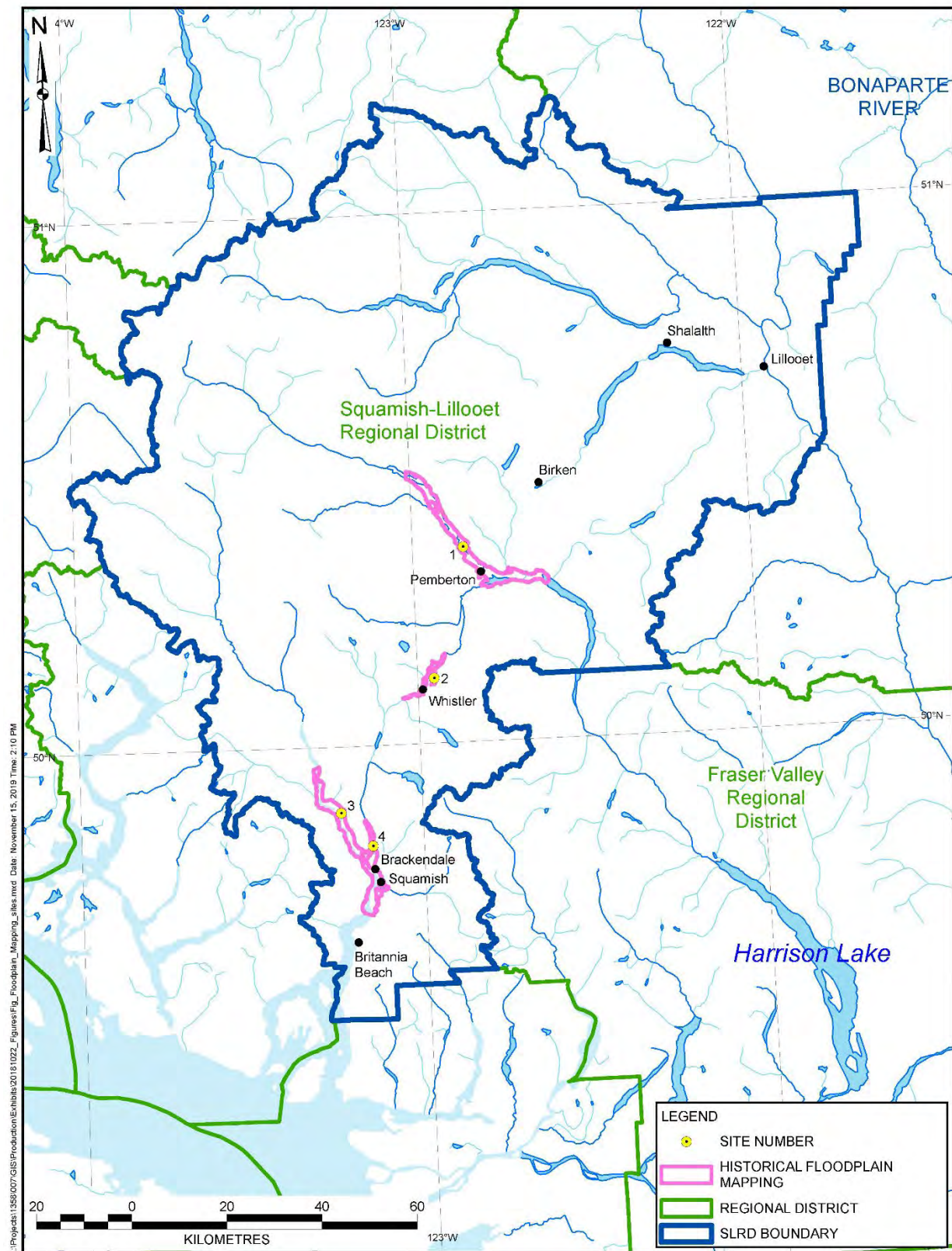


Figure E-5. Historical floodplain mapping in the SLRD.



#### E.2.2.2. Third-Party Mapping Sources

BGC is aware of the following floodplain mapping completed by third parties (private consultants) that post-dates historical mapping. The mapping shown in bold was available in geospatial (GIS) format and incorporated into this study:

- Squamish - Coastal flood hazard area (KWL, October 2017)
- Lillooet River (NHC, August 31, 2018)
- Upper Squamish River (NHC, April 10, 2019)
- Fitzsimmons Creek mapping conducted for the Resort Municipality of Whistler (RMOW).

BGC is also aware of the following flood mitigation projects that received 2019 Union of BC Municipalities (UBCM) funding in the SLRD including:

- Lillooet River floodplain flood mitigation planning (Village of Pemberton and SLRD)
- Squamish River Dike, Judd Slough Dike seismic risk assessment and mitigation strategy (SLRD)
- Fitzsimmons Creek flood mitigation (RMOW).
- National Disaster Mitigation Program (NDMP) Stream 2 funding was awarded in 2019 to conduct detailed flood mapping of six high priority creeks and rivers within RMOW's jurisdiction to inform potential mitigation strategies and emergency planning. These flood hazard areas include Fitzsimmons Creek, Alta Creek, Crabapple Creek, Van West Creek, Spring Creek and Cheakamus River. NDMP funding was also awarded to the District of Squamish to complete engineering designs and planning for dike upgrades in the Eagle Viewing / Seacichem area.

As a result of the limited existing floodplain mapping available within the SLRD, BGC developed an approach to predict floodplain extents for locations where historical floodplain mapping was not available as described in above.

#### E.2.3. Coastal Flooding Extent

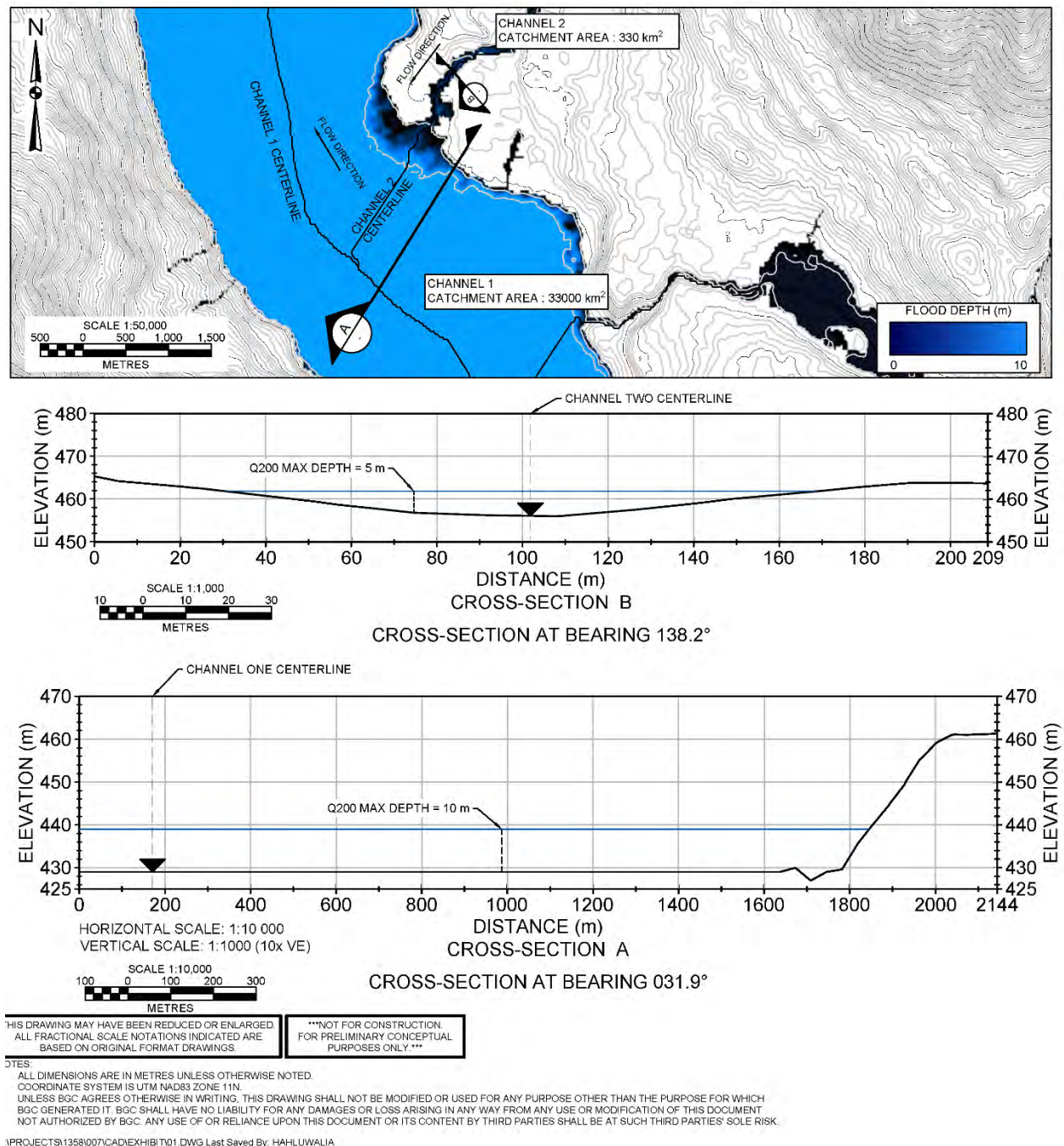
Results of an inundation study indicate that downtown Squamish is at risk of coastal flooding in a less than 200-year return period event with 1 m of projected sea level rise (KWL, October 2017). A potential coastal flood hazard area in Howe Sound was developed from a 2013 Lidar DEM incorporating all cells where the elevation was less than the future (1 m sea-level rise) 200-year coastal flood level of 3.99 m elevation as determined in the Integrated Flood Hazard Management Plan (IFHMP) for the District of Squamish (KWL, October 2017). The IFHMP defines a 200-year return period "still-water" coast flood for coastal flooding in Squamish that does not account for wave or wind allowances.

#### E.2.4. Screening-Level Flood Hazard Identification

BGC carried out a terrain-based flood hazard identification exercise within the SLRD using the HAND approach, originally proposed by Rennó et al. (2008). This approach is a practical alternative to hydraulic modelling over large areas, when the goal is to generate horizontal floodplain extents. Whereas conventional modelling requires knowledge of anticipated flow, the only required data for the HAND approach is a DEM. This concept is illustrated in Figure E-6

which shows that the HAND value for a given point represents the relative height between that point and the nearest stream that it drains to (Zheng et al., 2018). Therefore, any cell with a HAND value below a given threshold (a maximum predicted flood-depth) can be assumed to be within the inundation extents in the event of a flood reaching this level.

The terrain-based analyses were used to identify and prioritize areas subject to clear-water flooding and do not replace detailed floodplain mapping that includes bathymetric surveys and hydraulic modelling. The output of this process also serves as a basis for identifying locations where detailed floodplain mapping is required in the future



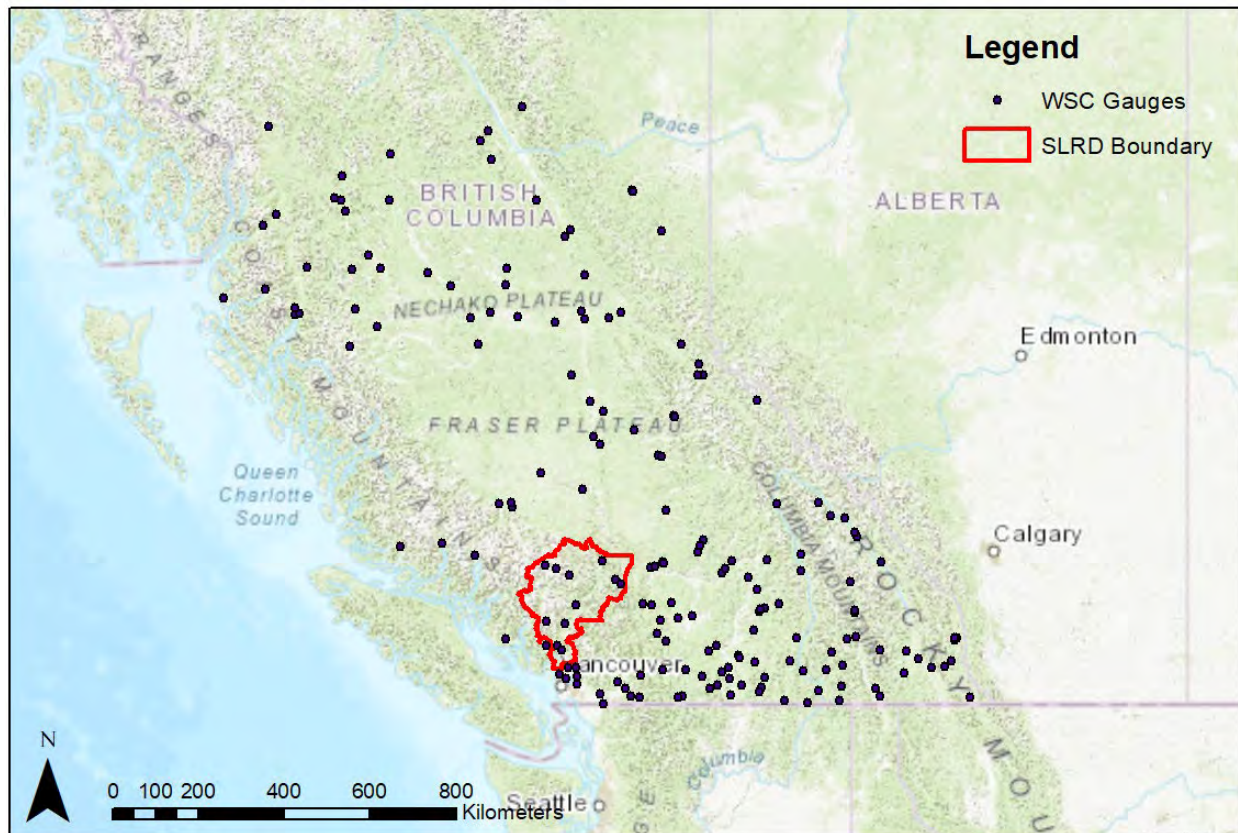
**Figure E-6. Illustration of the HAND concept (Modified from Zheng et al., 2018).**

The HAND processing was performed using the 30 m digital elevation model (DEM) for the study area acquired from the Shuttle RADAR Topography Mission (SRTM) (Farr et al., 2007). The analysis was performed using the Terrain Analysis Using Digital Elevation Models (TauDEM) GIS tool suite (Tarboton, 2016). TauDEM is a set of GIS-based tools designed for large-scale hydrological analysis of topographic data. The “Vertical Drop” function within this suite allows for the calculation of HAND using a stream network and flow accumulation model as inputs.

For this study, the HAND model was used to estimate the approximate area that could be inundated in a 200-year return period flood event for all watercourses within the study area. In order to identify appropriate HAND values to associate with flood depths, the relationship between catchment area and flood depth during a 200-yr return period flood was assessed. Hydrometric data from 205 Water Survey of Canada (WSC) (Environment and Climate Change Canada [ECCC], July 16, 2018) gauging stations with over 10 years of records located in southern BC were analyzed to provide a relationship between catchment area and flood depths (Figure E-7). For each gauge, a stage-discharge curve was built using readings collected between June and July. These two months were selected as the rating curves are seasonally adjusted by the WSC so a stable period to generate the rating curves was required.

The HAND mapping exercise was carried out for all waterbodies existing within the drainage network generated through TauDEM, these included rivers as well as lakes and reservoirs. The methodology for calculating the maximum 200-year flood depth did not differ based on type of waterbody (i.e., lakes, rivers and reservoirs were all treated the same way).

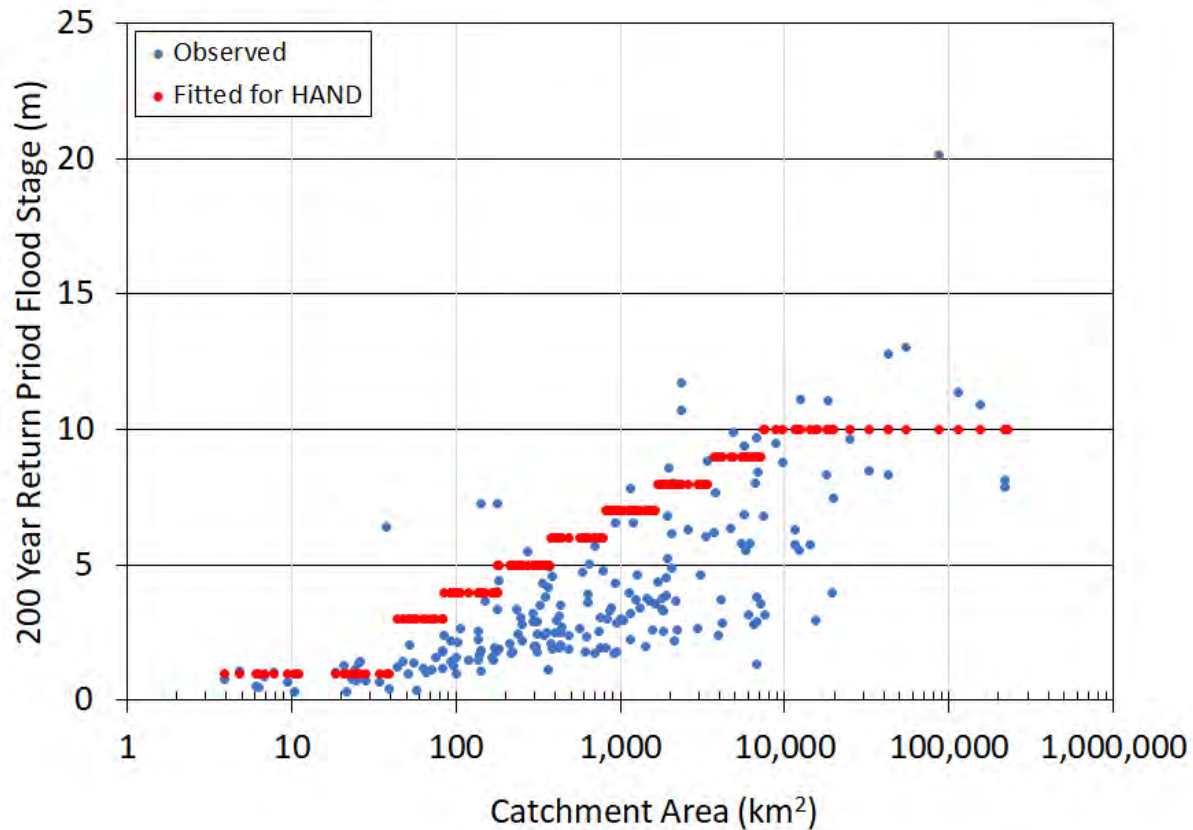




**Figure E-7.** Location of the 205 WSC hydrometric stations used in the analysis to extract the flood stage for the 200-year return period flood.

The 200-year return period flood was estimated by fitting a generalized extreme value (GEV) curve to the annual maximum daily flow records. The flood stage associated with the 200-year return period event was then estimated using the stage-discharge curve based on the 200-year flood discharge. The 200-year flood stage was plotted against the catchment area for the gauge as shown in Figure E-8. An upper bounding curve was fit to the relationship between the 200-year flood stage and the catchment area to ensure the model was conservative. Because the SRTM DEM is an integer-based DEM, discrete flood depths were rounded to the nearest meter as shown in Table E-3.





**Figure E-8.** 200-year return period flood stage versus catchment area for 205 WSC hydrometric gauging stations in southern BC. Red dots represent the curve fitted to observed values to relate catchment area to flood stage for estimating HAND flood depths.

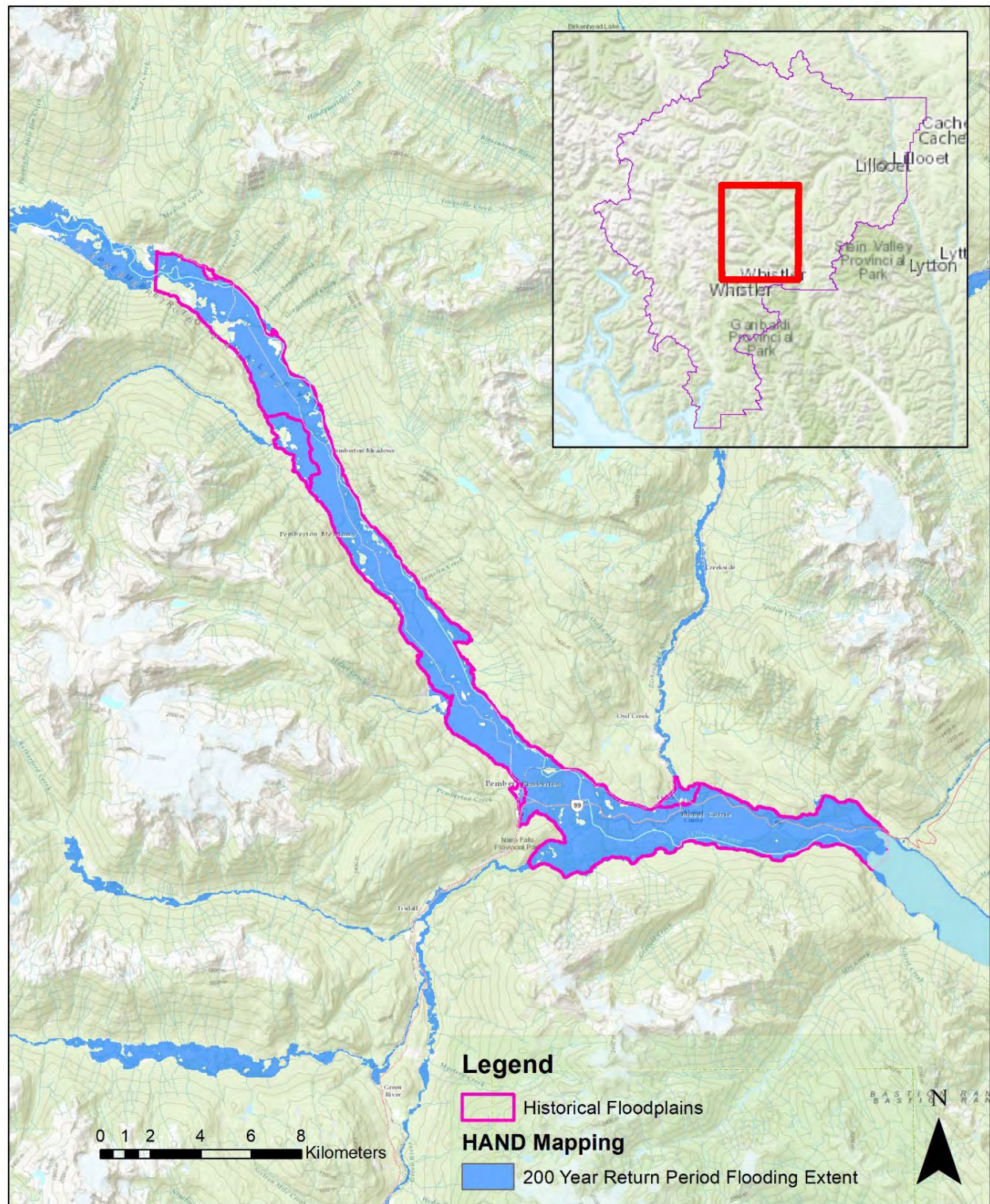
**Table E-3.** Flood depths by catchment area used for estimating the 200-year flood elevations.

Catchment Area Categories		Maximum Estimated Flood Depth (m)
Lower Bound (km²)	Upper Bound (km²)	
0	40	2
40	85	3
85	180	4
180	375	5
375	785	6
785	1,650	7
1,650	3,455	8
3,455	7,250	9
>7,250		10

Based on these results, a stream network for each catchment area group was generated and used as input to the Vertical Drop function within TauDEM. For each HAND output (result of the Vertical Drop function), all raster cells exceeding the maximum flood depth were eliminated. All remaining cells were combined into a single raster which makes the final 200-year floodplain boundary. Figure E-6 illustrates this concept; here there are two watercourses; one with a total catchment area of 330 km<sup>2</sup> the other 33,000 km<sup>2</sup>. The maximum HAND (based on the information in Table E-3) for the former is 5 m and 10 m for the latter.

The results from HAND mapping were compared to existing detailed floodplain mapping in the SLRD (Figure E-9). In general, HAND mapping is able to capture the extent of the flooding and to a lesser extent, the potential flood depths suggesting that the HAND modelling results can be used as a proxy for the '0.5% AEP' flood extent in the absence of existing mapping. Studies comparing the HAND modelling approach to the results from hydraulic models found that it was able to produce similar inundation extents (e.g., Afshari et al., 2018; Johnson et al., 2019).

However, the results should not be considered a specific representation of potential flood inundation and do not replace hydraulic modelling or detailed floodplain mapping. The HAND modelling is not a hydraulic model and therefore does not account for backwater effects created by obstructions in the watercourse from man-made structures (bridges, culverts) or natural constructions. The quality of the results also relies on the ability of the DEM data to capture topographic features that influence the extent of the floodplains and is typically better suited for wider floodplains.



**Figure E-9. Comparison between the historical floodplain mapping and the 200-year return period flooding extents based on the HAND mapping for the Lillooet River.**



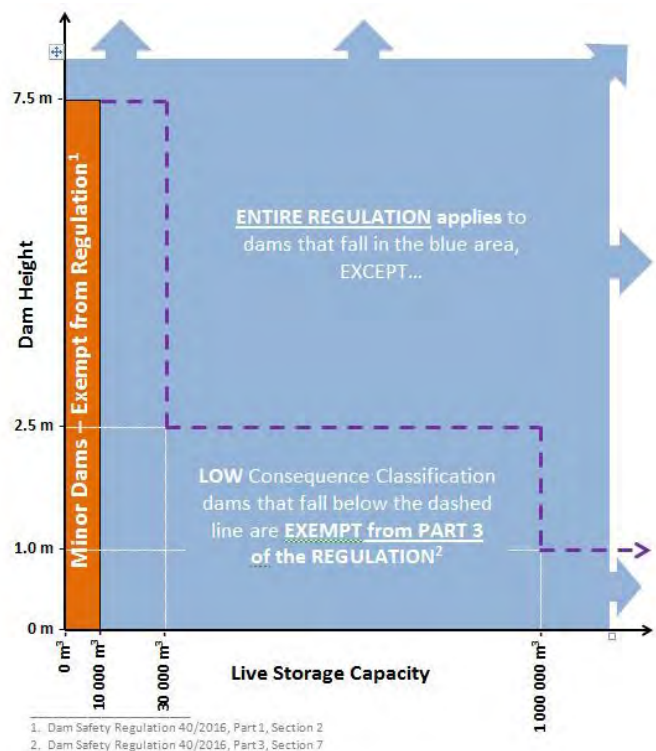
## E.2.5. Additional Considerations

The following sections describe additional data sources that were reviewed for the SLRD but were not incorporated into the characterization and prioritization of clear-water flood geohazard areas for the level of study.

### E.2.5.1. Regulated Dams

Within the SLRD, there are currently 28 dams out of the 1,971 inventoried dams in BC that are regulated under the *Water Sustainability Act*, SBC 2014, c.15. Most of these dams occur on smaller watercourses within the SLRD and flows are generally unregulated. Although flow regulation due to the occurrence of dams has an impact on flood hydrology and could potentially reduce the magnitude of flood events, the impact of regulation on flows is outside the scope of this study.

Regulated dams require a water licence issued under the *Act* and must meet the requirements specified in the *Dam Safety Regulation*, BC Reg 40/2016. A total of 5 dams are classified as low consequence dams, which are exempt from portions of the Regulation (Figure E-10). Fourteen dams have a height greater than 7.5 m based on BC MFLNRO (2017a) and are fully regulated dams as listed in Table E-4 (two of which have been breached or decommissioned at Britannia Creek, the site of the former Britannia Mine).



**Figure E-10. Dam height (m) versus dam live storage capacity (m³) as defined by the Dam Safety Regulation, BC Reg 40/2016, which along with the dam failure consequence classification determines which portion of the Regulation applies to the dam.**

Dam failure of the Daisy Lake Dam (BC Hydro, 1984) in the upper Cheakamus River is identified as a remote but potentially severe consequence hazard in the IFHMP (KWL, October, 2017). BC Hydro maintains emergency plans and a flood alert system to notify local stakeholders in the unlikely occurrence of a dam breach at this location.

Three dams constructed as part of BC Hydro's Bridge River hydroelectric system influence the hydrology of Bridge River near Lillooet (BC Hydro, 2011). The system includes three reservoirs, three dams (La Joie Dam, Terzaghi and Seton Dams) and four generating stations. The system is designed to use water three times before releasing it to the Fraser River (BC Hydro, 2011).

The web application displays all the inventoried dams in the SLRD to support subsequent detailed flood hazard studies within the SLRD and should consider the potential flood hazards from high and extreme consequence dams such as the list provided in Table E-4 and Figure E-11.

**Table E-4. List of dams located within the SLRD.**

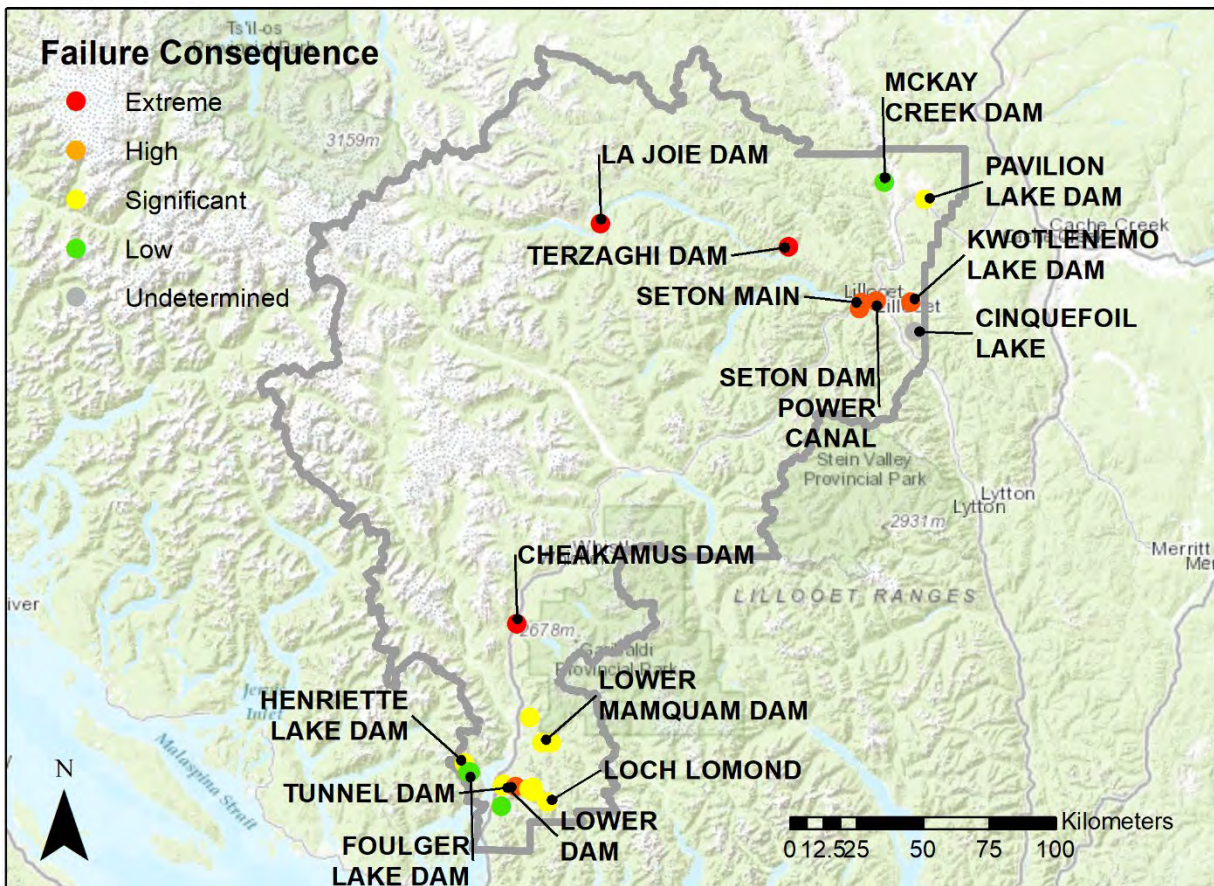
Dam Name	Owner	Dam Type	Ht (m)	Failure Consequence Category <sup>1</sup>	Status	Waterbody
Terzaghi Dam	BC Hydro & Power Authority	Earthfill	61	Extreme	Active	Bridge River, Carpenter Lake
La Joie Dam	BC Hydro & Power Authority	Rockfill	86.7	Extreme	Active	Bridge River, Downton Lake
Daisy Lake (Cheakamus) Dam	BC Hydro & Power Authority	Concrete gravity	29	Extreme	Active	Cheakamus River, Daisy Lake
Seton Dam Power Canal	BC Hydro & Power Authority	Earthfill	13	High	Active	Seton River
Seton Main	BC Hydro & Power Authority	Concrete gravity	11.3	High	Active	Seton River, Seton Lake
Tunnel Dam	Crown Land Opportunities and Restoration	Concrete gravity	9.8	High	Inactive	Britannia Creek
Kwotlenemo Lake Dam	Xaxli'p First Nation	Earthfill	3.7	High	Active	Kwotlenemo Lake
Walden Power	Cayoos Creek Power Lp	Concrete gravity	8.7	High	Active	Cayoos Creek
Lower Mamquam Dam	Atlantic Power (Coastal Rivers) Corporate	Concrete gravity	3.4	Significant	Active	Mamquam River



Dam Name	Owner	Dam Type	Ht (m)	Failure Consequence Category <sup>1</sup>	Status	Waterbody
Loch Lomond	Greater Vancouver Water District	Other	5.8	Significant	Active	Loch Lomond
Pavilion Lake Dam	Diamond "S" Ranch Limited	Earthfill	2.5	Significant	Active	Pavilion Lake
Mountain Lake	Crown Land Opportunities and Restoration	Concrete gravity	-	Significant	Active	Mountain Lake
Mineral Creek	Crown Land Opportunities and Restoration	Concrete gravity	20	Significant	Active	Mineral Creek
Upper Mamquam Hydro	Canadian Hydro Developers Inc.	Concrete gravity	13.4	Significant	Active	Mamquam River
Mashiter Creek Dam	District of Squamish	Concrete gravity	4	Significant	Active	Mashiter Creek
Henriette Lake Dam	Western Pulp LTD Partnership	Concrete–slab/buttress	17.4	Significant	Active	Henriette Lake, Henriette Creek
Mckay Creek Dam	The Blue Goose Cattle Company Ltd.	Earthfill	2.5	Low	Active	Mckay Creek
Foulger Lake Dam	Western Forest Products Inc.	Rockfill	4.7	Low	Active	Foulger Lake
South Valley Dam	Tanac Development Canada Corporation	Concrete gravity	17.1	Low	Decommissioned	Turrey Creek
Brennan Lake Dam	Western Forest Products Inc.	Rockfill	9.1	Low	Active	Brennan Lake

Note:

1. Failure consequence represents the consequence to downstream should the dam fail based on the estimated loss of life, loss to the environment and cultural values and economic and infrastructure losses. Failure consequence categories were not assigned by BGC.



**Figure E-11. Map showing the location of the dams located within the SLRD and their associated failure consequence classification.**

#### E.2.5.2. Dikes

Low-lying areas within river or coastal floodplains in the SLRD are often protected by dikes, though the condition of the dikes vary. A majority of the dikes are regulated by the Province of BC; however some private landowners and First Nations bands have dikes and flood protection works that are not provincially regulated. The provincial database for flood protection works includes structural works (MFLRNO, 2017b) and appurtenant structures (MFLRNO, 2017c). The database was developed through a provincial, GPS-based mapping project in 2004 and facilities shown in the database are regulated under the provincial *Dike Maintenance Act*, RSBC 1996, c. 95. As defined in the *Act*, a dike is “embankment, wall, fill, piling, pump, gate, floodbox, pipe, sluice, culvert, canal, ditch, drain, or any other thing that is constructed, assembled, or installed to prevent the flooding of land”. In addition, some dikes are considered “orphaned dikes.” These are flood protection works that are often constructed under emergency flooding conditions and are not maintained by a diking authority.

The web application displays the inventoried flood protection works in the SLRD including the location of documented orphaned dikes. However, no condition assessment, ground-truthing, survey or detailed evaluation of the infrastructure was completed as part of the prioritization

study, and the presence of such infrastructure was not accounted for in the prioritization. It is further noted that there may be additional structures not captured by the provincial database. The rationale for this approach reflects the study objective (prioritization) and level of detail of study.

#### E.2.5.3. Erosion Protection Structures

Riprap armouring or man-made erosion protection structures such as sheet piles are often used to protect against erosion in locations subject to riverine or coastal flooding. Although, these hard structures can provide protection from progressive channel migration and erosion, they do not eliminate the flood risk or prevent the channel from avulsing and forming a new active channel. The locations of erosion protection structures in the SLRD are not spatially inventoried for display on the web application.

#### E.2.5.4. Flood Conveyance Infrastructure

Although flood conveyance infrastructure such as culverts affect flood hydrology, assessment of this effect is outside the scope of this study. However, the location of culvert and road structures were included on the web application to support future detailed flood hazard studies within the SLRD. Because no single dataset exists for watercourse crossings in the SLRD, information was compiled from two MoTI databases to display on the web application including:

1. Culverts (BC MoTI, 2017a).
  - Point dataset for culverts or half-round flumes less than 3 m in diameter that are used to transport or drain water under or away from a road and/or Right of Way (RoW).
  - The majority of the data points are for culverts not on specific watercourses and many of the locations of culverts that are on specific watercourses do not align well with the stream network dataset described in Section B.2.1. Data on culvert parameters required for hydraulic analyses is typically not available.
2. Road Structures (BC MoTI, 2017b).
  - Polyline dataset for bridges, culverts ( $\geq 3$  m), retaining walls (perpendicular height greater than 2 m), sign bridges and tunnels/snowsheds that are located on a road and/or RoW that is owned and/or maintained by MoTI. The database includes structure names and reference numbers to the Bridge Management Information System (BMIS) but does not provide specifications for the structures.

The dataset is only for MoTI-owned infrastructure as included in the Road Features Inventory (RFI) (BC MoTI 2017c), and significant gaps exist for municipal, rail and industry-owned infrastructure.

### E.3. GEOHAZARD RATING

Hazard sites were prioritized based on the relative likelihood that an event will occur, impact an element at risk and result in some level of undesirable consequence. The largest floodplain polygons in proximity to elements at risk were divided into sub-catchments and intersected with electoral boundaries where appropriate to provide a relatively consistent area for comparing ratings.

#### E.3.1. Hazard Likelihood

Frequency analysis estimates how often geohazard events occur, on average. Frequency can be expressed either as a return period or an annual probability of occurrence. As described, floodplain maps are typically based on the designated flood as represented by the 0.5% AEP event. For consistency, the 200-year flood event likelihood was used as the basis to define approximate flood hazard extents and prioritize clear-water flood sites across the SLRD, which corresponds to a representative AEP of 0.5% or a “low” geohazard likelihood.

#### E.3.2. Consequence Rating

The main report presents a matrix used to assign consequence ratings to each hazard area based on the following two factors:

- Exposure of elements at risk to geohazards (exposure rating)
- Destructive potential of uncontrolled flows that could impact elements at risk (hazard intensity rating).

This section describes how BGC developed a proxy rating for hazard intensity, for clear-water floods.

Elements at risk can be vulnerable to flood and steep creek processes through direct impact by water or debris and through secondary processes such as channel avulsion, channel aggradation or scour, bank erosion, channel encroachment, or landslides. Detailed analysis of hazard intensity requires numerical modelling of parameters such as flow depth and velocity, which are not available for all areas assessed. As a result, flood depth was used as a measure of hazard intensity or destructive potential for clear-water flood hazards.

Estimated flood depths associated with the 200-year return period event were developed for clear-water flood hazard areas by finding the relationship between flood depth and catchment area. This was then used to screen the HAND modelling output (as described in Section E.2.4) to only include areas within the 200-year floodplain. Table E-5 shows the hazard intensity classes for clear-water hazard areas. The flood depth thresholds shown in Table E-5 are criteria developed from the HAND modelling and are conservatively high but provide a relative ranking of hazard areas. As well, the flood depths do not account for the occurrence of flood protection structures that could potentially alter the extent of flood inundation and cannot replace the use of flood stage-damage curves for detailed flood consequence estimation (e.g., Federal Emergency Management Association [FEMA], 2016).

**Table E-5. Summary of proposed criteria to be used for intensity rating for clear-water hazards.**

Hazard Intensity Rating	Estimated Maximum Flood Depth (m)
Low	< 3 m
Moderate	4 to 6 m
High	> 6 m



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# APPENDIX F

## STEEP-CREEK HAZARD ASSESSMENT METHODS



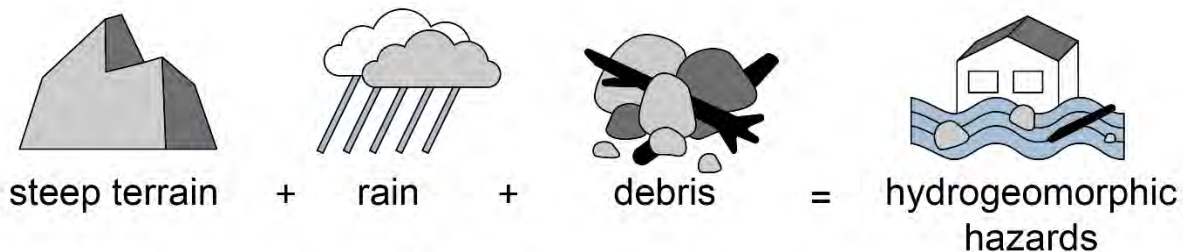
## F-1 INTRODUCTION

This appendix describes methods used by BGC to identify and characterize steep creek geohazards, and rate consequences within the study area. This appendix is organized as follows:

- Section F-1 provides background information and key terminology on steep creek geohazards, high level introduction to climate change effects on steep creek geohazards, introduction to the effect of wildfires on steep creek geohazards, and the workflow used to rate steep creek geohazard areas.
- Section F-2 describes methods and criteria used to identify steep creek geohazard areas.
- Sections F-3 and F-4 describe methods and criteria used to assign geohazard and consequence ratings, respectively.

