SQUAMISH-LILLOOET REGIONAL DISTRICT

Geohazard Risk Prioritization

FINAL
April 10, 2020

Project No.:
1358007

Prepared by BGC Engineering Inc. for:
Squamish-Lillooet Regional District

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April 10, 2020
Project No.: 1358007

Sarah Morgan
Emergency Program Manager
Squamish-Lillooet Regional District
Box 219, Pemberton, BC V0N 2L0

Dear Sarah,

Re: Geohazard Risk Prioritization – FINAL

Please find attached the above referenced report for your review. The web application accompanying this report can be accessed at www.cambiocommunities.ca. Username and password information will be provided in a separate transmission.

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

Yours sincerely,

BGC ENGINEERING INC.
per:

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

TABLE OF REVISIONS

ISSUE	DATE	REV	REMARKS
DRAFT	January 31, 2020		Original issue
FINAL	April 10, 2020		Original issue

CREDITS AND ACKNOWLEDGEMENTS

BGC Engineering would like to express gratitude to the Squamish-Lillooet Regional District (SLRD, the District) for providing background information, guidance and support throughout this project. Key SLRD staff providing leadership and support included:

- Sarah Morgan, Emergency Program Manager
- Ana Koterniak, GIS Coordinator.

The following BGC personnel were part of the study team:

- Kris Holm (Project Manager)
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- Patrick Grover
- Philip LeSueur
- Melissa Hairabedian
- Alistair Beck.

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 to be based on it is the responsibility of such third parties. BGC accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions based on this document.

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EXECUTIVE SUMMARY

The Squamish-Lillooet Regional District (SLRD, the District) retained BGC Engineering Inc. (BGC) to carry out a geohazard risk prioritization study (the regional study) for the District. The primary objective of this study is to characterize and prioritize flood, steep creek (debris flood and debris flow), and non-eruptive volcanic geohazards (lahars) in the SLRD that might impact developed properties. Collectively these processes are referred to as "geohazards" in this document. While the study encompasses both electoral areas and municipalities, BGC was retained to complete prioritization from the perspective of SLRD (not individual municipalities).

The goal 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 risk prioritization study is a step towards this goal.

The regional study provides the following outcomes across the SLRD:

- Identification and prioritization 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 prioritized 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, but 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 provincial and federal funding applications to undertake additional work related to geohazard risk management within the SLRD.

This study provides results in several ways:

- This report summarizes methods and results, with additional details in appendices.
- Access to the Cambio™ web application displaying prioritized geohazard areas and supporting information. This application represents the easiest way to interact with study results. Appendix B provides a guide to navigate Cambio Communities.
- Geodatabase with prioritized geohazard areas.
- Excel spreadsheet with attributes of prioritized geohazard areas.
- Risk Assessment Information Template (RAIT) form as required by the National Disaster Mitigation Program (NDMP).

In total, BGC identified and prioritized 2058 geohazard areas encompassing over 1615 km^2 (10%) of the SLRD (Table E-1).

Table E-1. Number of prioritized areas in the SLRD, by geohazard type.

Geohazard Type	Priority Level					Grand Total
	Very High	High	Moderate	Low	Very Low	
Clear-Water Floods (water courses and water bodies)	0	143	247	1455	0	**1845**
Steep Creeks (Fans)	16	54	57	71	3	**201**
Volcanic Geohazards	1	11	0	0	0	**12**
Grand Total (Count)	**17**	**208**	**304**	**1526**	**3**	**2058**
Grand Total (%)	**< 1%**	**10%**	**15%**	**74%**	**< 1%**	**100%**

Table E-2 lists the results worksheets, which are provided in Appendix H. These worksheets can be filtered and sorted according to priority 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-2. Results worksheets provided in Appendix H.

Appendix H (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	Summary statistics of prioritization results by jurisdiction.
Steep Creek Hazard Attributes	Attributes for all steep creek geohazard areas.
Clear-water Flood Hazard Attributes	Attributes for all clear-water flood geohazard areas.
Volcanic Hazard Attributes	Attributes for all volcanic geohazard areas.

Gaps identified in this study can be categorized as those limiting the understanding of geohazards: in the characterizing of geohazard exposure and vulnerability (i.e., the built environment); and in the characterization of existing flood protection measures and flood conveyance infrastructure. In no case does this study replace site-specific geohazard risk assessments that aim to identify tolerable or acceptable risk or that support design of mitigative works. BGC also identified opportunities to improve geohazard information management and integrate risk-informed decision making into policy.

Table E-3 lists recommendations for consideration by SLRD and local, regional, and provincial authorities. The rationale for each recommendation is 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 within the watershed. This effort would be greatly facilitated by long-term provincial support to take advantage of efficiencies of scale.

Table E-3. List of recommendations.

Type	Description
Data Gaps	• Develop a plan to resolve the baseline data gaps outlined in this study, including gaps 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).
Further Geohazards Assessments	• Geohazard areas: review prioritized geohazard areas and develop a plan to implement next steps in a framework of geohazard risk management
Long-term Geohazard Risk Management	• Consider long-term geohazard risk management programs that would build on the results of this study.
Geohazards Monitoring	• Develop criteria for hydroclimatic monitoring and alert systems informing emergency management.
Policy Integration	• Review Development Permit Areas (DPAs) following review of geohazard areas defined by this study. • Review plans, policies and bylaws related to geohazards management, following review of the results of this study. • 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).
Information Management	• 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. • Develop a maintenance plan to keep study results up to date as part of ongoing support for bylaw enforcement, asset management, and emergency management.
Training and Stakeholder Communication	• Provide training to stakeholders who may rely on study results, tools and data services.

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1. INTRODUCTION

1.1. Objectives

The Squamish-Lillooet Regional District (SLRD, the District) retained BGC Engineering Inc. (BGC) to carry out a geohazard risk prioritization study (the regional study) for the District (Figure 1-1). Funding was provided by Emergency Management BC (EMBC) and Public Safety Canada under Stream 1 of the Natural Disaster Mitigation Program (NDMP, 2018). This work is being carried out under the terms of a contract between SLRD and BGC dated December 20, 2018.

The primary objective of this study is to characterize and prioritize flood, steep creek (debris-flood and debris-flow), and non-eruptive volcanic geohazards (lahars) in the SLRD that might impact developed properties. Collectively these processes are referred to as "geohazards" in this document. The goal 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 risk prioritization study is a step towards this goal.

The regional study provides the following outcomes across the SLRD:

- Identification and prioritization 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 prioritized geohazard areas and supporting information
- Evaluation of the relative sensitivity of geohazard areas 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, but 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.

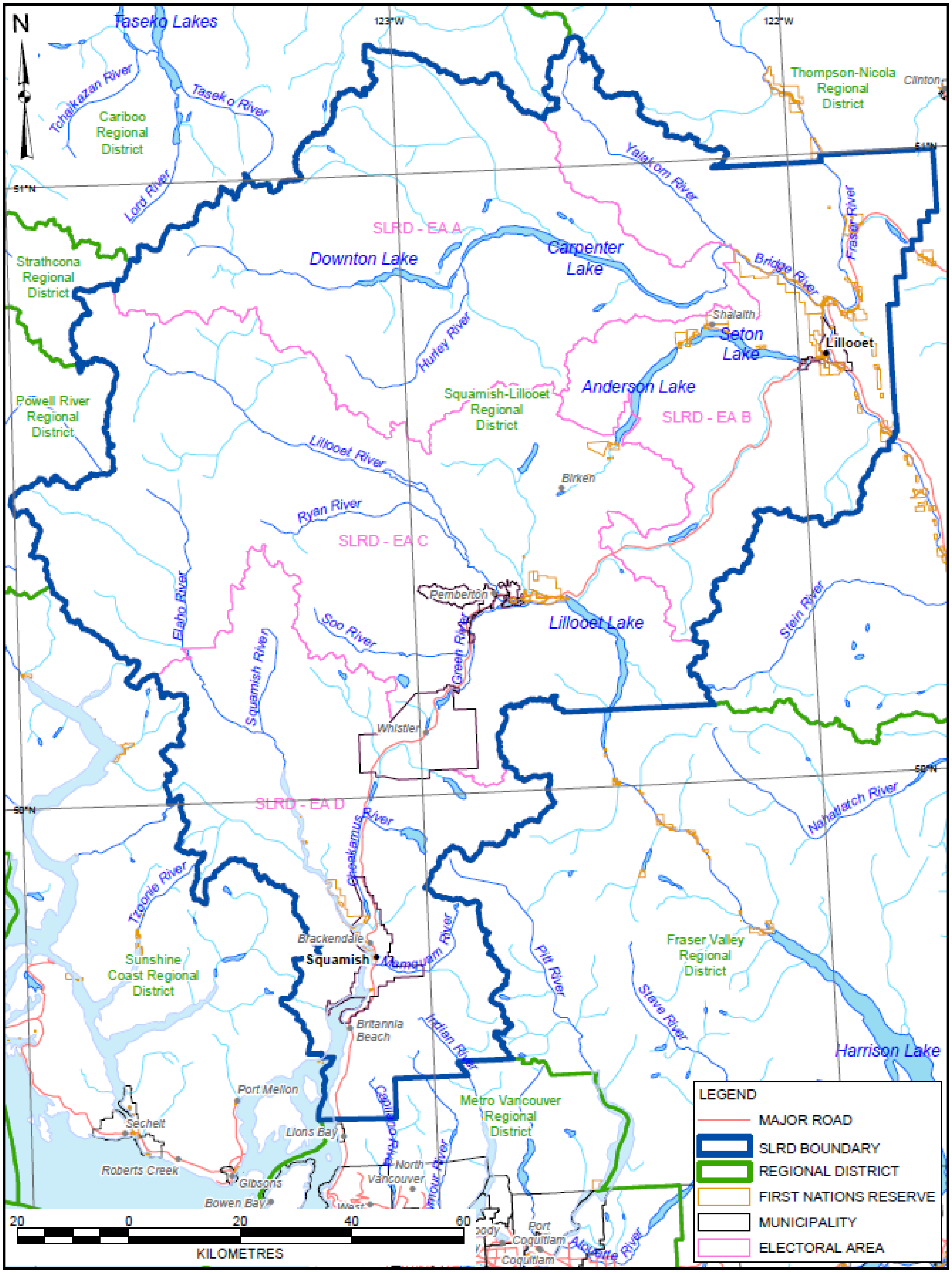

Figure 1-1. Study area.

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), as well as the Draft Alberta Guidelines for Steep Creek Risk Assessments[1] (BGC, March 31, 2017). 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 starting point for the remaining priorities, which focus on strengthening disaster risk governance, improving resilience, and enhancing disaster preparedness.

1.2. Why This Study?

Valleys within the SLRD are prone to flooding and flood-related hazards. Past flood events have occurred on large rivers such as the Squamish, Cheakamus, Lillooet, Cheekeye and Mamquam Rivers and on smaller steep creeks that are prone to debris flows. These rivers can also be affected by landslides that can potentially trigger an outburst flood event. In 2010, a large landslide on Mount Meager near Pemberton caused a temporary blockage of the Lillooet River that gradually eroded without resulting in an outburst flood. However, the event prompted the installation of an early warning system on the Lillooet River to monitor for potential sediment events in the upper valley.

Specific gaps identified at the outset of this regional study included:

- Incomplete extent: many areas subject to flood-related hazards had not yet been identified in the SLRD.
- Inconsistent extent or versions of hazard mapping between different areas: some data are potentially inconsistent across different sources and scales of assessment.
- Process range insufficiently identified: flood processes are highly diverse. Particularly at high return periods (greater than 100 years), issues such as extensive bank erosion, landslide dam outbreak floods (LDOFs), debris flows and debris floods may dominate the flood hazard.
- Inconsistent methods and scale: flood and steep creek hazards have not been assessed and/or mapped with consistent methods or level of detail across the entire SLRD.
- Inconsistent data standards: some data on flood and steep creek geohazards in the District reside in disconnected databases with inconsistent data fields and attributes.
- Inconsistent hazard ratings: prior to the current regional study, no region-wide, geospatial dataset existed, nor had consistent ratings for flood geohazards type, likelihood, magnitude or intensity been established (destructive potential).
- Incomplete metadata: documentation is rarely sufficient to make informed decisions about the use and limitations of flood geohazards data.
- Incomplete classification of elements at risk: for example, building footprints that could be used to assess flood vulnerability are only available for select buildings in the study area, and some cadastral parcels contain residential buildings that have not been identified and included in BC Assessment data.

[1] No equivalent guidelines have yet been prepared by the Engineers and Geoscientists BC or the Province of BC.

- Inconvenient format: some clear-water flood and steep creek hazard data exist within pdf format reports that cannot easily be georeferenced and integrated together to build a common knowledge base.
- Not risk-based: prior to the current study, information had not been available to support flood management decisions based on systematic assessment of both flood hazards and relative consequences at the scale of the entire SLRD.
- Limited consideration of climate change: there is currently a lack of integration between climate change and geohazards-focused studies, and there is a lack of consideration of indirect effects (i.e., changes to watershed hydrology resulting from wildfires).

These gaps are being partially addressed by this regional study and support the mandate of the SLRD to reduce or prevent injury, fatalities, and damages during flood events. The work partially fulfills the first recommendation of the Auditor General of British Columbia's February 2018 report, titled *Managing Climate Change Risks: An Independent Audit*, which is to "undertake a province-wide risk assessment that integrates existing risk assessment work and provides the public with an overview of key risks and priorities" (Auditor General, 2018).

This regional study:

- Helps address recommendations of a 2017 province-wide review of government response to flood and wildfire events during the 2017 wildfire and freshet season (Abbott & Chapman, 2018). The Abbott-Chapman report included a total of 108 recommendations to assist the Province in improving its systems, processes and procedures for disaster risk management.
- Helps advance the first recommendation in the February 2018 Auditor General Report on managing climate change risks, to complete a comprehensive risk assessment of climate-driven risks across the province.
- Supports implementation of the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015), of which the Province of British Columbia (BC) is a signatory. Specifically, it advances the first Sendai priority, to improve disaster risk understanding, and helps advance the remaining Sendai priorities: to improve disaster risk governance, invest in disaster risk reduction, and enhance disaster preparedness.
- Supports modernization of BC's Emergency Management Legislation (EMBC, 2019), specifically the first pillar, mitigation, of the four pillars of emergency management. Specific areas of support include:
    - Consistently developed flood and steep creek (debris flow/flood) hazard maps.
    - Through the delivery of consistently prepared hazard and exposure (elements at risk) datasets across large regions, support data sharing about hazard, exposure, vulnerability and risk assessments.
    - Through the preparation of large volumes of data, establish standardized taxonomies and processes for data management and delivery, and web-based mapping, that support assessment at the scale of the SLRD that is consistent with Provincial scale mapping.