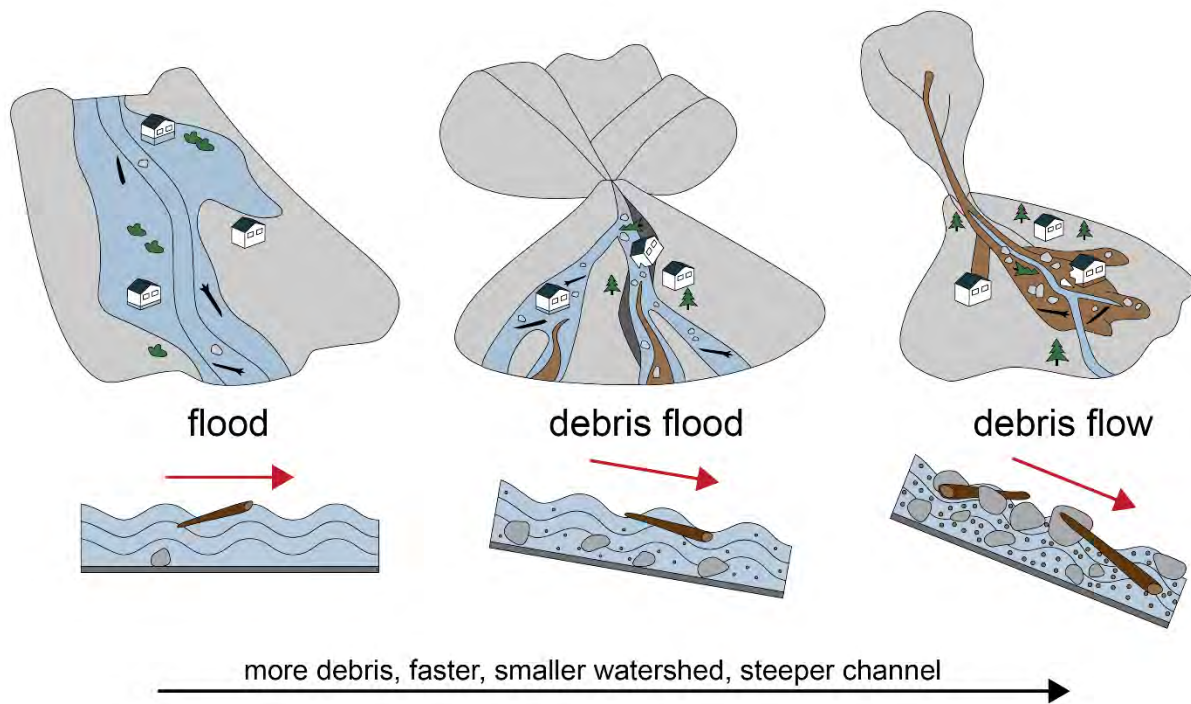
### F-1.1 What Are Steep Creek Geohazards?

Steep creek or hydrogeomorphic hazards are natural hazards that involve a mixture of water and debris or sediment (Figure F-1). These hazards typically occur on creeks and steep rivers with small watersheds (usually less than 100 km<sup>2</sup>) in mountainous terrain, usually after intense or long rainfall events, sometimes aided by snowmelt and worsened by forest fires. Steep creek hazards span a continuum of processes from clearwater floods (flood) to debris flows (Figure F-2). The following sections further describe steep creek watersheds and fans, debris flows, debris floods, and clearwater floods on fans.



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





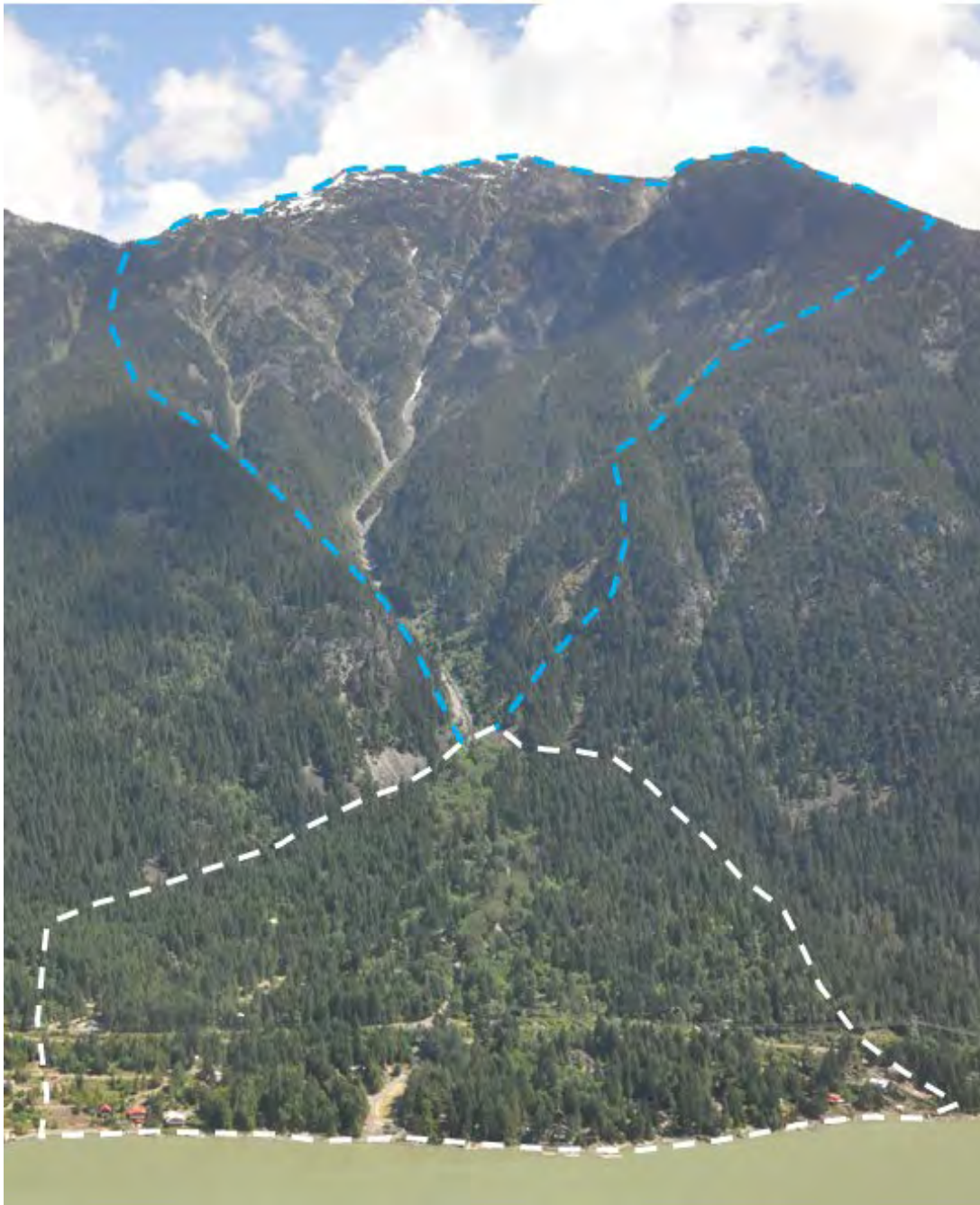
**Figure F-2. Continuum of steep creek hazards.**

#### F-1.1.1 Steep Creek Watersheds and Fans

A steep creek watershed consists of hillslopes, small feeder channels, a principal channel, and an alluvial fan composed of deposited sediments at the lower end of the watershed. Figure F-3 provides a typical example of a steep creek in the SLRD. Every watershed and fan are unique in the type and intensity of mass movement and fluvial processes, and the hazard and risk profile associated with such processes. Figure F-4 schematically illustrates two fans side by side. The steeper one on the left is dominated by debris flows and perhaps rock fall near the fan apex, whereas the one on the right with the lower gradient is likely dominated by debris floods.

In steep creek basins (or watersheds), most mass movements on hillslopes directly or indirectly feed into steep mountain channels from which they begin their journey downstream. Viewed at the scale of the catchment and over geologic time, distinct zones of sediment production, transfer, erosion, deposition, and avulsions may be identified within a drainage basin (Figure F-4 and Figure F-5).

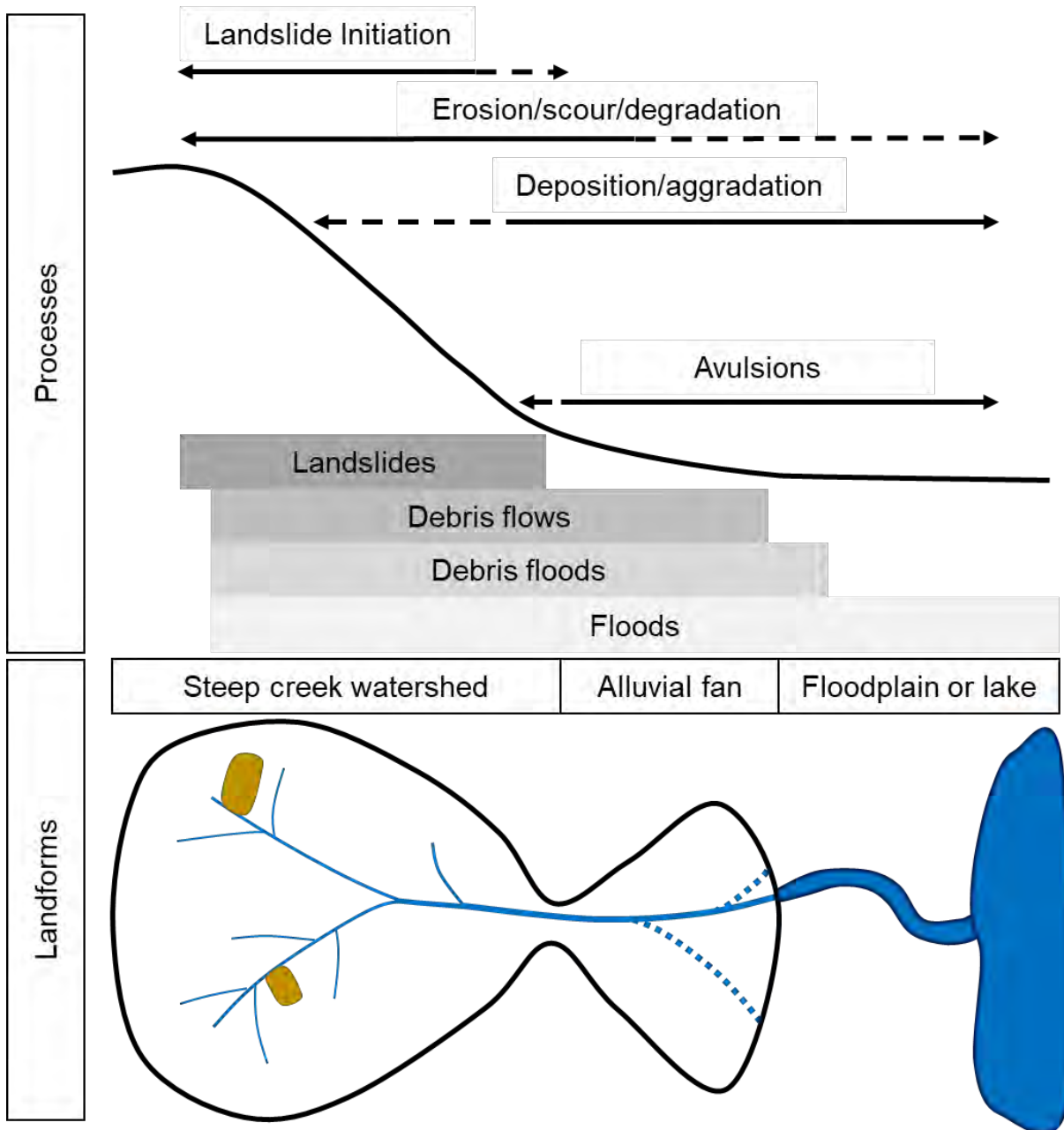
Steep mountain slopes deliver sediment and debris to the upper channels by rock fall, rock slides, debris avalanches, debris flows, slumps and raveling. Debris flows and debris floods characteristically gain momentum and sediments as they move downstream and spread across an alluvial fan where the channel enters the main valley floor. Landslides may also create temporary dams that pond water along a channel, and can fail catastrophically. In these scenarios, a debris flood may be initiated in the channel that travels further than the typical steep creek processes.



**Figure F-3.** A typical steep creek watershed and fan (Cataline Creek) located near Pemberton in the SLRD, with Lillooet Lake in the foreground. The approximate watershed and fan boundary are outlined in blue and white, respectively. Photo: BGC, taken on June 17, 2014.



**Figure F-4. Typical steep and low-gradient fans feeding into a broader floodplain. On the left a small watershed prone to debris flows has created a steep fan that may also be subject to rock fall processes. On the right a larger watershed prone to debris floods has created a lower gradient fan. Development and infrastructure are shown to illustrate their interaction with steep creek geohazard events. Artwork: Derrill Shuttleworth.**



**Figure F-5. Schematic diagram of a steep creek watershed system that shows the principal zones of distinctive processes and sediment behaviour. Landslides are shown in brown. The alluvial fan is thought of as the long-term storage landform with a time scale of thousands to tens of thousands of years. Sketch developed by BGC from concepts produced by Schumm (1977), Montgomery & Buffington (1997), and Church (2013).**

The alluvial fan represents a mostly depositional landform at the outlet of a steep creek watershed. Alluvial fans are dynamic and potentially very dangerous (hazardous) landforms that represent the approximate extent of past and future hydrogeomorphic processes. This landform is more correctly called a colluvial fan when formed by debris flows because debris flows are classified as a landslide process, and an alluvial fan when formed by clear-water floods (those which do not carry substantial bedload or suspended load) or debris floods. For simplicity the



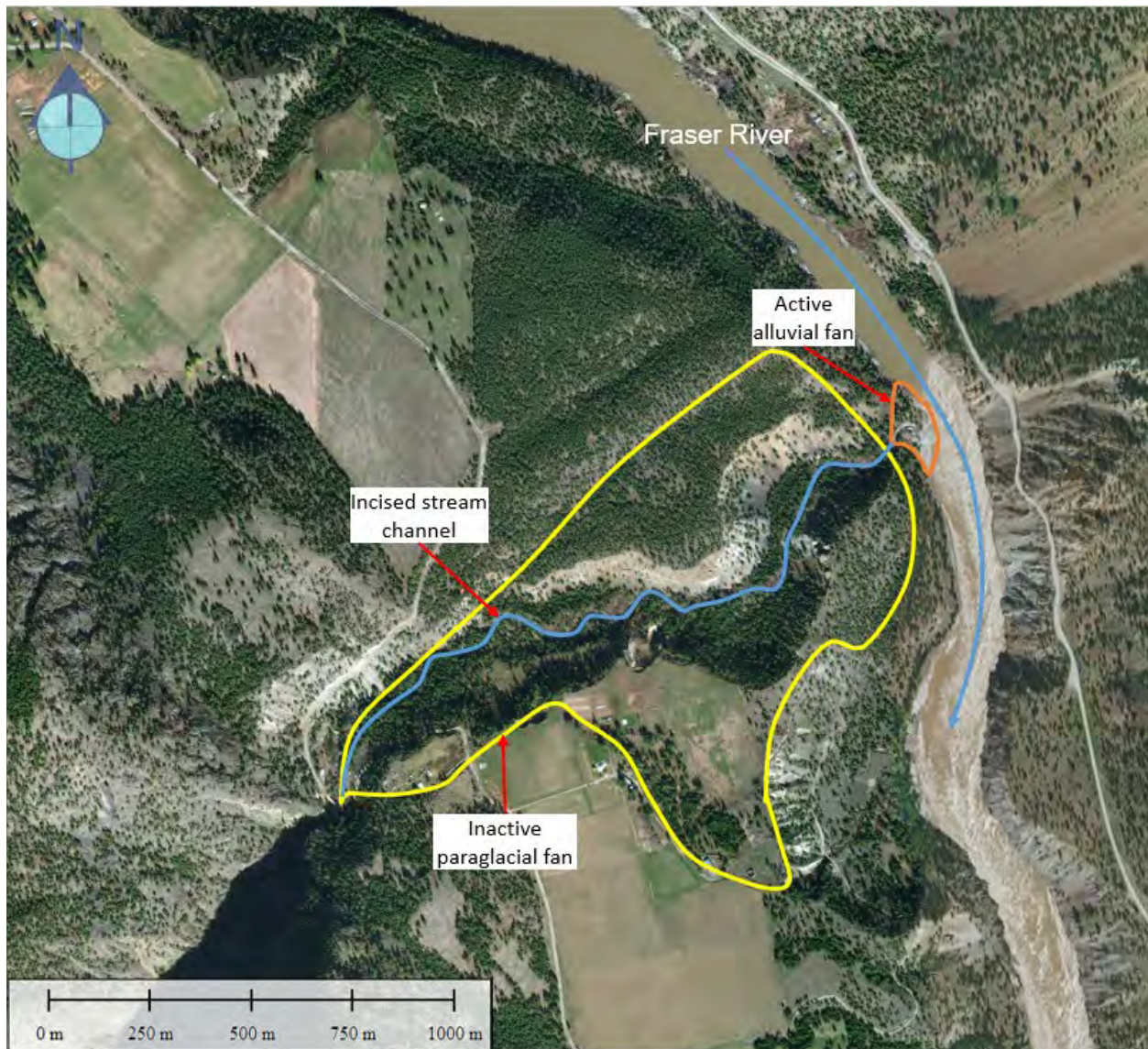
term alluvial fan is used herein irrespective of geohazard type. “Classic” alluvial fans are roughly triangular in planform, but most fans have irregular shapes influenced by the surrounding topography. Redistribution of sediments from the upper steeper fan to the lower flatter fan, primarily through bank erosion and channel scour, is common (Lau, 2017).

Stream channels on the fan are prone to avulsions, which are rapid changes in channel location, due to natural cycles in alluvial fan development and from the loss of channel confinement during hydrogeomorphic events (e.g., Kellerhals & Church, 1990; van Dijk et al., 2009; 2012; de Haas et al., 2017; Zubrycky et al., 2021). If the alluvial fan is formed on the margin of a still water body (lake, reservoir, ocean), the alluvial fan is termed a fan-delta. These landforms differ from alluvial fans in that sediment deposition at the margin of the landform occurs in still water, which invites in-channel sediment aggradation due to a pronounced morphodynamic backwater effect. This can increase the frequency and possibly severity of avulsions (van Dijk et al., 2009; 2012).

The term “paleofan” is used to describe portions of fans interpreted as no longer active (under present climate and geomorphic/geological setting) and entirely removed from the channel processes described previously (i.e., with negligible potential for channel avulsion and flow propagation) due to deep channel incision (Kellerhals & Church, 1990). Two paleofans were mapped as part of this study.

Some paraglacial fans are located throughout the SLRD. These are defined as fans primarily deposited shortly after the landscape was deglaciated (Ryder, 1971a; 1971b; Church & Ryder, 1972). Paraglacial fans are found overlying broad terraces bordering large river systems in the SLRD (e.g., along the Fraser River between Lillooet and Lytton, but also in the lower Squamish River valley where raised fan deltas have been incised by modern-day fluvial processes). Unlike paleofans, paraglacial fans are not necessarily inactive. Post-wildfire debris flows in nearby Hat Creek Valley in 2018 have shown that paraglacial fans can still experience debris flows if the watershed stream is still connected to the alluvial fan. Thus, the term paleofan is only applied to paraglacial fans if the stream had incised into the fan and removed the connection between the stream and the landform (e.g., Figure F-6).





**Figure F-6.** Example of an inactive paraglacial fan and active alluvial fan on Texas Creek, near Lillooet. The distinction of the paraglacial fan being classified as an inactive paleofan is due to the incised stream channel. The inactive paraglacial fan and active alluvial fan delineated in this example are for illustration only and are not part of the inventory.

#### F-1.1.2 Debris Flows

'Debris flow', as defined by Hungr et al. (2014), is a very rapid, channelized flow of saturated debris containing fine grained sediment (i.e., sand and finer fractions) with a plasticity index of less than 5%. Debris flows originate from a single or distributed source area(s) from sediment mobilized by the influx of ground or surface water. In areas with limited vegetation, or where wildfires have removed vegetation, abundant rilling and gullying may deliver sediment to the main channel and form debris flows. In those cases, no single source is required to initiate or maintain debris-flow mechanics.

Debris flows travel in confined channels bordered by steep slopes. In confined channels, the flow volume, peak discharge, and flow depth increase, and the debris becomes sorted along the flow path. Flow velocities typically range from 1 to 10 m/s, although very large debris flows from volcanic edifices, often containing substantial fines, can travel at more than 20 m/s along much of their path (Major et al., 2005). The front of the rapidly advancing flow is steep and commonly followed by several secondary surges that form due to particle segregation and upwards or outwards migration of boulders. Hence, one of the distinguishing characteristics of coarse granular debris flows is vertical inverse grading, in which larger particles are concentrated at the top of the deposit. This characteristic behaviour leads to the formation of lateral levees along the channel that become part of the debris-flow depositional legacy. Similarly, depositional lobes are formed where frictional resistance from unsaturated coarse-grained or large organic debris-rich fronts is high enough to slow and eventually stop the motion of the trailing liquefied debris.

Due to their high flow velocities, peak discharges during debris flows are at least an order of magnitude larger than those of comparable return period floods but can be 50 times larger or more (Jakob & Jordan, 2001; Jakob et al., 2016). Channel banks can be severely eroded during debris flows, although lateral erosion is often associated with the trailing flow characterized by lower volumetric sediment concentrations. The most severe damage caused by debris flows results from direct impact of large clasts or coarse woody debris against structures that are not designed for the impact forces (Jakob et al., 2012). Linear infrastructure such as roads, and railways are subject to damage from debris flows either from direct impact or erosion. Buried infrastructure can be damaged by debris flows if it is exposed by erosion and then impacted by boulders or woody debris.

Debris flow avulsions are likely in poorly confined channel sections and on the outside of channel bends where debris flows tend to superelevate. A sudden loss of confinement and decrease in channel slope cause debris flows to decelerate and slow the advancing bouldery front, which blocks the channel. Further flows are often deflected by the slowing front, leading to secondary avulsions and the creation of distributary channels on the fan. Because debris flows often display surging behaviour, in which bouldery fronts alternate with hyperconcentrated afterflows, the cycle of coarse bouldery lobe and levee formation and afterflow deflection can be repeated several times during a single event (Iverson, 2014).

#### F-1.1.3 Debris Floods

Church and Jakob (2020) define debris floods as “floods during which the entire bed, barring the very largest clasts, becomes mobile for at least a few minutes and over a length of at least 10 times the channel width”. Accordingly, debris floods represent flood flows with high transport of gravel to boulder size material. Debris floods typically occur on creeks with channel gradients between 5 and 30% (3 and 17°) but can also occur on lower gradient gravel bed rivers.

Due to their initially relatively low sediment concentration, debris floods can be more erosive along low-gradient alluvial channel banks than debris flows. Channel and bank erosion introduce large amounts of sediment to the fan where they accumulate (aggrade) in channel sections with decreased slope. Debris floods can also be initiated on the fan itself through rapid

bed erosion and entrainment of bank materials, as long as the stream power is high enough to transport clasts equal to at least the D84 of the bed material. Because typical long-duration storm hydrographs fluctuate several times over the course of the storm, several cycles of aggradation and remobilization of deposited sediments on channel and fan reaches can be expected during the same event (Jakob et al., 2016). Similarly, debris floods triggered by outbreak floods may lead to single or multiple surges irrespective of hydrograph fluctuations that can lead to cycles of bank erosion, scour and infill. This is important for interpretations of field observations as only the final deposition or scour can be measured.

Church and Jakob (2020) developed a three-fold typology for debris floods (Table F-1). Identifying the correct debris-flood type is key in preparing for numerical modeling and hazard assessments. Type 1 debris floods are a result of flows with a sufficient magnitude and shear stress to mobilize the channel bed. Type 2 debris floods are initiated by the transition of a debris flow to a debris flood in the channel or from a debris flow in a tributary channel entering a larger channel. Type 3 debris floods are associated with the landslide dam outbreak flood (LDOF) parameter presented in Section F-3.2.5.

Hyperconcentrated flows are a special case of debris floods that are typical for volcanic sources areas or fine-grained sedimentary rocks. They can occur as Type 1, 2 or 3 debris floods. The term “hyperconcentrated flow” was defined by Pierson (2005) based on sediment concentration as “a type of two-phase, non-Newtonian flow of sediment and water that operates between normal streamflow (water flow) and debris flow (or mudflow)”. The use of the term “hyperconcentrated flow” should be reserved for volcanic or weak sedimentary fine-grained slurries.

#### F-1.1.4 Clear-water Floods on Alluvial Fans

Clear-water floods are defined as “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”. Further information on clear-water floods and the methodology used for in the Phase 1 study (BGC, April 10, 2020).

Clear-water floods on alluvial fans are treated separately in this study to account for avulsion potential, which is controlled by similar parameters as for steep creek geohazards. These parameters include evidence for previous avulsion and LDOFs, and they are discussed in Section F-3.2.



**Table F-1. Debris-flood classification based on Church and Jakob (2020).**

Term	Definition	Typical sediment concentration by volume (%)	Typical $Q_{max}$ factor compared to clear-water	Physical Characteristics	Typical impacts	Typical return period range (years)
Type 1	Rainfall/snowmelt generated through exceedance of critical shear stress threshold when most of the surface bed grains are being mobilized	< 5	1.05 (or higher should there be multiple side slope landslides expected or large organic debris)	Steep fans (1% to 10%), shallow but wide active floodplain, widespread boulder carpets, clast to matrix-supported sediment facies, poorly sorted, subrounded to rounded stones, imbrication of elongate clasts, occasional crossbedding, disturbed riparian vegetation, frequent avulsions on fan	Widespread bank instability, avulsions, alternating reaches of bed aggradation and degradation, blocked culverts, scoured bridge abutments, damaged buried infrastructure particularly in channel reaches u/s of fans	>2
Type 2	Transitional as a consequence of debris flows. Substantially higher sediment concentration compared to a Type 1 debris flood and accordingly greater facility to transport larger volumes of sediment. All grain calibers mobilized, except from lag deposits (big glacial or rock fall boulders)	< 50	2–5 (but possibly larger at the transition zone)	As for Type 1 but rarely clast-supported and with higher matrix sediment concentration, unsorted, inverse grading near debris flow tributary. Stones subangular to angular, boulder carpets on fans often display abrupt sediment deposit edges	Widespread bank instability, avulsions, substantial bed aggradation particularly on fans, blocked culverts, scoured bridge abutments, damaged and buried infrastructure on fans	>50
Type 3	Type 3 (outbreak floods) (artificial-, landslide-, glacial-, moraine-, beaver, or log-jam outbreaks)	<10 (except immediately downstream of the outbreak where it can reach greater than 30%)	2 to 100 depending on size of dam and distance to dam failure	High matrix fines content especially in volcanic sources or fine-grained soil (e.g., loess), sometimes inverse grading near outbreak flood source, unsorted near source. Increasing sorting and stratification with downstream distance, erosion and fill structures	Extreme bank erosion, avulsions, substantial bed degradation along channels and aggradation on fans, destroyed culverts, outflanked or overwhelmed bridges, damaged and buried infrastructure on channels and fans	>100 (can be singular event in the case of a moraine dam or glacial breach)

## F-1.2 Climate Change

### F-1.2.1 Background

Section 2.6 in the Phase 1 study (BGC, April 10, 2020) provides an overview of how climate change is expected to affect SLRD. This section outlines some of the climate change affects specifically related to steep creek hazards. Climate change is expected to impact steep creek geohazards both directly and indirectly through complex feedback mechanisms. Given that hydrological and mass movement processes are higher order effects of air temperature increases, their prediction is highly complex and often site-specific.

Jakob (2022) provides a general overview of how climate change is expected to affect steep creek hazards based on sediment availability:

- Supply-limited: meaning that debris available 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.
- Supply-unlimited: meaning that debris available 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.

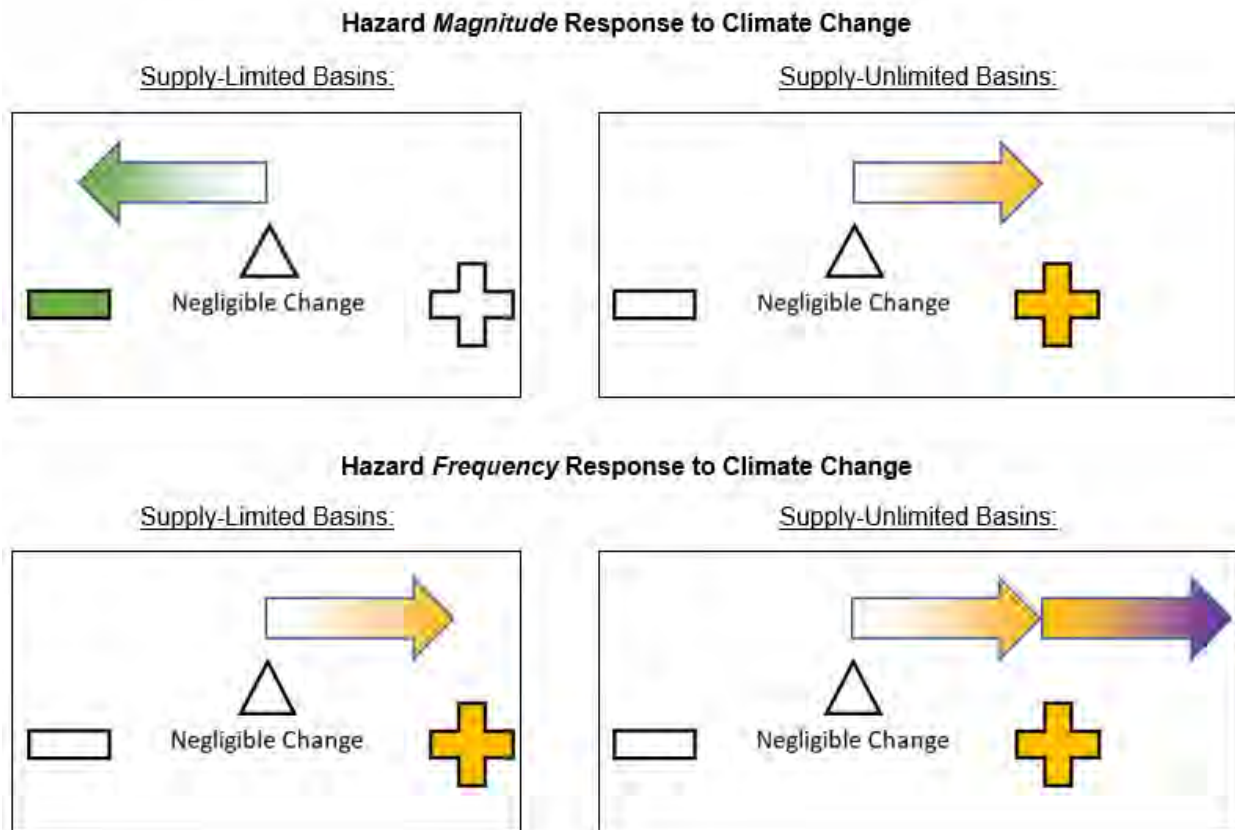
Further subdivisions into channel supply-limited and unlimited and basin supply-limited and unlimited are possible but not considered herein.

Climate change is expected to increase the short-duration rainfall intensity in the SLRD (Prein et al., 2016). The sensitivity of the two basic types of basins to climate-related increases in rainfall (intensity and frequency increases) differ (Figure F-7):

- 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).

Supply-limited basins can transition into supply-unlimited due to landscape changes. For example, sediment supply could be increased by wildfires, landslide occurrence, or human activity (e.g., related to road building or resource extraction).





**Figure F-7. Steep creek hazard sensitivity to climate change – supply-limited and supply unlimited basins.**

Climate change is projected to increase the conditions for extreme fire weather (high temperature, low humidity, and high winds) and lengthen the fire season resulting in increased fire sizes (Utzig et al., 2011; Wang et al., 2015). Wildfire are discussed in Section F-1.3.

#### F-1.2.2 Climate Change Adjustment in Steep Creek Geohazard Assessment

Climate change was considered in steep creek hazard characterization by applying climate change adjusted estimates of peak discharge as inputs for hazard intensity ratings (Section F-4.1). Adjustment of the geohazard likelihood ratings that consider the ‘sensitivity’ of geomorphic activity in a watershed to climate change is not applied in the current risk study, because the adjustment would be applied to all geohazard areas, and therefore would not have any effect on the relative risk ratings.

#### F-1.3 Wildfire

Wildfires in steep mountainous terrain are often followed by a temporary period of increased geohazard activity. The intense heat of a wildfire can cause a variety of changes to the overall hydrologic response of a watershed to rainfall resulting in destructive debris flows, debris floods and floods. Changes to the hydrologic response of a drainage basin to rainfall have been attributed to the intense heat of a wildfire removing vegetation and causing changes to the

ability of the soil to infiltrate water (Ebel et al., 2012; Moody and Martin, 2001). Ash on the soil surface can absorb water, seal off pore spaces in the soil and reduce the amount of water that can infiltrate the soil (Woods and Balfour, 2008). Hydrophobic compounds in vegetation are combusted during fire and can travel downwards into the soil column and precipitate on a layer 5 to 10 cm deep, creating a water-repellant layer (DeBano, 1981; Doerr et al., 2000). The removal of the vegetative canopy, litter and duff by fire exposes bare ground to rainfall (Moody and Martin, 2001). The combustion of vegetation and shallow rootlets that anchors soil at the surface leads to dry raveling of material that accumulates in channels and provides easily eroded material for erosion by debris flows and debris floods (Lamb et al., 2011; Wells, 1987). The combination of these changes to the soil surface by wildfire results in increased overland flow of rainfall that erodes material and concentrates in gullies and channels to form hazardous debris flows and debris floods (Cannon and Gartner, 2005; Moody and Martin, 2001; Wells, 1987).

A range of erosive processes are possible in burned areas due to rainfall. Following wildfire, rills (small channels that are less than about 20 cm wide and 30 cm deep) can erode hillslope material and entrain sediment in progressively larger channels to form destructive debris flows (Cannon et al., 2003). Debris-flow material deposited in flooded creeks with larger contributing drainage areas can result in debris floods that are highly erosive and capable of transporting significant volumes of sediment and woody debris. These erosive responses of a burned area to rainfall may be the result of relatively normal rainfall events with frequent recurrence intervals (Cannon et al., 2008). Therefore, changes to short duration (one hour and less) rainfall intensities are relevant for post-fire situations, because debris-flows can be triggered within the year to a few years after a wildfire from short duration and high intensity rainfall that previously would not trigger debris flows or debris floods in a watershed.

The period of increased geohazard activity following fire is most pronounced within the first three to five years after the fire (Cannon and Gartner, 2005; DeGraff et al., 2015). After about three to five years following fire, vegetation can reestablish 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 and Helvey, 1976; Sidle, 1991; 2005). This second period of heightened debris-flow activity is rare and post-wildfire debris flows are most predominant immediately following the fire and continuing for up to about three to five years.

In the past, wildfires have been rare in the SLRD owing to the cool and wet coastal climate. However, climate change is causing increased temperatures, more frequent heat extremes, prolonged dry periods and changing precipitation patterns in western North America (USGCRP 2018; Zhang et al. 2019). In southern British Columbia, reduced precipitation is projected during summer (Zhang et al. 2019; Brown et al. 2022). These changes are increasing wildfire activity (Flannigan et al. 2009; Hanes et al. 2018; Coogan et al. 2019).

In 2015, a dry summer in Southern British Columbia resulted in numerous wildfires throughout the province, two of which (the Elaho Fire and the Boulder Creek Fire) burned over 20,000 ha in the SLRD and produced numerous debris flows (Tom Millard, personal communication). Recent post-wildfire debris flows and debris floods occurred the Elaho and Mackay Creek Fires.

In B.C., the Ministry of Forests Lands and Natural Resource Operations (MFLRNO), B.C. Wildfire Service, in partnership with Natural Resources Canada, has developed wildfire probability mapping for the province using the Burn P3 software. The Burn P3 software combines fire growth models with spatial data for forest fuels and topography to simulate wildfires and map wildfire susceptibility based on the probability of a wildfire occurrence (Parisien et al., 2019). Wildfire susceptibility mapping is a powerful tool for identifying watersheds that are likely to experience a period of increased flood hazard due to the occurrence of wildfire.

#### F-1.3.1 Wildfire Adjustment in Steep Creek Risk Ratings

The steep creek geohazard assessment and risk ratings are provided for two scenarios:

Baseline risk scenario: ratings reflect the observed conditions of watershed and fan at the time of this study.

Wildfire-adjusted risk scenario: ratings reflect potential conditions associated with increasing likelihood of wildfire due to climate change.

Past wildfire was accounted for in the baseline risk scenario by assigning basin activity ratings based on current observations at the time of the assessment, including observations of recent post-wildfire debris flows. Information on the occurrence of wildfires in the watershed (based on data from the Government of BC, 2023) is shown for informational purposes in *Cambio*.

The wildfire-adjusted risk scenario is based on a wildfire-adjusted geohazard rating (basin activity rating) and a wildfire-adjusted consequence rating (intensity rating), which were estimated using the wildfire susceptibility mapping provided by the BC Wildfire Service and using empirical models for predicting post-wildfire debris-flow volumes. The methods are detailed in Section F-3.1.2 and Section F-4.1.3. The wildfire adjusted risk scenario is intended to help rate steep creek geohazard assessments as well as to provide an initial hazard estimate if a watershed were to burn. Note that depending on the extent and severity of a future wildfire, the basin activity rating may increase by one or more categories from what is provided by the wildfire adjusted rating. Therefore, if a steep creek geohazard site is burned, a re-assessment may be warranted.

#### F-1.4 Workflow

The workflow for the steep creek geohazard assessment and risk rating includes three main phases: geohazard identification, geohazard rating, and consequence rating. Figure F-8 summarizes the parameters used in each phase. The methods and criteria used to estimate each parameter are detailed in Sections F-2, F-3 and F-4.



Steep creek geohazard identification for the SLRD focused on the delineation of alluvial fans, as these are the landforms commonly occupied by elements at risk (see Main Report Section 1.3.2). The boundaries of alluvial fans define the steep creek geohazard areas in this study (Section F-2.1). Watersheds upstream of each mapped fan were assessed to identify geohazard processes and determine geohazard ratings but were not mapped. The streams of the entire SLRD were delineated (Section F-2.2), classified (Section F-2.3), and used for both susceptibility modeling (impact likelihood rating, in Section F-3.2) and peak discharge estimation (intensity rating, in Section F-4).

## F-2.1 Fan Inventory

Fan extents were manually delineated in an ESRI ArcGIS Online web map based on a review of previous mapping (e.g., BGC, January 22, 2015; BGC, January 31, 2017; Lau, 2017; Northwest Hydraulic Consultants Ltd., April 10, 2019; Baumann & Yonin, 1994; Blais-Stevens, 2008; Ministry of Environment and Climate Change Strategy, 2016), and from hillshade images built from the available lidar Digital Elevation Models (DEM). At sites where lidar DEMs were not available, low resolution (approximately 25 m)<sup>1</sup> Canadian Digital Elevation Model (CDEM) terrain models, aerial photographs, and satellite imagery available within ArcGIS were used for terrain interpretation. A total of 473 fans were mapped within the SLRD.

The accuracy of each fan's boundary and hazard rating depends, in part, on the resolution of the available terrain data. Lidar DEMs, where available, provide 1 m or better resolution (e.g., Figure F-9). Mapped fan boundaries, even where lidar coverage is available, are approximate, but are less certain where lidar coverage was not available. For areas without lidar coverage, the minimum fan size that can be mapped at regional scale with the available information is about 2 ha. Local variations in terrain conditions over areas of 1 to 3 ha, or over distances of less than about 200 m, may not be visible. Future site investigations could alter the locations of the fan boundaries mapped by BGC.

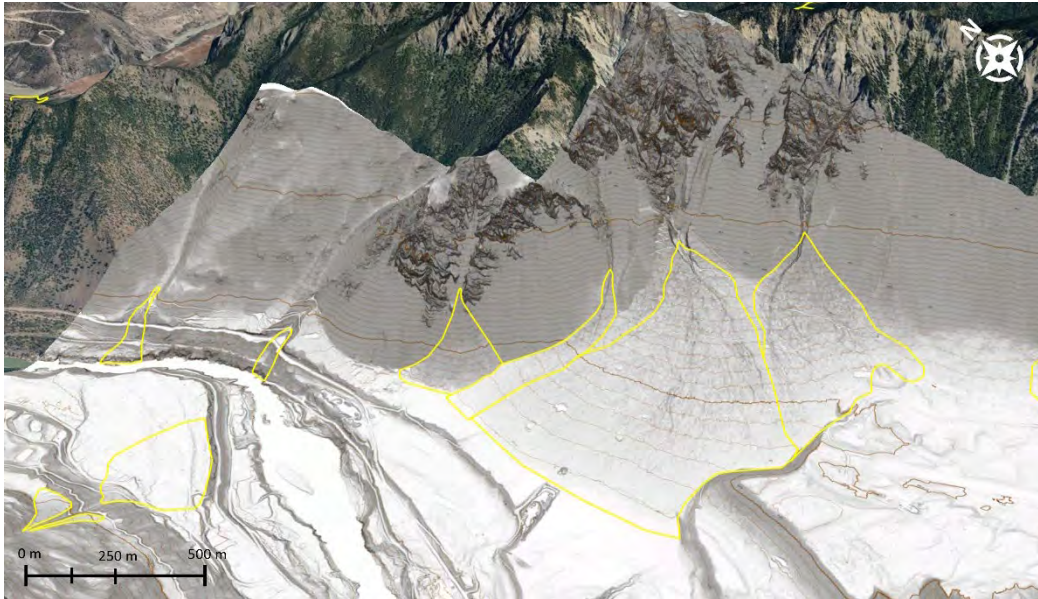
While the presence of a fan indicates past geohazard occurrence, the lack of a fan on a steep creek does not necessarily rule out the potential for future geohazard occurrence. As such, the geohazard assessment completed in this study should not be considered exhaustive. In addition, in some cases, BGC does not rule out the potential for steep creek geohazards to extend beyond the limit of the mapped fan boundary. The fan boundary approximates the extent of sediment deposition since the beginning of fan formation<sup>2</sup>. Geohazards can potentially extend beyond the fan boundary due to localized flooding, where the fan is truncated by a lake or river, in young landscapes where fans are actively forming (e.g., recently deglaciated areas), or where large landslides (e.g., rock avalanches) trigger steep creek events larger than any previously occurring. Section F-3.2.2 describes steep creek hazard susceptibility modelling that was applied on every watercourse classed as potentially subject to debris floods or debris flows, including those without mapped fans. Areas modelled as potentially susceptible to steep creek geohazards, but that do not contain a mapped fan, are shown on *Cambio* for reference but are not otherwise characterized.