- Advances UBCM Resolution B98, which was endorsed at the 2019 UBCM Annual Convention (Union of BC Municipalities, 2019) and resolves to resourcing a collaborative system of data sharing in BC related to geohazard risk management.

1.3. Terminology

This report refers to the following key definitions[1]:

- **Asset:** anything of value, including both anthropogenic and natural assets[2], 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 merely serves to differentiate from other flood forms such as LDOFs or debris floods. Appendix D provides a more comprehensive description of clear-water flood processes.
- **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 is used in this report as a collective term for debris flows and debris floods. Appendix E provides a comprehensive description of steep creek processes.
- **Volcanic geohazards:** geohazards associated with volcanic complexes. These may include eruptions, rock avalanches, LDOFs, and lahars (volcanic debris flows) (Appendix F). This assessment does not consider eruptions.
- **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 considers the value of elements at risk and 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.
- **Flood Construction Level (FCL):** a designated flood level plus freeboard, or where a designated flood level cannot be determined, a specified height above a natural boundary, natural ground elevation, or any obstruction that could cause flooding.

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[1] CSA (1997), EGBC (2017, 2018).
[2] 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 flood lines and elevations on a base map, typically taking the form of flood lines on a map that show the area that will be covered by water, or the elevation that water would reach during a flood event. For more complex scenarios, the data shown on the maps may also include flow velocities, depth, other hazard parameters, and vulnerabilities.
- **Flood setback:** the required minimum distance from the natural boundary of a watercourse or waterbody to maintain a floodway and allow for potential erosion.
- **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 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 (Figure 1-2).
- **Waterbody:** ponds, lakes and reservoirs.
- **Watercourse:** creeks, streams and rivers.

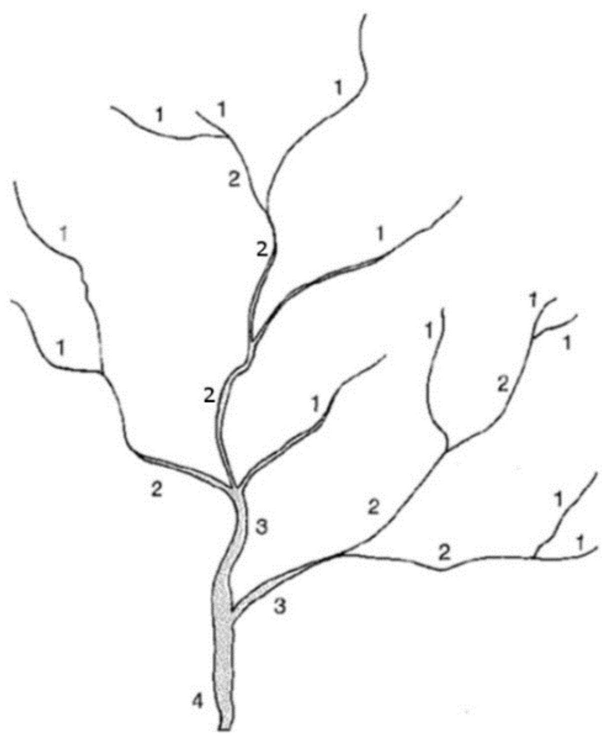


Figure 1-2. Illustration showing Strahler stream order (Montgomery, 1990).

1.4. Scope of Work

1.4.1. Summary

BGC's scope of work was described in a proposal dated June 30, 2017 and was completed under the terms of the SLRD Contract dated December 20, 2018. The work was based on collating previous assessments and collection of desktop-based hazard information. Section 1.4 defines the assessment framework, geohazard types and mechanisms for damage included in our assessment.

Table 1-1 summarizes tasks for each project stage. The table presents the same scope described in the contract but has been re-formatted to reflect the workflow of the assessment. The assessment was based on the existing elements at risk. Proposed or future development scenarios were not examined.

Outcomes of this study include both documentation (this report) and digital deliverables. Digital format results are provided for download, and through a web application called *Cambio Communities™ (Cambio)*. The web application will be provided until March 31, 2021 and thereafter hosted for a license fee if requested by SLRD or on behalf of SLRD by other agencies (e.g., Province of BC).

Table 1-1. Overview of project tasks.

Activity	Related Tasks	Deliverable(s)
1. Project Management	Meetings, project management, administration, budget and schedule control	• Presentations and updates
2. Data Compilation and Review	Project initiation and study framework development; Compilation of basemap, hazards and elements at risk information	• Study objectives, scope of work and study area. • Roles of the parties involved in the project. • Over-arching study framework. • Definition of the hazard types and damage mechanisms assessed. • Reviewed information on study area physiography, climate and climate change, hydrology, and flood history, with reference to floodplain management policies. • Compiled basemap and hazard data in geospatial format. • Compilation of elements at risk for vulnerability assessment, including critical infrastructure layer. • Compilation of hazards to be assessed and prioritized.
3. Analysis	Geohazard Prioritization	• Characterization of elements considered vulnerable to geohazard impact. • Hazard characterization. • Assignment of geohazard, consequence and priority ratings for the relative likelihood that geohazards will occur and reach elements at risk vulnerable to some level of consequence. • Identify climate change considerations (inputs) and describe key mechanisms for hazard change due to climate change.
4. Report	Reporting and Documentation	• Description of methods, results, limitations, gaps, and considerations for future work. • Preparation of the Risk Assessment Information Template (RAIT).
5. Data	Web Application and Data Services	• Study results and supporting information displayed on Cambio Communities web map; data and web services for dissemination of study results.

1.4.2. Geohazard Types Assessed

This study assesses the following geohazards within 'settled' urban and rural areas of the SLRD:

- Clear-water floods (see Section 3.1 and Appendix D)
- Steep-creek processes: debris floods and debris flows (see Section 3.2 and Appendix E)
- Non-eruptive volcanic hazards (see Section 3.3 and Appendix F).

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[1]
- Overland urban flooding[2]
- Sewer-related flooding[3]
- Ice jam flooding
- Detailed assessment of floods associated with reservoir regulation (see Section 2.6.3).
- 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).

Given the study objective is to provide a baseline prioritization of geohazard areas, this 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 priority ratings 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).

In addition, more than one hazard type can potentially be present at a given location, such as a fan-delta (fan entering a lake) subject to both steep creek events and lake flooding. BGC displays hazards on the web application such that a user can identify overlapping hazards if present at a given location. However, hazard prioritization is completed separately for each hazard type.

In the case of steep creek geohazards, geohazard area identification and prioritization entirely focused 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 prioritized. As such, steep creek geohazard risk exists within the SLRD that that was not

[1] 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.

[2] 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.

[3] Flooding within buildings due to sewer backups, issues related to sump pumps, sewer capacity reductions (tree roots, infiltration/inflow, etc.).

included in this prioritization because the elements exposed to geohazards did not intersect a mapped fan.

Lastly, the boundary between settled areas and wilderness is not always sharp. Prioritized geohazard areas typically include buildings improvements 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. Hazards were also not mapped in areas that were undeveloped except for minor dwellings (i.e., backcountry cabins).

1.5. Deliverables / Web Map

Outcomes of this study include documentation (this report) and digital deliverables. This report summarizes each step of the study with more detailed information provided in appendices.

Digital deliverables include geospatial information provided in a geodatabase (prioritized geohazard areas), and hazard area attributes provided in an excel spreadsheet. The prioritized hazard areas are presented on a secure web application, *Cambio* (Figure 1-3), at www.cambiocommunities.ca.

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

1. Prioritized geohazard areas and information (see Section 3).
2. Elements at risk (i.e., community assets; see Section 4).
3. Additional information provided for visual reference, including geohazard, hydrologic and topographic features.
4. 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 or Edge. Appendix B provides a more detailed description of *Cambio* functionality.

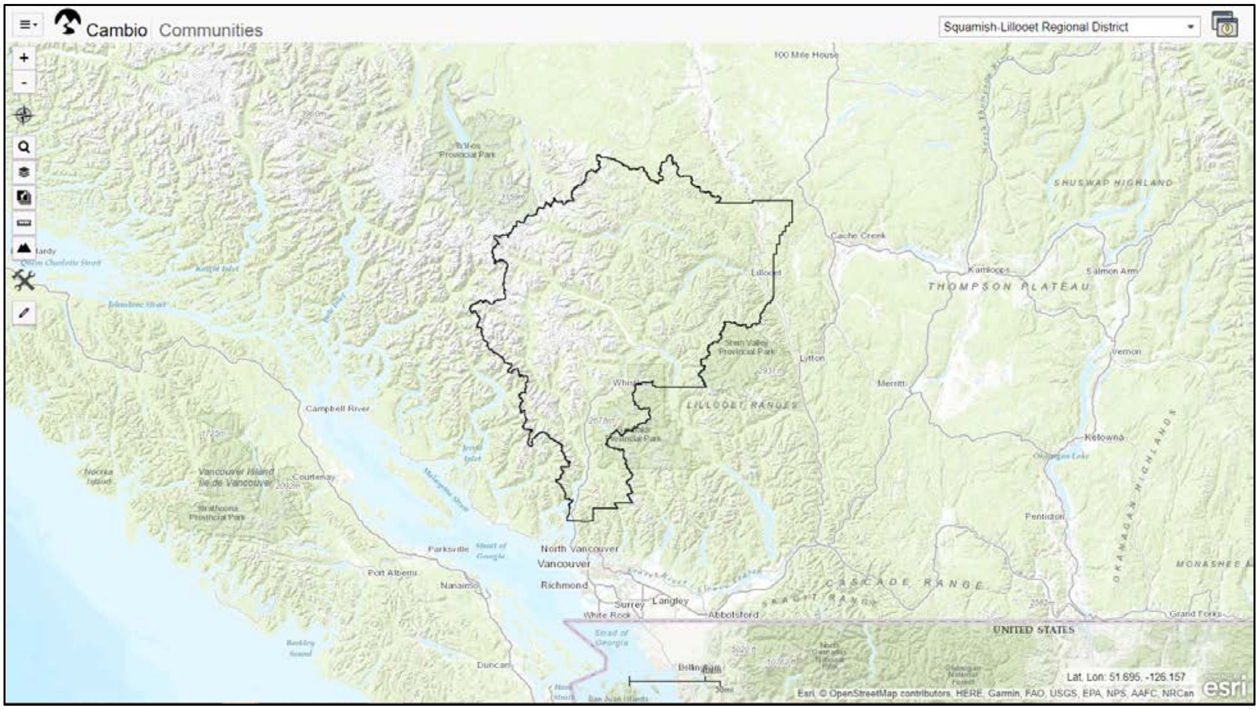


Figure 1-3. Example of *Cambio* web application.

2. BACKGROUND

This section provides an overview description of the study area.

2.1. Administration

The SLRD covers approximately 17,000 km^2 in southwestern British Columbia (Figure 2-1). The SLRD is divided into four electoral districts (A to D) and four municipalities as follows (Figure 2-1; also shown on the web map):

- District of Squamish
- Resort Municipality of Whistler
- Village of Pemberton
- District of Lillooet.

The total Census population is approximately 43,100 people (Statistics Canada, 2016), and the region contains an assessed $9 billion in building improvements (BC Assessment, 2018).

2.2. 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)[1] data were used for this study in areas without Lidar coverage.

2.3. Physiography and Ecoregions

The SLRD is located mostly within the Coast Mountain physiographic region[2] 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 2-1). Table 2-1 outlines the characteristics of each ecoregion and associated eco-section.

[1] 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, 2016b).

[2] Referring to landforms and geology.

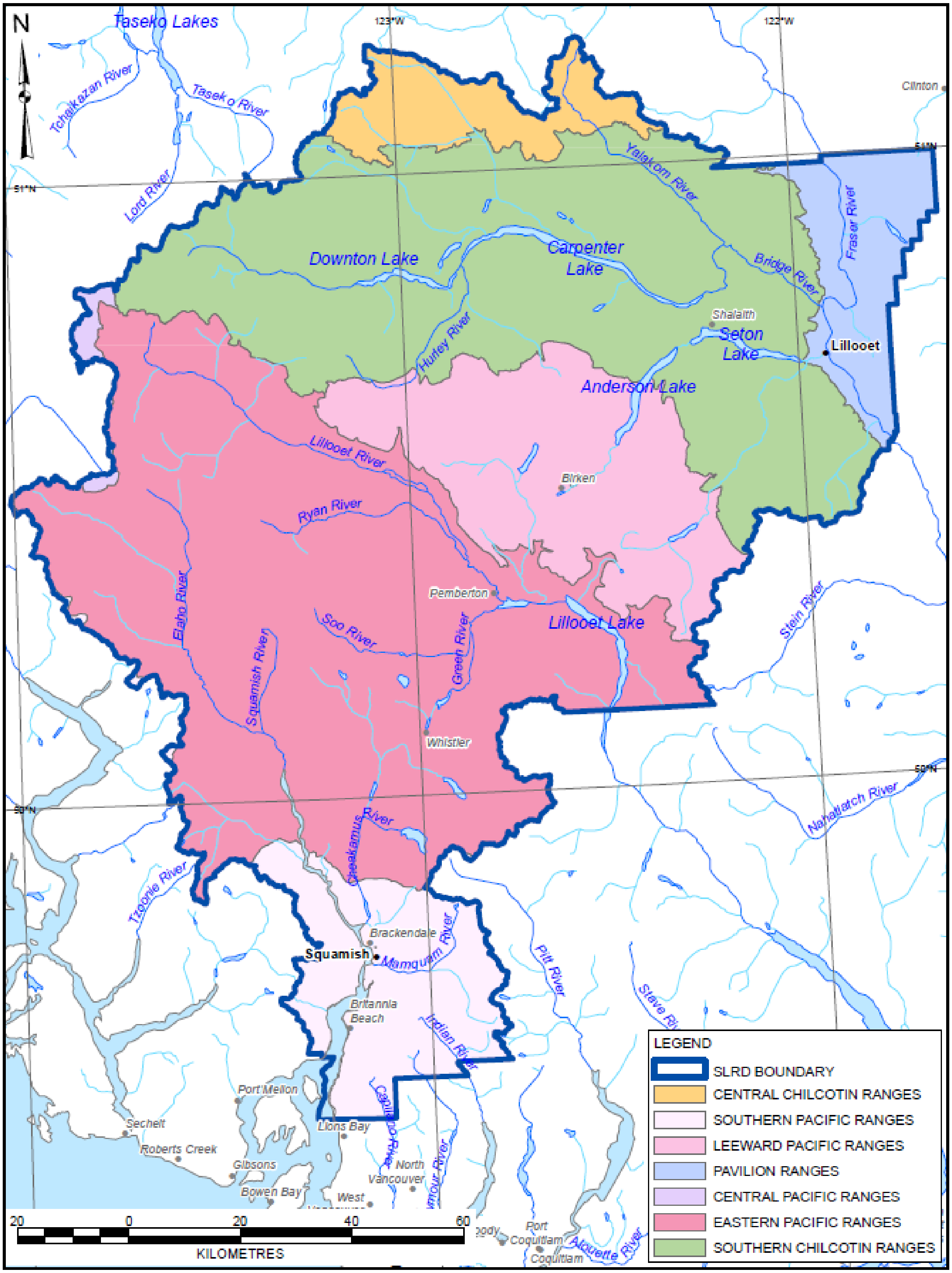


Figure 2-1. Ecosections within the SLRD (DeMarchi, 2011).