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<sup>1</sup> CDEM resolution varies according to geographic location. The base resolution is 0.75 arc second along a profile in the south-north direction and varies from 0.75 to 3 arc seconds in the east-west direction, depending on location. In the SLRD, this corresponds to approximately 25 m grid cell resolution (Government of Canada, 2016).

<sup>2</sup> Most of the alluvial fans mapped in this study represent the accumulation of sediment over the Holocene period (since about 11,000 years BP).





**Figure F-9. Example of oblique lidar hillshade and 20 m contours showing alluvial fans at the base of Fountain Ridge in Lillooet. Lidar DEM provided by Government of BC (2019).**

### F-2.2 Stream Network

The streams of the entire SLRD were extracted from BGC's River Network Tools™ (RNT). RNT is a web-based application developed by BGC for analysis of hydrotechnical geohazards associated with rivers and streams. The basis for RNT is a digital stream network that is used to evaluate catchment hydrology, including delineating catchment areas and analyzing flood frequencies over large geographical areas. RNT incorporates hydrographic data with national coverage from Natural Resources Canada's (NRCan's) National Hydro Network (NHN) at a resolution of 1:50,000 (NRCan, January 25, 2016). The publicly available stream network is enhanced by algorithms within the RNT database to ensure the proper connectivity of the stream segments even through complex braided sections. Modifications to the stream network within RNT are made as necessary based on review of satellite imagery (e.g., Google Earth™) at approximately 1:10,000 scale.

In the RNT, the stream network is represented as a series of individual segments that includes hydraulic information such as:

- A water flow direction
- The upstream and downstream stream segment connections
- A local upstream catchment area for each stream segment (used to calculate total catchment area)
- A Strahler stream order classification (Strahler, 1952)
- A local channel gradient, which is determined using a topographic dataset to assess the elevation differential between the upstream and downstream limit of the segment.

Strahler stream order is used to classify stream segments by its branching complexity within a drainage system and is an indication of the significance in size and water conveying capacity at points along a river (Strahler, 1952). Strahler order 4 and higher streams are typically larger

streams and rivers (e.g., Lillooet River), while Strahler order 3 and lower streams are typically smaller, headwater streams (e.g., Millar Creek). An illustration of Strahler stream order classification is shown in Figure F-10 and described conceptually for the SLRD in Table F-2.

BGC supplements these data with 1:50,000-scale CanVec digital watercourse linework to represent lakes and reservoirs and 1:20,000 scale GeoBase digital elevation models (DEMs; NRCan, January 25, 2016) to generate catchment areas and a local stream gradient for each segment in RNT. Dam locations are represented using the inventory provided by the BC MFLNRO (MFLNRO, 2017).

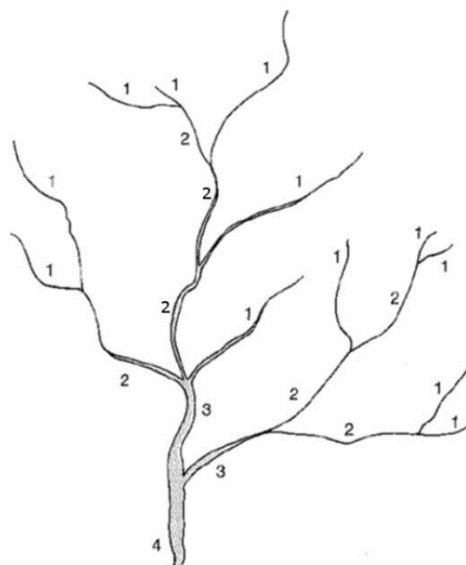


Figure F-10. Illustration showing Strahler stream order (Montgomery, 1990).

Table F-2. Strahler order summary for the SLRD stream network.

Strahler Order	Description	% of SLRD Stream Segments	SLRD Examples
1 – 3	Small, headwater streams generally on steeper slopes and typically subject to steep-creek processes (debris floods/ flows). Channel may be dry for a portion of the year. They are tributaries to larger streams and are typically unnamed.	85	Millar Creek, Fitzsimmons Creek, Whistler Creek
4 – 6	Medium stream or river. Generally, less steep and lower flow velocity than headwater streams.	13	Alta Creek, Brandywine Creek, Ryan River, Birkenhead River, Cheakamus River
7+	Large river. Larger volumes of runoff and potentially debris conveyed then from smaller waterways.	1	Squamish River, Lillooet River, Bridge River, Fraser River

### F-2.3 Geohazard Process Type Identification

BGC used terrain interpretations and morphometric statistics to assign each creek as “dominantly” subject to debris flows, debris floods or clear-water floods. The term “dominant” refers to the process type that primarily controlled hazard assessment methodology and ratings. Recognizing that there is a continuum between clear-water floods and debris flows, BGC notes the following assumptions:

- Fans classified as subject to debris flows may also be subject to floods and debris floods at lower return periods (debris flows may transition to watery afterflows in the lower runout zone and after the main debris surge).
- Fans classified as subject to debris floods may be subject to clear-water floods, but generally not to debris flows.
- Fans classified as subject to clear-water flood are dominated by clear-water floods.

The morphometric statistical approach was applied to every stream segment in the entire study area, including both developed and undeveloped areas. For the alluvial fans, the morphometric statistical approach was considered alongside terrain interpretations. The major advantage of statistically based methods is that they can be applied to much larger regions than would be feasible to manually assess. However, interpretation of steep creek process types from multiple lines of evidence (statistical, remote-sensed, field observation) provides higher confidence. Therefore, BGC also interpreted manually the dominant fan-forming process types for the geohazard areas (Section F-2.3.2).

The sections below outline these approaches.

#### F-2.3.1 Morphometric Statistics

BGC applied the following morphometric statistical approach to predict steep creek process type for all segments of every mapped creek within the study area:

1. Collect statistics on Melton Ratio<sup>3</sup> and watershed length<sup>4</sup> for each segment of each creek. These terrain factors are a good screening level indicator of the propensity of a creek to dominantly produce floods, debris floods or debris flow (Holm et al., 2016).
2. Apply class boundaries to predict process types for all stream segments in the study area, regardless of whether they intersect fans.

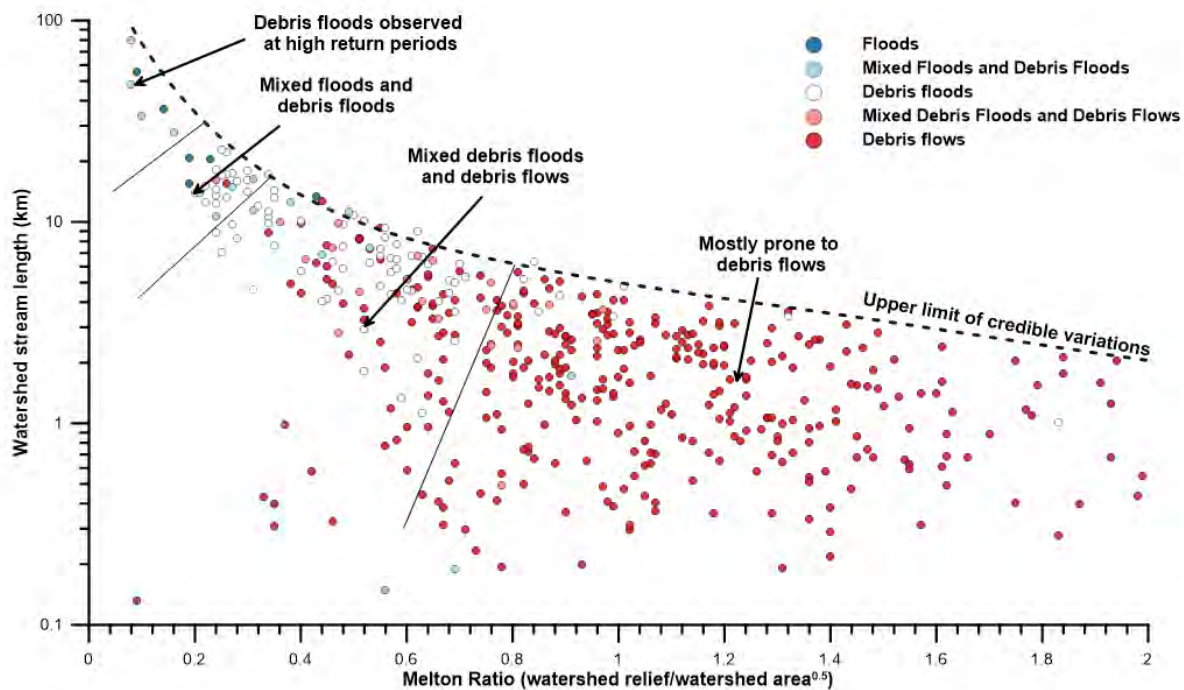
Figure F-11 plots creeks of the study area with respect to Melton Ratio and watershed length<sup>5</sup>. Although there is overlap, creeks with the highest Melton ratio and shortest watershed stream length are mostly prone to debris flows, and those with the lowest Melton ratio and longest watershed stream lengths are mostly prone to clear-water floods. Debris floods fall between these types. Table F-3 lists class boundaries used to define process types on each segment of

<sup>3</sup> Melton ratio is watershed relief divided by the square root of watershed area (Melton, 1957).

<sup>4</sup> Stream network length is the total channel length upstream of a given stream segment to the stream segment farthest from the fan apex.

<sup>5</sup> The process type shown in the figure represents the process at the location of the fan apex. Many creeks subject to debris-floods are also subject to debris-flows on steeper creeks higher in the basin.

each creek within the SLRD, based on recommendations from previous studies in BC (Holm et al., 2016).



**Figure F-11. Steep creek processes in the SLRD as a function of Melton Ratio and stream length. Process boundaries are derived from this study and additional fans in Alberta and BC (Holm et al., 2016; Lau, 2017).**

**Table F-3. Class boundaries using Melton ratio and total stream network length.**

Process	Melton Ratio	Stream Length (km)
Floods	< 0.2	all
Debris floods	0.2 to 0.5	all
	> 0.5	> 3
Debris flows	> 0.5	≤ 3

Steep creek process types predicted from watershed morphometry are subject to limitations:

- Creeks at the transition between debris flows and debris floods may generate either type of process and do not fall clearly into one category or another. The classification describes the potential dominant process type but does not consider the geomorphic or hydroclimatic conditions needed to trigger events. In rare occasions, channels may be classified as “debris flow” or “debris flood” without evidence for previous such events. Some streams subject to debris floods are subject to clear-water floods at lower return periods.
- Watershed conditions that affect hydrogeomorphic process types cannot be considered using a purely statistical approach. For example, a fan could be located at the outlet of a

gentle valley, but a debris flow tributary enters near the fan apex. In this situation, debris flows could run out onto a fan that is otherwise subject to floods or debris floods from the main tributary.

- The morphometric statistical approach may not be appropriate for hanging valleys, where the lower channel sharply steepens below a gentle upper basin.
- Finally, as explained in Section F-1.1, there is a continuum between each of the geohazard processes and consequently, a steep creek could have an event that has characteristics that fall between a debris flood and debris flow. Similarly, not every debris flood shows the same characteristics (see Section F-1.1.3).

#### F-2.3.2 Terrain Interpretations

BGC interpreted the dominant fan-forming process types from the following information sources:

- The geomorphology of fans and their associated watersheds observed in the available imagery
- Field observations
- Records of previous events
- Review of statistically predicted process type for channel(s) intersecting the fan (Section F-2.3.1).

Table F-4 summarizes the characteristics used to differentiate hydrogeomorphic processes on fans from imagery and field evidence. In some cases, remotely sensed (lidar and air photo) or field observations indicated that the stream may be subject to mixed processes (e.g., Rubble Creek is subject to debris flows and debris floods). Where possible, BGC noted these “mixed-type” alluvial fans during terrain interpretation.



**Table F-4. Characteristics used to classify hydrogeomorphic process types on fans (after Lau, 2017). Grey shading indicates key characteristic used to classify the process.**

	Debris flow	Debris flood	Flood
Air photo	<ul style="list-style-type: none"> <li>Steep (<math>&gt;15^{\circ}</math>) average watershed channel gradient and typically small (<math>&lt; 3 \text{ km}^2</math>) watersheds with high relief</li> <li>Frequent sediment sources in upper watershed (rockfalls, debris avalanches, etc.)</li> <li>Inconsistent breaks in tree canopy on fan along stream channel.</li> </ul>	<ul style="list-style-type: none"> <li>Moderately steep (<math>3-15^{\circ}</math>) average watershed channel gradient, medium to large watersheds with moderate to high relief</li> <li>Sediment sources in upper watershed (rockfalls, debris avalanches, etc.)</li> <li>Consistent break in tree canopy on fan along stream channel.</li> </ul>	<ul style="list-style-type: none"> <li>Low (<math>&lt;3^{\circ}</math>) average watershed channel gradient, medium to large watersheds with moderate to low relief.</li> <li>Wide channels</li> <li>Large gap in tree canopy along stream channel.</li> <li>Overbank deposits</li> </ul>
Lidar	<ul style="list-style-type: none"> <li>Fan gradient <math>&gt; 5^{\circ}</math></li> <li>Levees along channel margin</li> <li>U-shaped channels</li> <li>(Boulder) lobes on fan surface</li> <li>Tongue-shaped boulder carpets</li> <li>Sharp deposit boundaries</li> </ul>	<ul style="list-style-type: none"> <li>Fan gradient <math>2-10^{\circ}</math></li> <li>No levees along channel</li> <li>Potential lobes on fan surface</li> <li>Paired terraces</li> </ul>	<ul style="list-style-type: none"> <li>Fan gradient <math>&lt; 5^{\circ}</math></li> <li>Wide channels</li> <li>Lack of lobes and levees along channel margin</li> </ul>
Field	<ul style="list-style-type: none"> <li>Matrix-supported deposits common, clast-supported rarely</li> <li>Inversely graded deposits</li> <li>No imbrication in deposits</li> <li>Levees along channel margins</li> <li>U-shaped channels</li> </ul>	<ul style="list-style-type: none"> <li>Clast-supported deposits</li> <li>Normally graded deposits</li> <li>Imbricated channel deposits (moderate frequency)</li> <li>Potential lobes on surface</li> <li>Paired terraces</li> <li>Impact scars on trees</li> </ul>	<ul style="list-style-type: none"> <li>Clast-supported deposits</li> <li>Normally graded deposits</li> <li>Imbricated channel deposits (common frequency)</li> </ul>

	Debris flow	Debris flood	Flood
	<ul style="list-style-type: none"> <li>Boulder lobes on surface</li> <li>Impact scars on trees</li> <li>Adventitious roots</li> <li>Buried tree trunks</li> </ul>	<ul style="list-style-type: none"> <li>Adventitious<sup>6</sup> roots</li> <li>Buried tree trunks</li> <li>Boulder carpets</li> <li>Deposition of bedload up to water surface elevation</li> </ul>	<ul style="list-style-type: none"> <li>Wide, shallow deposits</li> <li>Wide and shallow channels</li> <li>Evidence of multiple tree stand ages along stream channel.</li> </ul>

### F-3 GEOHAZARD RATING

The geohazard ratings are a function of:

1. Geohazard likelihood: What is the likelihood of steep creek geohazard events large enough to potentially impact elements at risk<sup>7</sup> (Section F-3.1)?
2. Geohazard impact likelihood: Given a geohazard event occurs, how susceptible is the hazard area to flows that could impact elements at risk (Section F-3.2)?

These two factors were combined in the qualitative geohazard rating matrix shown in Table F-5 to rate each geohazard area. Sections F-3.1 and F-3.2 describe methods and criteria used to estimate geohazard likelihood and impact likelihood, respectively. In these methods, terrain interpretation was based on a combination of lidar, air photos, satellite imagery, recorded events (Section 2.7 of the main report) and past assessments.

**Table F-5. Geohazard rating.**

Geohazard Likelihood	Geohazard Rating				
Very High	M	H	H	VH	VH
High	L	M	H	H	VH
Moderate	L	L	M	H	H
Low	VL	L	L	M	H
Very Low	VL	VL	L	L	M
<b>Impact Likelihood</b>	Very Low	Low	Moderate	High	Very High

<sup>6</sup> Adventitious roots are roots arising in abnormal places

<sup>7</sup> Elements at risk are defined as assets exposed to potential consequences of geohazard events (see Section 4 of the main report, and Appendix C).

### F-3.1 Geohazard Likelihood Rating

BGC assigned a geohazard likelihood rating to each fan based on terrain analysis. The geohazard likelihood rating represents a single, “typical” event frequency assigned to each fan and watershed based on surface evidence for previous events, recorded events, and reference to previous work. The typical event corresponds to an event of sufficient magnitude to have credible potential for consequences<sup>8</sup>.

#### F-3.1.1 Baseline Geohazard Likelihood Rating

Geohazard likelihood rating was estimated based on surface evidence for geomorphic activity within the basin and fan. The relative **basin activity** and relative **fan activity** ratings were combined to generate a geohazard likelihood rating (Table F-6) for each geohazard area, as discussed in the section below.

**Table F-6. Geohazard likelihood hazard rating matrix.**

		Typical Basin Activity Characteristics				
		Very Low	Low	Moderate	High	Very High
Fan Activity Characteristics	Very High	Moderate	Moderate	High	Very High	Very High
	High	Low	Moderate	High	High	Very High
	Moderate	Low	Low	Moderate	High	High
	Low	Very Low	Low	Low	Moderate	Moderate
	Very Low	Very Low	Very Low	Low	Low	Moderate

Table F-7 and Table F-8 summarize the criteria used to rate basin activity and fan activity, respectively. Figure F-12 and Figure F-13 show examples of events large enough to produce visible surface evidence of activity. It should be noted that dense tree cover could obscure small events that would not be detected at the scale of this study. Accordingly, the ratings are relative measures and can be subject to the limitations of available records and datasets. Specifically, terrain interpretation on less vegetated fans can be biased in favour of relatively smaller, more frequent events that would not have been visible under tree cover. All ratings are potentially subject to revision following future more detailed study.

No geohazard likelihood rating was assigned to fans whose dominant process is clear-water flood, because the criteria for terrain interpretation listed in Table F-7 and Table F-8 are not applicable for clear-water floods. Therefore, for clear-water flood fans, the geohazard rating of Table F-5 is only based on impact likelihood.

<sup>8</sup> While a single geohazard likelihood rating was assigned for rating (i.e., to compare areas in relative terms), BGC notes that events of different frequencies and magnitudes (volume of sediment deposited on a fan, peak discharge) can occur on any given steep creek.

**Table F-7. Relative basin activity for steep creeks organized by dominant process type.**

Basin Activity	Description	Characteristic Observations	
		Debris-flood dominated steep creeks	Debris-flow dominated steep creeks
Very Low	<ul style="list-style-type: none"> <li>Minimal sediment sources.</li> <li>Supply limited watershed.</li> </ul>	<ul style="list-style-type: none"> <li>Negligible sediment sources in or along channel or in tributaries.</li> </ul>	<ul style="list-style-type: none"> <li>Absence of landslide scars or erodible terrain.</li> <li>Basin is treed.</li> <li>Several rounded slopes.</li> </ul>
Low	<ul style="list-style-type: none"> <li>Identifiable sediment sources, but most show limited evidence of activity or connectivity.</li> <li>Supply limited watershed</li> </ul>	<ul style="list-style-type: none"> <li>Minimal sediment sources in or along channel and any existing channel material is not easily mobilized (e.g., dense till, partially bedrock controlled).</li> </ul>	<ul style="list-style-type: none"> <li>Some exposed soil or rock occurs.</li> <li>Absence of fresh landslide scars or debris below exposed terrain.</li> <li>Absence of channel deposits.</li> <li>Basin and channel are mostly treed</li> </ul>
Moderate	<ul style="list-style-type: none"> <li>Active sediment sources, but the material is not easily mobilized AND is not connected to the main channel or fan.</li> <li>Supply limited or unlimited watershed.</li> </ul>	<ul style="list-style-type: none"> <li>Sediment sources are present in or along channel.</li> <li>Channel material is not easily mobilized (e.g., dense till, partially bedrock controlled)</li> <li>Tributaries with identifiable sediment sources (e.g., debris-flow tributaries) typically stall before reaching main channel.</li> <li>Main channel often has variable width.</li> </ul>	<ul style="list-style-type: none"> <li>Sediment sources are present on slopes (e.g., presence of landslide scars in soil or rock).</li> <li>Source material or in channel deposits are not easily mobilized (e.g., coarse, angular colluvium, dense till, or partially bedrock controlled).</li> <li>Landslide deposits typically stall before the main channel.</li> </ul>
High	<ul style="list-style-type: none"> <li>Active sediment sources, but the material is either not easily mobilized, or not clearly connected to the main channel or fan.</li> <li>Supply unlimited watershed</li> </ul>	<ul style="list-style-type: none"> <li>Numerous, actively producing source areas along main channel and tributaries (i.e., debris slides, debris avalanches, raveling in lacustrine, glaciofluvial, or morainal sediments);</li> <li>Evidence of temporary sediment storage along main channel.</li> </ul>	<ul style="list-style-type: none"> <li>Numerous, actively producing source areas on slopes or in channel.</li> <li>Channel is choked with debris, but the material is not easily entrained (e.g., coarse angular colluvium)</li> <li>Source material could be easily entrained (e.g., talus, loose glacial deposits, volcanic), but there is no clear connection between the sources and main channel (e.g., hanging valley).</li> </ul>
Very High	<ul style="list-style-type: none"> <li>Active sediment sources that could be easily mobilized and are well connected to the main channel or fan.</li> <li>Supply unlimited watershed</li> </ul>	<ul style="list-style-type: none"> <li>Numerous, actively producing source areas along main channel and tributaries (i.e., debris slides, debris avalanches, raveling in lacustrine, glaciofluvial, or morainal sediments);</li> <li>Source material could be easily entrained.</li> <li>Tributaries with identifiable sediment sources (e.g., debris-flow tributaries) deposit straight into main channel.</li> </ul>	<ul style="list-style-type: none"> <li>Numerous, actively producing source areas on slopes or in channel.</li> <li>Channel choked with debris.</li> <li>Easily entrained source materials along channels (e.g., talus, glacial deposits, volcanics)</li> </ul>

**Table F-8. Relative fan activity for steep creeks organized by dominant process type. Fan activity refers to the frequency of steep creek events reaching the fan.**

Fan Activity <sup>1,2</sup>	Return Period	Number of Recorded Events <sup>3</sup>	Fan Observations	
			Debris-flood dominated creeks	Debris-flow dominated creeks
Very Low	500 year	None	<ul style="list-style-type: none"> <li>• Vegetated mainstem.</li> <li>• No distinguishable debris-flood related landforms.</li> <li>• Uniform tree canopy of mature forest.</li> </ul>	<ul style="list-style-type: none"> <li>• No observable mainstem.</li> <li>• No distinguishable debris-flow related landforms.</li> <li>• Uniform tree canopy of mature forest.</li> </ul>
Low <sup>3</sup>	200 year	None	<ul style="list-style-type: none"> <li>• Partially vegetated mainstem.</li> <li>• Muted channels or over bank deposits (most likely only visible in lidar).</li> <li>• Uniform tree canopy of mature forest.</li> </ul>	<ul style="list-style-type: none"> <li>• Vegetated mainstem.</li> <li>• Muted channels, lobes or levees (most likely only visible in lidar).</li> <li>• Uniform tree canopy of mature forest.</li> </ul>
Moderate	50 year	0 to 1	<ul style="list-style-type: none"> <li>• Unvegetated mainstem.</li> <li>• Channels and over bank deposits are visible in lidar, but potentially not in imagery.</li> <li>• Persistently includes swaths of mixed deciduous or conifer trees in riparian zone.</li> </ul>	<ul style="list-style-type: none"> <li>• Partially vegetated mainstem;</li> <li>• Channels, lobes or levees are visible in lidar, but potentially not in imagery.</li> <li>• Persistently includes swaths of mixed deciduous or coniferous trees associated with debris-flow landforms.</li> </ul>
High	20 year	1 to 2	<ul style="list-style-type: none"> <li>• Unvegetated mainstem;</li> <li>• Channels and over bank deposits are visible in imagery and lidar.</li> <li>• Persistently includes variable tree stand ages in riparian zone.</li> <li>• Regenerative vegetation and exposed sediment along channel.</li> <li>• Undersized channel in comparison with active floodplain width.</li> <li>• Partially vegetated bank erosion scars.</li> </ul>	<ul style="list-style-type: none"> <li>• Partially vegetated mainstem.</li> <li>• Channels, lobes or levees are visible in imagery and lidar.</li> <li>• Persistently includes swaths of regenerative (&lt;10 year) or immature (&lt;50 year) forest, potential areas of bare sediment.</li> </ul>
Very High	5 year	8 (or at least two in the past 10 years where records are not available over a longer period)	<ul style="list-style-type: none"> <li>• Unvegetated mainstem;</li> <li>• Channels and over bank deposits are visible in imagery and lidar.</li> <li>• Persistently includes areas of pioneer vegetation in riparian zone.</li> <li>• Fresh deposits are visible.</li> <li>• Undersized channel in comparison with active floodplain width.</li> <li>• Fresh bank erosion scars along mainstem.</li> </ul>	<ul style="list-style-type: none"> <li>• Fresh deposits are visible.</li> <li>• Channels, lobes or levees are visible in imagery and lidar.</li> <li>• Persistently includes swaths of bare sediment or low (&lt;2 year) pioneer vegetation.</li> </ul>
Cannot determine <sup>3</sup>	n/a	n/a	<ul style="list-style-type: none"> <li>• Anthropogenic modifications across most of fan, and no evidence of past events in air photo record.</li> </ul>	

Notes:

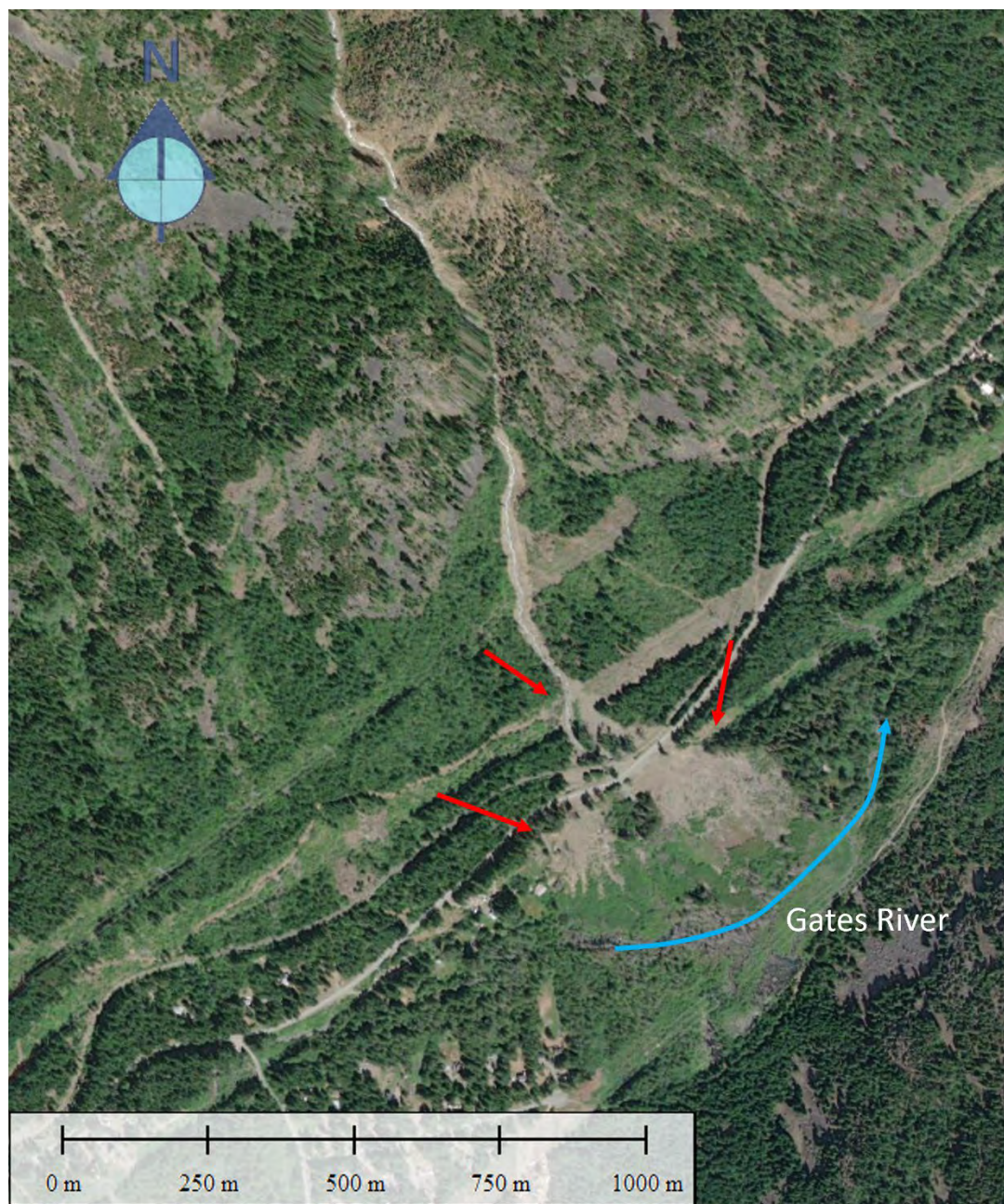
1. In cases where fan activity cannot be determined from available data, the basin activity rating was applied as the likelihood rating.
2. Very low vs. low classification cannot reliably be determined without lidar. A classification of low is conservatively applied in such cases.
3. For the purposes of this assessment, BGC defined the record event span to be 1980 to present, for which there are readily and freely available air photo and recorded event records in the study area. The true number of recorded events at each geohazard area depends on the length and quality of air photo, imagery, and media records.





**Figure F-12. Example of evidence for recent landslide or in-channel debris-flow initiation (red arrows) within the basin of unnamed creeks on Mount Currie, south of Pemberton.**





**Figure F-13. Example of evidence (red arrows) for a recent (2015) debris-flow deposit on Neff Creek, located north of Pemberton (Imagery: Maxar, 2021).**

### F-3.1.2 Wildfire Adjusted Geohazard Likelihood Rating

The wildfire adjusted geohazard likelihood rating was based on the average probability of a wildfire based on the Burn P3 mapping provided to BGC by the B.C. Wildfire Service. The adjustment hinged on the assumption that if a basin burns, then it produces a debris flow. Given that most post-wildfire debris flows are triggered by rainstorms with return periods ranging from one to two years (Staley et al., 2020 Hoch et al., 2021), basin burn probability can be directly linked to event probability.

The wildfire adjustment to the geohazard likelihood rating involved adjusting the basin activity rating based on the average burn probability in the watershed. The basin activity ratings in Table F-8 can be linked to approximate geohazard event return periods and event probabilities using Table 5-3 in the main report. If the average burn probability of a basin was higher than the approximate geohazard event probability assessed for the basin activity rating, then the basin activity rating was modified to reflect the burn probability in the basin. The wildfire adjusted basin activity rating was then routed through Table F-6 to arrive at the wildfire adjusted geohazard likelihood rating.

Two examples of how the wildfire adjusted geohazard likelihood ratings would be estimated are shown in Table F-9. Note that the “Watershed B” example has an average basin burn probability value that would be associated with a “Moderate” basin activity rating, however, the wildfire adjusted basin probability rating is kept at “High” to reflect the baseline case despite there being a low likelihood of fire.

**Table F-9. Examples of how the basin and fan activity ratings factor into the geohazard likelihood ratings for the baseline and wildfire adjusted scenarios.**

	<b>Watershed A</b>	<b>Watershed B</b>
Basin Activity Rating	Moderate	High
Fan Activity Rating	Low	Moderate
Geohazard Likelihood Rating (Baseline)	Low	High
Average Basin Burn Probability	0.03	0.01
Basin Activity Rating (Wildfire Adjusted)	High	High
Geohazard Likelihood Rating (Wildfire Adjusted)	Moderate	High

### F-3.2 Geohazard Impact Likelihood

BGC assigned an impact likelihood rating to each fan that considered the relative spatial likelihood that geohazard events result in flows that could impact elements at risk. Given the study objective of regional risk ratings, the geohazard impact likelihood rating was assigned as an average for the fan. It is not an estimate of spatial probability of impact for specific elements

at risk, which would vary depending on their location. This section describes the methods used to determine this geohazard impact likelihood rating.

Geohazard impact likelihood is predominantly concerned with avulsions. Avulsion refers to a sudden change in stream channel position on a fan due to partial or complete blockage of the existing channel by debris or due to exceedance of bankfull conditions. During an event, part of or all of a flow may avulse from the existing channel and travel across a different fan portion.

#### F-3.2.1 Impact Likelihood Rating

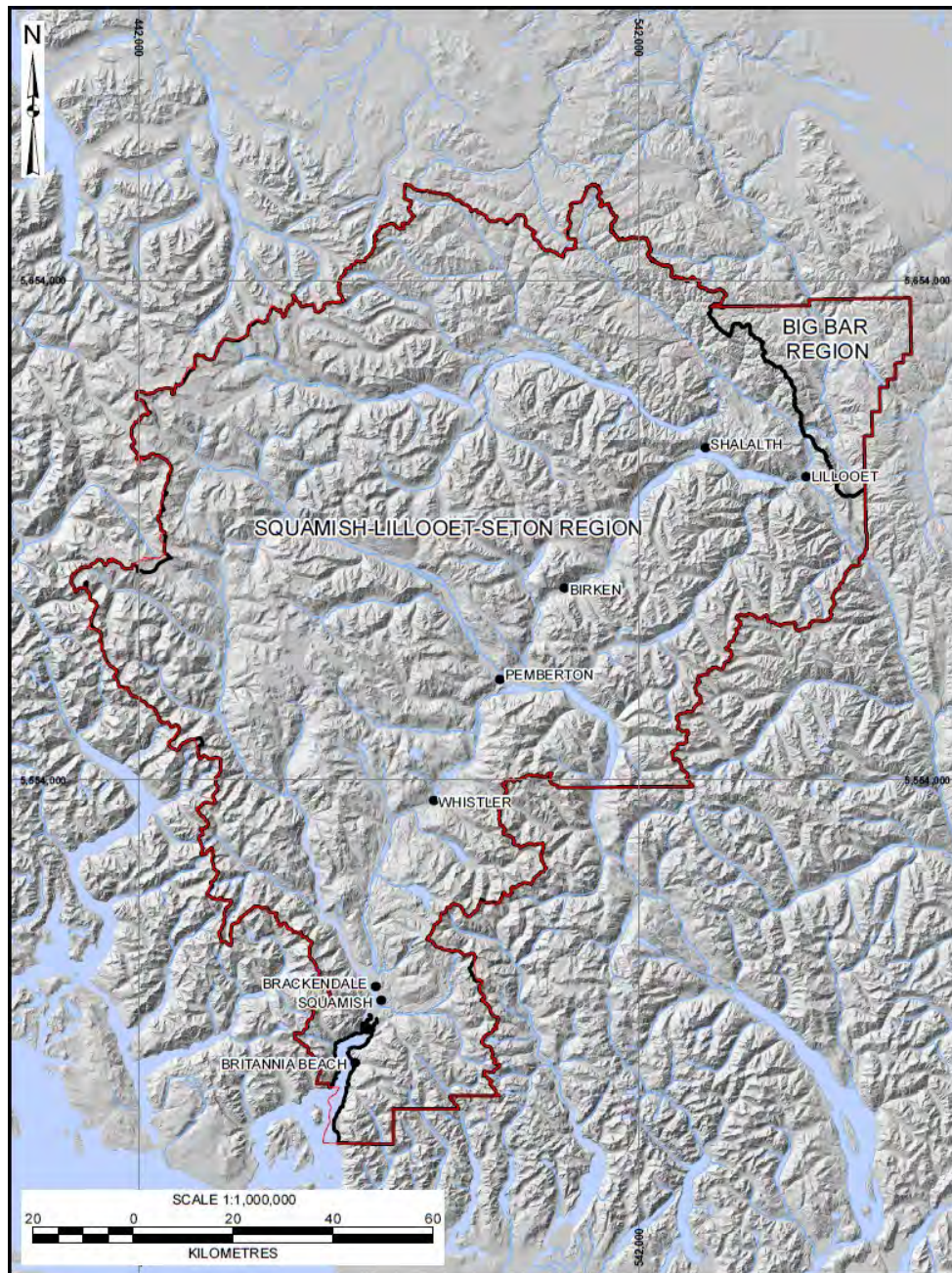
BGC estimated geohazard impact likelihood based on a combination of susceptibility modeling and terrain interpretations. The results of the susceptibility model provided an initial estimate of impact likelihood (Sections F-3.2.2 and F-3.2.3), which was then complemented by observations on avulsion activity (Section F-3.2.4) and the potential for a LDOF (Section F-3.2.5). Previous assessments and event records were referenced where available. The methods described in this section are applicable for regional-scale assessment.

Calibration of the debris flow and debris flood susceptibility model required subdividing the SLRD study area into two regions, Big Bar and Squamish-Lillooet-Seton, to account for physiographic and climatic differences (Figure F-14). Consistent with this regionalization, the impact likelihood rating was calibrated separately in the two regions. The calibrated impact likelihood rating thresholds per region for debris flow and debris flood are shown in Table F-10.

In each region, an initial impact likelihood rating was first calculated as the proportion of “moderate” and/or “high” modelled susceptibility classes included within the area of each fan. For clear-water flood, the initial impact likelihood rating was calculated as the proportion of fan inundated by the HAND model (Table F-11; Appendix E). This initial estimate of impact likelihood was then adjusted based on the other factors (avulsion activity and LDOF potential) as follows:

- The initial impact likelihood rating was increased by a factor of 1 if the evidence for previous avulsion rating (see Section F-3.2.4) was “moderate”; and by a factor of 2 if it was “high” or “very high”.
- The initial impact likelihood rating was further increased by a factor of 1 if (i) the LDOF potential rating was “high” or “very high” (Section F-3.2.5); or (ii) there was evidence of steep-creek mixed processes. This adjustment serves to flag fans where there is a possibility of major flooding events associated with potential LDOF events.





**Figure F-14. Regions used during calibration of the susceptibility model, overlaid on the Canadian Digital Elevation Model (CDEM).**



**Table F-10. Summary of criteria used for impact likelihood rating for debris flows and debris floods, in the Big Bar and Squamish-Lillooet-Seton region.**

Impact Likelihood Rating <sup>1</sup>	Criteria	
	Big Bar Region	Squamish-Lillooet-Seton region
Very Low	Fan area is rated Very Low susceptibility; no evidence of previous avulsion	Fan area is rated Very Low or Low susceptibility; no evidence of previous avulsion
Low	Less than 5% of fan area is rated Moderate or High susceptibility; none to poor evidence of previous avulsion	Less than 25% of fan area is rated Moderate or High susceptibility; none to poor evidence of previous avulsion.
Moderate	Poor evidence of previous avulsion where 5 to 30% of fan area is rated Moderate or High susceptibility; OR moderate evidence of previous avulsion where less than 5% of fan area is rated Moderate or High susceptibility	Poor evidence of previous avulsion where more than 25% of fan area is rated Moderate or High susceptibility but less than 60% of the fan area is rated High susceptibility; OR moderate evidence of previous avulsion where less than 25% of fan area is rated Moderate or High susceptibility
High	Poor evidence of previous avulsion where more than 30% of fan area is rated High susceptibility; OR moderate evidence of previous avulsion where 5 to 30% of fan area is rated Moderate or High susceptibility; OR strong evidence of previous avulsion where less than 5% of the fan area is rated Moderate or High susceptibility	Poor evidence for previous avulsion where more than 60% of fan area is rated High susceptibility; OR moderate evidence of previous avulsion where more than 25% of fan area is rated Moderate or High susceptibility but less than 60% of the fan area is rated High susceptibility; OR strong or very strong evidence of previous avulsion where less than 25% of the fan is rated Moderate or High susceptibility
Very High	Moderate evidence of previous avulsion where more than 30% of fan area is rated High susceptibility; OR strong evidence of previous avulsion where 5 to 30% of fan area is rated Moderate or High susceptibility	Moderate or stronger evidence of previous avulsion where more than 60% of fan area is rated High susceptibility; strong or very strong evidence of previous avulsion where more than 25% of fan area is rated moderate or high susceptibility but less than 60% of the fan area is rated High susceptibility

Note:

1. The impact likelihood rating was increased by a factor of 1 if (i) the LDOF potential criteria are “high” or “very high”; or (ii) there is evidence of steep-creek mixed processes.

**Table F-11. Summary of criteria used for impact likelihood rating for clear-water floods on fans.**

Impact Likelihood Rating <sup>1</sup>	Criteria
Very Low	Less than 10% of fan is inundated by clear-water floods; no evidence of previous avulsion
Low	Between 10% and 40% of fan area is inundated by clear-water floods; no to poor evidence of previous avulsion
Moderate	Poor evidence of previous avulsion where between 40% and 90% of fan area is inundated by clear-water floods; OR moderate evidence of previous avulsion where between 10% and 40% of fan area is inundated by clear-water floods
High	Poor evidence of previous avulsion where between 90% and 100% of fan area is inundated by clear-water floods; OR moderate evidence of previous avulsion where between 40 % and 90% of the fan area is inundated by clear-water floods; OR strong evidence of previous avulsion where between 10% and 40% of fan area is inundated by clear-water floods
Very High	Moderate evidence of previous avulsion where between 90% and 100% of fan area is inundated by clear-water floods; strong evidence of previous avulsion where between 40% and 90% of fan area is inundated by clear-water floods

Note:

1. The impact likelihood rating was increased by a factor of 1 if (i) the LDOF potential criteria are "high" or "very high"; or (ii) there is evidence of steep-creek mixed processes.

### F-3.2.2 Debris-Flow- and Debris-Flood Susceptibility Modelling

Debris-flow or debris-flood hazard assessment based on terrain interpretation alone is limited by the availability of surface evidence for previous events, which may be hidden by development or obscured by progressive erosion or debris inundation. To address this limitation, BGC used a semi-automated approach based on the stream channel morphometric statistics (Sections X and F-2.3.1), and the Flow-R model<sup>9</sup> developed by Horton *et al.* (2008, 2013) to identify potential debris-flow or debris-flood hazards and model their runout susceptibility. Others that have modelled debris-flow susceptibility using comparable approaches include Blahut *et al.* (2010), Baumann *et al.* (2011), and Blais-Stevens & Behnia (2016). This approach allowed estimation of potential debris-flow or debris-flood hazard extent within the entire study area, including both developed and undeveloped areas. The results were used as an initial impact likelihood rating to each fan, as described in Section F-3.2.1.

Flow-R propagates landslides across a surface defined by a DEM. Sections of the freely available CDEM at 20 m resolution were used in the current project. Flow-R simulates flow propagation based on both spreading algorithms and simple frictional laws. The source areas are identified as stream segments associated with debris-flow or debris-flood processes, based on the stream network and morphometric statistics presented in Sections F-2.2 and F-2.3. Both

<sup>9</sup> "Flow-R" refers to "Flow path assessment of gravitational hazards at a Regional scale". See <http://www.flow-r.org>

spreading algorithms and friction parameters need to be calibrated by back-analysis of past events or using geomorphological observations.

Flow-R can calculate the maximum susceptibility that passes through each cell of the DEM, or the sum of all susceptibilities passing through each cell. The former is calculated in Flow-R using the “quick” calculation method and is used to identify the area susceptible to landslide processes. The “quick” method propagates the highest source areas, and iteratively checks the remaining source areas to determine if a higher energy or susceptibility value will be modelled. The latter is calculated in Flow-R using the “complete” method and can be used to identify areas of highest relative regional susceptibility. The complete method triggers propagation from every cell in the source segments.

For this study, the sum of susceptibilities using the “complete” method was calculated once the final model parameters were calibrated. Although the absolute value of susceptibility at a given location has no physical meaning, areas of higher relative regional susceptibility account for both larger source zones (increased the number of potential debris flows or debris floods that reach a susceptibility zone), as well as increased control of topographic features (i.e., incised channels or avulsion paths within alluvial fans).

BGC used the following steps to complete debris-flow/flood susceptibility modelling using Flow-R:

- BGC had already modeled susceptibility for steep creeks where detailed assessment had previously been completed. These steep creeks are in the Canmore, Alberta (Holm et al., 2018), which have been previously assessed by BGC at a higher level of detail than any creeks within the SLRD with the exception of Cheekeye River (District of Squamish), Cataline Creek (east of Pemberton), and Bear Creek (at Seton Portage) (Appendix A). As such, the Canmore-area creeks provide a good starting point to calibrate the model.
- BGC then calibrated the Flow-R model parameters by attempting to reproduce the extent of fans at selected locations within the SLRD (e.g., Cataline Creek). As explained in Section F-3.2.1, Flow-R parameters were calibrated separately in two regions of the SLRD (Big Bar region, east and north of Lillooet; and the Squamish-Lillooet-Seton region).
- Finally, BGC applied the model to map debris-flow and debris-flood susceptibility on all creeks in the stream network, within the SLRD. The results were further compared to terrain analyses and the database of past events.

Table F-12 and Table F-13 show Flow-R calibrated parameters for debris flows and debris floods, respectively. The debris-flow and debris-flood scenarios are modelled separately.

**Table F-12. Calibrated debris-flow parameters used in Flow-R.**

Selection	Flow-R Parameter	Value	
		Big Bar Region	Squamish-Lillooet-Seton Region
Directions algorithm	Holmgren (1994) modified	dh = 2 exponent = 1	dh = 2 exponent = 1
Inertial algorithm	Weights	Gamma (2000)	Default
Friction loss function	travel angle	9°	7°
Energy limitation	Velocity	< 15 m/s	< 15 m/s

**Table F-13. Calibrated debris-flood parameters used in Flow-R.**

Selection	Flow-R Parameter	Value	
		Big Bar Region	Squamish-Lillooet-Seton Region
Directions algorithm	Holmgren (1994) modified	dh = 2 exponent = 1	dh = 2 exponent = 1
Inertial algorithm	weights	Gamma (2000)	Default
Friction loss function	travel angle	5°	2°
Energy limitation	velocity	< 15 m/s	< 15 m/s

Debris-flow/flood susceptibility results are displayed in *Cambio* and generally correspond well to the extent of known debris-flow or debris-flood events and fan boundaries within the study area (Figure F-15). The summed susceptibility values throughout the SLRD follow a negative exponential distribution. Zones of the DEM with summed susceptibility values lower than a threshold corresponding to the 70<sup>th</sup> percentile were attributed 'very low' regional susceptibility (i.e., 'very low' susceptibility include the majority of areas covered by Flow-R simulations). Zones of 'low' regional susceptibility were defined between the 70<sup>th</sup> and 85<sup>th</sup> percentile (the 85<sup>th</sup> percentile corresponding approximately to the mean susceptibility value); 'moderate' and 'high' susceptibility were defined between the 85<sup>th</sup> and 95<sup>th</sup> percentile, and greater than the 95<sup>th</sup> percentile, respectively. Portions of alluvial fans not encompassed by susceptibility modelling were interpreted as having 'very low' regional susceptibility, where modern fan morphometry encourages flow away from the unaffected area, or not affected by debris flows/floods where deep channel incision indicate paleofans.

BGC notes that regional scale susceptibility modelling contains uncertainties and should be interpreted with caution. BGC highlights the following specific limitations:

- Susceptibility modelling on creeks without mapped fans contains much higher uncertainty.
- Susceptibility modelling does not imply any specific hazard likelihood. Some areas mapped as susceptible to debris flows or debris floods may not have credible potential for events due to factors not considered in regional scale modelling, such as lack of sediment supply.

- Susceptibility modelling is only completed for creeks within the mapped stream network. Because debris flows can also initiate in areas without mapped streams, additional debris-flow hazard areas exist that are not mapped.
- Debris-flow and debris-flood susceptibility model calibration was optimized for flow propagation on the fan. Susceptibility in the upper basin should be considered a proxy for debris sources, not necessarily an accurate representation of actual source areas.
- Flow-R propagation was simulated using parameters calibrated at regional scale. It is not applicable for detailed runout simulations, risk analyses and risk control design at specific sites. In addition, the model is not physics-based (it is an empirical model) and not attached to any specific return period. Thus, it cannot inform on return period-specific runout distance, nor does it provide flow depths and velocity estimates which are necessary to calculate debris-flow intensities.
- Susceptibility mapping does not replicate specific scenarios undertaken as part of detailed hazard and risk assessment, e.g., modelled avulsions of the Cheekeye debris flow in BGC (August 30, 2019).



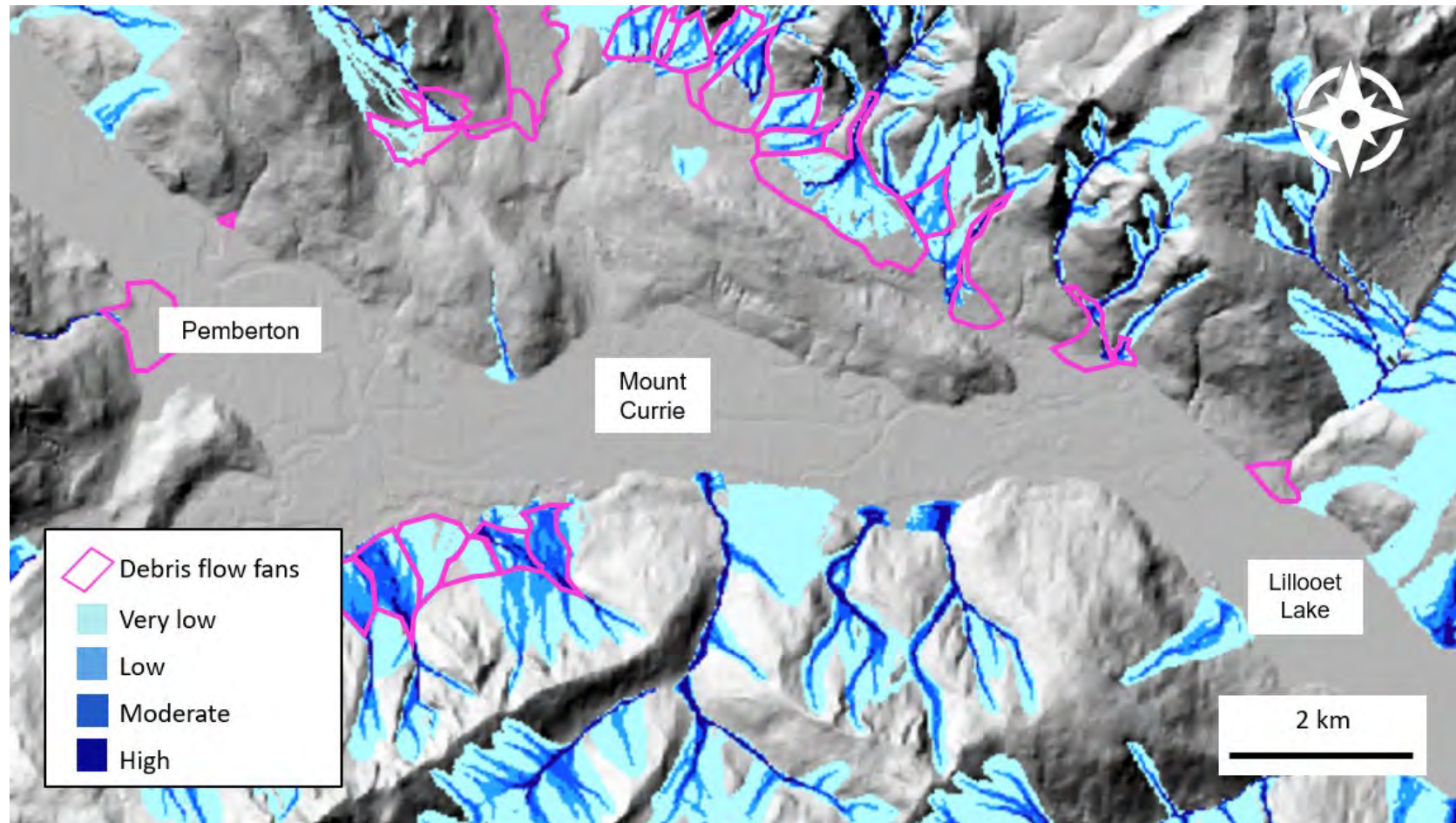


Figure F-15. Debris-flow susceptibility map for a section of the study area showing the spatial distribution of the four different susceptibility classes and developed debris-flow fans.

### F-3.2.3 Clear-water Flood Susceptibility

Appendix E describes methods to identify the extent of clear-water flood hazards using the HAND approach. This approach is applied to alluvial fans classified as dominantly subject to clear-water floods. The modelled 200-year floodplain extent was used as a proxy for channel confinement: the deeper and more incised a channel, the narrower the floodplain is expected to be. Similarly, the shallower and less incised a channel, the wider the floodplain.

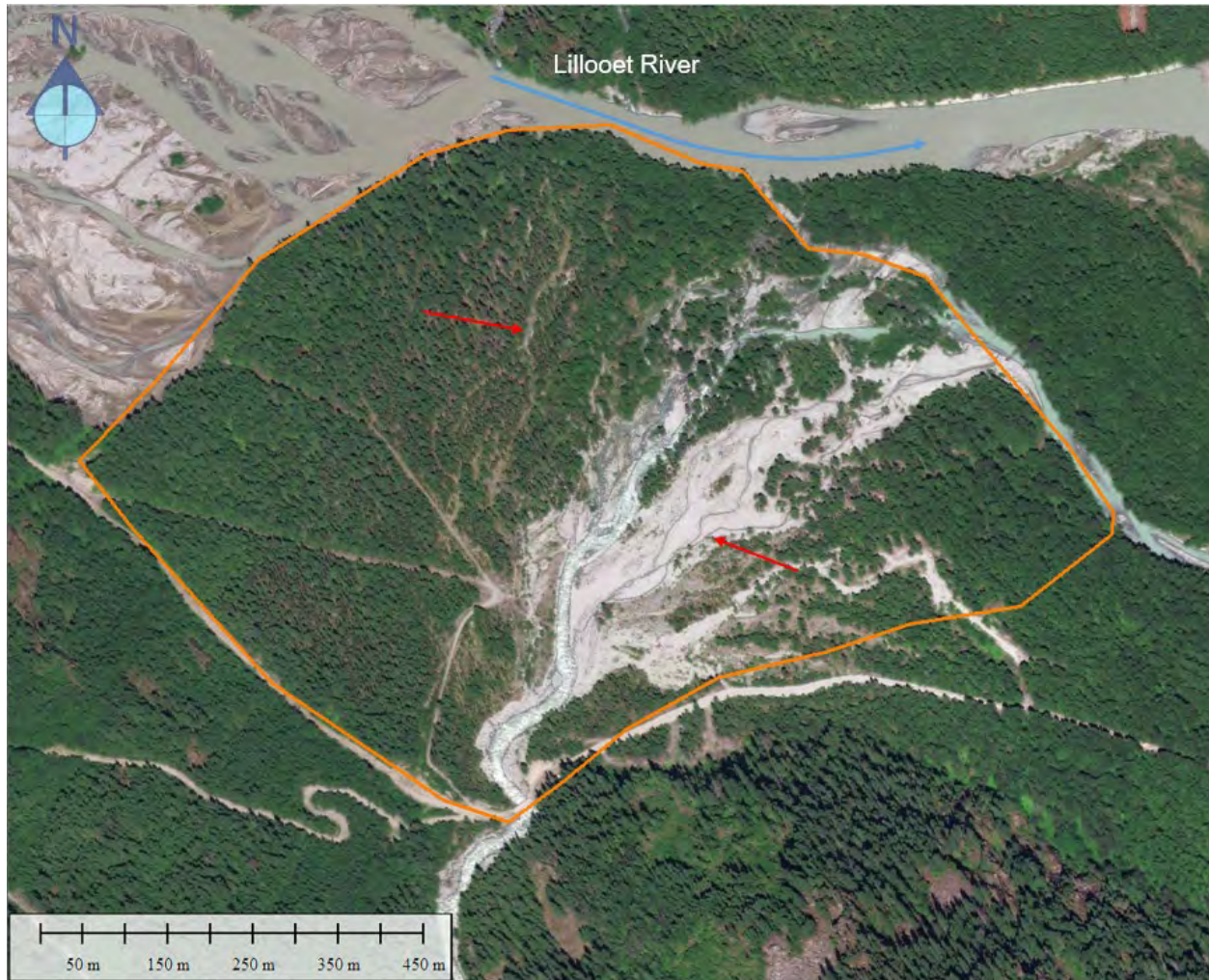
### F-3.2.4 Avulsion Activity

BGC used terrain interpretations of evidence of previous avulsions and description of potential avulsion mechanisms to assess the potential for avulsion to impact elements at risk at each fan. Surface evidence for previous avulsions includes pioneer vegetation on gravel deposits and the presence of relict channels, lobes, and deposits on the fan surface or along the channel (Table F-14; Figure F-16). These features are usually detectable on lidar hillshades and high-resolution satellite images; interpretations are less certain for areas without lidar or satellite image coverage. The rating is subject to greater uncertainty where development has obscured previous evidence for flow avulsions (e.g., channel modification or highly developed fans) or where avulsions deposits are removed by emergency works.

Fan-deltas (fans that form in standing water bodies, such as lakes, oceans and reservoirs) typically have a higher potential for avulsion than terrestrial (land-based) alluvial fans due to channel back-filling effects from the stream-lake/reservoir interface. As such, these fans typically exhibit characteristics of a “Very High” or “High” avulsion evidence rating, if the channel is not entrenched (highly incised) into the fan and the water level at any time of the year is well below the fan surface. Fan deltas with steeper gradients are less influenced by lake level and their avulsion rating remains unchanged.

The potential for avulsion can be variable along a channel due to relative confinement of the channel within the fan landform. For example, flows can more easily fill and overtop a channel that has low channel banks, rather than a deeply incised channel. In addition, structures such as bridges and culverts can become blocked during hydrogeomorphic events and encourage avulsion upstream.





**Figure F-16. Example of high evidence for previous avulsion on South Creek, located west of Pemberton. The approximate fan boundary is shown in orange.**

**Table F-14. Evidence of previous avulsions criteria. These criteria refer to the frequency of events avulsing on the fan, as opposed to Table F-8, which refers to the frequency of events reaching the fan regardless of avulsing or not.**

Surface Evidence of Previous Avulsions <sup>1</sup>	Representative Return Period (years)	Number of Recorded Events <sup>2</sup>	Description	Characteristic Observations <sup>3</sup>
<b>Very Low</b>	500	None	Active or historical channels cannot be identified in lidar or imagery.	Vegetated fan with consistent, mature tree stand age. No avulsion channels visible in lidar if available.
<b>Low<sup>1</sup></b>	200	None	Historical channels visible with lidar or air photographs, but they are muted and vegetated and not discernable on satellite imagery.	Vegetated fan with consistent, mature stand age. Muted historical channels visible in lidar if available.
<b>Moderate</b>	50	0 to 1	Historical channels on fan surface are visible in lidar, air photo and satellite imagery.	Swaths of young (<50 year) deciduous or coniferous vegetation exist in previous avulsion paths. Relict channels clear in lidar. Channels have similar characteristic geomorphic observations (e.g., debris-flow levees) as described in the fan activity rating.
<b>High</b>	20	1 to 2	An avulsion path is visible.	Swaths of bare sediment or low (<20 year) pioneer vegetation exist on previous avulsion path. Channels have similar characteristic geomorphic observations (e.g., boulder levees) as described in the fan activity rating.
<b>Very High</b>	5	8 (or at least two in the past 10 years where records are not available over a longer period)	At least one fresh avulsion path exists.	Swaths of bare sediment or low (<2 year) pioneer vegetation exist on previous avulsion paths. Channels have similar characteristic geomorphic observations (e.g., debris-flow levees) as described in the fan activity rating.

Notes:

1. Very low vs. low classification cannot reliably be determined without lidar. A classification of low is conservatively applied in such cases.
2. For the purposes of this assessment, BGC defined the record event span to be 1980 to present, for which there are readily and freely available air photo and recorded event records in the study area. The true number of recorded events at each geohazard area depends on the length and quality of air photo, imagery, and media records.
3. Fans classified as being a flood geohazard type are assessed according to these characteristics, but smaller flood events can be difficult to discern in air photos or satellite imagery. lidar, historical records and judgement is used where applicable. A low classification is conservatively applied as the lowest option for flood type fans.

#### F-3.2.5 Landslide Dam Outbreak Flood (LDOF) Potential

Some steep creek watersheds are prone to LDOFs, which could trigger flooding, debris floods, or debris flows with larger magnitudes than “typical” hazards. An example of this hazard in the SLRD is landslides in the Mount Meager volcanic complex, which have generated several landslide dams along Meager Creek and Lillooet River (Figure F-17; Bovis & Jakob, 2000; Guthrie et al., 2012). In this assessment, LDOF potential is expected to be a factor that can increase the potential for avulsion; therefore, it is considered in the impact likelihood rating (see Section F-3.2.1). However, LDOFs are a distinct population of events from the “typical” debris flows and debris floods defined in Section F-1. Therefore, this rating serves as a flag for consideration of more specific analyses to address this type of geohazard.



**Figure F-17. Landslide dam on Meager Creek from the August 6, 2010 rockslide-debris flow from Capricorn Creek. The dam impounded Meager Creek for some time. Photo by D. Steers.**

Table F-15 lists terrain criteria used to estimate LDOF potential. Ratings are assigned based on evidence of past landslide dams, presence of large landslides with the potential to travel to the valley floor, and presence of channel sections potentially susceptible to blockage (e.g., channel constrictions).



**Table F-15. Landslide dam outbreak flood potential criteria.**

Relative Frequency	LDOF Potential
Very High	<p>Presence of active landslides that are potentially large enough to reach the valley floor and block the typically confined stream channel.</p> <p>Historical evidence of several landslide dams in the main channel.</p> <p>Main stem channel is entrenched and confined within a steep sided and narrow valley, resulting in multiple constriction points (e.g., bedrock canyon).</p>
High	<p>Evidence of historical landslides that are potentially large enough to reach the valley floor and block the river channel.</p> <p>Historical evidence of at least one landslide dam in the main channel.</p> <p>Main stem channel is entrenched and confined within a narrow valley and may have constrictions (e.g., bedrock canyon).</p>
Moderate	<p>Evidence of historical landslides that are potentially large enough to reach the valley floor and block the river channel. Landslide damming is considered possible.</p> <p>No evidence of historical landslide dams in the main channel.</p> <p>Main stem channel has moderately steep valley walls and is partially confined (e.g., U-shaped valleys, glacial deposits, river terraces).</p>
Low	<p>No evidence of historical landslides potentially large enough to reach the valley floor and block the river channel. Landslide damming is improbable.</p> <p>No evidence of historical landslide dams in the main channel. Main stem channel is broad, with low angle to flat valley floor (e.g., floodplain).</p>
Very Low	<p>No evidence of historical landslides in the watershed. Main stem channel is broad and flat (e.g., floodplain). Landslide damming is impossible.</p>

## F-4 CONSEQUENCE RATING

BGC assigned consequence ratings that considered the following two factors:

1. Geohazard intensity: What is the destructive potential of an event?
2. Geohazard exposure: What are the elements at risk exposed to an event?

These two factors are combined in the qualitative consequence rating matrix shown in Table F-16 and further discussed in Sections F-4.2 and F-4.3.

Destructive potential is characterized based on intensity, which is usually quantified by a combination of parameters such as flow depth, velocity, and density. At a regional scale, these parameters are difficult to estimate, because they are specific to individual watersheds. To address this limitation, at the scale of the SLRD, and in the context of the current risk study, BGC used peak discharge as a proxy for flow intensity. The methods to estimate peak discharge are presented in Section F-4.1.

Geohazard intensities were estimated for both the baseline condition and the wildfire-adjusted condition.

**Table F-16. Consequence rating.**

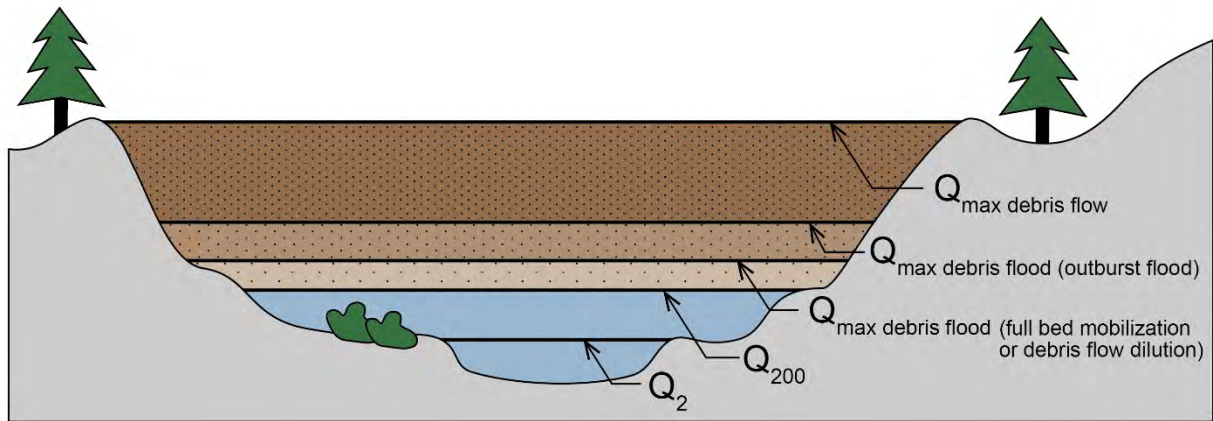
Hazard Exposure	Relative Consequence Rating				
Very High	Moderate	Moderate	High	Very High	Very High
High	Low	Moderate	High	High	Very High
Moderate	Low	Low	Moderate	High	High
Low	Very Low	Low	Low	Moderate	Moderate
Very Low	Very Low	Very Low	Low	Low	Moderate
<b>Hazard Intensity Rating</b>	Very Low	Low	Moderate	High	Very High

### F-4.1 Peak Discharge Estimation

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 F-18 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)
- $Q_{\max}$  debris flood (full bed mobilization); Type 1 debris flood generated by full bed mobilization
- $Q_{\max}$  debris flood (outburst flood); Type 3 debris flood generated by an outburst flood
- $Q_{\max}$  debris flow; debris flow.



**Figure F-18. Conceptual steep creek channel cross-section showing peak discharge levels for different events. Note that for some outburst floods the discharge may reach or exceed that of debris flows.**

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 in case of a debris flow. For debris floods, the longer duration of the event will also affect the total volume of sediment transported and the amount of bank erosion occurring. Due to the differences in peak discharges associated with each process type, the maximum peak discharge at the geohazard areas is calculated depending on the interpreted geohazard process type, using the methods described below. Results of this analysis are provided in *Cambio*.

To account for the relative projected climate change effect on steep creek geohazard magnitude (Section F-1.2), the peak discharge for debris-flow fans associated with supply-limited basins was reduced by 10%<sup>10</sup>, and the peak discharge for debris-flow fans associated with supply-unlimited basins was increased by 10%. These percentages are expected to reflect climate change effect by 2050 for “typical” steep creek geohazard events, i.e., where entrained sediments include in-channel material and a small amount of sediments from slope failures. A 10% increase in peak discharge is applied to all fans with clear-water flood and debris flood processes.

#### F-4.1.1 Debris Floods

Type 1 and 2 debris floods vary in discharge between 1.05 times to several times (see Table F-1) the corresponding clear-water flood discharge (Church & Jakob, 2020). At the regional scale of this risk study, splitting debris floods into different types and their associated varying discharges is not possible. Therefore, BGC uses a proxy discharge multiplier, which is designed as a relative rating. BGC chose a multiplier of 1.5, which is applied to peak discharge of the clear-water flood at the 100-year return period in the same creek. This multiplier reflects heavy sediment and organic debris load and is conservative in most cases. Type 3 debris floods

<sup>10</sup> The 10% decrease/increase is based on judgment due to the lack of literature currently available on this topic.

(LDOF) are addressed as a parameter in the geohazard impact likelihood rating (see Section F-3.2.5).

The following sections describe methods to estimate clear-water flood discharges to which multipliers were applied.

#### F-4.1.1.1 Hydrological Rainfall-runoff Modelling

Rainfall-runoff modelling uses catchment characteristics to estimate runoff for a given rainfall. While this method is widely used across the United States, its application is limited in Canada. Van Hove (April 10, 2020) developed an approach for estimating rainfall-runoff generated flows through RNT. The flow model uses the Soil Conservation Service (SCS) curve number method in Hydraulic Engineering Center's Hydrologic Modelling System (HEC-HMS) and utilizes the following catchment characteristics:

- Catchment Characteristics (e.g., area, elevation)
- Curve Number (CN)
- Initial Abstraction
- Lag Time
- Rainfall
- Model Time Step
- Storm Type.

Catchment boundaries were determined using geographic information systems (GIS) and were based on topographic data (Shuttle Radar Topography Mission, approximately 1 arcsecond resolution) and the mapped stream network in RNT. Topographic and stream network data were also used to determine catchment characteristics such as maximum and minimum elevations and channel lengths.

A weighted CN for each catchment was determined based on the overlap between the catchment area and the GCN250 dataset produced by Jaafar et. al. (2019), which provides global CN estimates at a grid spacing of 250 m. The GCN250 dataset provides CN values for three antecedent moisture conditions<sup>11</sup>: dry (AMC I), average (AMC II), and wet (AMC III). For this study the CN for the average moisture conditions (AMC II) were used.

The initial abstraction was approximated empirically by Equation E-1 (USDA, 1986).

$$I_a = 0.2 \cdot S \quad [\text{Eq. E-1}]$$

Where

$I_a$  is the initial abstraction (mm) and

$S$  is the maximum potential retention (mm) (Equation E-2):

$$S = K \cdot \left( \left( \frac{1000}{CN} \right) - 10 \right) \quad [\text{Eq. E-2}]$$

Where

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<sup>11</sup> In other literature this may be referred to as antecedent rainfall condition.

$K$  is a conversion factor from inches to mm (i.e., 25.4) and  
 $CN$  is the curve number.

Lag time was estimated using Equation F-3 (USDA, 2010).

$$L = \frac{l^{0.8}(S + 1)^{0.7}}{1900\sqrt{Y}} \quad [\text{Eq. E-3}]$$

Where

$L$  is the lag time (hrs),

$l$  is the longest channel length (ft),

$S$  is the maximum potential retention (in), and

$Y$  is the average watershed slope (%).

Rainfall intensity-duration-frequency (IDF) data from the closest Environment and Climate Change Canada (ECCC) weather station were used in the modelling. Thiessen polygons were used to determine the closest station. The 24-hr rainfall is used in HEC-HMS because it is usually the most readily available data and is most applicable for the catchment sizes for which SCS curve number modelling is appropriate (USDA, 1986). Return periods considered range from 1 in 2-year to 1 in 100-year.

Model time steps were estimated by multiplying the lag time by 0.29 (per recommendation of United States Army Corps of Engineers) and rounded down the closest, acceptable time step. The time steps that are accepted by the HEC-HMS model are 1 min, 2 min, 3 min, 4 min, 5 min, 6 min, 10 min, 15 min, 20 min, 30 min, 1 hr, 2 hr, 3 hr, 6 hr, 12 hr, 18 hr, and 1 day.

SCS storm types are divided into four categories: Type I, Type 1A, Type II, and Type III. Widely accepted SCS storm type zones for Canada have not previously been developed. Storm type data from the United States of America (US) was extended into Canada. Type II storms were selected for the SLRD and are convective storms typical of the central and eastern lowlands of Canada. This storm type has the highest peak rainfall intensity in the SCS storm classifications.

#### F-4.1.1.2 Flood Frequency Analysis

RNT contains all publicly available hydrometric gauges in Canada and the US. The flood quantiles for the gauges are available in RNT and modelled using the Generalized Extreme Value (GEV) distribution based on the observed instantaneous maximum peak flows.

RNT performs an FFA at a watercourse crossing such as at a fan using one of two methods:

- Pro-rated FFA based on a single-station FFA
- Regional FFA (RFFA).

The pro-rated FFA is performed at a watercourse where a suitable hydrometric gauge is located on the same watercourse (i.e., it is gauged). The pro-rated FFA consists of two steps:

1. Selection of a suitable hydrometric gauge on the same stream network as the watercourse.



2. Pro-rating the flood quantiles from a selected hydrometric gauge to the outlet of the watershed based on the difference in catchment area at both the gauge and the watershed under consideration.

RNT searches upstream and downstream for a suitable hydrometric gauge. A suitable gauge is one where:

- The gauge has a suitably long period of record to perform a single-station FFA – at least 30-years (Stedinger et al., 1993)
- Both the watercourse and the gauge are on the same Strahler order number
- The catchment area of the gauge is between 0.5 and 2 times the drainage area of the watercourse being estimated.

If those criteria are met, then the flood quantiles from the hydrometric gauge are transferred to the watercourse by pro-rating the flood quantile based on the catchment areas:

$$Q_w^T = Q_g^T \left( \frac{A_w}{A_g} \right)^n \quad [\text{Eq. E-4}]$$

where  $Q_w^T$  and  $Q_g^T$  refer to the flood quantile for return period  $T$  for the watercourse and gauge respectively,  $A_w$  and  $A_g$  are the catchment areas of the watercourse and gauge respectively and  $n$  is an exponent. Within the RNT, the exponent  $n$  is taken to be 0.8 as is recommended for preliminary estimates (Watt, 1998).

If the criteria for performing a pro-rated FFA are not met, or the watercourse is ungauged then a RFFA is performed. RNT performs the RFFA using the direct regression of flood quantiles in which a separate regression equation is developed for each flood quantile of interest. The RFFA consists of three steps:

1. Hydrometric gauge selection.
2. Development of the linear regression model.
3. Application to the watercourse of interest.

The hydrometric gauge selection involves selection of gauges to be used to develop the linear regression model. This consists of two steps:

1. Selection of candidate gauges based on general proximity to the watercourse (within +/- 5° latitude and longitude) and a suitably long period of record to perform a single-station FFA (more than 20-years).
2. Ranking of the candidate gauges based on a ranking metric which considers the distance between the gauge and the watercourse and the similarity in the catchment areas.
3. Selection of the top ranked gauges.

After the gauges have been ranked, a final selection is made to determine a subset which will be used in the calculation of the flood quantiles. The flood quantiles are estimated using the following relation:

$$Q^T = \alpha A_w^\beta \quad [\text{Eq. E-5}]$$

which is then log-transformed to form a linear equation:

$$\log(Q^T) = \log(\alpha) + \beta \log(A_w) \quad [\text{Eq. E-6}]$$

The coefficients  $\alpha$  and  $\beta$  are estimated using linear regression solved using Ordinary Least Squares (OLS) based on the flood quantiles from the final subset of hydrometric gauges.

#### F-4.1.2 Debris Flows

Debris-flow peak discharge was estimated using the following procedure:

- A regional frequency-magnitude (F-M) relationship was developed for debris flows in the study area, based on data from previous studies.
- A hypothetical site-specific F-M was developed from the regional F-M (Jakob et al., 2020), based on the fan area for each debris-flow fan.
- The hypothetical sediment volume of a 100-year return<sup>12</sup> period debris-flow event was calculated from the site-specific F-M.
- The peak discharge of the hypothetical 100-year return period event was calculated from the event volume using empirical relationships.
- Where necessary, the peak discharge was capped at 50 times the 200-year clearwater flood (Hung et al., 1984).

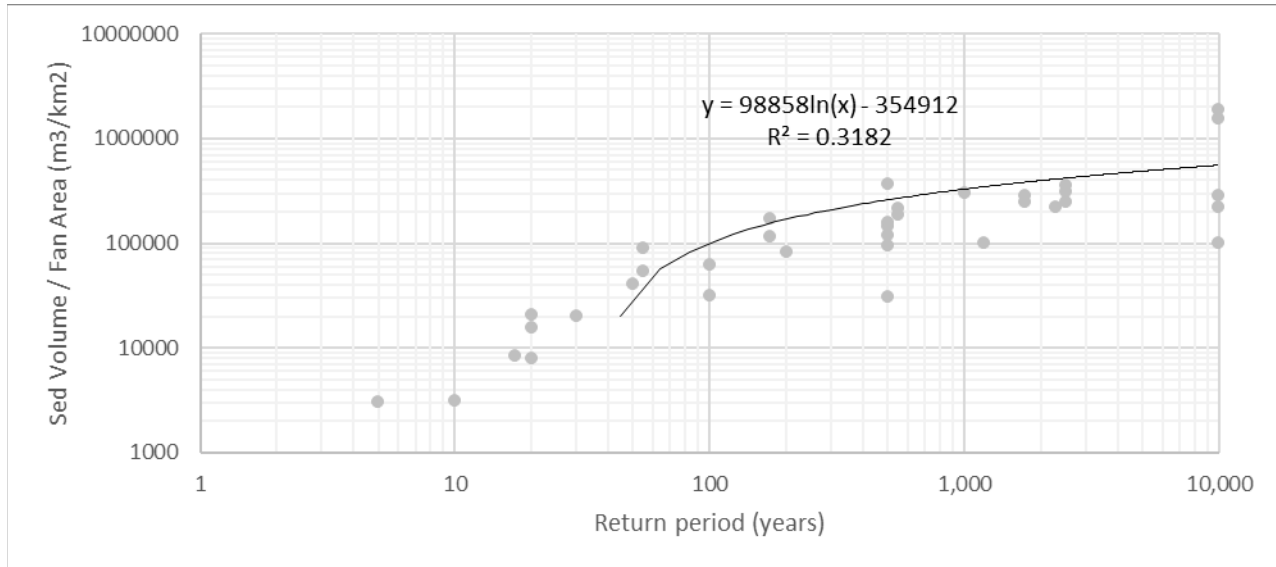
Typically, F-M relationships for debris flows are challenging because of the scarceness of direct observations, the discontinuous nature of event occurrence, and the obfuscation of field evidence due to progressive erosion or debris inundation. Detailed F-M analyses involve a high level of effort for each creek that is outside the current scope of work. However, where several reliable F-M curves have been assembled, regional relations can be developed (Jakob et al., 2020). These relations can then be applied to watersheds for which detailed studies are unavailable, unaffordable or impractical due to lack of dateable field evidence. The number of watersheds with detailed F-M analyses is increasing, but at present is still limited.

BGC cautions against the indiscriminate use of regionally based F-M curves, especially in watersheds where multiple geomorphic upland processes are suspected, or where drastic changes (mining, major landslides) have occurred in the watershed that are not yet fully responded to by the fan area. These site-specific factors could result in data population distributions that violate underlying statistical assumptions in the regional F-M curves.

In this assessment, BGC used F-M curves outlined in Jakob et al. (2020) from detailed studies of ten creeks in southwestern British Columbia (B.C.). Individual F-M curves were normalized by dividing sediment volume by fan area and then plotted collectively versus return period. A logarithmic best-fit curve was then fit to the data. Figure F-19 shows the resulting normalized F-M curve for debris flows in southwestern B.C.

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<sup>12</sup> The 100-year return period was used, as intensity-duration-frequency data in Canada (used in the post-wildfire ratings) is only available to the 100-year return period. This differs from the Phase II study, which used the 200-year return period.



**Figure F-19. F-M curve for debris flows in southwestern B.C. using data from ten study creeks. Curves are truncated at the 40-year return period (Jakob et al., 2020).**

The regional F-M relationship (Equation E-7), based on the best-fit line from Figure F-19 for the detailed study<sup>13</sup> of sixteen creeks in southwestern BC, is then derived:

$$V_s = A_f [98858 \ln(T) - 354,912] \quad [\text{Eq. E-7}]$$

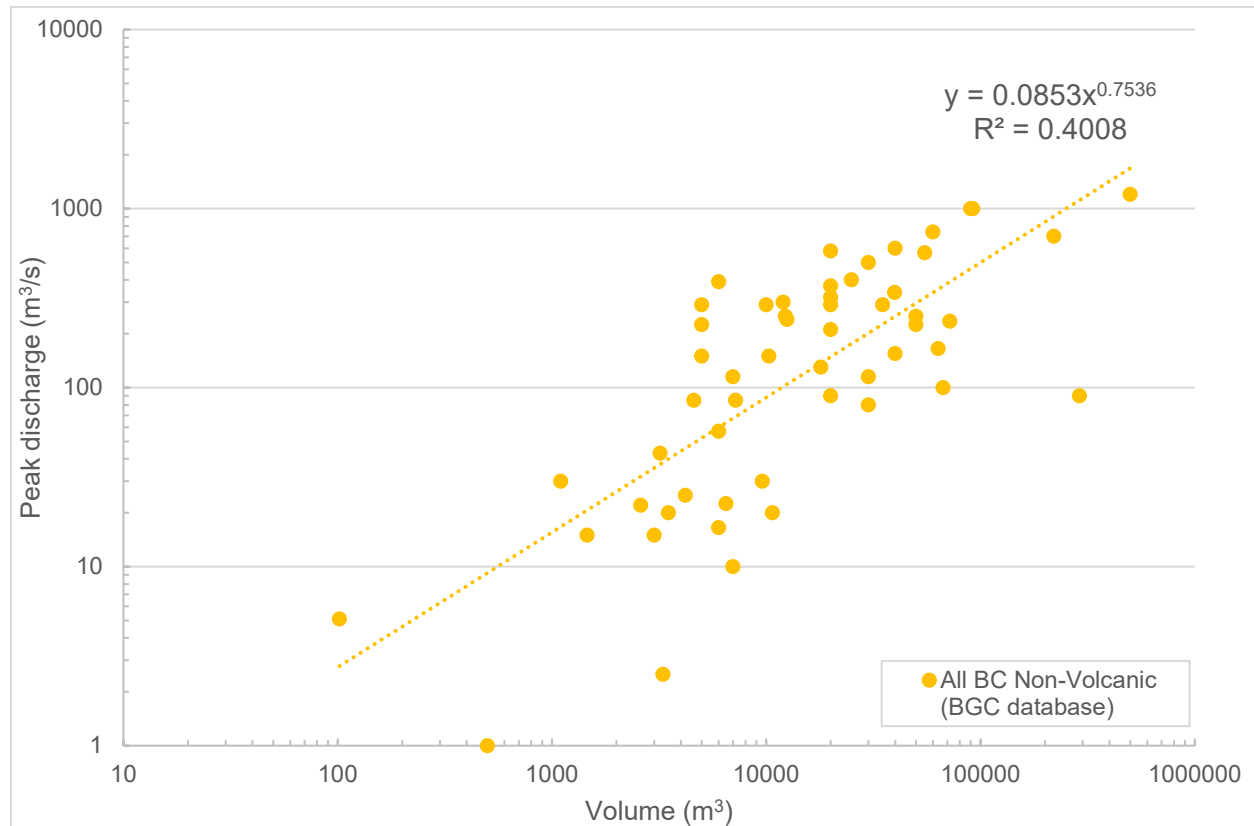
Using this equation, BGC predicted sediment volumes ( $V_s$ ) for each geohazard area within SLRD using the fan area ( $A_f$ ) and an average return period ( $T$ ) of 100 years. This equation was used for comparative analysis amongst the geohazard area in this study.

Having estimated sediment volume, peak discharges for all drainages were estimated through the unpublished BC relationship (Figure F-20) and given by the following equation:

$$Q_p = 0.0853V^{0.7536} \quad [\text{Eq. E-8}]$$

where  $V$  is the debris-flow volume in  $\text{m}^3$  and  $Q$  is peak discharge in  $\text{m}^3/\text{s}$ . The above equations are solved for  $Q$  using the sediment volumes ( $V$ ) derived using Equation E-7.

<sup>13</sup> BGC, March 28, 2013; January 2014; January 22, 2015; January 31, 2017; May 31, 2017; April 6, 2018; Cordilleran Geoscience, 2008 and 2015; Clague et al., 2003; and Michael Cullen Geotechnical Ltd. & Cordilleran Geoscience, 2015.



**Figure F-20. Empirical correlation between volume and peak discharge, developed using a dataset for non-volcanic debris flows in BC.**

It should be noted that debris-flow peak discharge estimates using this method may result in overestimation. To address this issue, BGC assumed that debris-flow peak discharge could not exceed the 200-year peak discharge of a clear-water flood in the same creek by more than 50 times (Hung et al., 1984).