Table 2-1. Ecoregions and ecosections of the SLRD (as defined by Demarchi, 2011 and shown on Figure 2-1).

Ecoregion	Ecosection	Area Within SLRD (km^2)	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 Donelly, 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 2.6.3).

The highest mountain ranges occur in the western part of the SLRD (Eastern Pacific Ranges Ecosection), 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, which differ from floods in terms of their sediment concentrations, velocities, and destructive potential (Section 3.2). 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 (Section 3.1).

2.4. 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.

2.4.1. 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 proces to form what is called the Coast Mountains Batholith, a tract of granitic and gneissic rocks. Due to the activity at magmatic activity at the continental margins, the SLRD also contains some volcanic complexes such as Mount Meager, Mount Cayley and Garibaldi Mountain.

Figure 2-2 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.

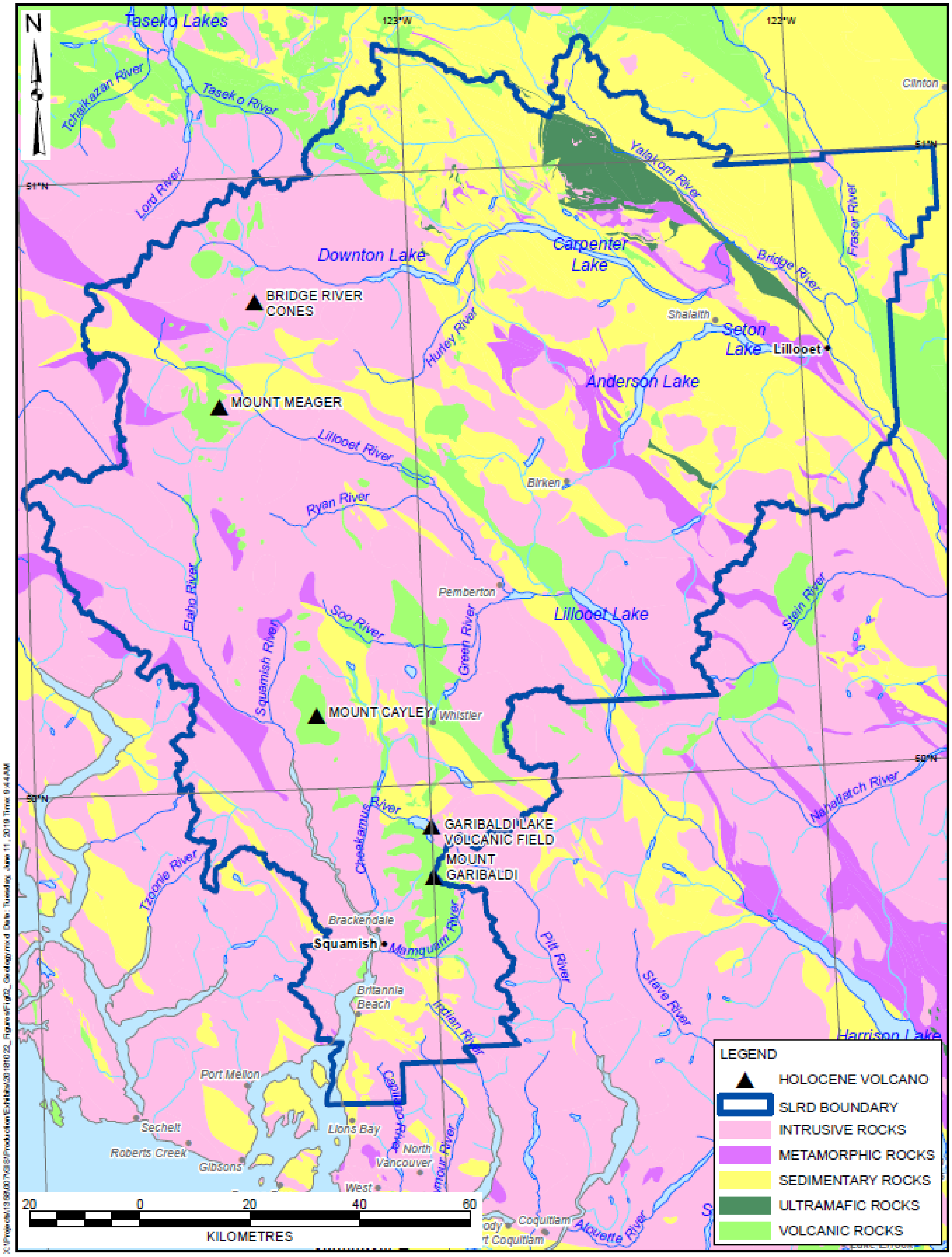


Figure 2-2. Bedrock geology of the SLRD. Digital mapping and bedrock classes from Cui et al. (2015).

2.4.2. 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 north eastern 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.

2.5. Climate

Climate is considered the average or typical weather in an area over a longer period of time and is often described in terms of variables such as average temperature, precipitation and seasonal changes[9]. 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[10]. An important distinction between climate 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

[9] http://www.wmo.int/pages/prog/wcp/ccl/faq/faq_doc_en.html. Accessed June 18, 2018.

[10] 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".

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.

2.5.1. 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 2-3).

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.

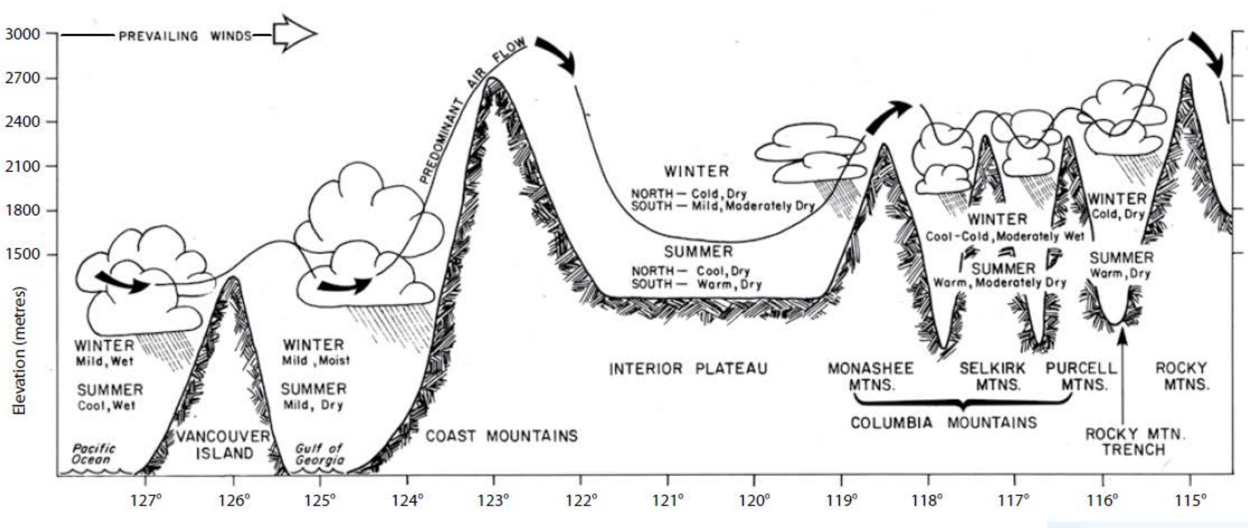


Figure 2-3. Latitudinal cross-section through southern BC depicting physiographic diversity and resulting climatic regimes. The SLRD is associated with the Coast Mountains and a portion of the Interior Plateau. (From Moore et al., 2008).

2.5.2. 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 2-2 provides a summary of the climate normals as averaged from four Environment and Climate Change Canada (ECCC) stations shown in Figure 2-4 for the period of 1981 to 2010.

Table 2-3 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 2-5 and Figure 2-6 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 2-7). 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 2-2).

Table 2-2. 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 2-3. 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
Whistler A[1] (ID 1048898)												
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[2] (mm)	176	105	98	76	67	59	45	48	55	155	192	154
Lillooet D[3] (ID 1114627)												
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
Squamish STP Central D[3] (ID 1047671)												
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[2] (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.

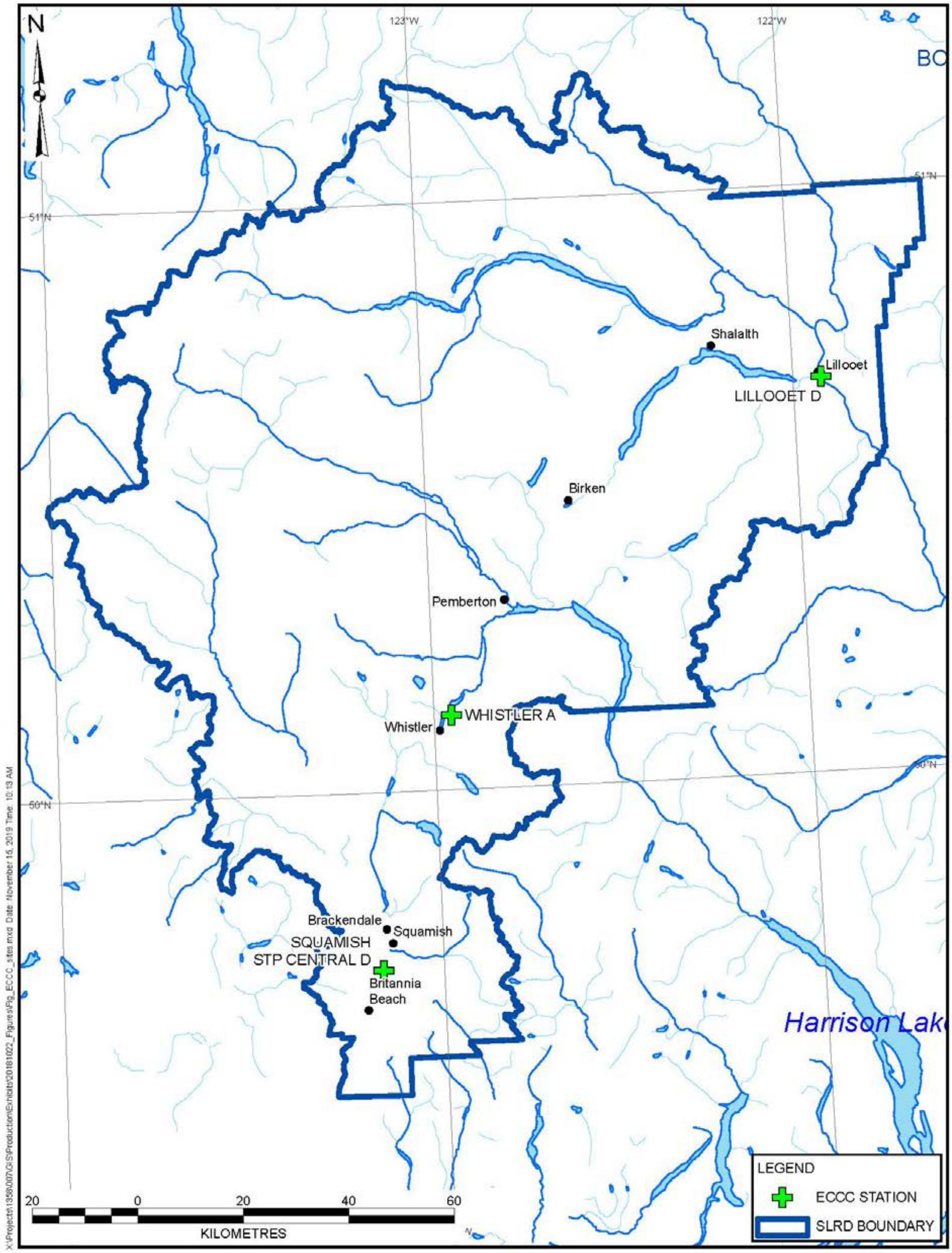


Figure 2-4. Environment and Climate Change Canada (ECCC) stations in the SLRD and referenced in this document.