#### F-4.1.3 Post-wildfire Peak Discharge

Flows in burned areas range from heightened flows in channels dominated by clearwater flood processes to extreme debris flows and debris floods generated by storms with frequent rainfall return periods (i.e., storms with a two- to five-year return period). Peak discharges were adjusted to reflect post-wildfire conditions to incorporate into the post-wildfire risk condition.

To account for anticipated increases in peak flows in the two- to five-year period following a wildfire, clearwater flows and debris floods on fans were bulked up by 150% and 200%, respectively. For debris flows, Gartner et al. (2014) provides a model for estimating the volume of a post-wildfire debris flow as a function of basin area burned, basin relief and the peak 15-minute rainfall intensity of a design storm (Gartner et al., 2014).

To estimate debris-flow peak discharge of post-wildfire debris flows for input into the post-wildfire condition, debris-flow volumes were estimated using the Gartner et al. (2014) model with the following inputs:

2/3<sup>rd</sup> of the basin area burned at moderate and high severity,

The 15-minute rainfall intensity of a storm with a 100-year return period

The basin relief.

The source data for the rainfall intensity inputs was provided by a gridded dataset of Intensity-duration-frequency (IDF) data for ungauged locations provided by the University of Waterloo, Ontario's IDF\_CC Tool 6.0 (downloaded from <https://www.idf-cc-uwo.ca/idfgrid> in January, 2022) which was then adjusted for climate change for a period 20 years in the future. Methods for estimating IDF data for ungauged locations is summarized in Gaur et al. (2020). The climate adjustment was done by estimating the change in the annual average temperature ( $\Delta T$ ) for the year 2040 using the Climate Atlas of Canada (available at <https://climateatlas.ca/>) and calculating the rainfall intensity ( $R_F$ ) for the rainfall intensity provided from the historical IDF data ( $R_H$ ) and using the equation  $R_F = R_H \times 1.07^{\Delta T}$ . The time since the fire variable was estimated to be two years since most post-wildfire flows occur within this time period (Staley et al., 2020)

The Gartner et al. (2014) model was developed using data from the Transverse Ranges of southern California and tends to over-predict post-wildfire debris flow volumes at locations outside of the Transverse Ranges. Comparison of volumes estimated by the Gartner et al. (2014) model and volumes of post-wildfire debris flows in southern B.C. measured by Jordan (2015) identified that the Gartner et al. (2014) model over-estimates post-fire debris flows in B.C. by two to four times. To account for this effect, the estimated volumes were multiplied by a factor of 0.3.

The volumes were converted to peak discharges using the volume-peak discharge relationship described in Figure F-20 to arrive at an estimate of post-wildfire peak discharge. The estimated post-wildfire peak discharge was compared to the baseline condition and the higher value was taken because the occurrence of a wildfire can only increase the potential magnitude of a debris flow.

#### F-4.2 Hazard Intensity Rating

As explained above, peak discharge was used as a proxy for intensity. Peak discharge estimates obtained based on the methods described in Section F-4.1 were grouped into five classes (modified from Jakob, 2005) using peak discharge, as summarized in Table F-17.

**Table F-17. Summary of peak discharge (approximated at the fan apex) used for intensity rating.**

Hazard Intensity Rating	Magnitude (Peak Discharge)
Very Low	< 5 m <sup>3</sup> /s
Low	5 to 25 m <sup>3</sup> /s
Moderate	25 to 100 m <sup>3</sup> /s
High	100 to 500 m <sup>3</sup> /s
Very High	> 500 m <sup>3</sup> /s



### F-4.3 Hazard Exposure Rating

The hazard exposure rating for each geohazard area was assigned a value from Very Low to Very High depending on the elements at risk present in the area. The methods used for estimation of the hazard exposure rating are outlined in Appendix H.

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# APPENDIX G

## VOLCANIC HAZARDS ASSESSMENT METHODS



## G-1 INTRODUCTION

### G-1.1 Overview

This appendix describes how BGC identified volcanic hazard scenarios, delineated volcanic geohazard extents, and assigned the geohazard and consequence ratings that were used to prioritize each area.

There are three notable volcanic complexes (VC) located within the SLRD: Mount Meager VC in the upper Lillooet River watershed, Mount Cayley VC in the upper Squamish River watershed, and the Mount Garibaldi VC towering above Squamish. While most of those volcanic complexes are believed to be at least dormant, they are highly unstable due to the relative youth of their edifices and the poor quality of volcanic rock often associated with some hydrothermal alteration, and the strong magmatic seismicity associated with previous eruptions.

Volcanic geohazards can impact areas far from the hazard source and include eruptions and geohazards related to slope failure. The latter may include rock avalanches, landslide dam outbreak floods (LDOFs), and lahars (volcanic debris flows). These hazards may occur in combination as part of a complex chain of events, and one hazard type can transform into another (i.e., rock avalanche transforming into a lahar).

This study considers non-eruptive lahars and LDOFs that originate from a volcanic complex and that have the potential to reach developed areas. Representative rock avalanche scenarios are also considered.

Lahars are large volcanic debris flows. As many volcanoes, including those within the SLRD, are partially glaciated, entrainment and melt of ice and snow is common even in absence of eruptions due to frictional heat. This process adds further mobility through the injection of water at the flow interface. Major et al. (2005) described the key flood generating processes as: (1) breaching of an eruption-induced meltwater lake; (2) eruption triggered meltwater floods; (3) breaching of landslide-dammed lakes; and (4) glacier outburst floods. With distance from the hazard source, lahars tend to lose mass and momentum by deposition or by dilution, eventually transforming to a flood with high suspended sediment concentration and bedload.

An LDOF is a flooding event that can occur when a landslide blocks the flow of a watercourse (e.g., stream or river) leading to the impoundment of water on the upstream side of the dam and potentially the rapid release of the impounded water due to dam failure. Figure G-1 provides an example in the upper Lillooet River valley. The formation and failure of a landslide dam is a complex geomorphic process because it involves the interaction of multiple geomorphic hazards. For this part of the project, the 'geohazard' is landslide-dam flooding (both upstream inundation floods and downstream outburst floods). Landslide source areas are considered as part of hazard source identification but are not otherwise characterized or prioritized.





**Figure G-1. Upper Lillooet River Valley with Plinth Peak on the left. The sketched outline shows a past landslide dam and the possible extent of a rock avalanche from the north flanks of Plinth Peak.**

A rock avalanche is a large mass of rock that can travel much further than fragmental rock fall from the same source area. Typically, a rock mass in excess of 100,000 m<sup>3</sup> is called a rock avalanche. They travel very rapidly and can achieve maximum velocities of up to 100 m/s (360 km/hr). Rock avalanches are prone to dam rivers as they deposit due to the high percentage of fines that develop via rock fragmentation during their descent.

#### G-1.2 Data Sources

The work described in this appendix was based on desktop study and the previous work summarized in Table G-1. The references provided are not exhaustive but provide some relevant data applicable to the present study.

**Table G-1. Summary of pertinent literature on volcanic hazards in the SLRD.**

Reference	Use in this study	Applicable Hazard Scenario (Section G-3)
NHC, 2018 – Flood Hazard Mapping and Risk Assessment, Upper Squamish	Squamish River	3a, 3b, 3c
LCI, 2012 – Hazard Assessment Report, Paradise Trails Development Site	Cheakamus River	2a, 2b, 2c, 2d, 2e
Cordilleran Geoscience, 2012 – Volcanic Landslide Risk Management, Lillooet River Valley, BC: Start of north and south FSRs to Meager Confluence, Meager Creek and Upper Lillooet River Roberti et. al., 2018 - Landslides and glacier retreat at Mt. Meager volcano: Hazard and risk challenges. Simpson et. al., 2006 – Evidence for catastrophic volcanic debris flows in Pemberton Valley, British Columbia	Lillooet River	1a, 1b, 1c, 1d

Data compiled to support desktop study include the following:

#### Elevation data

- 20-meter digital elevation models (DEM) downloaded from Canada Digital Elevation Model<sup>1</sup> (CDEM)
- Lidar data provided to BGC by the SLRD.

#### Flood Mapping Polygons

- Clear-water flood hazard areas prioritized by BGC, as described in Appendix E.
- 500-year floodplain mapping, conducted by NHC (2018) and provided to BGC by the SLRD.

#### Imagery

- Google Earth™, which was used for analysis of aerial imagery.

<sup>1</sup> CDEM data downloaded from URL:  
<https://open.canada.ca/data/en/dataset/7f245e4d-76c2-4caa-951a-45d1d2051333>.

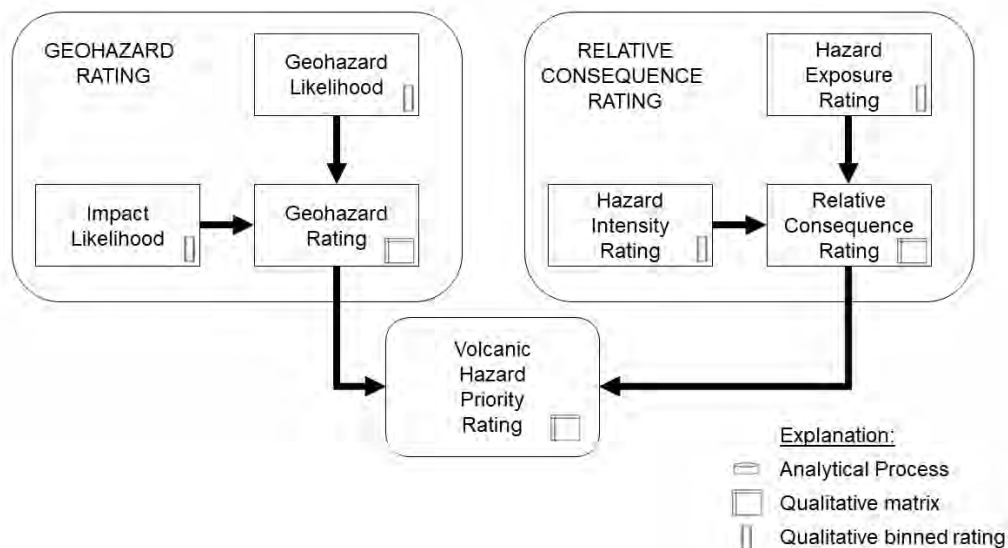
## G-2 ASSESSMENT WORKFLOW

Section 5.0 of the main document describes the risk prioritization framework, which is consistent across the clear-water flood, steep creek, and volcanic geohazard types considered in this study. In all cases, the assessment involves determining geohazard and relative consequence ratings for a given area (section of river), which combine to form a priority rating.

The assessment workflow is built around several questions:

1. Geohazard identification and mapping:
  - What volcanic hazard scenarios can be identified (excluding eruptive hazards)?
  - What reasonable subset of volcanic hazards can be identified that act as proxy for the myriad of other possible scenarios?
  - Given the volcanic hazards, what is a reasonable upstream and downstream limit to potentially impacted areas, for the purpose of prioritization?
2. Geohazard Rating:
  - Given a specific scenario what is the presumed likelihood of impact of the mapped elements at risk?
3. Relative Consequence Rating:
  - Given the expected lahar and its transition to hyperconcentrated floods and eventually floods, what is the destructive potential (intensity)?
  - What types and relative value of elements at risk are potentially exposed to the volcanic hazards assessed?
4. Priority Rating:
  - What is the combined, relative probability that a volcanic hazard occurs and result in an undesirable consequence at the estimated intensity?

Figure G-2 outlines the assessment workflow steps, and the following sections describe each step in more detail.



**Figure G-2. Volcanic hazard analysis workflow. Geohazard rating and relative consequence rating elements are described in this Appendix.**

### G-3 VOLCANIC HAZARD SCENARIOS

Table G-2 lists the volcanic hazard scenarios considered in this study, organized by volcanic hazard source. Lahars would travel from the tributary streams into either Lillooet River, Squamish River, or Cheakamus River with conveyance to Squamish River.

Estimated geohazard extents for each scenario were developed using the work flow summarized in Section G-2 and are shown on the Cambio web application. It is important to point out that there are many more volcanic hazard scenarios conceivable. The ones listed are considered proxies for the principal ones.

**Table G-2. Volcanic hazard scenarios.**

Hazard Scenario	Description
<b>Mount Meager Volcanic Complex</b>	
1a	A rock avalanche from Plinth Peak impacts Pumice Mine, Hydro project, and future development in the Meager Creek area.
1b	A rock avalanche from Plinth Peak or other source area dams Lillooet River and causes a lahar reaching at least Pemberton Meadows.
1c	A rock avalanche from any basin draining into Meager Creek dams Meager Creek and causes an outbreak flood reaching Pemberton Meadows and beyond.
1d	An LDOF from any flank of the Mount Meager Volcanic Complex.
<b>Mount Garibaldi Volcanic Complex</b>	
2a	Barrier collapse and debris flow or debris flood down Cheakamus River (LDOF or debris flood).
2b	Barrier rock slide hitting the parking lot for access to Garibaldi Lake trail.
2c	Culliton Creek debris flow (impacting homes on the fan, power intake, and the powerhouse at the Big Orange Bridge).
2d	Culliton Creek debris flow (lowest frequency with damage potential), 5 m landslide dam.
2e	Culliton Creek debris flow (lowest frequency with high damage potential), 10 m landslide dam.
<b>Mount Cayley Volcanic Complex</b>	
3a	Turbid Creek debris flow and outbreak flood (lowest frequency with damage potential).
3b	Turbid Creek debris flow and outbreak flood (lowest frequency with high damage potential).
3c	Turbid Creek debris flow and outbreak flood (lowest frequency with high damage potential).

For each scenario, the runout distance was estimated using judgement informed by the data sources listed in Table G-1.

Once runout distance was estimated, geohazard extent was approximated from the hazard extents developed for clear-water floods (Appendix E) with reference to previous work. This process resulted in 12 polygons that range in length from 6 km to 90 km, which are displayed in

*Cambio.* As noted, the hazard extents are subject to high uncertainty. For example, the NHC (2018) study only modeled flows on Squamish River as far as the Cheakamus River confluence. BGC extended the estimated geohazard area past the confluence under the conservative assumption that a volcanic lahar, or the derivative hyperconcentrated flow or outbreak flood would not stop at this confluence but continue downstream.

#### G-4 GEOHAZARD RATING

Table G-3 displays the matrix used to assign geohazard ratings to volcanic hazard areas based on the following two factors:

1. Geohazard likelihood: What is the likelihood of a volcanic geohazard event with credible potential to reach the sections of watercourse within the hazard area.
2. Impact Likelihood: Given a geohazard event occurs, how susceptible is the hazard area to uncontrolled flooding that could impact elements at risk.

Several of the scenarios considered have an estimated annual probability of less than 0.3% (less than 1:300). Those were all binned into one Geohazard Likelihood category (Very Low). Geohazard likelihood estimates were assigned using judgement with reference to the data sources listed in Table G-3.

**Table G-3. Geohazard rating for volcanic hazard potential.**

Geohazard Likelihood (AEP)	Geohazard Rating				
Very High (< 10%)	M	H	H	VH	VH
High (>10% - <3.3%)	L	M	H	H	VH
Moderate (>3.3% - 1%)	L	L	M	H	H
Low (>1% - <0.33%)	VL	L	L	M	H
Very Low <0.33%)	VL	VL	L	L	M
<b>Impact Likelihood (estimated chance of occurrence)</b>	Very Low (< 5%)	Low (5 to 33%)	Moderate (33 to 66%)	High (66 to 95%)	Very High (>95%)

#### G-5 CONSEQUENCE RATING

Table G-4 shows the matrix used to assign relative consequence ratings to each volcanic geohazard area. The rating considers the value of elements at risk (exposure rating) that could be impacted by a geohazard with some level of destructive potential (intensity rating). For example, a more highly developed area subject to more destructive geohazards would be assigned a higher consequence rating.

Methods used to determine the hazard exposure rating are outlined in Appendix H.

Hazard intensity ratings were applied as averages to each prioritized geohazard area, using judgement with reference to the data sources summarized in Table G-1. Estimating hazard



intensity for volcanic geohazards is highly uncertain in the absence of detailed assessment and scenario modelling. At an order-of-magnitude level of precision, the ratings correspond to a hazard intensity index ( $I_{DF}$ ) (Jakob et. al., 2012), which is defined as the product of flow velocity squared and flow depth. The resolution and confidence in the intensity estimates would not be satisfactory for detailed geohazard mapping but is considered reasonable for comparing sites as part of relative risk prioritization.

**Table G-4. Geohazard relative consequence rating for volcanic hazard potential.**

Hazard Exposure	Relative Consequence Rating				
Very High	M	H	H	VH	VH
High	L	M	H	H	VH
Moderate	L	L	M	H	H
Low	VL	L	L	M	H
Very Low	VL	VL	L	L	M
<b>Hazard Intensity</b>	Very Low	Low	Moderate	High	Very High
$I_{DF}$	< 0.1	0.1 to 1	1 to 10	10 to 100	> 100

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# APPENDIX H

## EXPOSURE ASSESSMENT METHODS



## H-1 INTRODUCTION

This study assessed areas that both contained elements at risk and that were subject to geohazards. Section H-2 describes different types of elements at risks, how their data were organized across the study area, and how weightings were assigned. Section H-3 describes how exposure ratings were calculated.

As described in the main report, this document updates a previous study by BGC (April 10, 2020), including the following changes to the hazard exposure assessment:

- *Building Improvement Values*: Estimates of the replacement value of building improvements have been added on First Nation reserves, to address gaps in BC Assessment data for these areas.
- *Building Locations*: The existing building footprint inventory was manually reviewed in First Nations reserve areas, with additional building footprint mapping completed as part of work to estimate building improvement values.
- *Social Vulnerability*: Based on a “Social Fabric” dataset compiled nationally by NRCan at a Census Block level of detail (Journeay et al., 2022b), a federal index of social vulnerability was added to the hazard exposure data model to weight hazard exposure more heavily in area of greater social vulnerability.

Table H-1 lists the elements at risk considered in this study. BGC divided them into two groups, termed “community” and “lifelines”, which were considered separately for the priority rating. The results are shown on Cambio™, where the user can select the type of priority rating most appropriate for their objective.

The data described in this appendix was organized using Cambio™ web application as an ArcGIS enterprise geodatabase stored in a Microsoft SQL Server spatial database. This software developed by BGC was used to automate queries to identify elements at risk falling within hazard areas. This will allow updates to be efficiently performed in future. Deliverables of this study are exported as an ESRI file geodatabase and in Excel format (Appendix K). Appendix I contains more details about Cambio™.

The elements at risk listed in Table H-1 were compiled from public sources, local and district government input, and data available from the Integrated Cadastral Information Society (ICI Society, 2019)<sup>1</sup> and Natural Resources Canada (NRCAN, 2020). It should not be considered exhaustive. The prioritized geohazard areas typically include buildings improvements and adjacent development (i.e., transportation infrastructure, utilities, and agriculture). Elements where loss can be intangible, such as objects of cultural value, were not included in the inventory. Hazards were not mapped or prioritized in areas that were undeveloped except for lifelines or minor dwellings (i.e., backcountry cabins).

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<sup>1</sup> Metadata stored with these data clarifies data sources and is available on request.

**Table H-1. Weightings applied to elements at risk within the hazard area.**

Hazard Exposure Group	Element at Risk	Description	Value	Weight
Community	Population	Total Census (2016) Population (Census Dissemination Block) <sup>1</sup>	0	0
			1-10	5
			11 – 100	10
			101 – 1,000	20
			1,001 – 10,000	40
			>10,000	80
	Buildings	Building Improvement Value <sup>2</sup> (summed by parcel)	\$0	0
			<\$100k	1
			\$100k - \$1M	5
			\$1M - \$10M	10
			\$10M - \$50M	20
			>\$50M	40
	Critical Facilities	Critical Facilities (point locations)	Emergency Response Services	36
			Emergency Response Resources	10
			Utilities	30
			Communication	18
			Medical Facilities	36
			Transportation	22
			Environmental	18
			Community	36



Hazard Exposure Group	Element at Risk	Description	Value	Weight
	Businesses	Business annual revenue (summed) (point locations)	0\$ Annual Revenue or 0 Businesses	0
			<\$100k Annual Revenue or 1 Business	1
			\$100k - \$1M Annual Revenue or 2-5 Businesses	5
			\$1M - \$10M Annual Revenue or 6-10 Businesses	10
			\$10M - \$50M Annual Revenue or 11-25 Businesses	20
			\$50M - \$100M Annual Revenue or 26-100 Businesses	40
			>\$100M annual revenue or >100 businesses	80
	Environmental Values	Active Agricultural Area	Presence of	15
		Fisheries	Presence of	15
		Species and Ecosystems at risk	Presence of	15
	Social Vulnerability	Applied as a regional proxy for a community's level of ability to withstand impacts of a disaster based on their demographics and other social characteristics (both on and off reserve).	Null or 0	0
			1-2	5
			3-5	10
			6-8	15
			>9	20
Lifelines	Lifelines	Roads (centerline)	Road present; no traffic data	1
			Highway present; no traffic data	5
			No Traffic Level	0

Hazard Exposure Group	Element at Risk	Description	Value	Weight
			No Summer Maintenance	1
			0-10 vehicles/day (Class 7)	1
			10-100 vehicles/day (Class 6)	5
			100-500 vehicles/day (Class 5)	10
			500-1,000 vehicles/day (Class 4)	20
			1,000-5,000 vehicles/day	40
			5,000-10,000 vehicles/day	40
			> 10,000 vehicles/day	40
		Railway	Presence of	10
		Petroleum Infrastructure	Presence of	15
		Electrical Infrastructure	Presence of	10
		Communication Infrastructure	Presence of	10
		Water Infrastructure	Presence of	10
		Drainage Infrastructure	Presence of	10
		Sanitary Infrastructure	Presence of	10

Notes:

1. Census population and building improvement value was scaled according to the proportion of census block area intersecting a hazard area. For example, if the hazard area intersected half the census block, then half the population or building improvement value was assigned. The estimate does not account for spatial variation of population density within the census block.
2. Large parcels with only minor outbuildings or cabins, typically in remote areas, were not included in the assessment.
3. Critical facilities and lifelines were assigned a weighting based on the presence of at least one of a given type within the hazard area. For example, if a geohazard area contained two critical facility elements classed as "utilities", the weighting was applied once (not multiplied by the number of elements). Where more than one is present, the maximum weighting is applied. This approach reflects how some elements are represented as geospatial features, to avoid accidental double counting where a single facility is spatially represented by multiple parts.

## H-2 GROUPS OF ELEMENTS AT RISK

### H-2.1 Building Improvements

BGC characterized the value of buildings (“improvement”) based on BC Assessment data joined to Cadastral data for all areas except for First Nation reserves, where these data do not exist. To address gaps on First Nations reserves, BGC obtained an estimated building asset value from a 2022 Physical Exposure dataset compiled nationally in GIS format by NRCan (Journey et al., 2022a) to resolve data gaps on-reserve. Journey et al. (2022a) describes methods to compile these data, which are reported in polygon format and referred to as the “NRCan data” herein.

### H-2.2 Cadastral Data

BGC characterized buildings (improvements) at a parcel level of detail based on cadastral data, which define the location and extent of title and crown land parcels: and municipal assessment data, which describe the usage and value of parcels for taxation.

Titled and Crown land parcels in British Columbia were defined using Parcel Map BC (ICI Society, 2019) joined to 2018 BC Assessment (BCA) data to obtain data on building improvements and land use. BGC applied the following steps to join these data and address one-to-many and many-to-one relationships within the data:

1. BGC obtained the “Parcel code” (PID) from the Parcel Map BC table. If no Parcel code was available on this table, BGC joined it to the “SHARED\_GEOMETRY” table using the “Plan ID”, and from this obtained the PID.
2. PID was then used to join to the “JUROL\_PID\_X\_REFERENCE” table, to obtain the “Jurol code”.
3. Jurol code was then joined to BCA data.

BCA data were then used to identify the predominant actual use code (parcel use) and calculate the total assessed value of land and improvement. Where more than one property existed on a parcel (e.g., multifamily residences), improvement values were summed. Table H-2 lists potential uncertainties associated with building improvements.

**Table H-2. Uncertainties related to building improvements.**

Data Element	Uncertainty	Implication
Building Value	Improvement value was used as a proxy for the ‘importance’ of buildings within a geohazard area. While assessed value is the only value that is regularly updated province-wide using consistent methodology, it does not necessarily reflect market or replacement value and does not include contents.	Underestimation of the value of building improvements potentially exposed to hazard.

Data Element	Uncertainty	Implication
Cadastral vs. NRCan Data	Cadastral and NRCan data is calculated differently and displayed at different scales.	Data examined at a finer scale than the district may lead to inaccuracies.
Unpermitted development	Buildings can exist on parcels that are not included in the assessment data, such as unpermitted development.	Missed or under-estimated valuation of development.
Actual Use Code	BGC classified parcels based on the predominant Actual Use Code in the assessment data. Multiple use buildings or parcels may have usages – and corresponding building, content, or commercial value – not reflected in the code.	Possible missed identification of critical facilities if the facility is not the predominant use of the building.
Parcel boundary	Cadastral parcels partially intersecting geohazard areas were conservatively assumed to be subject to those geohazards.	Possible over-estimation of hazard exposure

### H-2.2.1 Buildings on First Nations Reserves

BGC estimated building values on First Nations reserves based on the proportion of a NRCan polygon intersecting a hazard area and First Nation reserve. For example, if the hazard area on a First Nation reserve intersected half the polygon of an NRCan dataset, then half the estimated building asset value was assigned. The estimate does not account for spatial variation of building asset value density within the census block. This data area was then treated as its own parcel and used in the same analysis as the rest of the building improvements of the SLRD.

BGC displays building footprint locations in Cambio™ using data from Microsoft Buildings Footprints layer (Microsoft Open Data, 2019). Inspection and quality control (QC) of this data was completed by comparison with aerial imagery by ESRI and Google Earth for all First Nation reserves in the SLRD. On this basis, the building footprint was calculated to be within plus or minus 5% accuracy to the aerial imagery. The differences observed were mostly from overcounting outbuildings (i.e., shed) or undercounting new constructions that occurred between the different datasets.

The Microsoft Buildings Footprints layer and aerial imagery data were then used to do a manual inspection and QC of the NRCan's data set for all First Nation reserves in the SLRD. This was done by comparing the number of visible footprints (from Microsoft and aerial imagery) to the number of buildings NRCan's data set reports for an area. In summary, NRCan's estimated number of buildings generally matched observations, but BGC did find several cases where structures were undercounted by up to 30%. This could be due to NRCan's data set being older and not accounting for new construction or excluding secondary homes. Therefore, some First Nation Reserves may have lower building improvement values than is present.

### H-2.3 Population

Population data was obtained from the 2016 Canada Census (2016) at a dissemination block<sup>2</sup> level of detail and has data for both on and off First Nation reserves. BGC estimated population exposure within hazard areas based on population counts for each census block. Where census blocks partially intersected a hazard area, population counts were estimated by proportion. For example, if half the census block intersected the hazard area, half the population count was assigned to the hazard area.

While Census data is a reasonable starting point for prioritizing hazard area, it contains uncertainties in both the original data and in population distribution within a census block. It also does not provide information about other populations potentially exposed to hazard, such as workers, and does not account for daily or seasonal variability. Because Census populations do not include the total possible number of people that could be in a geohazard area, they should be treated as a minimum estimate.

### H-2.4 Critical Facilities

Critical facilities were defined as facilities that:

- Provide vital services in saving and avoiding loss of human life
- Accommodate and support activities important to rescue and treatment operations
- Are required for the maintenance of public order
- House substantial populations
- Confine activities or products that, if disturbed or damaged, could be hazardous to the region
- Contain irreplaceable artifacts and historical documents.

BGC distinguished between “critical facilities” and “lifelines” (Section H-2.5), where the latter includes linear transportation networks and utility systems. While both may be important in an emergency, linear infrastructure can extend through multiple geohazard areas and were inventoried separately.

BGC compiled critical facilities data provided as point shapefiles by SLRD (email from Anna Koterniak, personal communication, August 19, 2019). Facility locations are shown on the web map, classified according to the categories shown in Table H-3.

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<sup>2</sup> A dissemination block (DB) is defined as a geographic area bounded on all sides by roads and/or boundaries of standard geographic area. The dissemination block is the smallest geographic area for which population and dwelling counts are determined. (Statistics Canada, 2016).



**Table H-3. Critical facility descriptions.**

Category	Example facilities in this category, based on Actual Use Value descriptions <sup>1</sup>
Emergency Response Services	Emergency Operations Center, Government Buildings (Offices, Fire Stations, Ambulance Stations, Police Stations).
Emergency Response Resources	Asphalt Plants, Concrete Mixing, Oil & Gas Pumping & Compressor Station, Oil & Gas Transportation Pipelines, Petroleum Bulk Plants, Works Yards, and other Manufacturing.
Utilities	Electrical Power Systems, Gas Distribution Systems, Water Distribution Systems, Hydrocarbon Storage.
Communication	Telecommunications.
Medical Facilities	Hospitals, Group Home, Seniors Independent & Assisted Living, Seniors Licenses Care.
Transportation	Airports, Heliports, Marine & Navigational Facilities, Marine Facilities (Marina), Service Station.
Environmental <sup>2</sup>	Dike Material, Garbage Dumps, Sanitary Fills, Sewer Lagoons, Liquid Gas Storage Plants, Pulp & Paper Mills.
Community	Financial Services, Grocers, Government Buildings, Hall (Community, Lodge, Club, Etc.), Recreational & Cultural Buildings, Schools & Universities, College or Technical Schools.

Notes:

1. From BC Assessment Data classification.
2. Includes facilities with potential environmental hazards.

## H-2.5 Lifelines

Lifelines considered in this assessment are shown on the web map and include roads; railways; and electrical, sanitary, drainage, petroleum, communication, and water infrastructure.

Table H-4 provides a more detailed breakdown of the utility classes shown in Table H-1 (ICI Society, 2019). BGC also obtained traffic frequency data from BC Ministry of Transportation and Infrastructure (MoTI), which were used to assign relative weights to different road networks as part of the prioritization scheme.

**Table H-4. Utility systems data obtained from ICI Society (2019).**

Id	Classified Type (BGC)	Description (ICI Society, 2019)	Position
1	Electrical Infrastructure	Electrical Duct Bank	Surface
2	Electrical Infrastructure	Electrical Junction	Surface
3	Electrical Infrastructure	Electrical Main	Surface
4	Electrical Infrastructure	Electrical Manhole	Surface
5	Electrical Infrastructure	Electrical Overhead Primary	Surface

<b>Id</b>	<b>Classified Type (BGC)</b>	<b>Description (ICI Society, 2019)</b>	<b>Position</b>
6	Electrical Infrastructure	Electrical Overhead Secondary	Surface
7	Electrical Infrastructure	Electrical Overhead Transmission Line	Surface
8	Electrical Infrastructure	Electrical Pole	Surface
9	Electrical Infrastructure	Electrical Pull Box	Surface
10	Electrical Infrastructure	Electrical Service Box	Surface
11	Electrical Infrastructure	Electrical Street Light	Surface
12	Electrical Infrastructure	Electrical Switching Kiosk	Surface
13	Electrical Infrastructure	Electrical Transmission Circuit	Surface
14	Electrical Infrastructure	Electrical Transmission Low Tension Substation	Surface
15	Electrical Infrastructure	Electrical Transmission Structure	Surface
16	Electrical Infrastructure	Electrical Underground Primary	Subsurface
17	Electrical Infrastructure	Electrical Underground Secondary	Subsurface
18	Electrical Infrastructure	Electrical Underground Structure	Subsurface
19	Electrical Infrastructure	Electrical Underground Transformer	Subsurface
20	Electrical Infrastructure	Electrical Vault	Subsurface
39	Sanitary Infrastructure	Municipal Combined Sewer and Stormwater	Subsurface
40	Sanitary Infrastructure	Municipal Sanitary Sewer Main	Subsurface
41	Drainage Infrastructure	Municipal Stormwater Main	Subsurface
21	Petroleum Infrastructure	Petroleum Distribution Pipe	Subsurface
22	Petroleum Infrastructure	Petroleum Distribution Station	Subsurface
23	Petroleum Infrastructure	Petroleum Distribution Valve	Subsurface
24	Petroleum Infrastructure	Petroleum Facility Site	Surface
25	Petroleum Infrastructure	Petroleum Kilometer Post	Surface
26	Petroleum Infrastructure	Petroleum Methane Main	Subsurface
27	Petroleum Infrastructure	Petroleum Pipeline	Subsurface
28	Petroleum Infrastructure	Petroleum Transmission Pipe	Subsurface
29	Petroleum Infrastructure	Petroleum Transmission Pipeline Facility	Subsurface
30	Petroleum Infrastructure	Petroleum Transmission Valve	Subsurface
31	Communication Infrastructure	Telcom Cable Line	Surface
32	Communication Infrastructure	Telcom Facility	Surface
34	Communication Infrastructure	Telcom Main	Surface

<b>Id</b>	<b>Classified Type (BGC)</b>	<b>Description (ICI Society, 2019)</b>	<b>Position</b>
33	Communication Infrastructure	Telcom Manhole	Surface
35	Communication Infrastructure	Telcom Pole	Surface
36	Communication Infrastructure	Telcom Structure	Surface
37	Communication Infrastructure	Telcom Underground Line	Subsurface
38	Water Infrastructure	Water Distribution	Subsurface

## H-2.6 Businesses

Business point locations were obtained in GIS format (point shapefile) and used to identify the location and annual revenue of businesses within hazard areas (InfoCanada Business File, 2018). Total annual revenue and number of businesses were used as proxies to compare the relative level of business activity in hazard areas.

Table H-5 summarizes uncertainties associated with the data. In addition to the uncertainties listed in Table H-5, business activity estimates do not include individuals working at home for businesses located elsewhere, or businesses that are located elsewhere but that depend on lifelines within the study area. Business activity in hazard areas is likely underestimated due to the uncertainties in these data.

**Table H-5. Business data uncertainties.**

<b>Type</b>	<b>Description</b>	<b>Implication</b>
Revenue data	Revenue information was not available for all businesses.	Under-estimation of business activity
Data quality	BGC has not reviewed the accuracy of business data obtained for this assessment.	Possible data gaps
Source of revenue	Whether a business' source of revenue is geographically tied to its physical location (e.g., a retail store with inventory, versus an office space with revenue generated elsewhere) is not known.	Over- or under-estimation of business activity.

## H-2.7 Environmental Values

Environmental values include active agricultural area, fisheries, and species and ecosystems at risk.

### H-2.7.1 Agriculture

BGC identified parcels used for agricultural purposes where the BCA attribute "Property\_Type" corresponded to "Farm". Given the regional scale of study, no distinction was made between agricultural use types.

### H-2.7.2 Fisheries

In the case of fish, the BC Ministry of Environment (MOE) maintains a spatial database of historical fish distribution in streams based on the Fisheries Information Summary System (FISS) (MOE, 2018a). The data includes point locations and zones (river segments) where fish species have been observed, the extent of their upstream migration, and where activities such as spawning, rearing and holding are known to occur. As a preliminary step and because fisheries values are of regulatory concern for structural flood mitigation works, FISS data was used to identify fan and flood hazard areas that intersect known fish habitat. Hazard areas were conservatively identified as intersecting fish habitat irrespective of the proportion intersected (e.g., entire hazard areas were flagged as potentially fish bearing where one or more fish habitat points or river segments were identified within the hazard zone), so these results should be interpreted as potential only.

### H-2.7.3 Species and Ecosystems at Risk

For endangered species and ecosystems, the BC Conservation Data Centre (BC CDC) maintains a spatial data set of locations of endangered species and ecosystems, including a version available for public viewing and download (MOE, 2018b).

### H-2.7.4 Assumptions and Limitations

BGC emphasizes that the information used to identify areas containing environmental values is highly incomplete, and estimation of vulnerability is highly complex. More detailed identification of habitat values in areas subject to flood geohazards starts with an Environmental Scoping Study (ESS), typically based on a review of existing information, preliminary field investigations, and consultation with local stakeholders and environmental agencies.

BGC also notes that environmental values are distinct from the other elements at risk considered in this section in that flood mitigation, not necessarily flooding itself, has the potential to result in the greatest level of negative impact. For example, flood management activities, particularly structural protection measures (e.g., dikes), have the potential to cause profound changes to the ecology of floodplain areas. The construction of dikes and dams eliminates flooding as an agent of disturbance and driver of ecosystem health, potentially leading to substantial changes to species composition and overall floodplain ecosystem function.

Within rivers, fish access to diverse habitats necessary to sustain various life stages has the potential to be reduced due to floodplain reclamation for agricultural use and wildlife management, restricting fisheries values to the mainstem of the river. Riparian shoreline vegetation also provides important wildlife habitat, and itself may include plants of cultural significance to First Nations peoples. On the floodplains, reduction in wetland habitat may impact waterfowl, other waterbirds, migratory waterbirds, and associated wetland species such as amphibians.

The ecological impacts of dike repair and maintenance activities can also be severe. Dike repairs often result in the removal of riparian vegetation compromising critical fisheries and

wildlife habitat values. The removal of undercut banks and overstream (bank) vegetation results in a lack of cover for fish and interrupts long term large woody debris (LWD) recruitment processes and riparian function. Alternative flood mitigation approaches could include setback dikes from the river, providing a narrow floodplain riparian area on the river side of the dike, and vegetating the dikes with non-woody plants so that inspections may be performed and the dike integrity is not compromised. Such approaches may prevent conflicting interests between the *Fisheries Act* and *Dike Maintenance Act*.

Lastly, BGC notes that increased impact to fish habitat may result where land use changes (e.g., logging, forest fires) have increased debris flow activity and the delivery of fine sediments to fish bearing streams.

## H-2.8 Social Vulnerability

BGC included a 2022 Social Vulnerability Index to the hazard exposure data model, based on a “Social Fabric” dataset compiled nationally by NRCan at a Census Block level of detail (Journey et al., 2022b). The purpose of the Social Fabric dataset is to indicate a community’s level of ability to withstand impacts of a disaster based on their demographics and other social characteristics compiled by Statistics Canada. Adding these data results in a higher weighting for populations with higher social vulnerability scores, increasing their estimated risk priority rating. For this analysis, the values of the social vulnerability were broken into relatively equal sized bins and given weightings based on judgement and iterative process of reviewing the results and adjusting to match known conditions more accurately. For consistency, these scores were added to the district-wide database (not solely First Nations reserves).

## H-3 HAZARD EXPOSURE RATINGS

BGC used the following steps to assign an exposure rating to each geohazard area:

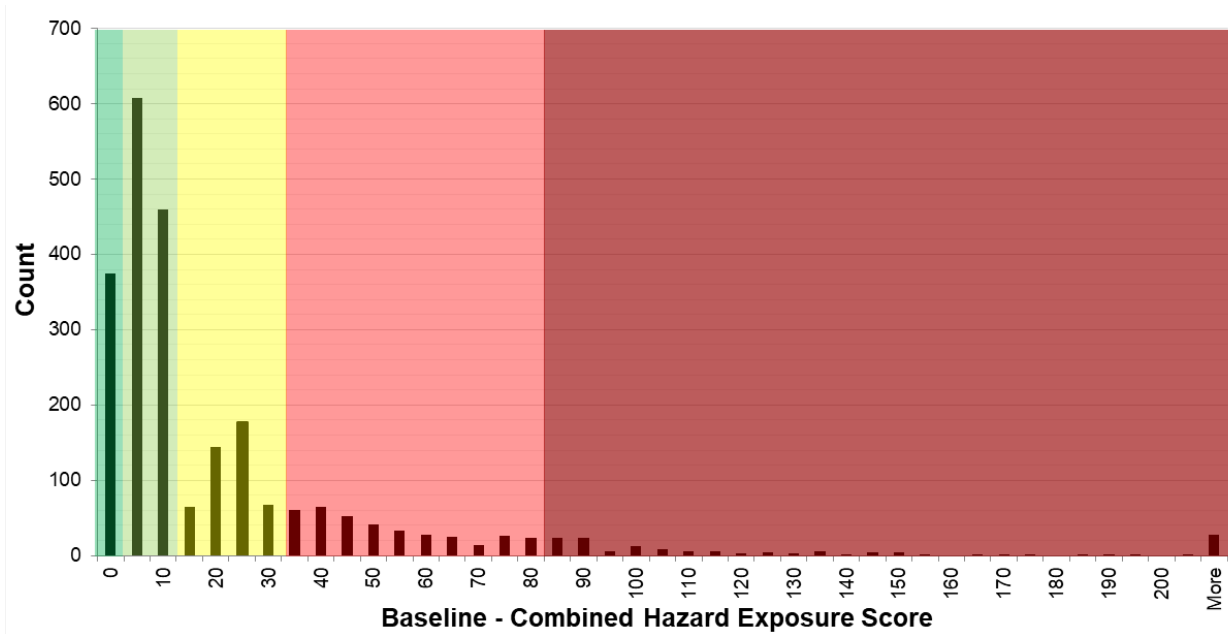
1. Identify the presence of elements at risk for each group.
2. Calculate their value and weight according to the categories listed in Table H-1.
3. Sum the weightings to achieve a total score for each geohazard area.
4. Assign relative exposure ratings to geohazard areas based on their percentile rank compared to other areas (Figure H-1 through Figure H-6 and Table H-6 and Table H-7).