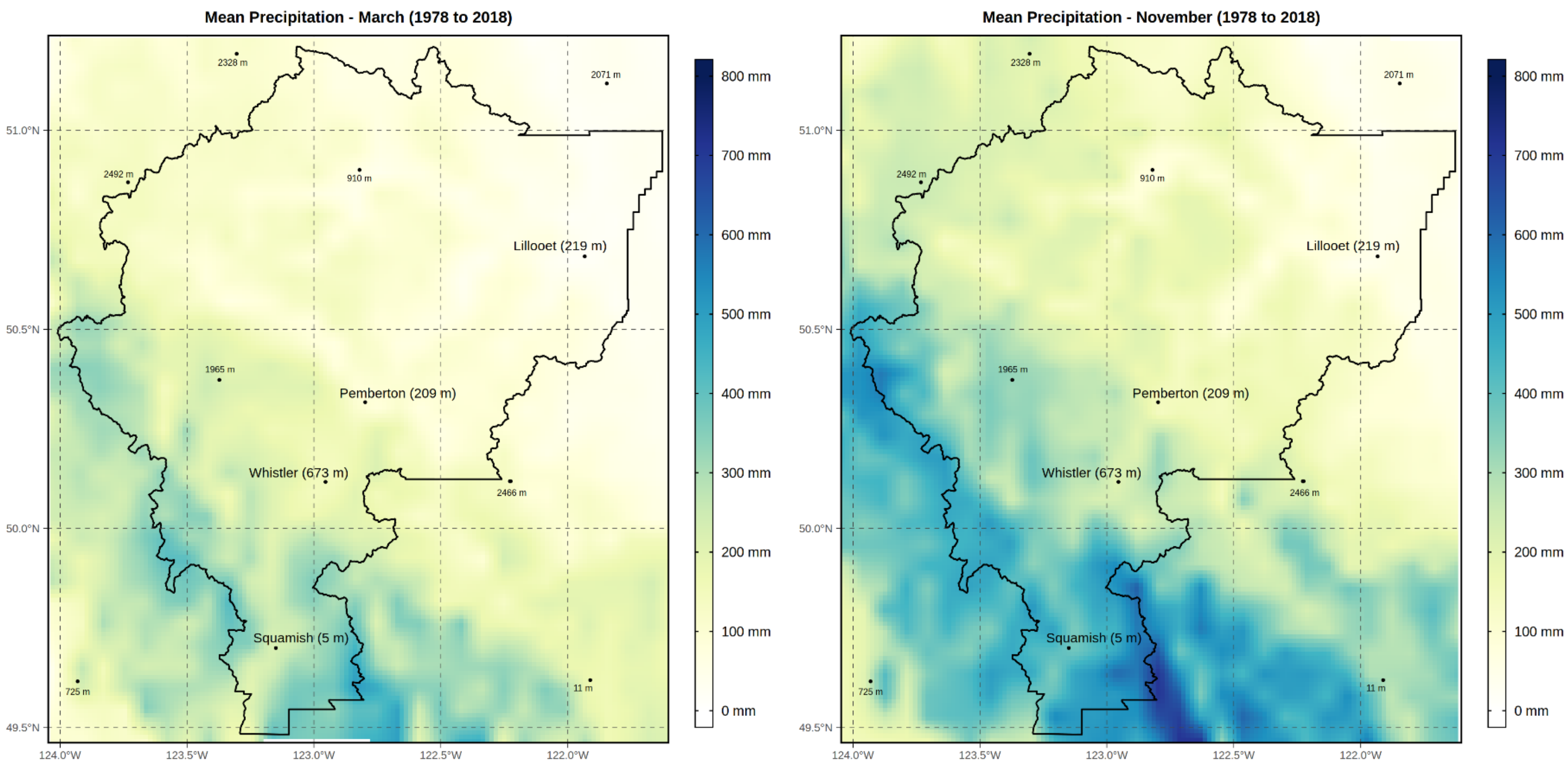


Figure 2-5. Mean precipitation normals for March and November from 1976 to 2018 for the SLRD (outlined in black). Data compiled and presented by BGC. Source data: ClimateBC (Wang et al., 2016).

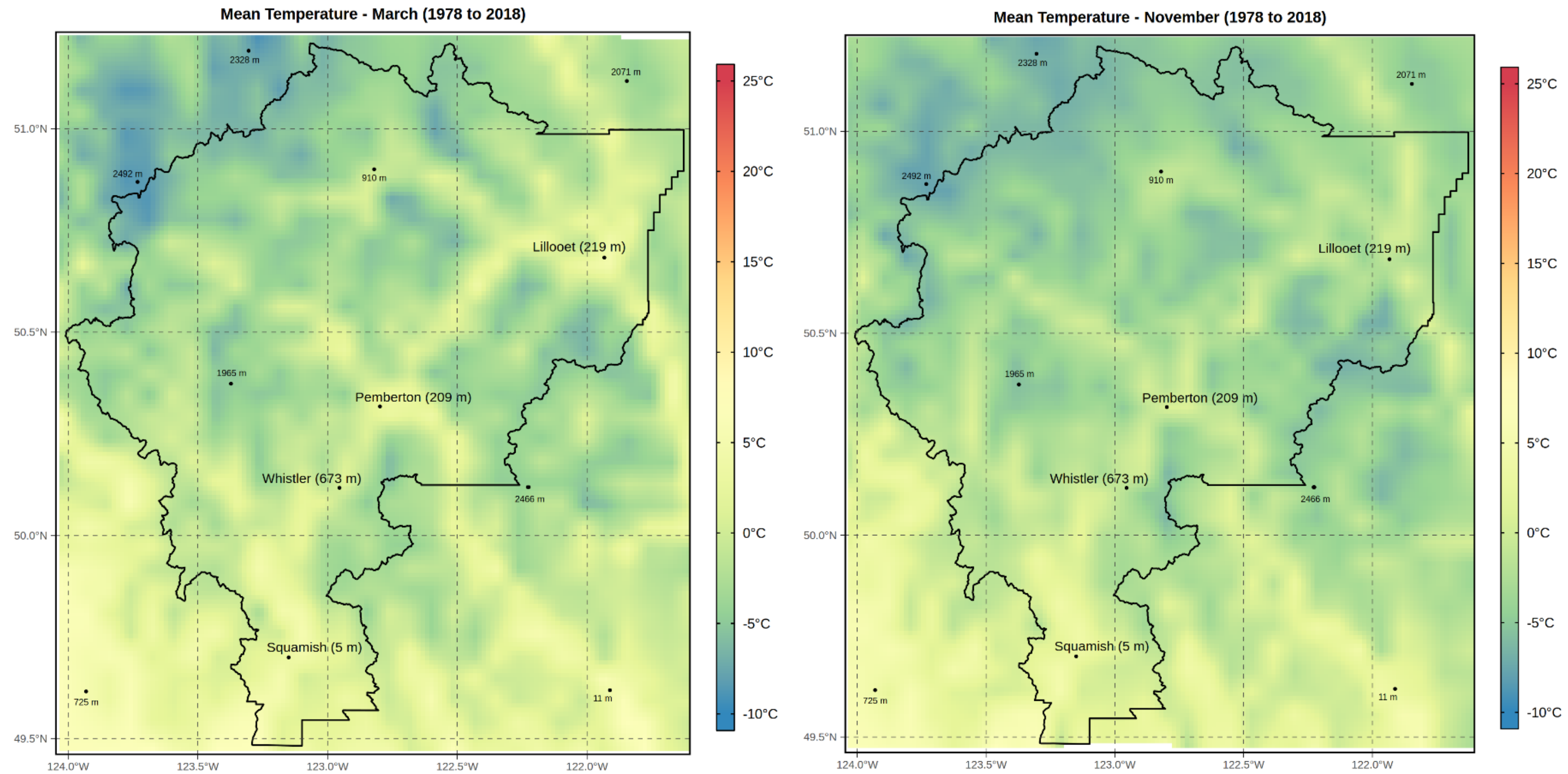
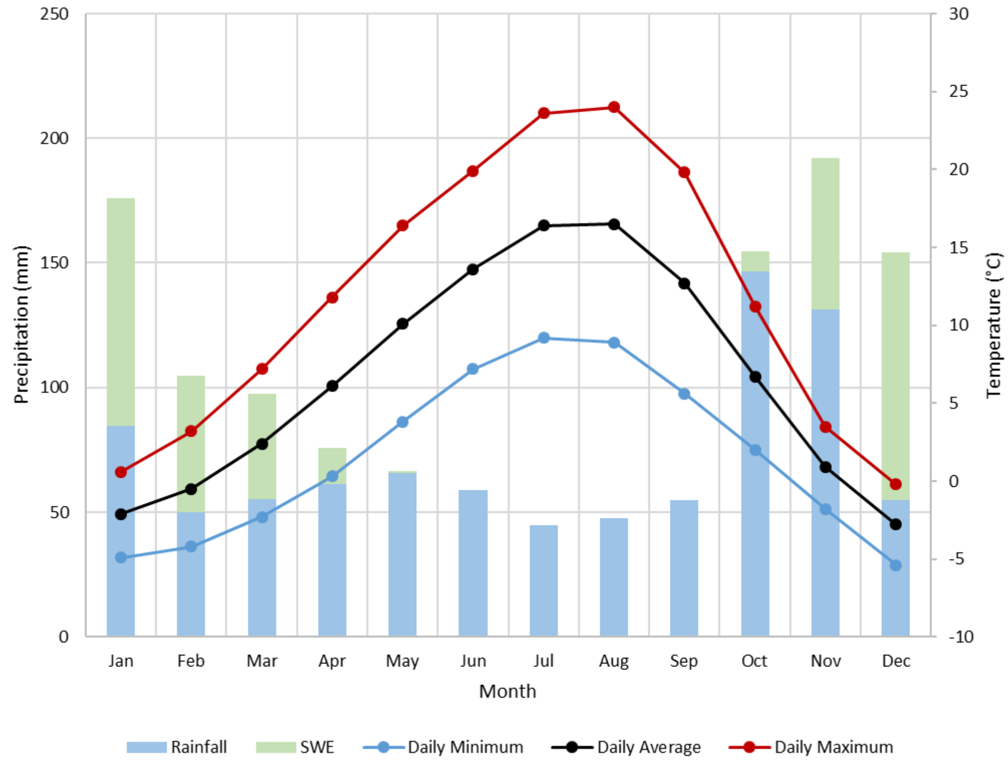
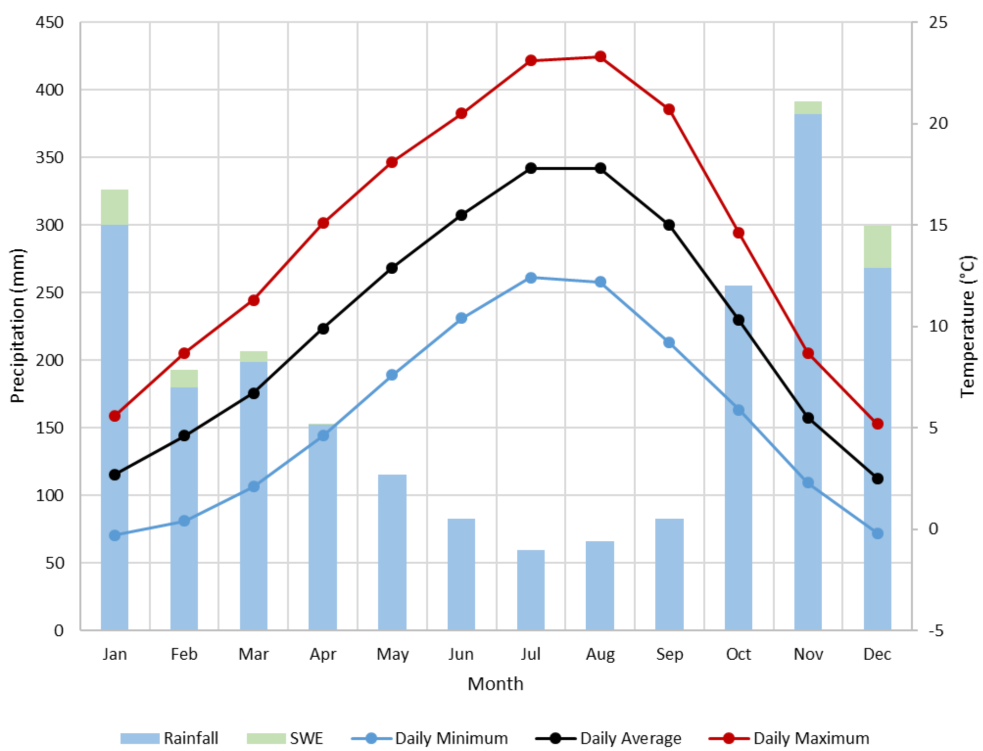


Figure 2-6. Mean temperature normal for March and November from 1976 to 2018 for the SLRD (outlined in black). Data compiled and presented by BGC. Source data: ClimateBC (Wang et al., 2016).



(a)



(b)

Figure 2-7. Climate normals at the ECCC Whistler A (a) and Squamish STP Central D (b) climate stations for 1981 to 2010.

2.5.3. 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[11] that are of interest for flood hazards on specific watercourses.

Projected changes in average climate variables across the SLRD (Table 2-4; (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 2-4. Plan2Adapt. Projected changes in average climate variables in SLRD (2050s, A2 and B1 scenarios, PCIC 2012).

Variable	Unit	Season	Projected Change from 1961 – 1990 Baseline[1]	
			Median	Range (10th to 90th Percentile)
Temperature	ºC	Annual	+1.7ºC	+1.1ºC to +2.6ºC
Precipitation[2]	%	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, 10th and 90th 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
2. Precipitation includes both rain and snow.

Historical data from the region shows that average annual temperatures and total annual precipitation increased 0.8ºC 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 there

[11] "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.

has been a 34% change in glacier area, corresponding to a 3 km^2 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[12]. 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 E 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 D. As a result, an additional factor was not added to account for climate change for clear-water hazards.

2.6. 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.

2.6.1. Physiographic Characterization of Watercourses

This report defines three general categories of watercourses that are differentiated by scale and physiography as per Table 2-5.

[12] BC Climate Action Toolkit Sea Level Rise Adaption Primer (https://www.toolkit.bc.ca/).

Table 2-5. Physiographic characterization of watercourses.

Category	Watershed Area Range	Strahler Order[1]	Example Watersheds
Major Valley Systems	>3,000 km^2	6+	Squamish River, Lillooet River, Bridge River, Fraser River, Cheakamus River
Minor Valley Systems	500 – 3,000 km^2	4 - 6	Alta Creek, Brandywine Creek, Ryan River, Birkenhead River
Tributary Creeks	<500 km^2	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^2. 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^2. 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^2 with many of the tributary creeks terminating at fans where they enter larger and lower-gradient valley bottoms. Many tributary creeks (typically < 10 km^2) are subject to steep creek processes (debris floods and debris flows). Methods to identify creeks subject to steep creek processes are provided in Section 3.1.2.