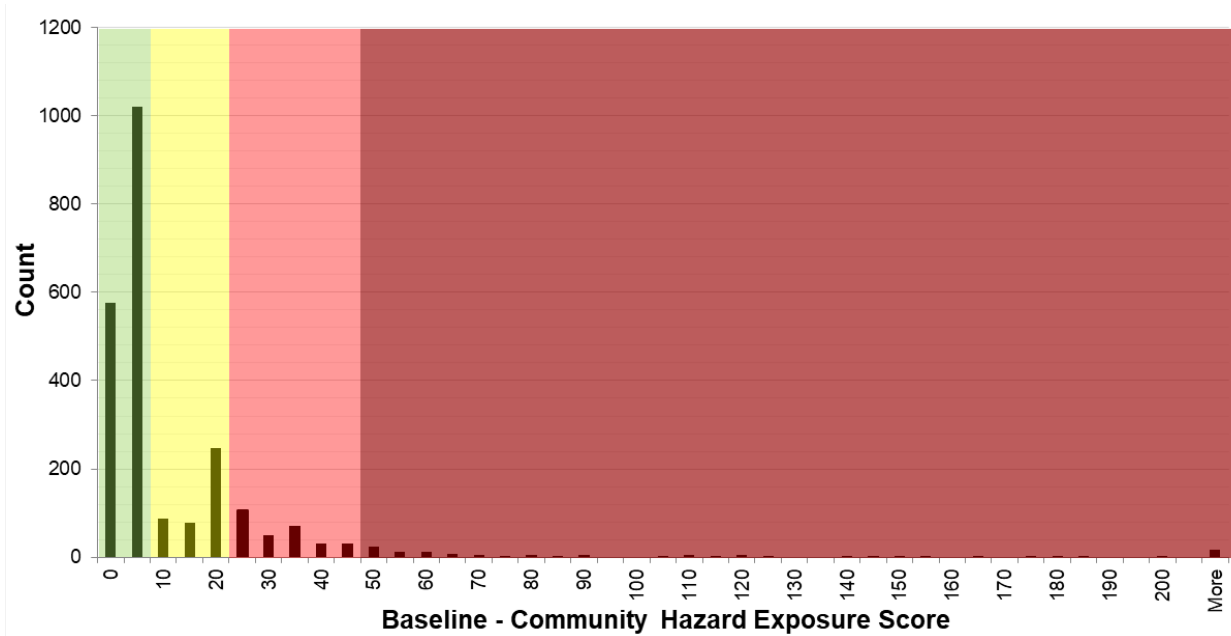
Three unique ratings for Community, Lifelines and Combined groups, respectively, were assigned for each geohazard area. Unique ratings were different for the baseline and wildfire-adjusted conditions, and consequently a total of six exposure scores were calculated.

As explained previously, for building improvements sourced from the NRCan Physical Exposure data, BGC assigned values to hazard areas on a proportional basis. For example, if only half of a physical exposure polygon intersected an alluvial fan, half of the Building Asset Value would be assigned. If both BC Assessment data (off-reserve) and Building Asset Value data (on-reserve) intersected a hazard area, their combined value was assigned. For the NRCan Social Vulnerability Scores, the higher value was chosen if more than one score intersected a hazard area.



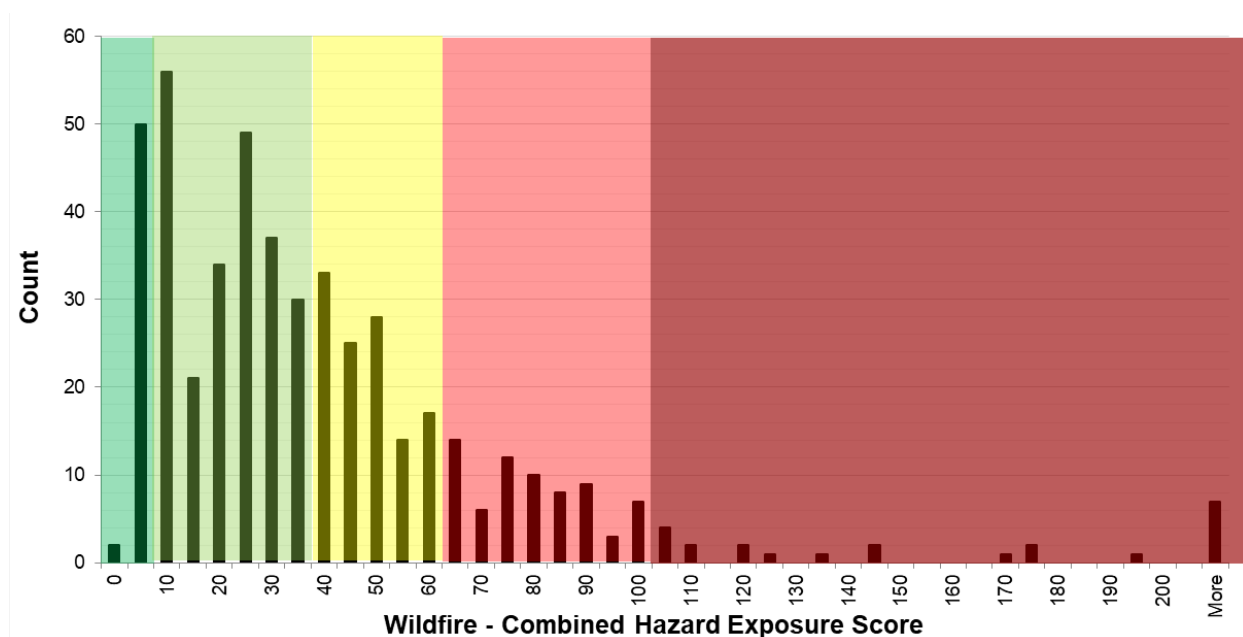
For consistency and application at provincial scale, BGC has applied the same ratings criteria (percentile thresholds) across multiple regional geohazard risk assessments for Regional Districts in BC<sup>3</sup>. However, BGC notes that the distribution of exposure scores is specific to the study area (SLRD), to compare the level of development between different hazard areas within this study area.



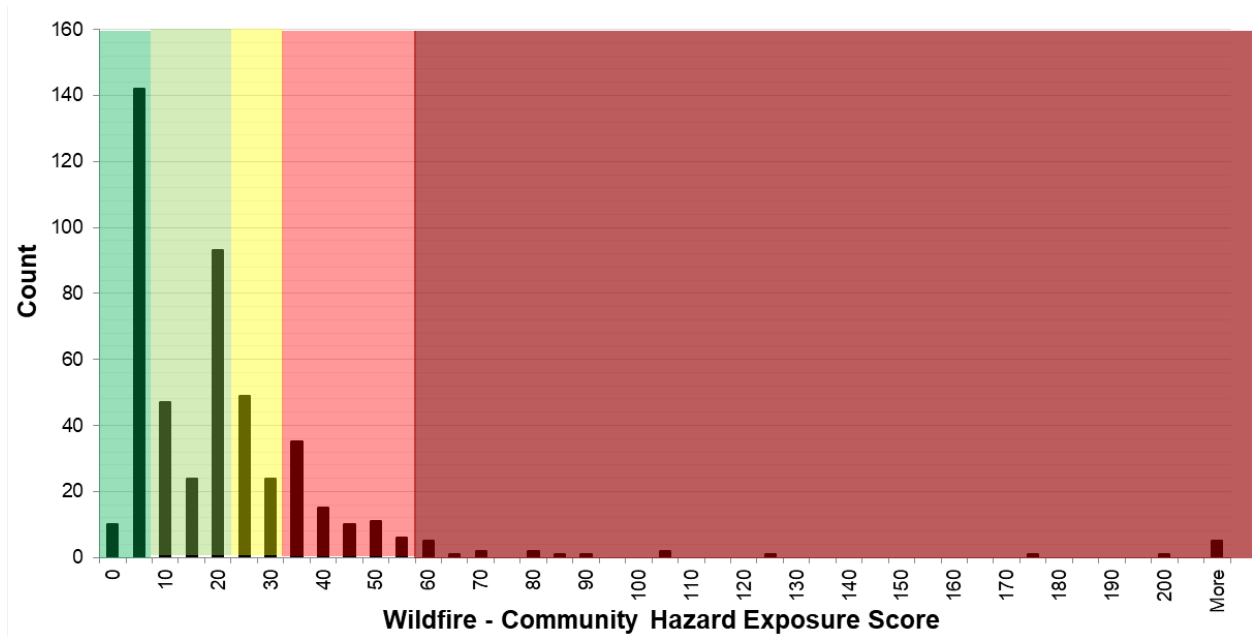


**Table H-6. Baseline Conditions - Hazard Exposure Rating and Thresholds.**

Baseline - Exposure Rating	Criteria	Total Score		
		Combined	Community	Lifeline
Very High	Greater than 95 <sup>th</sup> percentile	> 85	> 60	> 75
High	Between 80 <sup>th</sup> and 95 <sup>th</sup> percentile	36 to 85	25 to 59	40 to 74
Moderate	Between 60 <sup>th</sup> and 80 <sup>th</sup> percentile	16 to 35	11 to 24	20 to 39
Low	Between 20 <sup>th</sup> and 60 <sup>th</sup> percentile	5 to 15	5 to 10	1 to 19
Very Low	Smaller 20 <sup>th</sup> percentile	0 to 4	0 to 4	0



**Figure H-4. Distribution of combined exposure scores in the SLRD for the wildfire-adjusted conditions.**



**Table H-7. Wildfire Conditions – Hazard Exposure Rating and Threshold.**

Wildfire - Exposure Rating	Criteria	Total Score		
		Combined	Community	Lifeline
Very High	Greater than 95 <sup>th</sup> percentile	> 99	> 54	> 70
High	Between 80 <sup>th</sup> and 95 <sup>th</sup> percentile	60 to 99	31 to 54	40 to 69
Moderate	Between 60 <sup>th</sup> and 80 <sup>th</sup> percentile	40 to 59	20 to 30	25 to 39
Low	Between 20 <sup>th</sup> and 60 <sup>th</sup> percentile	7 to 39	5 to 19	1 to 24
Very Low	Smaller 20 <sup>th</sup> percentile	0 to 6	0 to 4	0



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# APPENDIX I

## CAMBIO COMMUNITIES



## I-1 INTRODUCTION

### I-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. Of the “four pillars” of emergency management – mitigation, preparedness, response, and recovery – the current version of *Cambio* primarily supports mitigation and provides input to preparedness.

Emergency Management BC defines “mitigation” as, “the phase of emergency management in which proactive steps are taken to prevent a hazardous event from occurring by eliminating the hazard, or to reduce the severity or potential impact of such an event before it occurs. Mitigation protects lives, property, cultural sites, and the environment, and reduces vulnerabilities to emergencies and economic and social disruption.” BGC notes that the full cycle of pro-active geohazard risk management, from hazard identification to risk analysis and the design and implementation of risk control measures, would fall under the EMBC definition of “mitigation”.

The results of this study are also provided separately from *Cambio*, in the form of this report and digital information (GIS data download). *Cambio* provides a platform to access the same results in a structure that supports decision making.

*Cambio* 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 geohazard areas are ranked highest priority, from a geohazard risk perspective?

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

#### Hazard information:

- Type, spatial extent, and characteristics of geohazard areas, presented on a web map.
- Supporting information such as hydrologic information, geohazard mapping and imagery.

#### Exposure information:

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

#### Tools:

- Identification of assets in selected geohazard areas (elements at risk).
- Prioritization of geohazard areas based on ratings for geohazards and consequences.

- Access to data downloads and reports for geohazard areas<sup>1</sup>.

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

### I-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.

Two levels of access are provided:

- Local/Regional Government users: Access to a single study area of interest (e.g., administrative or watershed area of interest for the user).
- Provincial/Federal Government users: Access to multiple study areas<sup>2</sup>.

The remainder of this guide is best read after the user has logged into *Cambio*. Users should also read the main document to understand methods, limitations, uncertainties and gaps in the information presented.

This guide describes information displayed across multiple administrative areas within British Columbia. Footnotes indicate cases where information is specific to certain regions.

## I-2 NAVIGATION

Figure I-1 provides a screen shot of *Cambio* following user login and acceptance of terms and conditions. Note that study area boundaries (outlines) only show up when a study area is selected. Section I-3 describes map controls and tools, including how to turn layers on and off for viewing. Section I-4 describes interactive features used to access and download information about geohazard areas.

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<sup>1</sup> 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.

<sup>2</sup> User access may be limited by client permissions. BGC does not expect this to be a barrier for provincially/federally funded studies currently being completed under the NDMP Program.



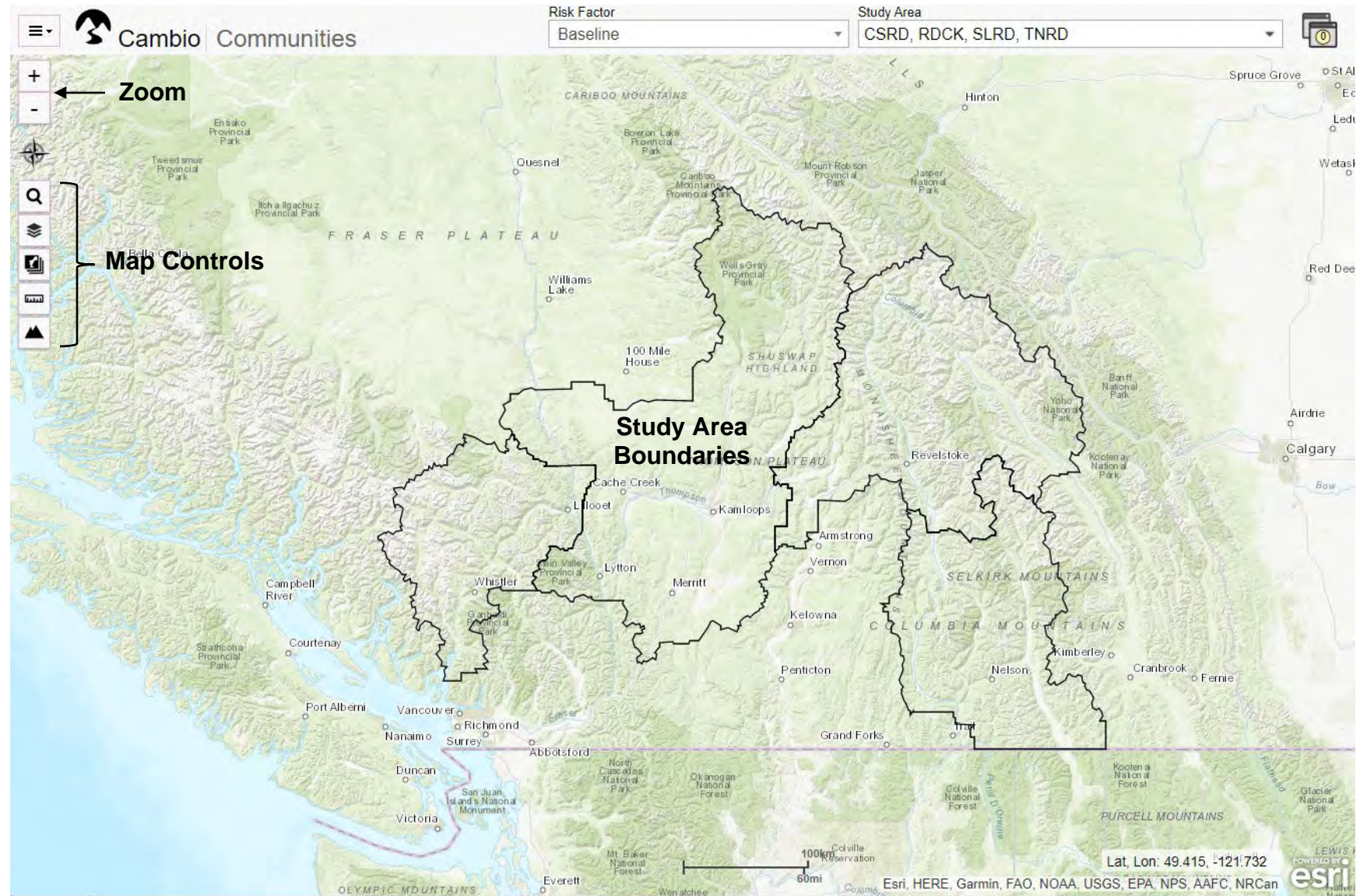


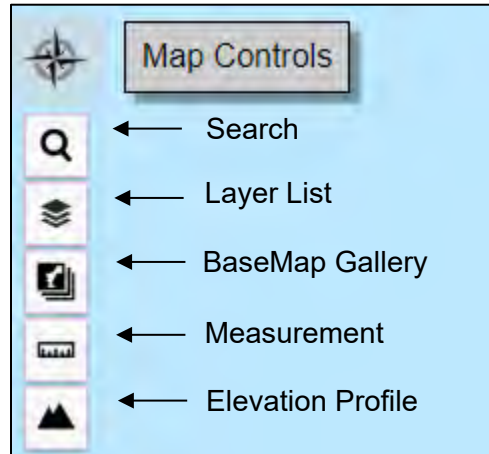
Figure I-1. Online map overview.



### I-3 MAP CONTROLS

Figure I-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 I-2). Sections I-3.1 to I-3.5 describe 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 I-2. Map controls and tools.**

#### I-3.1 Search

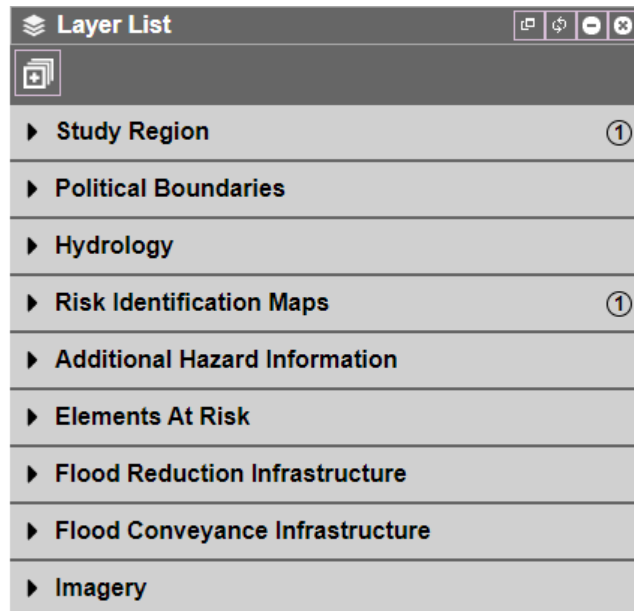
Search is currently available for geohazard area names and street addresses. To search for hazards:

- Select the hazard type from the drop-down menu.
- Scroll through the dropdown list to select the feature of interest or begin typing the feature's name.

#### I-3.2 Layer List

This control (Figure I-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.



**Figure I-3. Layers list.**

### I-3.3 Basemap Gallery

The basemap gallery allows the user to switch between 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.

### I-3.4 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.

### I-3.5 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.

## I-4 GEOHAZARD FEATURES

This section summarizes how users can display and access information about geohazard features displayed on the map.

### I-4.1 Geohazard Feature Display

Geohazard areas can be added to the map by selecting a given geohazard type under “Risk Identification Maps” in the layer list. Once selected, the geohazard area outlines can be colored by hazard type, risk (priority) rating, hazard rating, or consequence rating, to view large areas at a glance.

The following geohazard features can be clicked to reveal detailed information:

- Steep creek fans (polygons)
- Clear-water flood areas (polygons)
- Volcanic hazard areas (polygons).

For steep-creek hazards, two risk assessment scenarios were completed and can be chosen using the “risk assessment scenario” drop down menu (Figure I-4). The “baseline risk” ratings reflect the observed conditions of watersheds and fans at the time of the assessment. The “wildfire-adjusted risk” ratings reflect potential conditions associated with increasing likelihood of wildfire due to climate change.

Clicking on an individual geohazard feature reveals a popup window indicating the study area, hazard code (unique identifier), hazard name, risk assessment scenario and geohazard process. At the bottom of the popup window are several options (Figure I-4). Clicking the Google Maps icon opens Google Maps in a new browser window at the hazard site. This feature can be used to access Google Street View to quickly view ground level imagery where available. Clicking the “i” opens a sidebar with detailed information about the individual feature, as described in Section I-4.2.

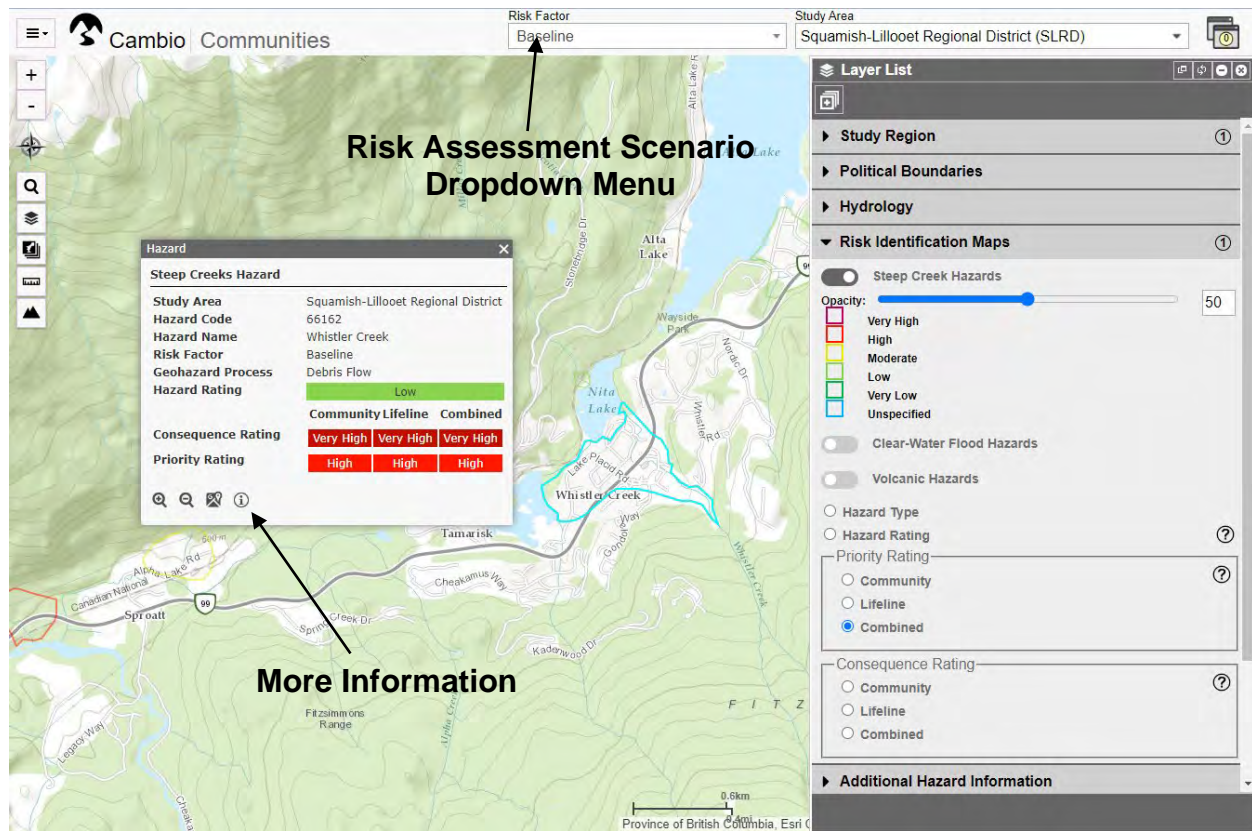
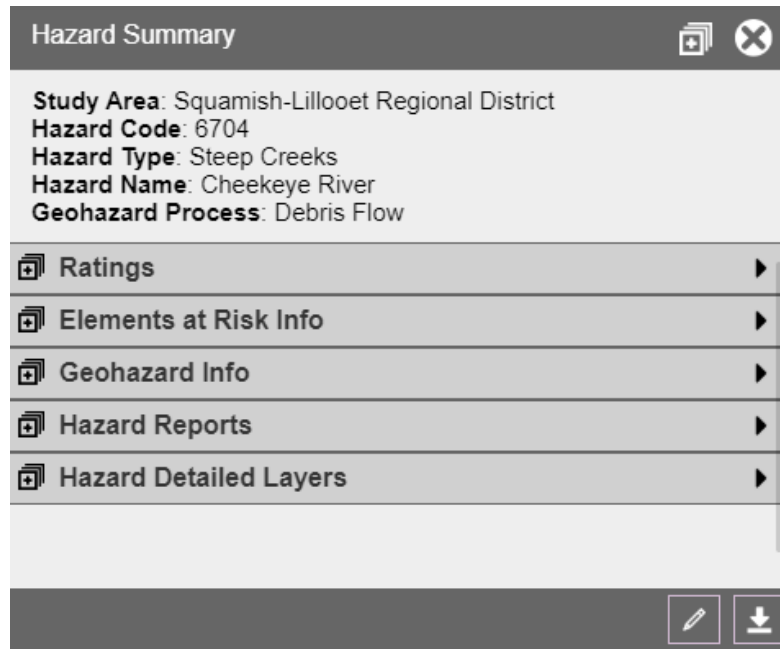


Figure I-4. Geohazard feature popup and risk assessment scenario dropdown menu.

#### I-4.2 Geohazard Information Sidebars

Clicking a geohazard feature and then the “i” within the popup opens additional information in a sidebar on the right side of the screen (Figure I-5). Dropdown menus allow the user to view as much detail as required.



**Figure I-5. Additional information sidebar.**

Table I-1 summarizes the information displayed within the sidebar. In summary, clicking Ratings reveals the site Risk, Consequence, and Hazard Ratings. See Chapter 5.0 of the main document for further description of these ratings. The geohazard, elements at risk, and hazard reports dropdowns display supporting information. Hover the mouse over the ⓘ to the right of a row for further definition of 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 I-1. Geohazard information sidebar contents summary.**

Dropdown Menu	Contents Summary
Ratings	Provides geohazard, consequence and priority ratings for an area, displayed graphically as matrices. The geohazard and consequence ratings combine to provide the priority rating. For more information on ratings methodology, see the main report.
Geohazards Info	Watershed statistics, hydrology and geohazard characterization, event history, and comments. These inputs form the basis for the geohazard rating and intensity (destructive potential) component of the consequence rating for a given area.
Elements at Risk Info	Summary of elements at risk types and/or values within the geohazard area. These inputs form the basis for the consequence rating for a given area.
Reports	Links to download previous reports associated with the area (if any) in pdf format. This feature is currently only available for some administrative areas (Regional Districts of Central Kootenay and Squamish-Lillooet).

## I-5 ASSET INFORMATION

Elements at risk, flood reduction, and flood conveyance infrastructure can be displayed to the map by selecting a given asset type in the layer list. Infrastructure labels will show up for select features at a higher zoom level. BGC notes that the data displayed on the map is not exhaustive, and much data is currently missing for some asset types (i.e., building footprints and stormwater drainage infrastructure).

## I-6 ADDITIONAL GEOHAZARD INFORMATION

### I-6.1 Additional Geohazard Layers

Additional geohazard-related layers can be displayed under “Additional Geohazard Information” in the layer list. These should be reviewed with reference to the main report document for context and limitations.

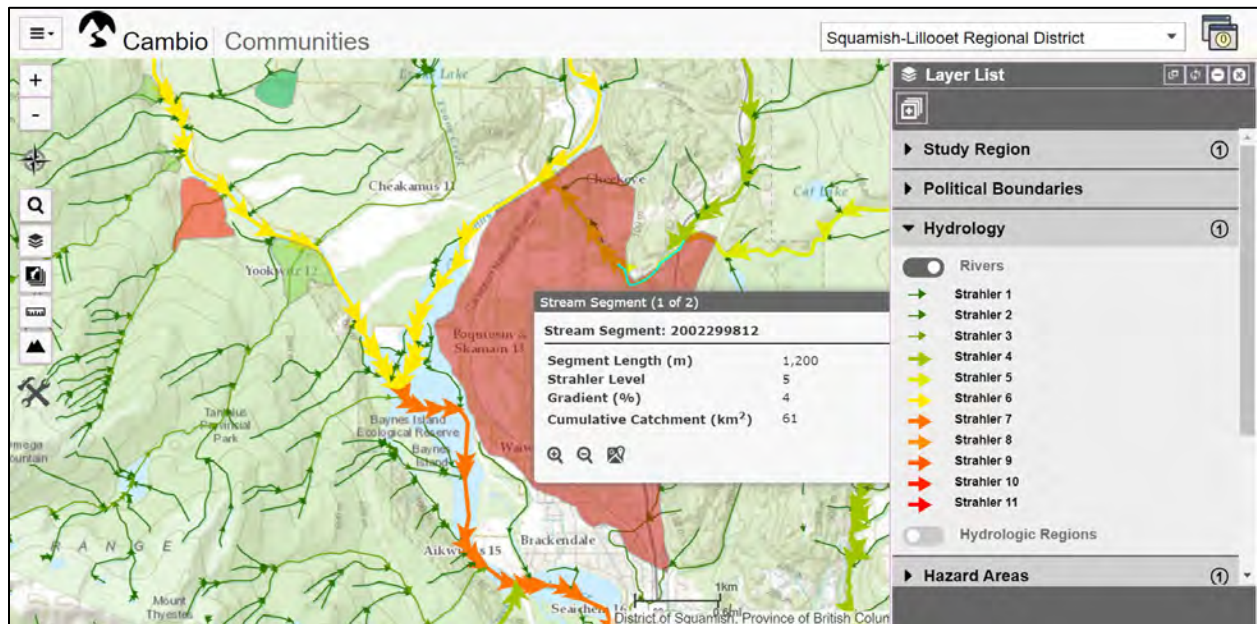
### I-6.2 Imagery

The imagery dropdown provides access to high resolution imagery where available (i.e., Lidar hillshade topography).

### I-6.3 River Network

In addition to geohazard areas, the river network can be displayed on the map by clicking on the Hydrology Layer and selecting “Rivers.” The river network 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 I-6). 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.

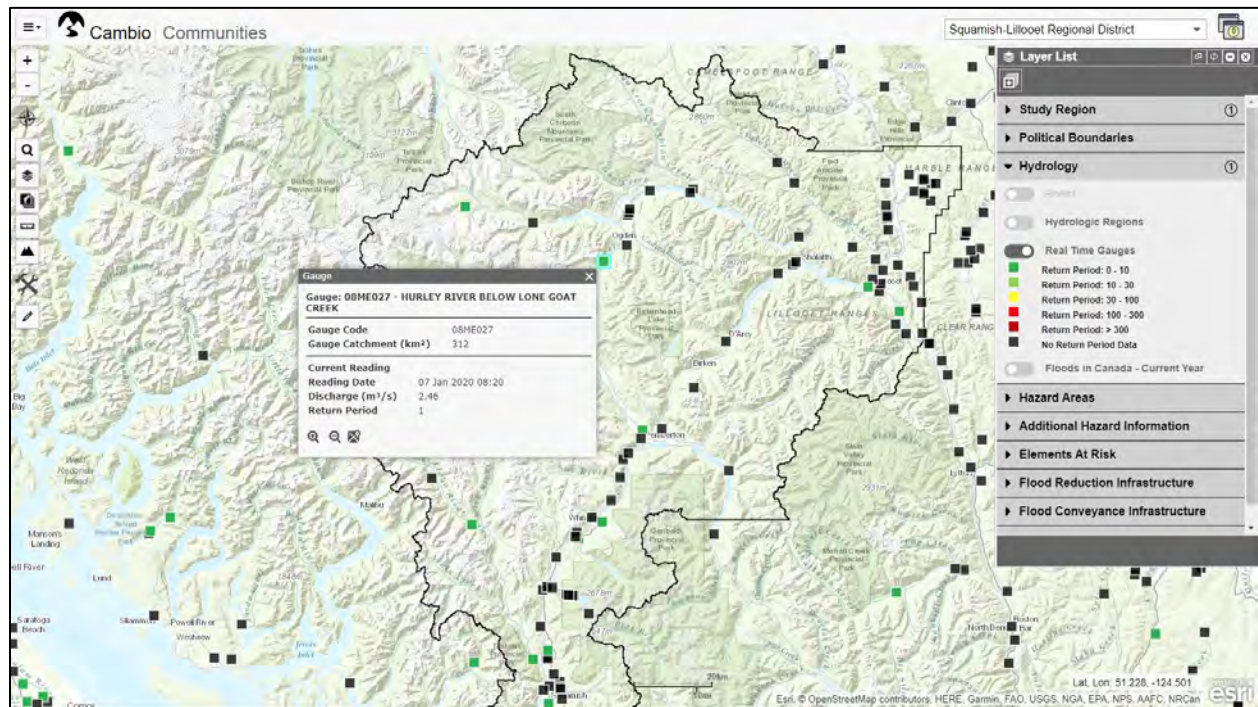


**Figure I-6. Interactive Stream Network.** The popup shows information for the stream segment highlighted in green.

#### I-6.4 Real-time Flow Gauges

*Cambio* also provides access to real-time<sup>3</sup> stream flow and lake level monitoring stations where existing. These can be accessed by clicking on the “Hydrology” tab in the layer list. The data is 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 I-7). The real time gauges are also colored on the map by their respective flow return period for the current reading date.

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



**Figure I-7. Near real-time flow gauge. The popup shows gauge information including measured discharge and return period for a given reading date and time.**

## I-7 FUTURE DEVELOPMENT

The current version is the first release of *Cambio*. BGC may develop future versions of the application, 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
- Ability to upload information via desktop and mobile applications
- Real-time<sup>4</sup> 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).

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

<sup>4</sup> i.e., information-refresh each time flow monitoring data is updated and provided by third parties.

# APPENDIX J

## RISK ASSESSMENT INFORMATION TEMPLATE



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Risk Event Details			
Start and End Date	Provide the start and end dates of the selected event, based on historical data.	Start Date:	End Date:
Severity of the Risk Event	Provide details about the risk, including: <ul style="list-style-type: none"><li>• Speed of onset and duration of event;</li><li>• Level and type of damaged caused;</li><li>• Insurable and non-insurable losses; and</li><li>• Other details, as appropriate.</li></ul>	This RAIT focuses on Catiline Creek, a steep, 4 km^2 watershed on the north side of Lillooet Lake near Pemberton, BC. This RAIT is an example of the range of proposed studies included with this funding application. Catiline Creek fan contains 155 residential lots, of which about 114 have been developed and are currently occupied. The in-SHUCK-ch Forest Service Road (FSR) crosses the lower fan, providing access to Pemberton as well as to development and resource operations to the south. At least 11 debris flows have reached the fan in the past 66 years, including five debris flows post-dating development in 1986, 1987, 2004, 2010 and 2013. A debris flow in 2010 traveled through part of the subdivision, damaging a small shed, narrowly missing several houses and a boat launch, burying a truck, and blocking several subdivision roads. A debris flow in 2013 (Figure 4) swept over the driveway of an A-frame house, pushed the same truck that was buried in 2010 into the lake, and destroyed several boats stored on land.	
Response During the Risk Event	Provide details on how the defined geographic area continued its essential operations while responding to the event.	Emergency response in the most recent events (2010 and 2013) included temporary (several day) evacuation of residents and closure of the FSR. The community is isolated and these events resulted in the loss of community function across much of the developed areas until access could be re-established. Prior to the current District-wide assessment (this study), BGC completed a quantitative debris flow safety risk assessment for persons within residential dwellings on Catiline Creek fan and evaluated three different risk control options. This detailed study is the primary reference source for this RAIT. The level of safety risk under current conditions was found to be intolerable according to international risk tolerance standards.	
Recovery Method for the Risk Event	Provide details on how the defined geographic area recovered.	Recovery measures have included excavation of the main channel to increase capacity, debris removal to restore channel conveyance at FSR bridge crossing, and the construction of structural mitigation (channel diversion).	



Recovery Costs Related to the Risk Event	Provide details on the costs, in dollars, associated with implementing recovery strategies following the event.	The total cost of recovery from the 2010 and 2013 events, including response, subsequent recovery (channel works), and life safety risk assessment, is not known, but is estimated to exceed \$1M.
Recovery Time Related to the Risk Event	Provide details on the recovery time needed to return to normal operations following the event.	Given the high frequency of recorded debris flows (average once per 6 years), recovery time occupies a relatively high proportion of time in relation to events. Recovery to restore basic community function was on the order of several weeks, or >1 year to initiate and complete channel cleanup and repair. At this site, "return to normal operations" has included recovery to a level of residual risk that remains intolerable by international standards for 76 of the 114 occupied, residential-classed lots within the study area.

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Risk Event Identification and Overview	
<div>Provide a qualitative description of the defined geographic area, including:</div> <ul style="list-style-type: none"><li>• Watershed/community/region name(s);</li><li>• Province/Territory;</li><li>• Area type (i.e., city, township, watershed, organization, etc.);</li><li>• Population size;</li><li>• Population variances (e.g., significant change in population between summer and winter months);</li><li>• Main economic areas of interest;</li><li>• Special consideration areas (e.g., historical, cultural and natural resource areas); and an</li><li>• Estimate of the annual operating budget of the area.</li></ul>	<p>Catiline Creek is located within a 4 km<sup>2</sup> watershed on the north side of Lillooet Lake in the Squamish-Lillooet Regional District (SLRD), British Columbia. The fan was subdivided in the early 1970s and contains 155 residential lots, of which about 114 have been developed and are currently occupied. Occupancy ranges from seasonal cabins to full-time residents, with a higher population in summer than winter and an average number of 2 residents per lot. The in-SHUCK-ch Forest Service Road (FSR) crosses the lower fan and provides access from Pemberton to the community as well as to development and resource operations to the south.</p>
Methodolgies, processes and analyses	

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<p>Provide the year in which the following processes/analyses were last completed and state the methodology(ies) used:</p> <ul style="list-style-type: none"><li>• Hazard identification;</li><li>• Vulnerability analysis;</li><li>• Likelihood assessment;</li><li>• Impact assessment;</li><li>• Risk assessment;</li><li>• Resiliency assessment; and/or</li><li>• Climate change impact and/or adaptation assessment.</li></ul> <p>Note: It is recognized that many of the processes/analyses mentioned above may be included within one methodology.</p>	<p>In 2015, BGC completed a quantitative debris flow safety risk assessment for persons within residential dwellings on Catiline Creek fan and evaluated three different risk control options. BGC estimated the probability that debris flows will impact residential dwellings and cause loss of life, and compared the estimates to individual and group risk tolerance criteria. The best-estimate of individual risk exceeded 1:10,000 risk of fatality per year for 76 of the 114 occupied, residential-classed lots within the study area, and estimated group risk fell entirely into the “Unacceptable” range of the F-N graph.</p> <p>In 2016, BGC and Kerr Wood Leidal Associates (KWL) evaluated three possible risk reduction options, including measures to improve channel capacity and reduce avulsion potential, construction of a diversion and new channel extending away from the development, and construction of a debris barrier at the fan apex. BGC also completed landslide modeling and residual risk analysis to evaluate the level of risk reduction achieved by the proposed risk control measures. On average, the proposed mitigation measures were estimated to reduce individual risk by about a factor of ten compared to existing conditions and by up to a factor of 20 for those lots currently at highest risk. No structural risk reduction measures have yet been constructed.</p> <p>In 2020, relevant results of detailed analysis were carried into a regional (District-wide) assessment of steep creek risk, further updated in 2023 to consider wildfires as an additional regional risk factor.</p>
Hazard Mapping	
<p>To complete this section:</p> <ul style="list-style-type: none"><li>• Obtain a map of the area that clearly indicates general land uses, neighbourhoods, landmarks, etc. For clarity throughout this exercise, it may be beneficial to omit any non-essential information from the map intended for use. Controlled photographs (e.g. aerial photography) can be used in place of or in addition to existing maps to avoid the cost of producing new maps.</li><li>• Place a grid over the maps/photographs of the area and assign row and column identifiers. This will help identify the specific area(s) that may be impacted, as well as additional information on the characteristics within and affecting the area.</li><li>• Identify where and how flood hazards may affect the defined geographic area.</li><li>• Identify the mapped areas that are most likely to be impacted by the identified flood hazard.</li></ul> <p>Map(s)/photograph(s) can also be used, where appropriate, to visually represent the information/prioritization being provided as part of this template.</p>	
Hazard identification and prioritization	
<p>List known or likely flood hazards to the defined geographic area in order of proposed priority. For example: (1) dyke breach overland flooding; (2) urban storm surge flooding ; and so on.</p>	<p>Debris flow, rock avalanche.</p>

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Provide a rationale for each prioritization and the key information sources supporting this rationale.	Catiline Creek is rated "Very High" priority in relation to other steep creek fans in the SLRD, according to the results of the current study. As previously noted, the best-estimate of individual risk exceeded 1:10,000 risk of fatality per year for 77 lots and estimated group risk fell entirely into the "Unacceptable" range of the F-N graph. Debris flows of all magnitudes considered would also block FSR access to communities south of Catiline Creek.
Risk Event Title	
Identify the name/title of the risk. An example of a risk event name or title is: "A one-in-one hundred year flood following an extreme rain event."	A one-in-ten year debris flow triggered by landslides and precipitation resulting in uncontrolled flows that avulse out of the main channel and impact buildings, resulting in damages and/or loss of life. A one-in-ten year debris flow that blocks the FSR, resulting in severed access to development, recreational facilities, and resource operations.
Type of Flood Hazard	
Identify the type of flood hazard being described (e.g., riverine flooding, coastal inundation, urban run-off, etc.)	Steep creek geohazard (debris flow) Rock avalanche.
Secondary hazards	
Describe any secondary effects resulting from the risk event (e.g., flooding that occurs following a hurricane).	Flood impact to residential development extending beyond the debris deposition zone of events.
Primary and secondary organizations for response	
Identify the primary organization(s) with a mandate related to a key element of a natural disaster emergency, and any supporting organization(s) that provide general or specialized assistance in response to a natural disaster emergency.	SLRD, EMBC.
Risk Event Description	

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Description of risk event, including risk statement and cause(s) of the event	
<div>Provide a baseline description of the risk event, including:<ul style="list-style-type: none"><li>• Risk statement;</li><li>• Context of the risk event;</li><li>• Nature and scale of the risk event;</li><li>• Lead-up to the risk event, including underlying cause and trigger/stimulus of the risk event; and</li><li>• Any factors that could affect future events.</li></ul>Note: The description entered here must be plausible in that factual information would support such a risk event.</div>	<div>Lillooet Lake Estates is subject to risk from Catiline Creek, which can produce debris flows during precipitation events at a 6-year average return period. Catiline Creek flows through the middle of the development, which is located on the fan. Debris flows may occur in the Spring, Summer or Fall, and may be triggered by high precipitation events occurring anytime during this period. Debris flows could also cut off evacuation routes and sever transportation along the in-SHUCK-ch Forest Service Road (FSR), which crosses the lower fan and provides access from Pemberton to the community as well as to development and resource operations to the south. Factors that could affect future damaging events including changing hazard associated with climate change, wildfire-related effects on watershed hydrology, and the ability of the village to reduce vulnerability through increased resiliency and improved debris flow mitigation and slope monitoring, supported by better access to geohazard and risk information.</div>



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Location	
<p>Provide details regarding the area impacted by the risk event such as:</p> <ul style="list-style-type: none"><li>Province(s)/territory(ies);</li><li>Region(s) or watershed(s);</li><li>Municipality(ies);</li><li>Community(ies); and so on.</li></ul>	<p>Province: BC Region: Squamish-Lillooet Regional District, Electoral Area C Watershed: Catiline Creek Community: Lillooet Lake Estates</p>
Natural environment considerations	
<p>Document relevant physical or environmental characteristics of the defined geographic area.</p>	<p>Catiline Creek is located within a 4 km<sup>2</sup> watershed. The watershed rises from 500 m at the fan apex to 2130 m at the crest of the watershed. The upper basin is extensively gullied and steep, with a Melton Ratio of 0.8, and abundant boulder lobes and levees on the fan indicate previous debris-flow activity. Areas of distressed slope and evidence of a rockslide deposit also exist on the fan, suggesting rockslides up to 400,000 m<sup>3</sup> could occur.</p>
Meteorological conditions	
<p>Identify the relevant meteorological conditions that may influence the outcome of the risk event.</p>	<p>Debris flow events on Catiline Creek are primarily triggered by high precipitation events. These may be regional or highly localized and may occur any time between Spring and Fall inclusive.</p>

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Seasonal conditions	
Identify the relevant seasonal changes that may influence the outcome of the risk assessment of a particular risk event.	Debris flow events on Catiline Creek may be triggered by regional or highly localized precipitation events that may occur any time between Spring and Fall inclusive. No debris flows have been recorded in winter, during periods of thick snowpack.
Nature and vulnerability	
Document key elements related to the affected population, including: <ul style="list-style-type: none"><li>Population density;</li><li>Vulnerable populations (identify these on the hazard map from step 7);</li><li>Degree of urbanization;</li><li>Key local infrastructure in the defined geographic area;</li><li>Economic and political considerations; and</li><li>Other elements, as deemed pertinent to the defined geographic area.</li></ul>	Lillooet Lake Estates contains 155 residential lots, of which about 114 have been developed and are currently occupied. Occupancy ranges from seasonal cabins to full-time residents, with a higher population in summer than winter. Total population was estimated for the purpose of baseline risk assessment at about 270 people. Some lots are currently undeveloped. The in-SHUCK-ch Forest Service Road (FSR) crosses the lower fan and provides access from Pemberton to the community as well as to development and resource operations to the south.