Major Lakes

Within the District there are a number of 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 2-6.

Table 2-6. Major lakes and reservoirs within the SLRD.

Name	Description	Surface Area (km^2)	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

2.6.2. 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 a number of 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 2-8 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^2. 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 2-9 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^2. Cayoosh Creek represents a nival-dominant regime with the peak flows occurring during the spring freshet (May, June and July).
- Figure 2-10 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^2. Bridge River is an example of a glacial-supported nival flow regime with snowmelt driven in spring and glacial melt driven in summer.

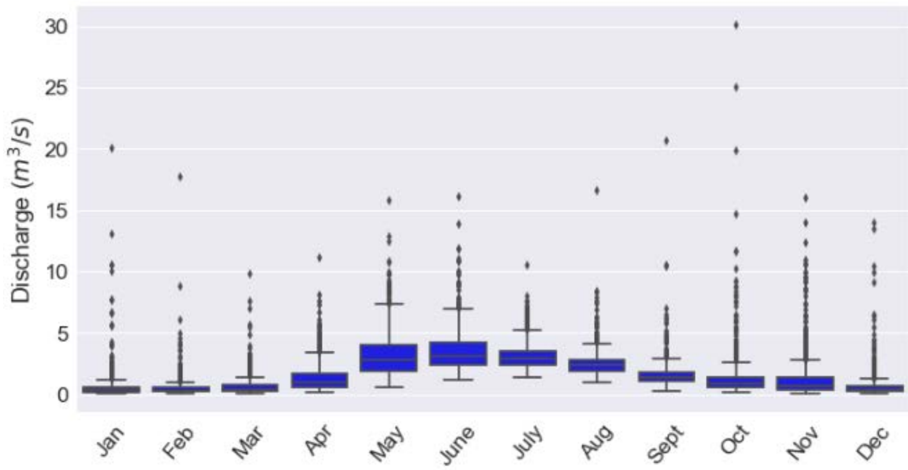


Figure 2-8. Boxplots of the monthly discharge data for WSC gauge 08MG025, *Pemberton Creek near Pemberton*. Pemberton Creek represents a pluvial-dominant hybrid regime.

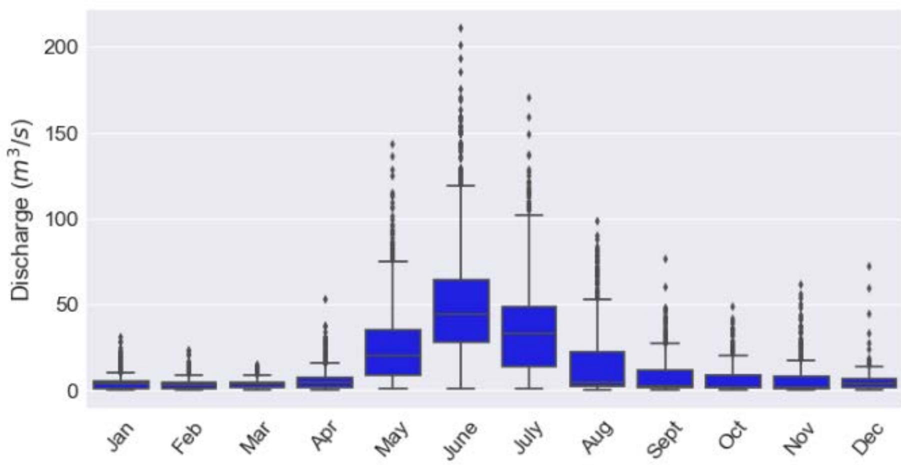


Figure 2-9. Boxplots of the monthly discharge for WSC gauge 08ME002, *Cayoosh Creek near Lillooet*. Cayoosh Creek represents a nival-dominant hybrid regime.

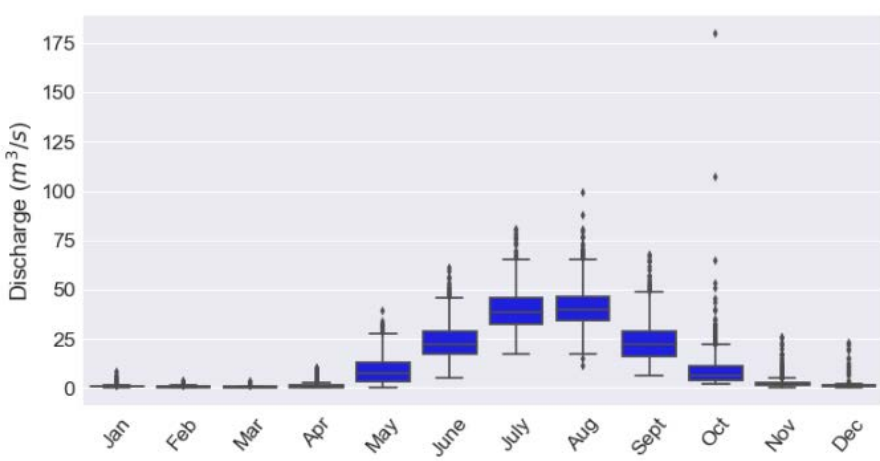


Figure 2-10. Boxplot of the monthly discharge for WSC gauge 08ME023, *Bridge River (South Branch) below Bridge Glacier*. Bridge River represents a glacial-supported nival regime.

2.6.3. 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 Rover 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 D. 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.

2.6.4. 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.

2.7. Historical Event Inventory

BGC reviewed historical accounts of flood, debris flood and debris flow events across the SLRD. Appendix I 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 I 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 (Section 3). 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.

3. GEOHAZARD ASSESSMENT

This section summarizes how BGC identified and characterized the geohazard extents prioritized in this study. Areas considered in this inventory both contained cadastral parcels of interest[13] and were subject to clear-water flood or steep creek processes. Appendices D and E provide further details on geohazard identification and characterization for clear-water flood and steep creek geohazards, respectively.

3.1. Clear-water Flood Geohazards

3.1.1. Hazard Area Delineation and Characterization Overview

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. Hazard areas were generated from the methods shown in Table 3-1 and amalgamated[14] into geohazard areas for prioritization. The resulting geohazard areas for prioritization 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.

Appendix D provides further details on the methodology and associated limitations.

[13] 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)).

[14] Amalgamation was based on the concept of "consultation zones", which define a geographic area considered for geohazard safety assessment (Geotechnical Engineering Office, 1998; Porter et al, 2009). Geographic areas were selected on the basis of hazard type and characteristics, jurisdiction/community continuity, future detailed study funding considerations and study efficiencies. See Section 5.4 for further comments on prioritization areas.

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 2016,2017) 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.

3.1.2. Geohazard Process Type

Every mapped stream segment in the SLRD was assigned a predicted process type (flood, debris-flood or debris flow) based on a statistical analysis of Melton Ratio[15] and watershed length[16]. These terrain factors are a useful screening-level indicator of the propensity of a creek to dominantly produce clear-water floods, debris floods or debris flows (Wilford et al., 2004; Jakob et al., 2016; Holm et al., 2016). The typical watershed characteristics that differentiate between these processes are shown in Table 3-2.

15 Melton ratio is watershed relief divided by the square root of watershed area (Melton, 1957).
16 Stream network length is the total channel length upstream of a given stream segment to the stream segment farthest from the fan apex or watershed outlet.

Table 3-2. Class boundaries using Melton ratio and total stream network length.

Process	Melton Ratio	Stream Length (km)
Clear-water flood	< 0.2	all
Debris flood	0.2 to 0.5	all
	> 0.5	> 3
Debris flow	> 0.5	≤ 3

The advantage of a statistically-based classification is that it can be applied to large regions. However, classification reliability is lower than detailed studies, which typically combine multiple lines of evidence such as statistical, remote-sensed, and field observation data. In this study, process type identification should be considered more reliable for creeks with mapped fans than those without mapped fans.

Classifying every stream segment in the SLRD into one of three likely process-types (i.e., clear-water, debris-flood or debris flow hazards) also does not recognize that there is a continuum between clear-water floods and steep-creek processes that is not accounted for in morphometrics. A site may be transitional between two process-types, for example, a longer watershed that would be classified as debris flood could still produce debris flows if there's a landslide-inducing processes in a hanging valley near the fan apex. To capture this uncertainty, a probabilistic approach was also used to determine the likelihood that a stream segment falls within each of the three categories, as described in Appendix D.

3.1.3. Hazard Likelihood

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% AEP (200-year return period) event. Therefore, the 200-year flood event likelihood was used to prioritize clear-water flood sites across the SLRD. Appendix D provides further description of methods and uncertainties.

3.1.4. Hazard Intensity

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 5.3.3.

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. Appendix D provides further details about the mapping approach (see Section D.2.4) and the approach used to assign intensity ratings (see Section D.3.1).

3.2. Steep Creek Geohazards

Steep creek or hydrogeomorphic hazards are natural hazards that involve a mixture of water ("hydro") and debris or sediment ("geo") (Figure 3-1). These hazards typically occur on creeks and steep rivers with small watersheds (usually less than 100 km^2) in mountainous terrain, usually after intense or long rainfall events, sometimes aided by snowmelt and often worsened by previous forest fires.

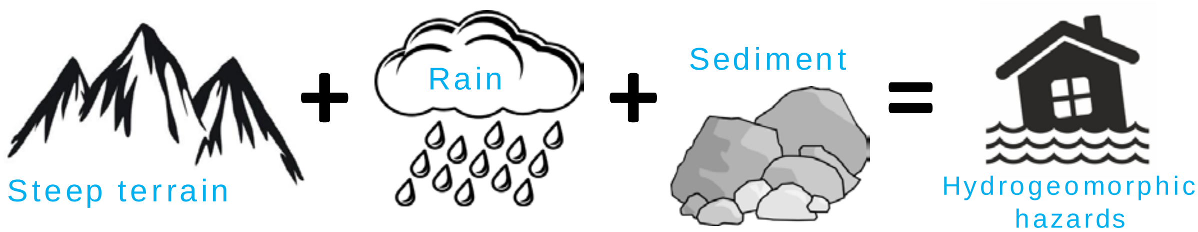


Figure 3-1. Main factors contributing to hydrogeomorphic hazards.

The main types of steep creek hazards are debris floods and debris flows. Debris floods occur when large volumes of water in a creek or river entrain the gravel, cobbles and boulders on the channel bed; this is known as "full bed mobilization". Debris flows involve higher sediment concentrations than debris floods. They are technically classified as landslides rather than floods, because their high sediment content and viscosity allows them to deposit at angles when water will continue to flow. The best common analogy of the behaviour of debris flows is wet concrete. It is easiest to think about hydrogeomorphic hazards as occurring in a continuum, as shown in Figure 3-2. Further details about steep creek hazards are provided in Appendix E.

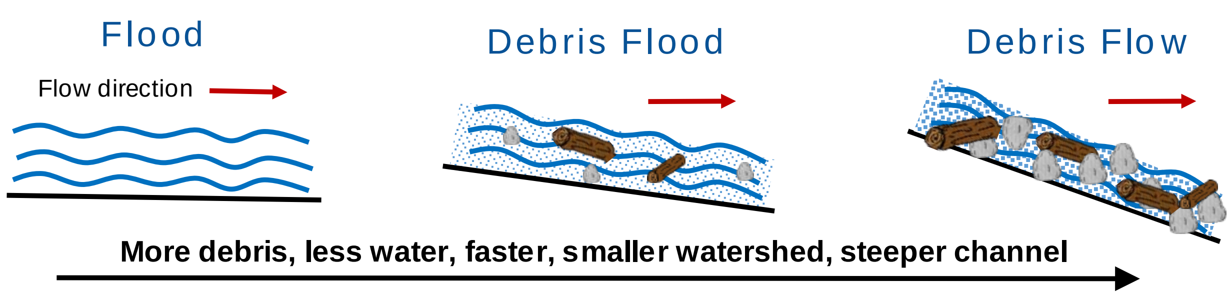


Figure 3-2. Main types of steep creek hazards.

Steep creek geohazard areas prioritized in this study focused on fans, as these are the landforms most commonly occupied by elements at risk. The boundaries of fans define the steep creek geohazard areas that were prioritized. Upstream watersheds were assessed to identify geohazard processes and determine geohazard ratings but were not mapped.

3.2.1. Overview

Table 3-3 lists the approaches used to identify and rank steep creek geohazards: alluvial fan inventory, process type identification, hazard likelihood estimation, impact likelihood estimation, and hazard intensity (destructive potential) estimation. Together, these factors reflect an estimated likelihood a geohazard process occurs and reaches areas with elements at risk with a certain level of intensity. This section provides a brief overview of assessment methods, with further details provided in Appendix E.

Table 3-3. Summary of steep creek geohazard identification and ranking approaches.

Approach	Area Assessed	Application
Alluvial fan Inventory	Prioritized geohazard areas	Delineation of alluvial fans to be prioritized; interpretation of terrain characteristics used to assign geohazard ratings.
Process type identification	All creeks	Classification of creeks as dominantly subject to clear-water floods, debris floods, or debris flows.
Hazard likelihood estimation	All prioritized geohazard areas prone to debris flows or debris floods	Screening level identification and estimate of geohazard likelihood for all prioritized geohazard areas; basis to assign geohazard ratings to prioritized geohazard areas.
Impact likelihood estimation	All prioritized geohazard areas prone to debris flows or debris floods	Screening level estimate of impact likelihood for all prioritized geohazard areas; basis to assign geohazard ratings to prioritized geohazard areas.
Intensity estimation	All prioritized geohazard areas prone to debris flows or debris floods	Screening level estimate of relative geohazard intensity (destructive potential) of debris flows, debris floods or clear-water floods; in combination with hazard exposure (elements at risk) formed the basis to assign consequence ratings to prioritized geohazard areas.