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Asset inventory	
<div>Identify the asset inventory of the defined geographic area, including:<ul style="list-style-type: none"><li>Critical assets;</li><li>Cultural or historical assets;</li><li>Commercial assets; and</li><li>Other area assets, as applicable to the defined geographic area.</li></ul>Key asset-related information should also be provided, including:<ul style="list-style-type: none"><li>Location on the hazard map (from step 7);</li><li>Size;</li><li>Structure replacement cost;</li><li>Content value;</li><li>Displacement costs;</li><li>Importance rating and rationale;</li><li>Vulnerability rating and reason; and</li><li>Average daily cost to operate.</li></ul>A total estimated value of physical assets in the area should also be provided.</div>	<div>Assets include 155 residential lots and buildings, roads, bridges, utilities infrastructure including power, communications, and water supply, and water treatment. Estimated value of physical assets exceeds \$15M. Total population was estimated for risk assessment at about 270 people. Some lots are currently undeveloped; maximum population at full build-out of all lots would be about 370 people (approximate). Residential lots are potentially exposed to direct impact by debris flows at return periods ranging from 5-10 to &gt;3000 years, with high vulnerability to loss of life.</div>
Other assumptions, variability and/or relevant information	
<div>Identify any assumptions made in describing the risk event; define details regarding any areas of uncertainty or unpredictability around the risk event; and supply any supplemental information, as applicable.</div>	<div>The regional risk prioritization (this study) rated Catiline Creek as Very High hazard. The detailed 2015 assessment considered multiple debris flow scenarios at return periods ranging from 5-10 to 3,000-10,000 years. The scenarios were developed for hazard modeling and risk analysis based on a frequency-magnitude relationship developed from previous events, interpretation of historical air photographs, test-trenching, fan surface observations, and dendrochronology. The events up to 100,000 m3 were considered “conventional” debris flows, while larger events were considered to involve a large bedrock failure in the upper basin. Numerical modeling of debris flows provided the basis to estimate spatial impact probabilities and corresponding debris-flow intensities for risk estimation. The model results were used to generate runout exceedance and hazard intensity maps as primary inputs to the risk assessment. BGC estimated the probability that debris flows will impact residential dwellings and cause loss of life, and compared the estimates to individual and group risk tolerance criteria, as described earlier in this form. Each step in the analysis was subject to uncertainty and required assumptions about event triggers, frequency-magnitude relations, debris-flow rheology, avulsion scenarios, and estimates of spatial impact probability, exposure, and vulnerability.</div>

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Existing Risk Treatment Measures	
Identify existing risk treatment measures that are currently in place within the defined geographic area to mitigate the risk event, and describe the sufficiency of these risk treatment measures.	Existing risk treatment measures included excavation of the main channel to increase capacity, debris removal to restore channel conveyance at FSR bridge crossing, and the construction of structural mitigation (channel diversion). The level of residual individual risk including these measures remains intolerable by international standards for 76 of the 114 occupied, residential-classed lots within the study area. Group risk also remains in the intolerable range.

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Likelihood Assessment		
Return Period		
Identify the time period during which the risk event might occur. For example, the risk event described is expected to occur once every X number of years. Applicants are asked to provide the X value for the risk event.	Eleven debris flows have been recorded in the past 66 years, or an average of once per 6 years.	
Period of interest		
Applicants are asked to determine and identify the likelihood rating (i.e. period of interest) for the risk event described by using the likelihood rating scale within the table below.		
Likelihood Rating	Definition	
5	The event is expected and may be triggered by conditions expected over a 30 year period.	5
4	The event is expected and may be triggered by conditions expected over a 30 - 50 year period.	
3	The event is expected and may be triggered by conditions expected over a 50 - 500 year period.	
2	The event is expected and may be triggered by conditions expected over a 500 - 5000 year period.	
1	The event is possible and may be triggered by conditions exceeding a period of 5000 years.	
Provide any other relevant information, notes or comments relating to the likelihood assessment, as applicable.		



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Impacts/Consequences Assessment			
There are 12 impacts categories within 5 impact classes rated on a scale of 1 (least impacts) to 5 (greatest impact). Conduct an assessment of the impacts associated with the risk event, and assign one risk rating for each category. Additional information may be provided for each of the categories in the supplemental fields provided.			
A) People and societal impacts			
	Risk Rating	Definition	Assigned risk rating
Fatalities	5	Could result in more than 50 fatalities	4
	4	Could result in 10 - 49 fatalities	
	3	Could result in 5 - 9 fatalities	
	2	Could result in 1 - 4 fatalities	
	1	Not likely to result in fatalities	
Supplemental information (optional)			
Injuries	5	Injuries, illness and/or psychological disablements cannot be addressed by local, regional, or provincial/territorial healthcare resources; federal support or intervention is required	4
	4	Injuries, illnesses and/or psychological disablements cannot be addressed by local or regional healthcare resources; provincial/territorial healthcare support or intervention is required.	
	3	Injuries, illnesses and/or psychological disablements cannot be addressed by local or regional healthcare resources additional healthcare support or intervention is required from other regions, and supplementary support could be required from the province/territory	
	2	Injuries, illnesses and/or psychological disablements cannot be addressed by local resources through local facilities; healthcare support is required from other areas such as an adjacent area(ies)/municipality(ies) within the region	
	1	Any injuries, illnesses, and/or psychological disablements can be addressed by local resources through local facilities; available resources can meet the demand for care	
Supplemental information (optional)			

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		Risk Rating	Definition	Assigned risk rating
Displacement	Percentage of displaced individuals	5	> 15% of total local population	5
		4	10 - 14.9% of total local population	
		3	5 - 9.9% of total local population	
		2	2 - 4.9% of total local population	
		1	0 - 1.9% of total local population	
	Duration of displacement	5	> 26 weeks (6 months)	4
		4	4 weeks - 26 weeks (6 months)	
		3	1 week - 4 weeks	
		2	72 hours - 168 hours (1 week)	
		1	Less than 72 hours	
Supplemental information (optional)				
B) Environmental impacts				
		5	> 75% of flora or fauna impacted or 1 or more ecosystems significantly impaired; Air quality has significantly deteriorated; Water quality is significantly lower than normal or water level is > 3 meters above highest natural level; Soil quality or quantity is significantly lower (i.e., significant soil loss, evidence of lethal soil contamination) than normal; > 15% of local area is affected	3
		4	40 - 74.9% of flora or fauna impacted or 1 or more ecosystems considerably impaired; Air quality has considerably deteriorated; Water quality is considerably lower than normal or water level is 2 - 2.9 meters above highest natural level; Soil quality or quantity is moderately lower than normal; 10 - 14.9% of local area is affected	
		3	10 - 39.9% of flora or fauna impacted or 1 1 or more ecosystems moderately impaired; Air quality has moderately deteriorated; Water quality is moderately lower than normal or water level is 1 - 2 meters above highest natural level; Soil quality is moderately lower than normal; 6 - 9.9 % of area affected	

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	2	< 10 % of flora or fauna impacted or little or no impact to any ecosystems; Little to no impact to air quality and/or soil quality or quantity; Water quality is slightly lower than normal, or water level is less than 0.9 meters above highest natural level and increased for less than 24 hours; 3 - 5.9 % of local area is affected		
	1	Little to no impact to flora or fauna, any ecosystems, air quality, water quality or quantity, or to soil quality or quantity; 0 - 2.9 % of local area is affected		
Supplemental information (optional)				
C) Local economic impacts				
	Risk Rating	Definition		Assigned risk rating
	5	> 15 % of local economy impacted		5
	4	10 - 14.9 % of local economy impacted		
	3	6 - 9.9 % of local economy impacted		
	2	3 - 5.9 % of local economy impacted		
	1	0 - 2.9 % of local economy impacted		
Supplemental information (optional)				

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D) Local infrastructure impacts			
	Risk Rating	Definition	Assigned risk rating
Transportation	5	Local activity stopped for more than 72 hours; > 20% of local population affected; lost access to local area and/or delivery of crucial service or product; or having an international level impact	5
	4	Local activity stopped for 48 - 71 hours; 10 - 19.9% of local population affected; significantly reduced access to local area and/or delivery of crucial service or product; or having a national level impact	
	3	Local activity stopped for 25 - 47 hours; 5 - 9.9% of local population affected; moderately reduced access to local area and/or delivery of crucial service or product; or having a provincial/territorial level impact	
	2	Local activity stopped for 13 - 24 hours; 2 - 4.9% of local population affected; minor reduction in access to local area and/or delivery of crucial service or product; or having a regional level impact	
	1	Local activity stopped for 0 - 12 hours; 0 - 1.9% of local population affected; little to no reduction in access to local area and/or delivery of crucial service or product	
Supplemental information (optional)			
Energy and Utilities	5	Duration of impacts > 72 hours; > 20% of local population without service or product; or having an international level impact	3
	4	Duration of impact 48 - 71 hours; 10 - 19.9% of local population without service or product; or having a national impact	
	3	Duration of impact 25 - 47 hours; 5 - 9.9% of local population without service or product; or having a provincial/territorial level impact	
	2	Duration of impact 13 - 24 hours; 2 - 4.9% of local population without service or product; or having a regional level impact	
	1	Local activity stopped for 0 - 12 hours; 0 - 1.9% of local population affected; little to no reduction in access to local area and/or delivery of crucial service or product	

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Supplemental information (optional)			
Information and Communications Technology	5	Service unavailable for > 72 hours; > 20 % of local population without service; or having an international level impact	4
	4	Service unavailable for 48 - 71 hours; 10 - 19.9 % of local population without service; or having a national level impact	
	3	Service unavailable for 25 - 47 hours; 5 - 9.9 % of local population without service; or having a provincial/territorial level impact	
	2	Service unavailable for 13 - 24 hours; 2 - 4.9 % of local population without service; or having a regional level impact	
	1	Service unavailable for 0 - 12 hours; 0 - 1.9 % of local population without service	
Supplemental information (optional)			
Health, Food, and Water	5	Inability to access potable water, food, sanitation services, or healthcare services for > 72 hours; non-essential services cancelled; > 20 % of local population impacted; or having an international level impact	3
	4	Inability to access potable water, food, sanitation services, or healthcare services for 48-72 hours; major delays for nonessential services; 10 - 19.9 % of local population impacted; or having a national level impact	
	3	Inability to access potable water, food, sanitation services, or healthcare services for 25-48 hours; moderate delays for nonessential services; 5 - 9.9 % of local population impacted; or having a provincial/territorial level impact	
	2	Inability to access potable water, food, sanitation services, or healthcare services for 13-24 hours; minor delays for nonessential; 2 - 4.9 % of local population impacted; or having a regional level impact	
	1	Inability to access potable water, food, sanitation services, or healthcare services for 0-12 hours; 0 - 1.9 % of local population impacted	

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Supplemental information (optional)			
Safety and Security	5	> 20 % of local population impacted; loss of intelligence or defence assets or systems for > 72 hours; or having an international level impact	4
	4	10 - 19.9 % of local population impacted; loss of intelligence or defence assets or systems for 48 – 71 hours; or having a national level impact	
	3	5 - 9.9 % of local population impacted; loss of intelligence or defence assets or systems for 25 – 47 hours; or having a provincial/territorial level impact	
	2	2 - 4.9 % of local population impacted; loss of intelligence or defence assets or systems for 13 – 24 hours; or having a regional level impact	
	1	0 - 1.9 % of local population impacted; loss of intelligence or defence assets or systems for 0 – 12 hours	
Supplemental information (optional)			



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E) Public sensitivity impacts			
	Risk Rating	Definition	Assigned risk rating
	5	Sustained, long term loss in reputation/public perception of public institutions and/or sustained, long term loss of trust and confidence in public institutions; or having an international level impact	4
	4	Significant loss in reputation/public perception of public institutions and/or significant loss of trust and confidence in public institutions; significant resistance; or having a national level impact	
	3	Some loss in reputation/public perception of public institutions and/or some loss of trust and confidence in public institutions; escalating resistance	
	2	Isolated/minor, recoverable set-back in reputation, public perception, trust, and/or confidence of public institutions	
	1	No impact on reputation, public perception, trust, and/or confidence of public institutions	
Supplemental information (optional)			

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Confidence Assessment

Based on the table below, indicate the level of confidence regarding the information entered in the risk assessment information template in the “Confidence Level Assigned” column. Confidence levels are language-based and range from A to E (A=most confident to E=least confident).

Confidence Level	Definition	Confidence Level Assigned
A	Very high degree of confidence Risk assessment used to inform the risk assessment information template was evidence-based on a thorough knowledge of the natural hazard risk event; leveraged a significant quantity of high-quality data that was quantitative and qualitative in nature; leveraged a wide variety of data and information including from historical records, geospatial and other information sources; and the risk assessment and analysis processes were completed by a multidisciplinary team with subject matter experts (i.e., a wide array of experts and knowledgeable individuals on the specific natural hazard and its consequences) Assessment of impacts considered a significant number of existing/known mitigation measures	
B	High degree of confidence Risk assessment used to inform the risk assessment information template was evidence-based on a thorough knowledge of the natural hazard risk event; leveraged a significant quantity of data that was quantitative and qualitative in nature; leveraged a wide variety of data and information including from historical records, geospatial and other information sources; and the risk assessment and analysis processes were completed by a multidisciplinary team with some subject matter expertise (i.e., a wide array of experts and knowledgeable individuals on the specific natural hazard and its consequences) Assessment of impacts considered a significant number of potential mitigation measures	

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C	Moderate confidence Risk assessment used to inform the risk assessment information template was moderately evidence-based from a considerable amount of knowledge of the natural hazard risk event; leveraged a considerable quantity of data that was quantitative and/or qualitative in nature; leveraged a considerable amount of data and information including from historical records, geospatial and other information sources; and the risk assessment and analysis processes were completed by a moderately sized multidisciplinary team, incorporating some subject matter experts (i.e., a wide array of experts and knowledgeable individuals on the specific natural hazard and its consequences) Assessment of impacts considered a large number of potential mitigation measures	A
D	Low confidence Risk assessment used to inform the risk assessment information template was based on a relatively small amount of knowledge of the natural hazard risk event; leveraged a relatively small quantity of quantitative and/or qualitative data that was largely historical in nature; may have leveraged some geospatial information or information from other sources (i.e., databases, key risk and resilience methodologies); and the risk assessment and analysis processes were completed by a small team that may or may not have incorporated subject matter experts (i.e., did not include a wide array of experts and knowledgeable individuals on the specific natural hazard and its consequences). Assessment of impacts considered a relatively small number of potential mitigation measures	
E	Very low confidence Risk assessment used to inform the risk assessment information template was not evidence-based; leveraged a small quantity of information and/or data relating to the natural risk hazard and risk event; primary qualitative information used with little to no quantitative data or information; and the risk assessment and analysis processes were completed by an individual or small group of individuals little subject matter expertise (i.e., did not include a wide array of experts and knowledgeable individuals on the specific natural hazard and its consequences). Assessment of impacts did not consider existing or potential mitigation measures	
Rationale for level of confidence		
Provide the rationale for the selected confidence level, including any references or sources to support the level assigned.	This RAIT was prepared with reference to a detailed quantitative debris-flow risk assessment prepared by subject matter specialists in steep creek risk assessment, as cited below.	

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Key Information Sources	
<p>Identify all supporting documentation and information sources for qualitative and quantitative data used to identify risk events, develop the risk event description, and assess impacts and likelihood. This ensures credibility and validity of risk information presented as well as enables referencing back to decision points at any point in time.</p> <p>Clearly identify unclassified and classified information.</p>	<p>BGC Engineering Inc. (2015, January 22). Catiline Creek Debris-Flow Hazard and Risk Assessment [Report]. Prepared for Squamish-Lillooet Regional District.</p>
Description of the risk analysis team	
<p>List and describe the type and level of experience of each individual who was involved with the completion of the risk assessment and risk analysis used to inform the information contained within this risk assessment information template.</p>	<p>Kris Holm, M.Sc., P.Geo. Mr. Holm is a Principal Geoscientist with 25 years of geoscience consulting experience. His experience includes geohazard and risk assessments for transportation, development and industry at scales ranging from site-specific studies to broad regions. Mr. Holm has led regional flood and geohazard risk prioritization studies for the Province of Alberta, Regional District of Central Kootenay, Columbia-Shuswap Regional District, Cariboo Regional District, Regional District of North Okanagan, Thompson-Nicola Regional District, Squamish-Lillooet Regional District, and Regional District of East Kootenay. He is also co-author of the Alberta Draft Provincial Guidelines for Steep Creek Risk Assessment, and has completed over 50 detailed, quantitative debris flow or debris flood risk assessments supporting risk-informed decision making and bylaw implementation by local government, including the District of North Vancouver and Town of Canmore.</p> <p>Matthias Jakob, Ph.D., P.Geo. Dr. Jakob’s expertise revolved primarily around steep creek processes and risk management but extended to landslide and flood risk management for a broad range of private and government clients. He authored some 40 peer reviewed journal papers and a total of over one hundred technical papers in journals, conference proceedings and books. He was adjunct professor at the Geography and Earth and Ocean Science departments at the University of British Columbia where he taught courses in applied geomorphology. Dr. Jakob passed away in October, 2022.</p>

# APPENDIX K

## RESULTS TABULATION

### (PROVIDED SEPARATELY IN EXCEL FORMAT)



# APPENDIX L

## RECOMMENDATIONS





## L-1 INTRODUCTION

The following sections provide recommendations for consideration by SLRD. They may require review by different groups within SLRD, including board members, managers, planners, emergency management staff, and geomatics staff.

Each section starts with an italicized, bulleted list of recommendations, followed by background and justification. Where applicable, recommended approaches and tasks for clear-water flood, steep creek, and volcanic geohazard assessments are provided.

### L-1.1 Data Gaps

*Recommendation:*

- Develop a plan to resolve the baseline data gaps outlined in this section.

Table L-1 summarizes gaps in baseline data that informed the current risk prioritization study and provides recommendations to resolve these gaps. Some of these recommendations are further developed in Sections L-1.2 to L-1.9.

Table L-1. Summary of data gaps and recommended actions.

Input	Description	Implication (Factor Affected)	Recommended Actions to Resolve Gaps
Traditional and local knowledge (see also Section L-1.9)	<ul style="list-style-type: none"><li>This assessment relies upon scientific methods as outlined within professional practice guidelines. However, at the regional scale of this assessment, it is difficult to collect and incorporate traditional and local knowledge into the assessment results. For example, Indigenous elders and land stewards may hold knowledge related to past flooding events, or farmers may have observed recent flooding extents.</li></ul>	<ul style="list-style-type: none"><li>Precision and accuracy of estimated geohazard area location/extents, likelihood, and intensity.</li></ul>	<ul style="list-style-type: none"><li>As part of ongoing engagement with First Nation communities and where permitted by First Nation authorities, incorporate Indigenous knowledge into hazard assessment results.</li><li>As part of citizen science initiatives, collect local knowledge related to geohazards information, such as flooding extents.</li><li>Display physical copies of hazard area maps during town hall sessions and create opportunities for local residents to provide feedback on the hazard extents (e.g., markers, feedback surveys, etc.).</li></ul>
Topography	<ul style="list-style-type: none"><li>The main valley corridors within the SLRD contain publicly available lidar, but gaps exist in the Birken-D'Arcy valley, the upper Squamish River valley, the upper Lillooet River valley, and north of Lillooet. In these areas, the lack of detailed topography (Lidar) limited the accuracy of terrain analysis for steep creek fans and for clear-water flood hazard area delineation and characterization.</li></ul>	<ul style="list-style-type: none"><li>Precision and accuracy of estimated geohazard area location/extents, likelihood, and intensity.</li></ul>	<ul style="list-style-type: none"><li>Lidar acquisition and processing.</li><li>Review and update to terrain analyses (i.e., fan boundary delineation) following Lidar acquisition.</li><li>Consider re-evaluating geohazard area delineation and characterization once Lidar data are available.</li></ul>
Bathymetry	<ul style="list-style-type: none"><li>Clear-water flood hazard assessment did not consider the channel geometry or river bathymetry.</li></ul>	<ul style="list-style-type: none"><li>Precision and accuracy of estimated geohazard area location/extents and intensity.</li></ul>	<ul style="list-style-type: none"><li>For more detailed, site-specific studies, bathymetry would be required such as high priority sites identified in Table L-2 that do not have an existing detailed assessment.</li></ul>
Stream network	<ul style="list-style-type: none"><li>Not all watercourses present within the SLRD are contained within provincial (TRIM) or national river networks, and some have changed location since mapping (i.e., due to channel avulsion or migration). Mapped watercourses may or may not be consistent with the definition of watercourse contained in Floodplain Management Bylaws.</li><li>In this study, floodplain identification was based on "Height over Nearest Drainage" (HAND) modelling that involved topographic-based modelling of stream flow. The HAND modelling was performed on the 30 m resolution DEM produced by the Shuttle RADAR Topography Mission (SRTM) (Farr et al., 2007). The flow networks defined using HAND modelling may not be consistent with TRIM or national river networks.</li></ul>	<ul style="list-style-type: none"><li>Gap in hydrologic analyses for fans not intersecting mapped streams</li><li>Watercourses that have moved since the original stream network mapping may lead to an apparent inconsistency between HAND modelling outputs and mapped river channels.</li><li>Low resolution of the DEM used in the HAND modelling may also result in inconsistencies between the HAND modelling outputs and the mapped river channels.</li></ul>	<ul style="list-style-type: none"><li>Manual revisions to stream networks may be required to facilitate hydrologic, hydraulic, and geomorphic analyses required for geohazard risk management.</li><li>Consider running algorithms on region-wide Lidar to identify watercourse and bank locations, and to identify stream segments that are consistent with the bylaw definition for watercourse.</li></ul>
Improved hazard knowledge (see also Section L-1.7)	<ul style="list-style-type: none"><li>Given the regional nature of this study, BGC was not able to compile site-specific information including sources, controls, or triggers for flood and steep creek geohazards. These information could be integrated into improved versions of the hazard data.</li></ul>	<ul style="list-style-type: none"><li>Ability to identify sources, controls, or triggers for flood and steep creek geohazard. For example - identification of landslide hazards informing the development of frequency-magnitude relationships for detailed steep creek geohazards assessments.</li></ul>	<ul style="list-style-type: none"><li>Maintain a data information management system that integrates existing knowledge, with tools to grow an accessible knowledge base over time as funding permits. Organizing geospatial data so that all studies take advantage of a common resource will greatly reduce the costs of data compilation.</li><li>Require assessments to provide results in geospatial formats when generated during a study and provide data standards that facilitate their inclusion in a larger data model.</li></ul>
Monitoring (see also Section L-1.5)	<ul style="list-style-type: none"><li>The WSC operates and manages a network of hydrometric stations across the SLRD. Many of these stations are no longer operational providing limited historical datasets to infer reliable flood quantiles. Furthermore, few stations offer real-time flood monitoring.</li></ul>	<ul style="list-style-type: none"><li>Reliable estimates of flood quantiles</li><li>Real-time streamflow monitoring</li></ul>	<ul style="list-style-type: none"><li>Advocate for improvements to the WSC gauging network in the RDEK, particularly for small streams (less than 10 km²) and regulated streams or watercourses.</li><li>Low-cost climate sensors co-located with stream gauges in the area would enhance understanding of climate-related risk and support the validation of model outputs.</li></ul>
Wildfires (see also Section L-1.3)	<ul style="list-style-type: none"><li>Post-wildfire geohazards assessments rely on remotely sensed burn severity mapping supplemented by field inspection of conditions at the</li></ul>	<ul style="list-style-type: none"><li>Ability to provide timely post-wildfire geohazards assessments for areas where changes in post-wildfire geohazard activity will have the strongest influence on risk.</li></ul>	<ul style="list-style-type: none"><li>Coordinate with the Province of BC to provide burn-severity mapping via their web service, in a format that can be directly incorporated into web-mapping of geohazard areas and elements at risk.</li></ul>

Input	Description	Implication (Factor Affected)	Recommended Actions to Resolve Gaps
	ground surface. At present, only burn perimeter mapping is made widely available for all fires and burn severity mapping is not necessarily available before the occurrence of debris flows.		<ul style="list-style-type: none"><li>• Use the existing study information in combination with burn severity maps to inform post-wildfire geohazard risk assessments when required</li></ul>
Volcanic Geohazard Extents (See also Section L-1.2.4)	<ul style="list-style-type: none"><li>• This work relies heavily on volcanic hazards and flood hazards that have been mapped by third parties and was completed at a lower level of detail than clear-water and steep creek geohazard characterization. None of the areas delineated should be interpreted as precise due to uncertainties with input parameters (volume, rheology), unknown or ignored auxiliary hazards and hazard cascades, or the lack of knowledge of streamflow at the time of occurrence of a volcanic hazard, which can strongly influence the hazard’s characteristics and impact.</li></ul>	<ul style="list-style-type: none"><li>• Precision and accuracy of estimated geohazard area location/extents – affecting hazard exposure and vulnerability estimation.</li><li>• Implications for asset management decisions resulting from volcanic hazard estimation.</li></ul>	<ul style="list-style-type: none"><li>• Systematic re-evaluation of hazard scenarios with experts in the field using various assumptions.</li><li>• Inclusion of eruptive hazards at least for the Mount Meager Volcanic Complex, which is the most active one in the SLRD.</li><li>• Seamless hazard chain modeling (rock avalanche, landslide-dammed lake, and subsequent event scenarios).</li><li>• Numerical lahar runout modelling conducted as part of a detailed assessment for specific areas or creeks.</li></ul>
Flood Protection Measures, and Flood Conveyance Infrastructure	<ul style="list-style-type: none"><li>• Dikes, bank erosion protection, and appurtenant structures, in addition to culverts and bridges were excluded from the evaluation due to the limited data available on the location, properties and condition of these facilities.</li><li>• Layers depicting the location of flood protection or conveyance infrastructure were sourced from provincial inventories and may contain gaps or inaccuracies.</li></ul>	<ul style="list-style-type: none"><li>• Precision and accuracy of estimated geohazard area location/extents, likelihood, and intensity.</li></ul>	<ul style="list-style-type: none"><li>• Develop data collection standards and sharing agreements between the various facility owners to facilitate their inclusion in a larger data model.</li><li>• More detailed inventories and characterization of assets based on consistent data standards would improve and reduce the cost of hydraulic assessments.</li><li>• Apply the results of this assessment to prioritize review of existing risk reduction measures and consideration in further, more detailed geohazards assessments.</li><li>• As a specific comment, dikes shown along Blackcomb Way north of Lorimer Road in Whistler may not be accurately represented on the map (Pers. Comm., Jim Dunlop, Resort Municipality of Whistler, March 27, 2020).</li></ul>
Exposure	<ul style="list-style-type: none"><li>• Gaps exist in the elements at risk (asset) data model developed for the SLRD, in terms of location, attributes, and data formats.</li><li>• Specifically, the layers showing land and improvements, lifelines, and environmental values on Cambio are based on the best information available at the time of study but are not complete.</li><li>• Population in hazard areas may change during business hours compared to weekends and evenings when population is in residences. These variations are not reflected in current approaches.</li></ul>	<ul style="list-style-type: none"><li>• Ability to provide information that supports:<ul style="list-style-type: none"><li>○ Hazard exposure and vulnerability estimation</li><li>○ Inclusion of assets required for later more detailed hazard modelling (i.e., drainage networks).</li><li>○ Level of detail of baseline data informing resiliency planning, the ability of a system to resist and recover from flooding or steep creek geohazard impact.</li><li>○ Level of detail of data informing asset management in geohazard areas.</li><li>○ Level of detail of elements at risk information supporting emergency response planning.</li><li>○ Accurate estimates of population at risk.</li></ul></li></ul>	<ul style="list-style-type: none"><li>• Building footprints could be joined to cadastral data to improve regional characterization based on available datasets (e.g. BC Assessment). For parcels with multiple structures, the “main” dwelling should be distinguished from out-buildings, to allow them to be distinguished when assessing safety risk to dwelling occupants.</li><li>• The NRCan Physical Exposure data set used to source building values in Reserve Areas for Phase II assessment also provides population estimates. A “transit” data field, which simulates “commuting” hours, could replace Census population counts as a more reasonable average for regional geohazards management planning.</li></ul>
	<ul style="list-style-type: none"><li>• BC Assessment (BCA) data reported for tax purposes are also key indicators to estimate geohazard vulnerability, but information gaps limit this application of the data.</li></ul>	<ul style="list-style-type: none"><li>• The use of BCA data to assess building vulnerability is helpful in that it is regularly updated and available in a consistent format province wide. However, it is limited in that the data are being applied to a different purpose than the original intent, which is to inform appraised improvement values.</li></ul>	<ul style="list-style-type: none"><li>• Because the collection and dissemination of assessment data for tax purposes is likely to be funded for the foreseeable future, it represents a reliable way to maintain up-to-date records. BGC suggests that assessment data collection and reporting procedures be reviewed and updated to consider requirements of geohazard risk management and emergency response. Relatively minor adjustments to how assessment data is collected (i.e., attributes) and communicated (i.e., data formats and types) would greatly facilitate risk analyses.</li><li>• Advocate for a standard data product, to be provided by BCA, that contains data elements for geohazard risk management and emergency response. This would reduce the cost per request, compared to custom data requests.</li></ul>

Input	Description	Implication (Factor Affected)	Recommended Actions to Resolve Gaps
	<ul style="list-style-type: none"><li>Gaps remain about culturally significant areas and risk considerations beyond primarily economic values considered in the current approaches, including both First Nations Reserves and traditional territories.</li></ul>	<ul style="list-style-type: none"><li>Under-representation of Indigenous perspectives in geohazard risk assessment projects.</li></ul>	<ul style="list-style-type: none"><li>Through facilitated, workshop – based sessions, validate and expand the ‘written observed’ record of hazard variables such as climate, weather, and hydrometrics. Obtain additional perspective on pressures that settler communities have put on natural landscapes (e.g., logging, shoreline development) and additional perspectives on hazard exposure and vulnerability.</li></ul>
	<ul style="list-style-type: none"><li>No information was readily available on road networks critical for use in a geohazard-related emergency. Some of these routes include forestry roads providing alternative access to remote communities. Because these roads are not typically high traffic, they do not weight heavily (i.e., are not assigned high importance) in the calculation of hazard exposure.</li><li>Additional geohazards exist within the District that are not included in the study, and that may also be considered high priority by asset owners. For example, clear-water flood and steep creek hazards exist along undeveloped roads that were not included in the scope of work.</li></ul>	<ul style="list-style-type: none"><li>Underestimation of priority where geohazard areas intersect evacuation routes along minor roads.</li></ul>	<ul style="list-style-type: none"><li>Prepare map layer identifying emergency evacuation road networks.</li><li>Include an evacuation road network layer in hazard exposure analysis and update the study results.</li></ul>

## L-1.2 Further Geohazards Assessments

### *Recommendation:*

- Review prioritized geohazard areas and develop a plan to implement next steps of geohazard risk management framework.

Table L-2 highlights examples of clear-water flood and steep creek geohazard areas considered high priority for consideration in risk management decision making. The appropriate next steps to manage risk will differ at each site depending on the current level of study.

The areas listed in Table L-2 were selected based on the regional geohazard risk assessment completed in the current study. This list of prioritized areas should be reviewed for decision making. The full list of prioritized areas should be reviewed for decision making. BGC emphasizes that the baseline priority ratings are not equivalent to an absolute level of risk, and SLRD will need to consider additional factors in decisions about next steps at any site (i.e., evaluation of costs and benefits to advance the steps of risk management). The prioritized geohazard areas tabulated in Appendix K can be sorted based on any factor listed in the tables, and additional factors could potentially be added by SLRD to aid in a selection process.

For reference, Table L-2 indicates cases where the highlighted geohazard areas have already been subject to detailed assessments (hazard, risk or mitigation). Note that the presence of previous study does not necessarily imply that geohazard and risk has been assessed and managed to a level considered tolerable by the District. BGC notes some areas that would benefit from improved hazard and risk assessments include:

- Birken-D'Arcy corridor (e.g., Gates River, Neff, Poole, Landsborough, and Young John Creeks,).
- Resort Municipality of Whistler (e.g., Alta Creek and Lake, Nineteen Mile Creek)
- Village of Lillooet (Seton and Fraser River)
- Lil'wat Nation (steep creeks draining Lil'wat Mountain).

BGC also emphasizes that this assessment was limited to settled areas in the SLRD. Additional geohazards exist within the District that are not included in the study, and that may also be considered high priority by asset owners. For example, clear-water flood and steep creek hazards exist along undeveloped roads that were not included in the scope of work. Extending the work herein to include transportation routes managed under the authority of FLRORD and MOTI would add substantial value to the current work.

Sections L-1.2.1 to L-1.2.3.3 summarize the rationale for further studies of each prioritized geohazard type, as well as for regulated water bodies (reservoirs).

Table L-2. Select geohazard areas highlighted as high priority.

Hazard Code	Hazard Type	Geohazard Process	Name	Baseline Geohazard Rating	Wildfire-Adjusted Geohazard Rating	Consequence Rating	Risk Rating	Existing Detailed Assessment? (See footer for letter definitions <sup>1</sup> )	Assessment Type <sup>2</sup>
10186	Steep Creek	Debris Flow/Debris Flood	Cheekeye River	High	High	Very High	Very High	A	HA, RA, MA
10351	Clear-water	Flood	Cheekeye River	Moderate		High	High	A	HA, RA, MA
10319	Steep Creek	Debris Flood	Fitzsimmons Creek	High	High	Very High	Very High	A	HA, MA
12164	Clear-water	Flood	Fitzsimmons Creek	Moderate	N/A	High	High	A	HA, RA, MA
10229	Steep Creek	Flood	Pemberton Creek	Very High	Very High	High	Very High	A	HA, MA
10619	Clear-water	Flood	Pemberton Creek	Moderate	N/A	Very High	High	A	HA, MA
10230	Steep Creek	Debris Flow	Birkenhead River Tributary 3	High	High	Very High	Very High	B	HA
66162	Steep Creek	Debris Flow	Whistler Creek	Low	Low	Very High	High	A	HA, MA
10197	Steep Creek	Debris Flood	Nineteen Mile Creek	High	High	High	High	B	MA
10157	Steep Creek	Debris Flood	Furry Creek	Moderate	Moderate	Very High	High	C	Unknown
66159	Steep Creek	Debris Flow	Green Lake Tributary 2	High	High	High	High	C	Unknown
10178	Steep Creek	Debris Flow	Bear/Pete's Creek	Very High	Very High	High	Very High	A	HA, RA, MA
65916	Steep Creek	Flood	Cheakamus River	High	High	Very High	Very High	A	HA, RA, MA
10356/10375	Clear-water	Flood	Cheakamus River	Moderate	N/A	High	High	A	HA, RA
10280	Steep Creek	Debris Flood/Flood	Miller Creek	Very High	Very High	High	Very High	B	HA, MA
10265	Steep Creek	Debris Flood	Spruce Creek	Moderate	Moderate	High	High	C	Unknown
10179	Steep Creek	Debris Flood	Spider Creek	Very High	Very High	Low	High	A	HA, RA
10218	Steep Creek	Debris Flow	Fountain N	Very High	Very High	Moderate	High	C	Unknown
10156	Steep Creek	Debris Flood	Britannia Creek	Very High	Very High	Very High	Very High	A	HA, MA
10196	Steep Creek	Debris Flood	Twentyone Mile Creek	Moderate	Moderate	High	High	B	MA
10232	Steep Creek	Debris Flow	Neff Creek	Very High	Very High	Moderate	Very High	C	Unknown
10261	Steep Creek	Debris Flood	Eight Mile Creek 1	Moderate	Moderate	High	High	C	Unknown
66045	Steep Creek	Debris Flow	Fraser River Tributary 10	High	High	Moderate	High	C	Unknown
10271	Steep Creek	Debris Flow	Fountain Creek Tributary 12	Moderate	Moderate	High	High	C	Unknown
65881	Steep Creek	Debris Flow	Gates River Tributary 2	Moderate	Moderate	High	High	C	Unknown
65936	Steep Creek	Debris Flow	Mungye Creek	Moderate	High	High	High	A	HA, RA, MA
10168	Steep Creek	Debris Flow	Gates Lake Tributary 4	High	High	Very High	Very High	C	Unknown
65905	Steep Creek	Debris Flow	Landsborough Creek	High	High	High	High	C	Unknown
65934	Steep Creek	Debris Flow	Jason Creek	Very High	Very High	High	Very High	A	HA, RA, MA
65968	Steep Creek	Debris Flow	Dickey Creek	Very High	Very High	High	Very High	C	Unknown
10174	Steep Creek	Debris Flow	Birkenhead River Tributary 2	Moderate	High	High	High	C	Unknown



Hazard Code	Hazard Type	Geohazard Process	Name	Baseline Geohazard Rating	Wildfire-Adjusted Geohazard Rating	Consequence Rating	Risk Rating	Existing Detailed Assessment? (See footer for letter definitions <sup>1</sup> )	Assessment Type <sup>2</sup>
10260	Steep Creek	Debris Flood	Poole Creek	High	High	High	High	C	Unknown
10267	Steep Creek	Debris Flow	Young John Creek	Low	High	High	High	C	Unknown
10173	Steep Creek	Debris Flow	Peq Creek	Moderate	High	High	High	B	HA
12166/10604	Clear-water	Flood	Squamish River	Moderate	N/A	Very High	High	A	HA, RA, MA
10349	Clear-water	Flood	Lillooet River	Moderate	N/A	Very High	High	A	HA, MA
10653	Clear-water	Coastal Flood	Howe Sound	Moderate	N/A	Very High	High	A	HA, RA, MA
10348	Clear-water	Flood	Upper Squamish River	Moderate	N/A	Very High	High	A	HA, RA
10403	Clear-water	Flood	Cheakamus River (Whistler)	Moderate	N/A	High	High	B	HA, MA
10442	Clear-water	Flood	Seton River (Seton Portage)	Moderate	N/A	Very High	High	A	HA, RA
10451	Clear-water	Flood	Seton River (Lillooet)	Moderate	N/A	Very High	High	C	-
10697	Clear-water	Flood	Mashiter Creek	Moderate	N/A	Very High	High	A	HA, RA, MA
10764	Clear-water	Flood	Brew Creek	Moderate	N/A	Very High	High	B	HA
10376/12166/ 10173	Clear-water	Flood	Mamquam River	Moderate	N/A	High	High	A	HA, RA, MA
10408	Clear-water	Flood / Reservoir	Daisy Lake (Cheakamus Dam)	Moderate	N/A	High	High	A	HA
10355	Clear-water	Flood / Lake	Millar River/ Nita Lake	Moderate	N/A	High	High	B	HA
10354/10881/ 10879	Clear-water	Flood / Lake	Alta Creek/ Alta Lake / Green Lake	Moderate	N/A	High	High	B	HA
10685	Clear-water	Flood	Stawamus River	Moderate	N/A	High	High	A	HA, RA, MA
10450/ 12071/ 10457 10453/ 10454	Clear-water	Flood	Fraser River (Lillooet)	Moderate	N/A	Very High	High	C	Unknown
10458	Clear-water	Flood	Gates River	Moderate	N/A	High	High	C	Unknown
10448/10441	Clear-water	Flood / Lake	Seton and Anderson Lakes	Moderate	N/A	Very High	High	C	Unknown
10698	Clear-water	Flood	Ring Creek	Moderate	N/A	High	High	C	Unknown
1A, 1B, 1C, 1D (10135/ 10136/ 10137 / 10138)	Volcanic	Volcanic	Mount Meager Volcanic Complex	Low to High		High to Very High	High to Very High	C	-
2A, 2B, 2C, 2D, 2E (10139/ 10140/ 10141/ 10142/ 10143)	Volcanic	Volcanic	Mount Garibaldi Volcanic Complex	Low to Moderate		High to Very High	High	C	-
3A, 3B, 3C (10144/ 10145/ 10146)	Volcanic	Volcanic	Mount Cayley Volcanic Complex	Moderate		High to Very High	High	C	-

Notes:

1. A = existing detailed assessment; B = existing detailed assessment may not be current or complete; C = no existing detailed assessment, or assessment exists but is not publicly available.
2. Types of assessments include hazard assessment (HA), risk assessment (RA) and mitigation assessment (MA). The assessments indicated are ones that BGC was aware of at the time of writing.

#### L-1.2.1 Clear-Water Floodplain Assessments

Clear-water flood hazard areas include areas containing historical floodplain mapping, detailed flood hazard mapping by third parties, and areas where detailed flood hazard mapping has not yet been completed. This study informs decisions to complete additional flood hazard mapping in new areas and where required to address the limitations of historical floodplain mapping. Flood hazard maps will help identify potential impacts to people and critical infrastructure in the floodplain and should be used to plan future development or inform mitigation planning.

Table L-2 highlights examples of clear-water flood hazard areas considered high priority for consideration in next steps of geohazard risk management framework (i.e., Seton River, Gates River, Fraser River at Lillooet).

For areas with existing detailed flood hazard mapping (Appendix E, Section E.2), BGC suggests that mapping results (detailed hazard maps) be organized for consistent display and data organization across mapping areas. While the outcome would be limited by the original mapping approaches, this would support consistent decision making and application in policy.

##### L-1.2.1.1 Clear-Water Floodplain Mapping Approach and Overview

Modernized floodplain maps should be consistent with the EGBC Guidelines for Floodplain Mapping and Flood Assessments in BC (2017). Flood Hazard Assessments at “Class 2 to 3” level of effort (EGBC, 2018) are recommended for clear-water flood sites. The suggested approach described herein should be adapted for individual sites.

##### L-1.2.1.2 Suggested Work Plan

Table L-3 lists recommended tasks for each area to be mapped. Some tasks are further described in the sections which follow. BGC notes that tasks will differ in detail for individual areas.

**Table L-3. Recommended clear-water floodplain mapping work plan.**

Activities	Tasks	Deliverables/Products	Resources
Base Data Compilation	Survey and Base Data Collection	Base inputs for hazard analyses and study integration such as historical air photographs, regional geology maps, land use coverage maps, lidar data, bathymetry data.	Bathymetric surveyors Qualified Professionals District staff Project stakeholders
	Asset and Elements at Risk Inventory Update	Base inputs for hazard analyses and study integration	BGC team Qualified Professionals Project stakeholders
Field Work	Site visit to evaluate conditions	Qualitative assessment of flood hazards including documentation of existing flood and erosion protection	Qualified Professionals
Analysis	Hydrology and Climate Change Assessment	Hydrologic inputs for hydraulic modelling including climate-change adjusted precipitation and runoff inputs and dam breach scenarios	Qualified Professionals
	Hydraulic Modelling	Model outputs showing flood extent, flow depth and velocity.	Qualified Professionals
	Channel Stability Investigation	Geomorphological inputs for flood hazard maps to show areas prone to erosion. Bank erosion assessment results and rates.	Qualified Professionals
	Study Integration	Integration of new hazard mapping with this current study, including updates to risk prioritization results and web application display.	Qualified Professionals District staff Project stakeholders
Final Deliverables	Hazard Map Production	Clear-water flood hazard maps showing the areas of inundation at different return periods	Qualified Professionals
	Reporting and Data Services	Description of methods, results, and limitations, and data and web services for dissemination of study results	District staff Project stakeholders

### Base Data Collection

Base data collection includes:

- Lidar DEMs
- Channel bathymetry data
- Historical airphotos
- High resolution ortho imagery
- Gauge rating curves and historical cross-section surveys
- Lake levels
- Historical highwater marks
- Detailed survey, condition assessment and geotechnical stability data for dikes, where applicable
- More detailed review of previous reports (e.g., flood hazard, risk assessments, terrain maps, watershed assessments, resource inventory maps, geological/geotechnical reports and/or maps).

Base data collection would also include items such as: thalweg delineation, top of bank, bridge details, culvert details, geometry details for all flood control structures, cross sections of structures such as dikes and berms, elevations of buildings located in the floodplain, geo-referenced photos of surveyed features, and interviews with stakeholders as feasible.

Lidar is used in flood mapping to provide detailed topographic information that is not evident on topographic maps generated from photogrammetry. However, Lidar surveys are unable to penetrate water surfaces. To account for channel capacity below the previously surveyed water elevation, bathymetric surveys would be required. These surveys develop cross-sections at set intervals for the length of the study watercourse. Post-processing of the bathymetric data is required to integrate the bathymetry with the Lidar to generate a digital elevation model (DEM) for use in hydraulic modelling.

A site visit will be required to evaluate bank and channel bed conditions, such as existing bank protection, grain size, vegetation type and rooting depths. This information will inform channel stability evaluations.

The asset and elements at risk inventory compiled as part of this assessment may also need to be updated if needed. This will include details not captured in the current work but required for hydraulic model setup.

### Hydrology and Climate Change Assessment

Relevant historical flow data from the systematic record will need to be gathered for each site, reviewed and compiled. Additional values will need to be incorporated based on historical accounts, where available. A flood frequency analysis (FFA) will need to be completed to develop return period design discharge values.

As part of the hydrology assessment, climate change predictions for the study area will also need to be reviewed and considered in the time-series analysis for climate (e.g., precipitation, temperature) and runoff used to develop peak flows for hydraulic models.

### Hydraulic Modelling

A hydraulic model – preferably two-dimensional – should be generated from the DEM and FFA for each site in order to develop inundation extents, flood depths and peak flow velocities for clear-water floods. Site-specific historical flood discharge and elevation, where available, would be used to validate the modelling. Discharge and survey water levels should also be collected as part of the bathymetric survey to help with model calibration. A sensitivity analysis would also be conducted for key parameters (e.g., roughness). Flood model scenarios may need to include dike breach modelling, where appropriate.

### Channel Stability Investigation

The main objectives of this task item are to provide qualitative and quantitative information about the lateral channel stability along a given study reach. Depending on site specific conditions, the main tasks could include:

- Georeference or orthorectify historical air photos
- Delineate channel banks and thalweg from historical air photos
- Compare channel cross-sections, where historical surveys exist
- Evaluate Lidar for relict channels
- Quantitative analysis of bank erosion threshold flows and erosion extents
- Evaluate and map areas with avulsion potential and bank erosion potential for design flood discharges.

#### **L-1.2.2    Reservoirs**

Appendix E describes the approach used to identify clear-water flood hazard areas, including flood hazard extents around the boundary of regulated water bodies (reservoirs). The scope of work did not consider regulation of lake levels or additional geohazard types that can result from high and/or fluctuating lake levels. For example, these hazards include:

- Flood inundation
- Shoreline erosion
- Impact by landslides and associated landslide-generated impulse waves
- Groundwater mounding
- Wind- and boat-generated waves
- Storm surge.

Table L-2 highlight one example of a high priority clear-water flood hazard areas that is a regulated water body (Daisy Lake). Following consideration of the full list of prioritized clear-water flood hazard areas, BGC suggests using an ‘impact line’ approach if further assessment is considered on regulated water bodies. The approach is based on guidelines provided by the International Commission on Large Dams (ICOLD, 2002), and has been adopted by BC Hydro (BCH) for the analysis of reservoir geohazards at Site C (McDougall et al., 2015). It recommends that individual lines be established to delineate the potential types of hazards around a reservoir, and where possible that the position of the lines be linked to a specified likelihood of event occurrence or exceedance. This approach provides for greater transparency

## Impact Line Approach

STABILITY IMPACT LINE

EROSION IMPACT LINE

GRAVEL, SAND, SILT AND CLAY

BEDROCK

FLOOD IMPACT LINE

MAXIMUM NORMAL RESERVOIR LEVEL (FULL SUPPLY LEVEL)

FLOOD AND WAVE ALLOWANCE

PREDICTED EROSION DISTANCE

RESERVOIR

CURRENT RIVER LEVEL

The *Flood Impact Line* is the boundary beyond which land would not be expected to be affected by floods, wind-generated waves, storm-surges and/or waves caused by boats and small landslides, and groundwater infiltration. Flood Impact Lines can be set to a specified elevation above the Maximum Normal Reservoir Level.

The *Stability Impact Line* is the boundary beyond which land would not be expected to be affected by landslide events caused by the impoundment and operation of the reservoir. It accounts for the predicted amount of shoreline erosion over a 100-year period of reservoir operation, potential changes in groundwater levels and gradual flattening of slopes above the reservoir shoreline using appropriate ultimate (long term, shallow) slope angles for the geological units present around the shoreline.

L-12



elevations higher than the Flood Impact Line. The inundation of these areas can be modelled numerically to estimate the Impact Line.

Raised reservoir levels can also increase the potential for fan-delta avulsions and bank erosion during steep creek geohazard events, i.e., where the coincidence of high lake levels and high creek flows can promote upstream avulsions. The Flood Impact Line approach cannot account for these types of reservoir hazards, and they are best considered as part of detailed steep creek assessments where this hazard is credible.

### L-1.2.3 Steep Creek Geohazards Assessments

Most of the stream channels prioritized in this current study are small creeks subject to steep creek processes that carry larger volumetric concentrations of debris (i.e., debris floods and debris flows) than conventional clear-water floods. These processes are typically more destructive than clear-water floods and require different assessment and mapping methods.

Table L-2 highlights steep creek hazard areas considered high priority for consideration in next steps of geohazard risk management framework, based on the current regional geohazard risk assessment.

#### L-1.2.3.3 Steep Creek Geohazard Assessment Approach and overview

As per EGBC Guidelines for Legislated Flood Assessments in BC (EGBC, 2018) and Landslide Assessments in British Columbia (EGBC, 2023), BGC suggests that “Class 3” Flood Hazard Assessments for Debris Floods, or a “Class 2” or “Class 3” Landslide Hazard Assessment for Debris Flows be completed for the prioritized steep creek flood hazard sites. The selection of appropriate level of effort will be dependent upon the size of the study area and elements at risk.

The objective of the assessment is to generate hazard maps for each fan. Steep creek geohazard maps would be created with similar objectives to clear-water flood hazard maps: to describe the threat of a series of steep creek flood hazard scenarios at a given location based on their anticipated extent and intensity (destructive potential). Intensity is a function of flow depth, velocity, scour and debris deposition, all of which vary depending on hazard magnitude and probability of occurrence.

The assessment would include a detailed characterization of in-scope steep creek flood hazards, in particular:

- Development of a preliminary frequency-magnitude (F-M) curve for steep creek flood hazards.
- Identification of active and inactive<sup>1</sup> portions of the alluvial fan and areas potentially susceptible to avulsion or bank erosion during the specified steep creek flood hazard return periods.

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

- Numerical modelling of geohazard scenarios to estimate impact areas, flow velocity, and flow depth for a spectrum of return periods where appropriate from the F-M analysis.
- Consideration of climate change impacts on the frequency and magnitude of steep creek flood hazard processes.
- Consideration of long-term aggradation scenarios on the fan.
- Consideration of processes specific to fan-deltas (rapid channel backfilling during times of high lake levels).

F-M relations are defined as sediment volumes or peak discharges related to specific return periods (or annual frequencies). This relation forms the backbone of any hazard assessment because it combines the findings from F-M analyses and is the basic input to any future numerical modeling and hence informs components of hazard mapping.

Table L-4 lists tasks suggested for each steep-creek hazard study area. Some tasks are further described in the sections which follow. BGC notes that tasks included in the table are generalized and will differ for individual project areas.

**Table L-4. Suggested steep-creek hazard mapping work plan for each steep-creek hazard area.**

Activities	Tasks	Deliverables/Products	Resources
Data Compilation	Base Data Collection	<ul style="list-style-type: none"> <li>Base inputs for hazard analyses and study integration.</li> </ul>	<ul style="list-style-type: none"> <li>Qualified Professional</li> <li>District staff</li> <li>Provincial staff</li> </ul>
	Asset and Elements at Risk Inventory Update	<ul style="list-style-type: none"> <li>Base inputs for hazard analyses and study integration.</li> </ul>	<ul style="list-style-type: none"> <li>Qualified Professional</li> <li>District staff</li> </ul>
Analysis	Steep Creek hazard characterization and analysis (desktop and field)	<ul style="list-style-type: none"> <li>Field observations to inform hazard analyses and modelling (surface observations and test pits)</li> <li>Field review of any existing structural protection structures (engineered or non-engineered)</li> <li>Regional F-M relationships</li> <li>Hydrologic inputs for hazard modelling.</li> </ul>	<ul style="list-style-type: none"> <li>Qualified Professional</li> </ul>
	Climate Change Assessment	<ul style="list-style-type: none"> <li>Qualitative description of anticipated changes to F-M under climate change scenarios</li> </ul>	<ul style="list-style-type: none"> <li>Qualified Professional</li> </ul>
	Hazard Modelling	<ul style="list-style-type: none"> <li>Model outputs showing flow intensity (flow extent, flow depth and velocity), that form the basis for hazard mapping</li> </ul>	<ul style="list-style-type: none"> <li>Qualified Professional</li> </ul>
	Landslide Dam Outburst Flood (LDOF) Analysis	<ul style="list-style-type: none"> <li>Model outputs showing flow intensity (flow extent, flow depth and velocity) that would result from a LDOF.</li> </ul>	<ul style="list-style-type: none"> <li>Qualified Professional</li> </ul>
	Channel Stability Investigation	<ul style="list-style-type: none"> <li>Geomorphological inputs for flood hazard maps.</li> <li>Bank erosion and set-back analysis</li> </ul>	<ul style="list-style-type: none"> <li>Qualified Professional</li> </ul>
	Study Integration	<ul style="list-style-type: none"> <li>Integration of new hazard mapping results with previous study.</li> </ul>	<ul style="list-style-type: none"> <li>Qualified Professional</li> <li>District staff</li> </ul>
Final Deliverables	Hazard Map Production	<ul style="list-style-type: none"> <li>Steep creek hazard maps.</li> </ul>	<ul style="list-style-type: none"> <li>Qualified Professional</li> <li>District staff</li> </ul>
	Reporting and Data Services	<ul style="list-style-type: none"> <li>Description of methods, results, and limitations, and data and web services for dissemination of study results.</li> </ul>	<ul style="list-style-type: none"> <li>Qualified Professional</li> <li>District staff</li> </ul>

### Data Compilation

The base data collection would include compiling all relevant site data relating to steep creek flood hazards. Items to collate would include:

- Lidar DEMs
- Historical airphotos
- High resolution ortho imagery
- Gauge rating curves and historical cross-section surveys (if applicable/available)
- Historical highwater marks (if readily available)
- Bathymetric maps for fan-deltas (if available)
- Accounts of historical steep creek floods and records of sediment deposition (if available)
- Previous reports (e.g., flood hazard, risk assessments, terrain maps, watershed assessments, resource inventory maps, geological/geotechnical reports and/or maps).

Derivative high-resolution DEMs from Lidar would be used to identify the locations of previous avulsions, aggradation, and historical steep creek flood deposits.

### Steep Creek Hazard Characterization and Analysis

Steep creek flood hazard characterization and mapping involves: developing an understanding of the underlying geophysical conditions (geological, hydrological, atmospheric, etc.); identifying and characterizing steep creek flood processes in terms of mechanism, causal factors, trigger conditions, intensity (destructive potential), extent, and change; developing steep creek F-M relationships; and identifying and characterizing geohazard scenarios to be considered in the steep creek flood hazard maps.

*Desktop Study:* Prior to field work, a desktop study would be completed to assess the frequency of past steep creek flood hazards from airphotos, previous reports, and historical records. Qualitative observations would be made of any changes in watershed condition over the historical record (e.g., clear cuts, road construction, wildfires, insect infestations), as well as changes in the steep creek geomorphology (e.g., aggradation, erosion, avulsion, sediment input, landslide frequency) and artificial fan surface alterations (e.g., excavations, fill placements, developments). The desktop study would inform the key locations to be observed during field work. BGC suggests that prior to field work being conducted, SLRD or stakeholders (i.e., those commissioning the work) should inform residents of the purpose and proposed timing for this field work.

*Fieldwork:* Fieldwork would provide key information for the steep creek flood hazard analysis. The steep creek channels would be traversed from the fan margins to as high as what can be accessed safely. Upper watersheds should also be accessed (on foot if possible) when important sediment sources have been identified that require field confirmation (e.g., landslides or artificial instabilities such as active or deactivated logging roads, waste rock placement, sumps). Helicopter overview flights would be used for channel sections that are not safely accessible from ground traverses. Stakeholder input would also be gathered during fieldwork, as feasible.

Surface field observations would include:

- Location and extent of past steep creek floods from surface geomorphic evidence (e.g., channel levees, boulder lobes, paleochannels, etc.)
- Channel measurements to identify high water/scour marks to estimate the peak flow of previous steep creek floods
- Channel cross-sections
- Grain size distributions where appropriate
- Sediment supply sources
- Stratigraphy of natural exposures
- Areas of channel aggradation and/or erosion
- Visual assessment of existing steep creek flood mitigation structures (e.g., bridges, dikes, rip rap, fills, groins, deflection berms, debris basins).

Where possible, dendrogeomorphological methods could be used to determine the timing and magnitude of past steep creek flood hazards. This sampling involves coring trees using a 4 mm-diameter incremental tree borer. Under ideal conditions, this method allows dating of past steep creek flood events several hundred years into the past. The dendrogeomorphological record can complement the historical airphoto record for developing a preliminary F-M assessment. The feasibility of applying dendrogeomorphological methods is usually determined during the site inspection.

Following field work, the preliminary F-M relationship would be developed for steep creek flood hazards and used to develop scenarios for numerical hazard modelling.

### Hazard Modelling

Hazard modelling is necessary to estimate flow inundation area, flow velocities, flow depth, erosion, and sediment aggradation. The most appropriate two- and three-dimensional modelling software would typically be selected after an initial assessment of site conditions. As new software packages constantly emerge, a decision as to the most appropriate model would be made at the time of the study. The modelling process may include:

- Model calibration of rheological and sediment entrainment parameters using the extents, thicknesses, and velocities (where available/applicable) of previous steep creek flood events, and measured sediment volumes in the channel. This calibration would be compared to empirical relationships.
- Predictive modelling of flows for the range of peak discharges associated with the return periods determined from the hazard analysis with rheological parameter combinations determined via the calibration process.

### LDOF Analysis

Watershed-fan systems with potential for Landslide Dam Outburst Floods (LDOFs) in the upper basins have been identified in the current regional geohazard risk assessment. LDOF have the potential to generate higher magnitude flows than “typical” steep creek processes occurring on

the creek. Table L-5 lists the creeks that were identified as subject to high or very high LDOF potential as a flag for consideration in future studies.

**Table L-5. List of creeks identified as subject to high LDOF potential.**

Hazard ID	Creek Name	LDOF Potential Rating
10280	Miller Creek	High
10179	Spider Creek	High
65962	Puck Creek	High
65986	Dickey Creek	High
10343	Culliton Creek	High
10194	Elaho River Tributary 1	High
10252	Rubble Creek	High
10325	Rutherford Creek	High
10312	Squamish River Tributary 7	High
65922	Ross	High
65926	Middle Lillooet W	High
66093	Camoo Creek	High
66098	Capricorn Creek	High
66100	Affliction Creek	High
66103	Canyon Creek	High
66130	Little Leon Creek South	High
66000	Little Leon Creek	High
10334	South Creek	Very High
66164	Turbid Creek	Very High
66163	Shovelnose Creek	Very High
66161	Wedgemount Creek	Very High

### Additional Considerations

Very low hazard areas on fans, which are sometimes defined as “inactive” portions of the fan, and which are often paleofans, formed during a particularly active period in the early Holocene, can also be identified, if they exist. These areas are often hydraulically removed from the steep creek channel due to deep channel erosion or other factors and identifying these areas can be helpful for land use and development planning.

Most fans are active landforms that change over time. Areas subject to aggradation, channel erosion, or channel avulsions will need to be identified through desktop studies, site visits, and from the hazard modelling. In particular, fan-deltas (fans entering into water bodies) can have higher frequencies of aggradation and avulsions than land-based alluvial fans due to the



interactions between the channel and still-water processes (van Dijk et al., 2012). All areas subject to these noted processes will be identified in the final hazard map.

#### L-1.2.4 Volcanic Hazards

*Recommendation:*

- *Detailed studies to evaluate potential impacts and inundation areas from non-eruptive volcanic hazards*

Volcanic hazard extents used in this study were interpreted based on mapping and modelling conducted by third parties as well as some qualitative interpretation by BGC. Thus, they should not be viewed as either complete or precise. BGC did not conduct any numerical modelling in order to estimate the hazard extents of the scenarios considered.

Table L-2 highlights examples of volcanic hazard areas considered high priority for consideration in risk management decision making. Table L-1 summarized data gaps and provides recommended actions to resolve these gaps. Such work could potentially:

- Assume various level eruptions of Mount Meager to determine downstream responses by uniting rock avalanche, dam outbreak and flood routing models with expected sedimentation in Lillooet River Valley.
- Assume various non-eruptive rock avalanches on the flanks of the Mount Meager volcanic complex with damming scenarios of Lillooet River and Meager Creek and subsequent outbreak floods.
- Probabilistically assess outbreak flood magnitude from Mt. Cayley rock avalanches damming Squamish River and route large LDOFs down the Squamish River valley all the way to Howe Sound.
- Assume various collapse scenarios and possibly rapid draining of lesser Garibaldi Lake and route such floods down Cheakamus and Squamish Rivers.
- Assume volcanic collapses in the headwaters of Culliton Creek and route ensuing debris flows to the Cheakamus -Culliton Creek confluence, run dam outbreak flood modeling and route flood flow down Cheakamus and Squamish Rivers.
- Assess and evaluate various possible warning systems for the above scenarios in terms of their cost, effectiveness and feasibility.

#### L-1.3 Post-wildfire Geohazards Assessments

*Recommendation:*

- *Detailed assessments following the occurrence of wildfire*

The wildfire-adjusted risk ratings presented in this assessment provide a foundation for more detailed hazard and risk assessments following a wildfire. Magnitudes of post-wildfire debris flows were estimated using watershed and rainfall data and estimated wildfire burn severity characteristics. Following a wildfire and generation of a burn severity map, post-wildfire debris flow volume estimates can be modified to reflect actual wildfire severity conditions in the watershed area. The refined post-wildfire debris-flow volume estimate can then be implemented into runoff modeling applications to refine the spatial probability of impact and flow intensity.

If a wildfire occurs in one of the watersheds associated with a hazard area assessed in this study, BGC recommends a detailed assessment be performed to refine the estimates provided in this study.

#### L-1.4 Long-Term Geohazard Risk Management

*Recommendation:*

- *Incorporate and build upon this study to develop a long-term geohazard risk management plan that adapts to changing conditions*

The results of this study is expected to help the SLRD and stakeholders identify the need and level of effort required for further assessments based on existing hazards and elements at risk. However, the assessment is a snapshot in time. It will require regular updates and maintenance to remain up-to-date for decision making over the long term. Procedures to identify requirements for updates and maintenance would need to consider factors such as:

- Data gaps such as those identified in this study
- Landscape changes affecting hazard levels (e.g., forest fires, new hazard events, or the construction of mitigation measures)
- Changes to elements at risk (e.g., new development)
- Future geohazards studies that should be incorporated into the integrated knowledge base.

This section summarizes points of consideration for long-term geohazard risk management that would build on the results of this study. A key objective is to support an iterative approach to long-term, multi-stage risk management that can:

- Dynamically address changing conditions (landscape, hydro-climate, and land use).
- That is not dependent on any single large grant for implementation (i.e., moves away from major, grant-funded studies towards annual maintenance of a knowledge base).
- That considers not only risk tolerance criteria, but a structured approach to determine how far can risk be reduced with available resources.

This framework encompasses applying a continuous algorithm of relative risk-based assessment between hazard areas (e.g., building from this study), then iterative management of at-risk sites based on their stage in the risk management process (Figure L-2).

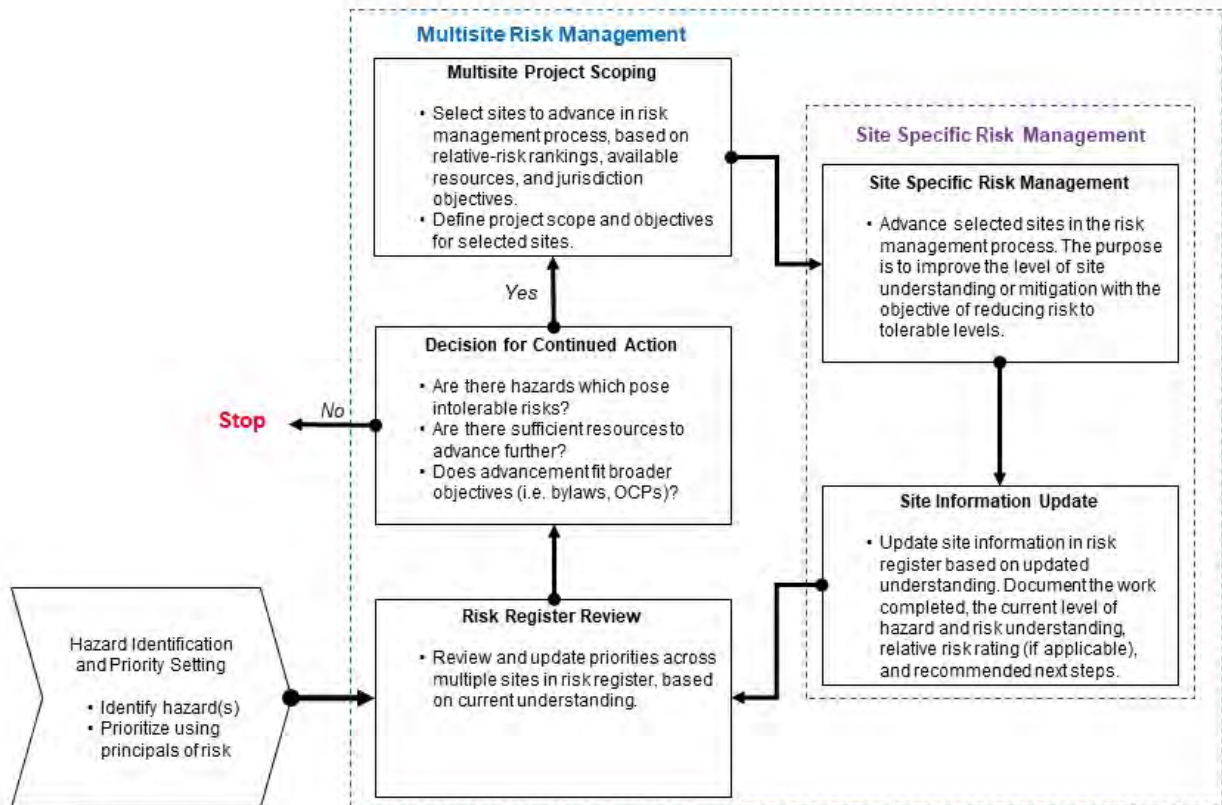
Once relative risk levels are established, high-level review of mitigation options and costs is also helpful to support decisions that maximize the level of risk reduction given constrained resources. For example, the “worst” (highest risk) location may not necessarily be where the greatest overall level of risk reduction can be achieved from the perspective of District-wide decision making, once the effort to reduce risk is considered. Following definition of risk tolerance levels and objectives, the intention would be to reduce risk “As Low As Reasonably Practicable” (ALARP), where the effort to reduce risk is considered in relation to the level of risk reduction gained.

This approach can be conceptualized as a ‘risk register’, where this assessment provides the starting register to build on. To continuously maintain priorities and actions between geohazard

areas (i.e., those tabulated in the risk register), any work carried out for a specific site should have two important outcomes:

1. An updated relative risk-level and associated ranking in the risk-register, based on the advancement of site understanding or implemented risk-reductions measures.
2. Recommendations for next steps in risk management.

The objective of the process is to provide a systematic, transparent, and cost-efficient approach to understand and continuously manage geohazard risks across multiple sites.



**Figure L-2. Schematic of multi-site risk management approach.**

### L-1.5 Geohazards Monitoring

#### *Recommendation:*

- Develop a path to design and implement geohazard monitoring and warning systems where appropriate.

Real-time precipitation and stream flow monitoring are key inputs informing flood-related emergency monitoring and response.

Environment and Climate Change Canada (ECCC) maintains the Canadian Precipitation Analysis (CaPA) system, which provides objective estimates of precipitation in 10 km by 10 km (at 60° N) grids across North America. Figure L-3 shows an example of 24-hour accumulated

precipitation in southern British Columbia, reported via BGC's RNT<sup>2</sup>. ECCC also provides the Regional Deterministic Prediction System (RDPS), which is a 48 hour forecast data (at an hourly timestep) that is produced four times a day at similar resolution to the CaPA data. The forecast dataset includes many climate variables, including forecasted precipitation.

The WSC maintains approximately 1900 real-time stream flow gauges across Canada, of which 13 are located in the SLRD (Table L-6). Figure L-4 shows example screen shots of a real-time flow gauge location and metadata from BGCs RNT™, and the WSC real-time hydrograph connected by a weblink.

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<sup>2</sup> Results anticipated to soon be made available at finer resolution (1-3 km grid).



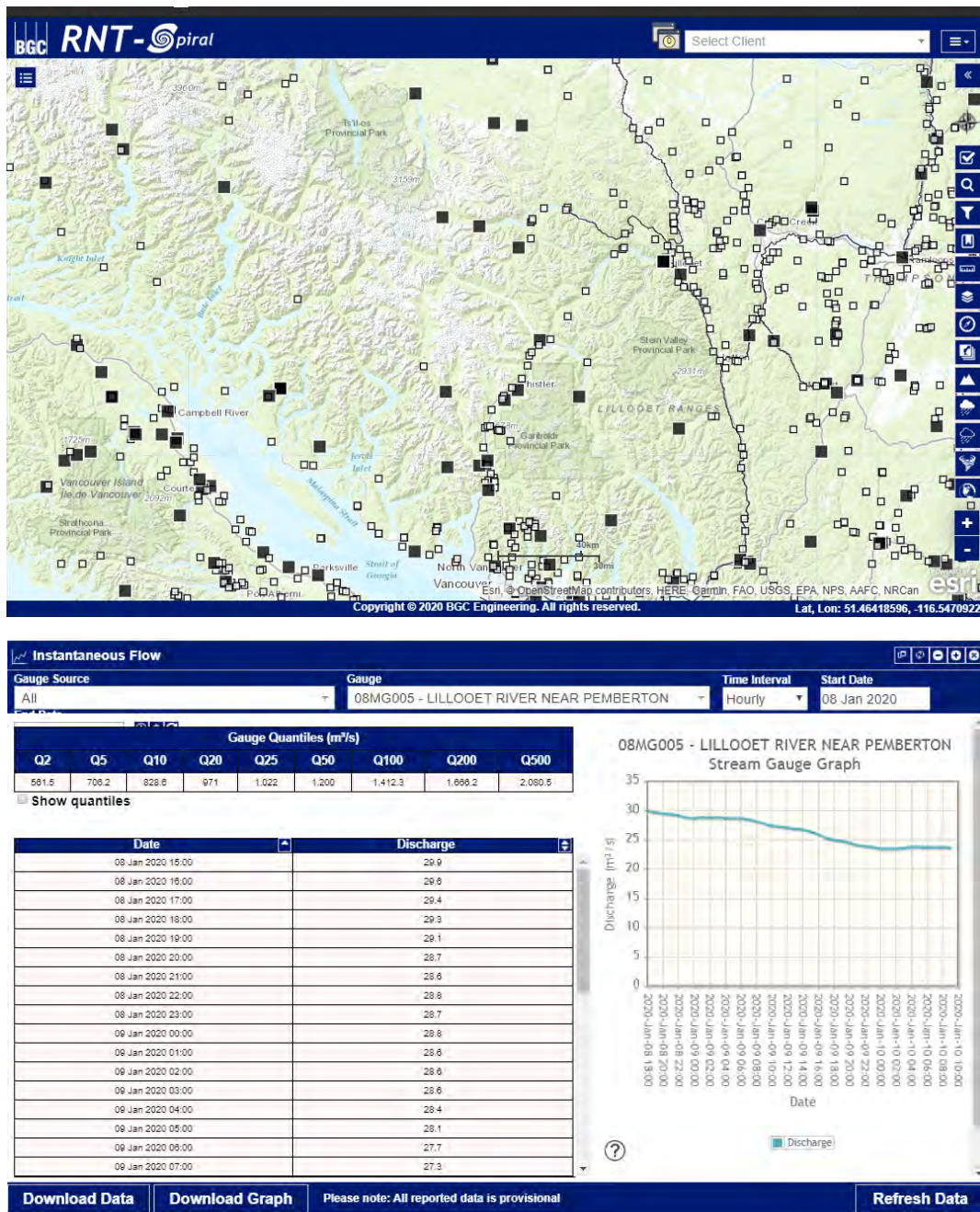


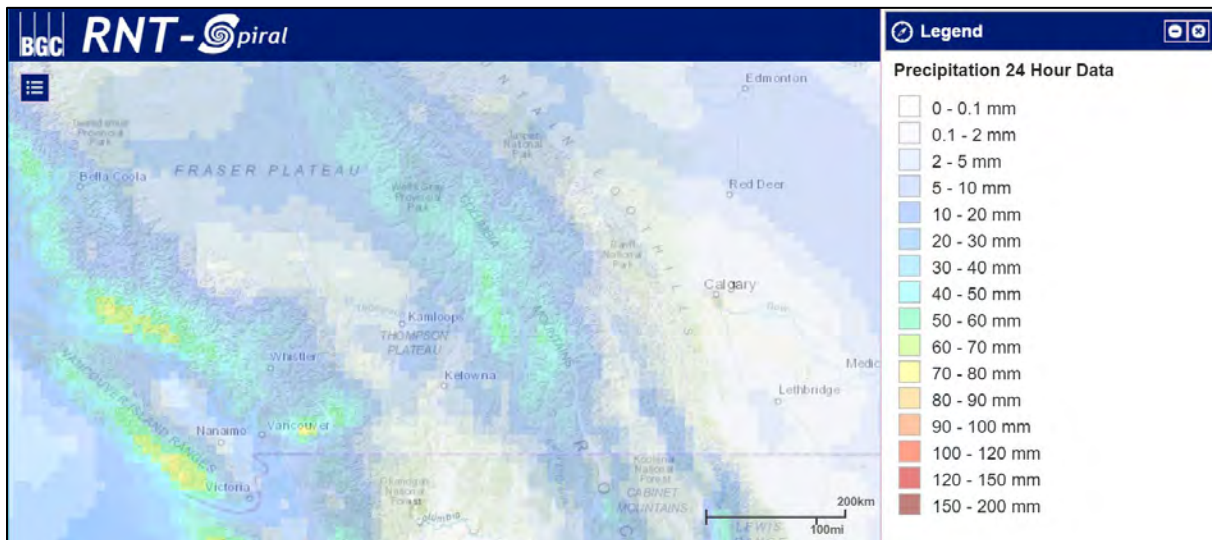
Figure L-3. Screen capture of BGC RNT™ showing available real-time streamflow gauges in the District (solid black squares) and window showing real-time flows from WSC gauge 08MG005 – Lillooet River near Pemberton. Source: WSC (2020, via BGC RNT™).

**Table L-6. List of WSC real-time streamflow gauges within SLRD**

WSC Station Number	Name
08GA022	Squamish River near Brackendale
08GA043	Cheakamus River near Brackendale
08GA071	Elaho River near the Mouth
08GA072	Cheakamus River above Millar Creek
08GA076	Stawamus River at Highway No. 99
08ME002	Cayoosh Creek near Lillooet
08ME003	Seton River near Lillooet
08ME023	Bridge River (South Branch) below Bridge Glacier
08ME027	Hurley River below Lone Goat Creek
08ME028	Bridge River above Downton Lake
08MF040	Fraser River above Texas Creek
08MG005	Lillooet River near Pemberton
08MG026	Fitzsimmons Creek below Blackcomb Creek

For real-time monitoring, a monitoring system could be compared to predetermined stage or discharge thresholds and an alert sent to relevant emergency response staff if the threshold is exceeded. The monitoring system could monitor multiple thresholds for a given site and hence provide staged warning levels. For forecasted data, a precipitation forecast monitoring system could calculate a weighted precipitation average over the catchment of a high priority stream. The weighted precipitation forecast could then be compared to a threshold and an alert sent to relevant emergency response staff if the threshold is exceeded. BGCs RNT™ also provides access to precipitation hindcasts and forecasts produced by ECCC's Meteorological Service. These data can be visualized and used to produce warnings of extreme rainfall (Figure L-4).





**Figure L-4. Example of 24-hour accumulated precipitation in southern British Columbia on November 3, 2018. Source: EC-MSC Canadian Precipitation Analysis (CaPA) (2018, via BGC RNT™).**

BGC understands that the display of hazard monitoring data is one objective in the development of the EMBC Common Operating Picture (COP). Similar systems have also been implemented with ongoing use over the past 15+ years in the private sector, such as geohazard risk management systems for major utilities (i.e., the energy sector). Such existing approaches could be adapted for application to communities. Implementation could be split into phases such as:

1. Addition of real-time stream flow gauges, CaPa precipitation data, and data from on-site weather stations to a web application for view alongside prioritized geohazard areas.
2. Determination of appropriate alert thresholds as part of more detailed assessment (i.e., scenario modelling), incorporating the results of detailed studies where existing.
3. Decision making and communication protocols for staff, elected officials, and the public, with reference to existing processes.
4. Development of alert functions and information management systems (software development) for implementation.

In this work, BGC emphasizes the difference between converting flow and precipitation data into information display for situational awareness (i.e., COP), versus their interpretation and use by subject matter specialists for hazard warning, communication, and decision making.

Determining alert thresholds would require more detailed geohazard assessment to determine input requirements, estimate thresholds and evaluate limitations and uncertainties. This work could also include estimation of alert thresholds for post-wildfire geohazard monitoring.

BGC also notes that there are substantial efficiencies of scale in hazard monitoring and warning systems. Prior to initiating such work, BGC suggests review of existing approaches and multi-stakeholder engagement to define interest and resources in supporting such work.

For example, BGC operated a debris-flow warning system on Cheekeye River fan in 2019, as part of site investigations (now concluded) for the design of a large debris-flow barrier. The system provided alert thresholds informing decisions to stop work during periods of elevated debris-flow hazard.

### L-1.6 Policy Integration

#### *Recommendations:*

- Review plans, policies and bylaws related to geohazards management
- Review Development Permit Areas (DPAs) within the SLRD, in light of the hazard extents identified in this study.

#### L-1.6.1 Policy Review

Jurisdictions within the SLRD administer policies and bylaws that rely on flood and steep creek hazard information and reference flood-related terminology. While standards-based approaches to geohazards management are the norm across Canada, risk-informed approaches that target a level of risk reduction, rather than a standard flood return period, are being increasingly considered (Ebbwater, 2016).

Through the application of risk-informed policy in jurisdictions such as the Town of Canmore and the District of North Vancouver, the benefits and challenges of such approaches are becoming apparent (Strouth et al., 2019). BGC suggests that SLRD review flood and steep-creek related policy, as well as geohazard and risk terminology, from the perspective of:

- Developing a risk-informed approach to geohazards management
- Defining risk evaluation criteria that provide the foundation for consistent risk reduction decision making (i.e., to define the term “safe for the use intended” in geohazards assessments for development approval applications)
- Reviewing the functional groups within government and information management systems that would be required to support the development and implementation of risk-informed community plans and bylaws by local authorities.

#### L-1.6.2 Development Permit Areas (DPAs)

Development Permit Areas (DPAs) are areas where special requirements and guidelines for any development or alteration of the land are in effect. In such areas, permits are typically required to ensure that development or land alteration is consistent with objectives outlined within applicable Official Community Plans (OCPs).

BGC recommends that government jurisdictions within the SLRD review the prioritized geohazard areas from the perspective of defining flood and steep creek DPAs.

### L-1.7 Information Management

#### *Recommendations:*

- Review approaches to integrate and share asset data and geohazard information across functional groups in government; major utility operators, stakeholders, data providers

and risk management specialists. Such an effort would assist long-term geohazard risk management, asset management, and emergency response planning.

One of the most significant barriers, and potential opportunities, to improve and reduce the cost of geohazard risk and asset management at regional scale is to increase the coordination and assembly of the data required for such work, across multiple levels and sectors of government and private industry.

Because data are commonly segregated between agency functional groups, and data models are not typically visible to the end-user, it is not necessarily obvious how important these data are to risk management. Without integrated data on geohazards and elements at risk, it is costlier to assess vulnerability and loss because there are gaps in the necessary supporting data, or more effort is required to span information silos across assets and agencies. Improving the management and provision of geohazards and elements at risk data at provincial scale is recommended by Abbott-Chapman (2018), is consistent with modernization of BC's Emergency Management Legislation (BCEMS, 2016), is the focus of 2019 UBCM Resolution B98: Resourcing A Collaborative System of Data Sharing in BC, and is an area of increased focus by the province in 2023 to develop a disaster risk and resiliency data hub.

BGC notes, however, that baseline information about geohazards and elements at risk provides the "ingredients" for geohazard risk management. Transforming this information into knowledge about risk levels and how such risks can be managed is still required. The feasibility to maintain and build a geohazards knowledge base long-term will hinge on access to well-organized and maintained information sources.

### L-1.8 Engagement

#### *Recommendation:*

- Provide training to SLRD staff who may rely on study results, tools and data services.
- Work with communities in the prioritized hazard areas to develop flood resiliency plans informed by stakeholder engagement.

The information collected for this assessment will have a broad range of application at the local jurisdiction level. BGC suggests SLRD identify potential end-users and develop a workshop for communication and training. For example, potential end users could include planners, building permit officers, geomatics/GIS support staff, and emergency response workers. Such a workshop could include the following:

- Overview of steps to identify, assess, and manage clear-water flood and steep creek risks as part of land use planning and development permitting
- Discussion of the use of information (maps and ratings) provided in this study
- Information sharing between local jurisdictions and provincial staff.

Workshops would also provide a forum to gather additional local information on hazard events and consequences to local communities that might otherwise be undetected.

### L-1.9 Indigenous Knowledge Gathering

*Recommendation:*

- Complete further work to resolve remaining gaps about culturally significant areas and risk considerations beyond primarily economic values considered in the current approaches. Indigenous-led projects should be explored as a process through which First Nations perspectives can be most directly incorporated.

There are a number of important benefits associated with including Indigenous perspectives in geohazard risk assessment projects:

- The 'written observed' record of climate, weather, hydrometrics, etc. is relatively short. In many cases, good data is only available for the last 40-50 years. Traditional Knowledge can greatly increase the period of record, which improves the robustness of analyses.
- Local and Traditional Knowledge can support better understanding of the pressures that settler communities have put on natural landscapes (e.g., logging, shoreline development), which improves understanding of present-day hazard, as well as the potential to reduce risk.
- Local and Traditional Knowledge can support better understanding of the consequence component of risk, through a more fulsome understanding of things of value and their vulnerabilities to impact than is available through public datasets.
- Indigenous perspective can be used to guide the way the study is designed, written about, and communicated to the public. Respect of data, how First Nations are portrayed in a study, and key wording around risk concepts can make a big difference in a study being received negatively or positively.

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