3.2.2. Alluvial Fan Inventory

The boundary of alluvial fans (e.g., Figure 3-3) represents the steep creek geohazard areas prioritized in this study. BGC mapped a total of 201 developed fans, based on the interpretation of available aerial and satellite imagery, Lidar Digital Elevation Models (DEM), and review of previous fan mapping (see Appendix A). Geobase terrain models and satellite imagery available within the ESRI web map were used for terrain interpretations where Lidar was not available. Previous reports used as reference can be downloaded by clicking on a given fan in *Cambio*.

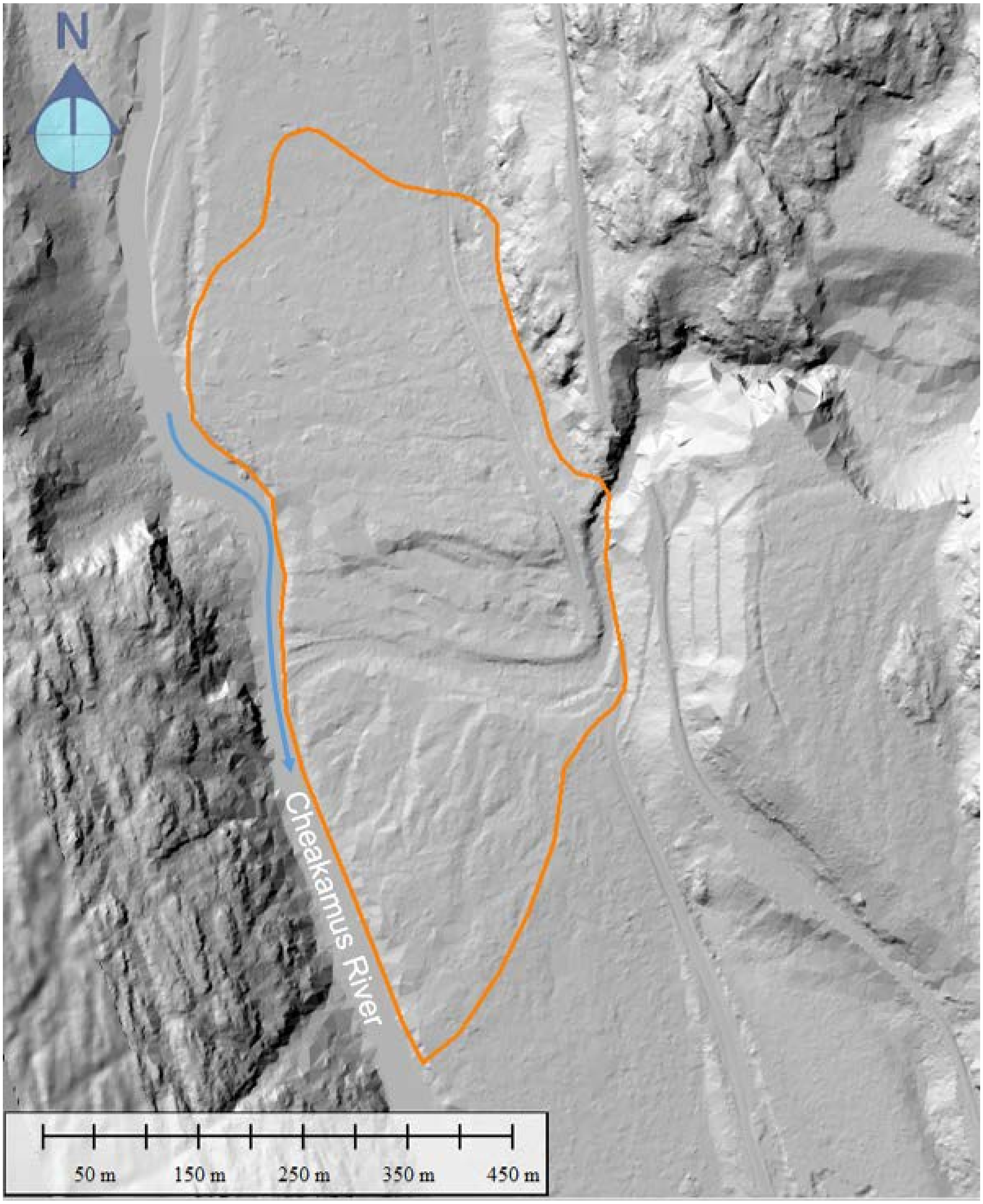


Figure 3-3. Example alluvial fan boundary at Culliton Creek, north of Squamish on the Cheakamus River.

Although this study was based on the best available information, the fan inventory is not exhaustive. Fans likely exist in some developed areas that were not detected at the screening level scale of study. For those mapped, BGC also notes that it is not possible to rule out the potential for steep creek geohazards to extend beyond the limit of the fan boundary in some cases. Most of the alluvial fans mapped in this study represent the accumulation of sediment over the Holocene period (since about 11,000 years BP). The fan boundary approximates the extent of sediment deposition since the beginning of fan formation. 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. Assessment of such scenarios could form part of more detailed study. The limits of geohazard areas identified in this assessment (the alluvial fan boundary) should be treated as transitions, not exact boundaries.

3.2.3. Process Type Identification

Two methods were used to interpret the dominant geohazard process type on a stream: terrain analysis and morphometric statistics.

Terrain analysis was used to interpret the dominant geohazard process entering prioritized geohazard areas (alluvial fans)[17]. The analysis included review of airphoto or satellite imagery, and review of historical records if available. Section 3.1.2 describes methods to assign a predicted process type (flood, debris-flood or debris flow) to every delineated stream in the SLRD based on statistical analysis.

For the prioritized geohazard areas, a dominant process type was then assigned based on both the results of terrain analysis and statistical predictions. For the remaining streams, statistical predictions were not validated by other means and should be treated with a lower level of confidence. Table 3-4 summarizes the number of fans by process type.

Table 3-4. Summary of number of fans mapped by process type.

Process Type	Number of fans mapped
Debris Flood	85
Debris Flow	109
Clear-water Flood	7
Total	**201**

3.2.4. Hazard Likelihood Estimation

Hazard likelihood was estimated based on terrain interpretation considering both basins and fan activity. Basin activity considered parameters such as identifiable source areas, the nature of channels, and whether watersheds are supply-limited or unlimited. Fan activity focused on evidence of fresh deposits and lobes on the fan, and the type of vegetation. Basin and fan activity criteria were combined in a matrix to estimate hazard likelihood rating. Appendix E provides further description of methods to estimate geohazard likelihood and describes limitations and uncertainties.

[17] Note that many creeks with debris floods entering the fan apex also contain debris flow channels in their upper basins.

3.2.5. Impact Likelihood Estimation

BGC estimated the relative likelihood that debris flows, debris floods or clear-water floods will result in avulsions on fans, given occurrence of a geohazard. Impact likelihood is estimated based on a combination of susceptibility modeling and terrain mapping of avulsion activity. Previous assessments and event records were also referenced where available. In the susceptibility modelling method, BGC used a semi-automated approach based on River Network Tool™ (RNT)[18], morphometric statistics (Section 3.1.2), and the Flow-R model[19] developed by Horton et al. (2013) to identify debris flow or debris flood hazards and model their runout susceptibility. Appendix E provides further description of methods to estimate impact likelihood and describes limitations and uncertainties. The results of susceptibility modelling are shown as a layer on *Cambio*.

3.2.6. Intensity Estimation

In a detailed steep creek analysis, destructive potential is characterized based on intensity, which is quantified by parameters such as flow depth and velocity. 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 prioritization study, BGC used peak discharge as a proxy for flow intensity. Appendix E provides further details about the approach used for determination of intensity ratings.

3.3. Volcanic Geohazards

3.3.1. Overview

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. Appendix F provides additional description of 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 (Figure 3-4). 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.

[18] RNT is BGC's versatile web-based application for analyzing hydrotechnical geohazards associated with rivers and streams.

[19] "Flow-R" refers to "Flow path assessment of gravitational hazards at a Regional scale". See http://www.flow-r.org.

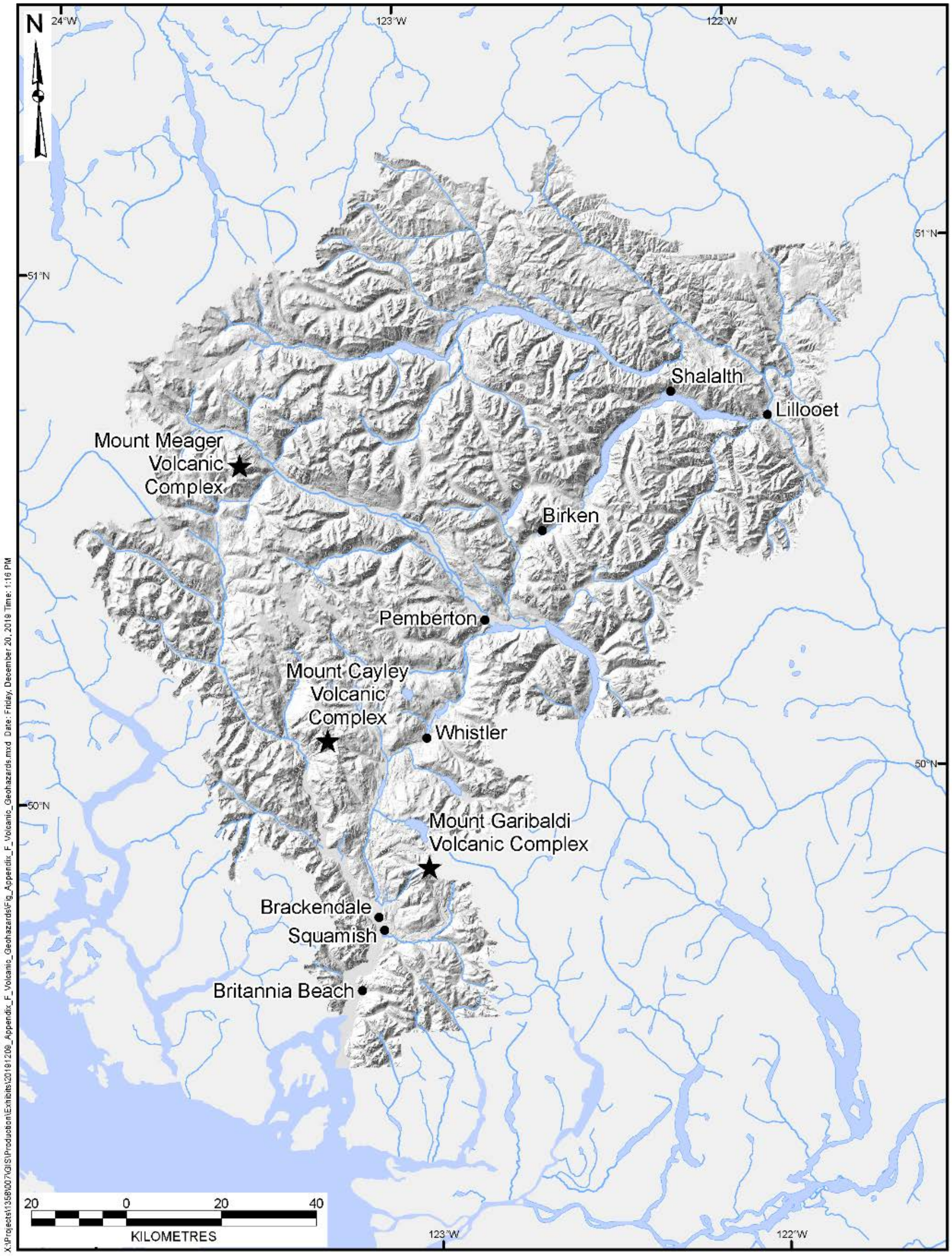


Figure 3-4. **Major volcanic complexes within the SLRD. Town locations shown for geographical reference. Grayscale basemap is the 20-m DEM slope map clipped to the SLRD boundary.**

3.3.2. Geohazard Scenarios

Appendix F lists the volcanic geohazard scenarios included in this assessment and describes the workflow to identify geohazard areas.

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.

3.3.3. Hazard Likelihood

Volcanic hazard likelihood was estimated for geohazard areas based on judgement with reference to the data sources listed in Appendix F. 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).

3.3.4. Hazard Intensity

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 applied as averages to each prioritized geohazard area, using judgement with reference to the data sources summarized in Appendix F. The hazard intensity ratings were used to define a consequence rating for each hazard area, as described in Section 5.3.3.

4. EXPOSURE ASSESSMENT

This section describes how BGC identified elements at risk in geohazard areas and assigned exposure ratings to a given area. Section 5 describes how exposure ratings were used as inputs for risk prioritization.

The objective of assigning exposure ratings is 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. Appendix C describes methods to compile and organize these data.

The exposure weightings were assigned by BGC and are subject to review by SLRD. They 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, 2016a). 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 for each area.
4. Assign exposure ratings to areas based on their percentile rank compared to other areas.

BGC notes that different weightings could result in adjustments to hazard area priority ratings. 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, 2016a).

Software developed by BGC was used to automate the identification of elements at risk within geohazard areas. The elements at risk compiled for risk prioritization are not exhaustive and did not include a complete inventory of municipal infrastructure (e.g., complete inventory of utility networks). Elements where loss can be intangible, such as objects of cultural value, were not included in the inventory.

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

Element at Risk	Description	Value	Weight
People	Total Census (2016) Population (Census Dissemination Block)[1]	1-10	5
		11 – 100	10
		101 – 1,000	20
		1,001 – 10,000	40
		>10,000	80
Buildings	Building Improvement Value[2] (summed by parcel)	<$100k	1
		$100k - $1M	5
		$1M - $10M	10
		$10M - $50M	20
		$50M - $100M	40
Critical Facilities	Critical Facilities[3] (point locations)	Emergency Response Services	36
		Emergency Response Resources	10
		Utilities	18
		Communication	18
		Medical Facilities	36
		Transportation	22
		Environmental	18
		Community	36
Businesses	Business annual revenue (summed) (point locations)	<$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

Element at Risk	Description	Value	Weight
Lifelines[3]	Roads (centerline)	Road present; no traffic data	1
		Highway present; no traffic data	5
		0-10 vehicles/day (Class 7)	1
		10-100 vehicles/day (Class 6)	5
		100-500 vehicles/day (Class)	10
		500-1000 vehicles/day (Class 4)	20
		> 1000 vehicles/day (Class <4)	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
	Sanitary Infrastructure	Presence of	10
	Drainage Infrastructure	Presence of	10
Environmental Values	Active Agricultural Area	Presence of	15
	Fisheries	Presence of	15
	Species and Ecosystems at risk	Presence of	15

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				**36**
Emergency Response Resources	Asphalt Plants, Concrete Mixing, Oil & Gas Pumping & Compressor Station, Oil & Gas Transportation Pipelines, Petroleum Bulk Plants, Works Yards	2				8		2	**10**
Utilities	Electrical Power Systems, Gas Distribution Systems, Water Distribution Systems	3		12	10	8			**30**
Communication	Telecommunications	4			10	8			**18**
Medical Facilities	Hospitals, Group Home, Seniors Independent & Assisted Living, Seniors Licenses Care	5	14	12	10				**36**
Transportation	Airports, Heliports, Marine & Navigational Facilities, Marine Facilities (Marina), Service Station	6		12		8		2	**22**
Environmental	Garbage Dumps, Sanitary Fills, Sewer Lagoons, Liquid Gas Storage Plants, Pulp & Paper Mills	7			10	8			**18**
Community	Government Buildings, Hall (Community, Lodge, Club, Etc.), Recreational & Cultural Buildings, Schools & Universities, College or Technical Schools.	8	14	12		8		2	**36**

Figure 4-1 shows the distribution of exposure scores for all geohazard areas, and Figure 4-1 and Table 4-3 shows how total weightings were grouped by percentile to assign exposure ratings.

For consistency and application at provincial scale, BGC has applied the same ratings criteria (percentile thresholds) across multiple risk prioritization studies for Regional Districts in BC[20]. However, BGC notes that the distribution of exposure scores is relative to the study area (SLRD), to compare the level of development between different geohazard areas inside this study area. Different choices of study area would affect this relative rating.

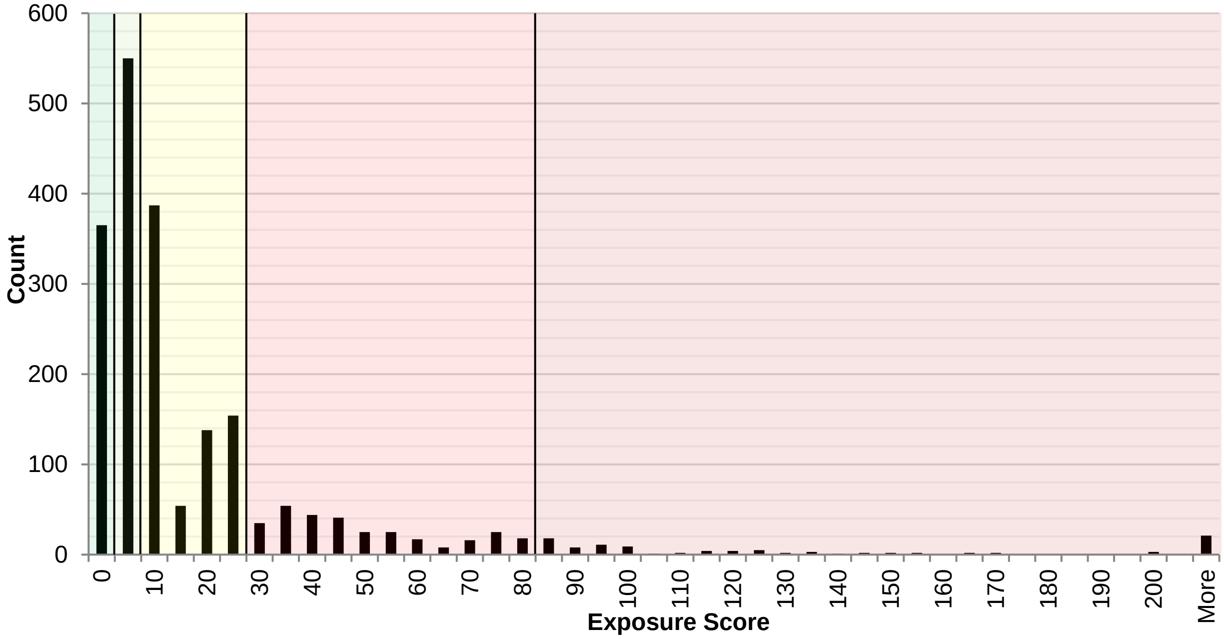


Figure 4-1. Distribution of exposure scores in the SLRD and definition of associated exposure ratings.

Table 4-3. Hazard exposure rating.

Hazard Exposure Rating	Criteria	Total Weighting Value
Very High	Greater than 95th percentile	> 80
High	Between 80th and 95th percentile	25 to 79
Moderate	Between 60th and 80th percentile	6 to 24
Low	Between 20th and 60th percentile	1 to 5
Very Low	Smaller 20th percentile	0

[20] To date, this includes the SLRD, Regional District of Central Kootenay, Columbia Shuswap Regional District, Regional District of North Okanagan, Thompson-Nicola Regional District, and Cariboo Regional District.

5. GEOHAZARD RISK PRIORITIZATION

5.1. Introduction

This section describes how geohazard areas were prioritized across the SLRD. The prioritization approach is consistent across the range of geohazards assessed, where methods to estimate input values are specific to each hazard type.

The prioritization framework used in this study is based on the following general 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 illustrates the three components of the risk prioritization 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.

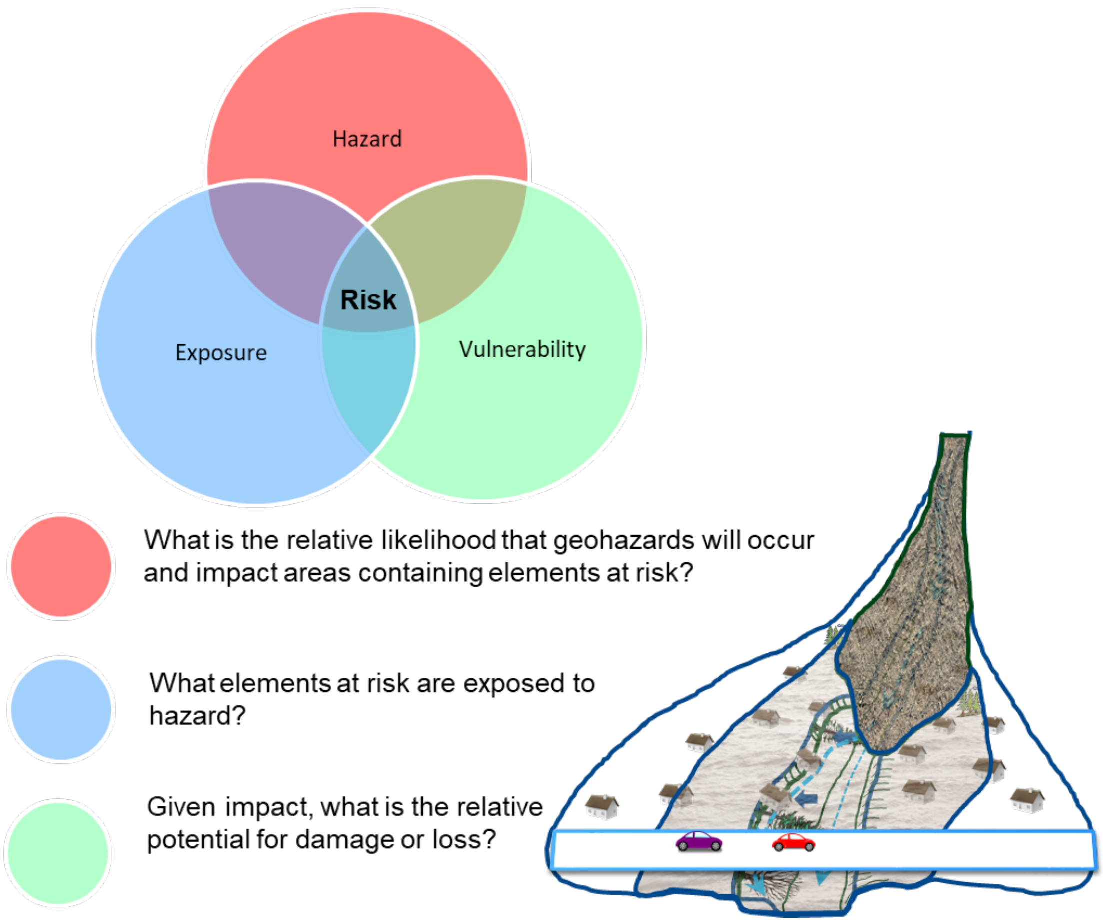


Figure 5-1. Elements of the prioritization approach.

The approach uses matrices to arrive at separate ratings for hazard and consequence, which are then combined to provide a priority rating for each hazard area. Higher ratings generally reflect a higher estimated likelihood that more destructive flows will impact more extensive development. 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.

At the same time, 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 describe the steps used to determine geohazard, consequence, and priority ratings for each area. Appendices D, E and F provide detailed description of methods to determine geohazard ratings for clear-water, steep creek and volcanic geohazard areas, respectively.

5.2. Geohazard Rating

Table 5-1 presents the qualitative 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
Impact Likelihood	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[21]. Appendix D and Appendix E describe the methods used to assign each rating.

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.

[21] 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.

	Clear-water floods	0.5% AEP (200-year) flood
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 (%)[1]	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.

BGC assigned consequence ratings by combining two factors rating the exposure of elements at risk (exposure rating) to destructive flows (vulnerability rating).

5.3.1. Exposure Rating

The exposure rating is based on weightings assigned based on the value or presence of the elements at risk listed in Table 4-1. BGC developed in-house software tools to identify the presence and value of elements at risk within hazard areas and calculate weightings. As noted in Section 4, the exposure rating is subjective and aims to weight the 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).

5.3.2. Hazard Intensity Rating

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. This study primarily focused on direct flood inundation and debris impact.

The elements at risk considered in this study have different vulnerabilities to flood impact, and some simplification is required to arrive at aggregate ratings for a given area. The vulnerability of specific elements at risk was not estimated. BGC assumed that elements at risk would be generally more vulnerable to more highly destructive flows and used average estimates of flow intensity as a proxy for relative vulnerability.

As noted in Sections 3.1.4 and 3.2.6, Appendices D, E and F provide further description of methods to estimate destructive potential and assign ratings for each geohazard type.

5.3.3. Consequence Rating

Table 5-4 displays the matrix used to combine hazard exposure and intensity ratings, to arrive at a consequence rating. 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
Hazard Intensity	Very Low	Low	Moderate	High	Very High

5.4. Priority Rating

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

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 I. These inputs can be used to consider additional or different combinations of factors in risk management plans, beyond the aggregate priority rating.

Table 5-5. Prioritization matrix (assets).

Geohazard Rating	Priority 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
Consequence Rating	Very Low	Low	Moderate	High	Very High

BGC notes that the geohazard areas prioritized are not identical in areal extent. This means that – all else being equal – larger areas may rank as higher priority because they contain more elements at risk. BGC did not normalize ratings by unit area. The rationale for this was based on the notion of "consultation zones", which define a geographic area considered for geohazard safety assessment (Geotechnical Engineering Office, 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.

6. RESULTS

This study provides baseline results in several ways:

- This report section provides a summary overview of results.
- Cambio (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 B provides a guide to navigate Cambio.
- Appendix H provides an Excel spreadsheet with tabulated results.
- Data download of prioritized, attributed geohazard areas in geodatabase format.

In total, BGC prioritized about 2058 geohazard areas encompassing about 1615 km^2 of the SLRD (Table 6-1). Table 6-2 lists the results worksheets provided in Appendix H, and Figure 6-1 provides summary statistics by jurisdiction.

Table 6-1. Number of prioritized areas in the SLRD, by geohazard type.

Geohazard Type	Priority Level					Grand Total
	Very High	High	Moderate	Low	Very Low	
Clear-Water Floods (water courses and water bodies)	0	143	247	1455	0	**1845**
Steep Creeks (Fans)	16	54	57	71	3	**201**
Volcanic Geohazards	1	11	0	0	0	**12**
Grand Total (Count)	**17**	**208**	**304**	**1526**	**3**	**2058**
Grand Total (%)	**< 1%**	**10%**	**13%**	**77%**	**< 1%**	**100%**

Appendix G provides the example RAIT form required by the NDMP.

Table 6-2. Results worksheets provided in Appendix H.

Appendix H (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	Summary statistics of prioritization results by jurisdiction (digital version of Table 6-1).
Steep Creek Hazard Attributes	Attributes displayed in the information sidebar on *Cambio* for all steep creek geohazard areas.
Clear-water Flood Hazard Attributes	Attributes displayed in the information sidebar on *Cambio* for all clear-water flood geohazard areas.
Volcanic Geohazards Attributes	Attributes displayed in the information sidebar on *Cambio* for all volcanic geohazard areas.

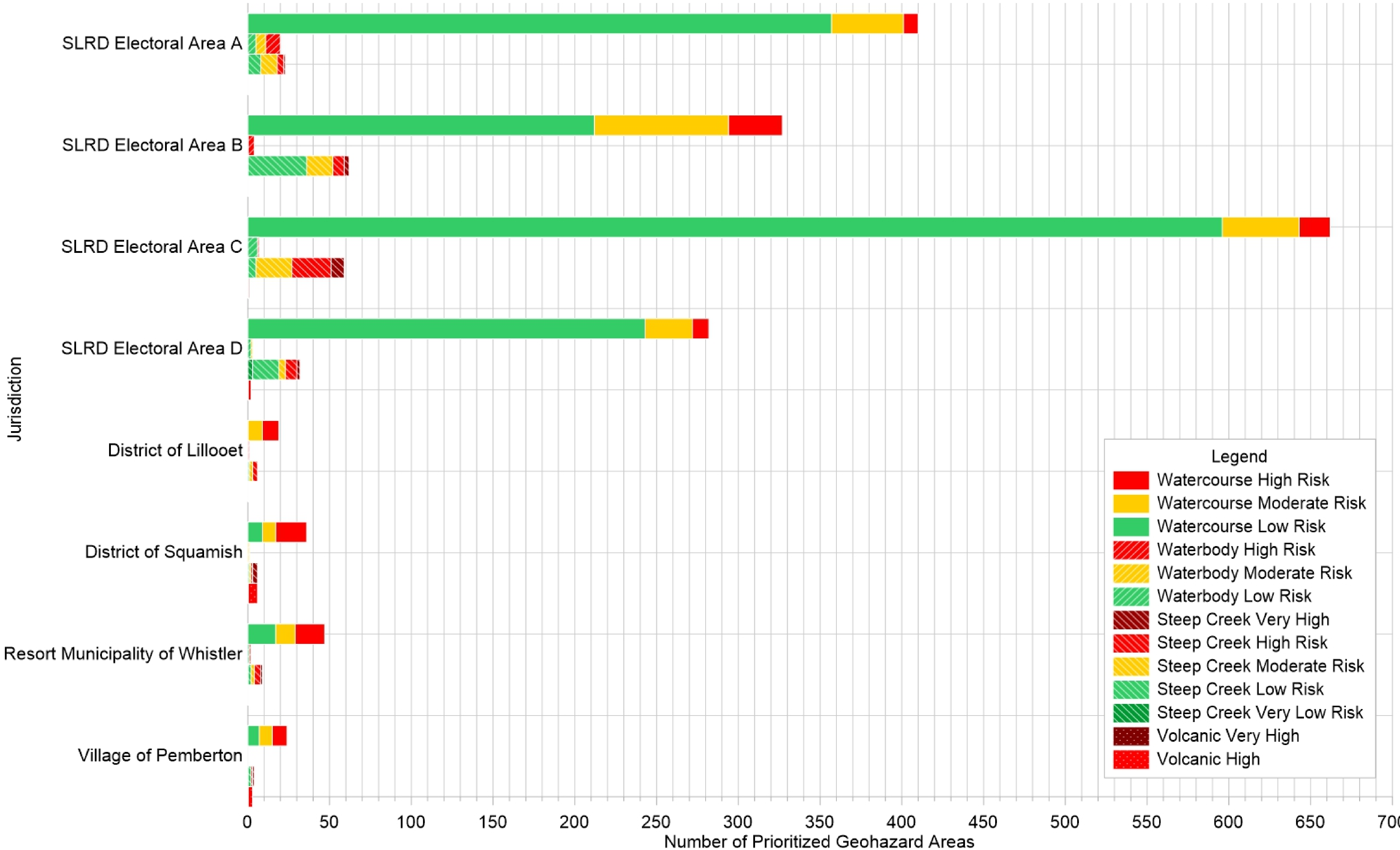


Figure 6-1. Number of prioritized areas in each jurisdiction within the SLRD.

7. RECOMMENDATIONS

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. Appendix I provides further detail on recommended approaches and tasks for clear-water flood and steep creek geohazard assessments.

7.1. Data Gaps

Recommendation:

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

Table 7-1 summarizes gaps in baseline data that informed the current risk prioritization study and provides recommendations to resolve these gaps.

Table 7-1. Summary of data gaps and recommended actions.

Input	Description	Implication (Factor Affected)	Recommended Actions to Resolve Gaps
Topography	• The main valley corridors within the SLRD contain Lidar, but gaps exist in the Ashlu Creek valley, the upper Squamish River valley, the upper Lillooet River valley, and in most of the valleys north and east of the Hamlet of Mt Currie (except in the Seton area). 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.	• Precision and accuracy of estimated geohazard location/extents, likelihood, and intensity.	• Lidar acquisition and processing. • Review and update to terrain analyses (i.e., fan boundary delineation) following Lidar acquisition. • Consider re-evaluating geohazard area delineation and characterization once Lidar data are available.
Bathymetry	• Clear-water flood hazard assessment did not consider the channel geometry or river bathymetry.	• Precision and accuracy of estimated geohazard location/extents and intensity.	• For more detailed, site-specific studies, bathymetry would be required such as high priority sites identified in Table 7-2 that do not have an existing detailed assessment.
Stream network	• 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. 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.	• Gap in hydrologic analyses for fans not intersecting mapped streams • Watercourses that have moved since the original stream network mapping may lead to an apparent inconsistency between HAND modelling outputs and mapped river channels. • 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.	• Manual revisions to stream networks may be required to facilitate hydrologic, hydraulic, and geomorphic analyses required for geohazard risk management. • 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.
Geohazard Sources / Controls / Triggers	• Gaps exist in the inventory of geohazards within the SLRD that represent sources, controls, or triggers for flood and steep creek geohazards. For example, landslides represent triggers for steep creek geohazards, and wildfires alter watershed hydrology in ways that can temporarily affect flood response and sediment transport. Landslides can also create temporary dams and associated inundation and outburst floods, as well as floods from waves triggered by landslides into lakes and reservoirs. Those have not been considered.	• 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.	• Given that not all studies can be completed at the same time, 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. • 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. • Initiate citizen science initiatives[22] to capture geohazards information, particularly events, in near-real time. A web application is currently being developed by Public Safety Canada that is anticipated to support this action for clear-water floods.
Regional Flood Frequency Analysis	• Not all watercourses within the SLRD are gauged and others do not have sufficient periods of records to accurately estimate flood quantiles from at-site data only. Regional flood frequency analysis (RFFA) can be used to estimate flood quantiles for ungauged watercourses and also to help improve estimates of quantiles for sites with short streamflow records. An RFFA is a statistical modelling process which pools information from nearby (regional) gauge stations which are 'similar' to the site of interest to determine the flood quantiles.	• Precision and accuracy of flood hazard location/extents, likelihood, and intensity.	• BGC has conducted an RFFA for southern British Columbia which included over 1,100 hydrometric stations from both Canada and the United States based on the index flood method (Dalrymple, 1960). The study has identified a number of hydrologically homogeneous regions which have been verified using statistical measures of homogeneity. • The homogenous regions within the SLRD have not yet been processed. Next steps would be to develop the regional growth curves (dimensionless flood frequency curves) for each of the regions and develop multivariate regression models for estimation of the Index Flood (e.g., 2-year Flood).
Geohazard Frequency-	• Flood magnitude and associated return periods were evaluated based on limited gauge data (gauge locations and record lengths) and were	• Precision and accuracy of estimated geohazard location/extents, likelihood, and intensity.	• Advocate for improvements to WSC gauging in the SLRD.

[22] i.e., collaborations between professionals and volunteer members of the public, to expand opportunities for data collection and to engage with community members.

Input	Description	Implication (Factor Affected)	Recommended Actions to Resolve Gaps
Magnitude Relationships	unavailable for rivers and lakes regulated by dams. Frequency-magnitude relationships have not been quantified for most steep creek geohazard areas in the SLRD based on detailed investigations.		• Establish frequency-magnitude relationships for individual steep creeks as part of detailed geohazards studies (Section 7.2, Appendix E).
Wildfires	• Post-wildfire geohazards assessments rely on remotely sensed burn severity mapping supplemented by field inspection of conditions at the ground surface. At present, only burn perimeter mapping is made widely available for all fires and burn severity mapping is not necessarily available for small wildfires. However, small fires occurring in basins prone to steep creek processes can still result in elevated geohazard levels.	• Ability to provide timely post-wildfire geohazards assessments for areas where changes in post-wildfire geohazard activity will have the strongest influence on risk.	• In advance of wildfire occurrence, apply the results of this assessment to define high priority areas where burn severity mapping should be completed, should a wildfire occur. High priority areas can be defined by watershed boundaries, which were already prepared as part of the current study. • 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. • Use the existing study information in combination with burn severity maps to inform post-wildfire geohazard risk assessments when required
Volcanic Geohazard Extents	• 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.	• Precision and accuracy of estimated geohazard location/extents – affecting hazard exposure and vulnerability estimation. • Implications for asset management decisions resulting from volcanic hazard estimation.	• Systematic re-evaluation of hazard scenarios with experts in the field using various assumptions. • Inclusion of eruptive hazards at least for the Mount Meager Volcanic Complex, which is the most active one in the SLRD. • Seamless hazard chain modeling (rock avalanche, landslide-dammed lake, and subsequent event scenarios). • Numerical lahar runout modelling conducted as part of a detailed assessment for specific areas or creeks.
Flood Protection Measures, and Flood Conveyance Infrastructure	• 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. • Layers depicting the location of flood protection or conveyance infrastructure were sourced from provincial inventories and may contain gaps or inaccuracies.	• Precision and accuracy of estimated geohazard location/extents, likelihood, and intensity.	• Develop data collection standards and sharing agreements between the various facility owners to facilitate their inclusion in a larger data model. • More detailed inventories and characterization of assets based on consistent data standards would improve and reduce the cost of hydraulic assessments. • Apply the results of this assessment to prioritize characterization of risk reduction measures and consideration in further, more detailed geohazards assessments. • 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).
Exposure	• Gaps exist in the elements at risk (asset) data model developed for the SLRD, in terms of location, attributes, and data formats. • 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. • Local knowledge, particularly as it relates to intangible losses and flood resiliency, also represents a key gap outside the scope of the current study.	• Ability to provide information that supports: o Hazard exposure and vulnerability estimation o Inclusion of assets required for later more detailed hazard modelling (i.e., drainage networks). o 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. o Level of detail of data informing asset management in geohazard areas. o Level of detail of elements at risk information supporting emergency response planning.	• Building footprints could be digitized for all parcels containing building improvements and intersecting geohazard areas. This information will be required for future detailed flood inundation modeling and risk assessments and to verify whether geohazards that intersect improved cadastral parcels intersect buildings on the parcel. Building footprints should include a unique identifier and Parcel ID to allow them to be joined to cadastral data. 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. This effort would also identify cases where properties contain buildings not recorded by BC Assessment.
	• 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.	• 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	• 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

Input	Description	Implication (Factor Affected)	Recommended Actions to Resolve Gaps
		original intent, which is to inform appraised improvement values.	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. • 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.
	• Data gaps exist for elements at risk located on First Nations Reserves.	• Underestimation of exposure and vulnerability on First Nations Reserves.	• Collection of data on elements at risk within First Nations reserves with a level of detail and format consistent with that outside reserve lands would facilitate geohazards assessments in these areas. BGC assumes this work would have to be led by a Federal government agency.
	• 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.	• Underestimation of priority where geohazard areas intersect evacuation routes along minor roads.	• Prepare map layer identifying emergency evacuation road networks. • Include an evacuation road network layer in hazard exposure analysis and update the study results.

7.2. Further Geohazards Assessments

Recommendation:

- *Review prioritized geohazard areas and develop a plan to implement next steps in the framework of geohazard risk management.*

Table 7-2 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 7-2 were selected as examples only. A 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 the Appendix I 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 7-2 also 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 also emphasizes that this assessment was limited to settled areas in the SLRD (Section 1.4). 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 otherwise 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 7.2.1 to 7.2.4 summarize the rationale for further studies of each prioritized geohazard type, as well as for regulated water bodies (reservoirs). Appendix H provides further detail on recommended approaches and tasks for clear-water flood and steep creek geohazard assessments.

Table 7-2. Select geohazard areas highlighted as high priority.

Hazard Code	Hazard Type	Geohazard Process	Name	Geohazard Rating	Consequence Rating	Priority Rating	Existing Detailed Assessment? (See footer for letter definitions[1])	Assessment Type[2]
11993	Steep Creek	Debris Flood	Britannia Creek	Very High	High	Very High	A	HA, MA
12001	Steep Creek	Debris Flow	Landsborough Creek	High	Very High	Very High	C	-
12005	Steep Creek	Debris Flow	Unnamed Creek	High	Very High	Very High	C	-
12015	Steep Creek	Debris Flow	Bear Creek	Very High	Very High	Very High	A	HA, RA, MA
12021	Steep Creek	Debris Flow	Cataline Creek	Very High	High	Very High	A	HA, RA, MA
12036	Steep Creek	Debris Flood	Mill Creek	Very High	High	Very High	B	Unknown
12040	Steep Creek	Debris Flow	Unnamed Creek	Very High	High	Very High	C	-
12083	Steep Creek	Flood	Gun Creek	Very High	High	Very High	C	-
12089	Steep Creek	Debris Flow	Rubble Creek	Very High	Very High	Very High	B	Unknown
12117	Steep Creek	Debris Flood	Miller Creek	Very High	High	Very High	B	HA, MA
12180	Steep Creek	Debris Flood	Culliton Creek	Very High	High	Very High	C	HA, MA
12156	Steep Creek	Debris Flood	Fitzsimmons Creek	High	Very High	Very High	A	HA, MA
12162	Steep Creek	Flood	Rutherford Creek	Very High	High	Very High	B	Unknown
12069	Steep Creek	Debris Flow	Neff Creek	Very High	Moderate	Very High	A	Unknown
12172	Steep Creek	Debris Flow	Unnamed Creek	Very High	High	Very High	C	-
12023	Steep Creek	Debris Flow	Cheekye Fan	High	Very High	Very High	A	HA, RA, MA
12068	Steep Creek	Debris Flood	Owl Creek	High	Very High	Very High	C	-
11956 / 11957	Clear-water	Flood	Squamish River	Moderate	Very High	High	A	HA, RA, MA
10136	Clear-water	Flood	Lillooet River	Moderate	Very High	High	A	HA
10438	Clear-water	Coastal Flood	Howe Sound	Moderate	Very High	High	A	HA, RA, MA
10238	Clear-water	Flood	Seton River	Moderate	Very High	High	C	-
10135	Clear-water	Flood	Upper Squamish River	Moderate	Very High	High	A	HA
10234	Clear-water	Flood	Cayoosh Creek	Moderate	Very High	High	C	-
10237 / 10239 / 10244 / 11861	Clear-water	Flood	Fraser River at Lillooet	Moderate	Very High	High	C	-
10417	Clear-water	Flood	Fraser River at Pavillion	Moderate	Very High	High	C	-
11954	Clear-water	Flood	Fitzsimmons Creek	Moderate	High	High	A	HA, RA, MA
10139 / 10140 / 10163	Clear-water	Flood	Mamquam River	Moderate	High	High	A	HA, RA, MA
10138	Clear-water	Flood	Cheekeye River	Moderate	High	High	A	HA, RA. MA
10195	Clear-water	Flood / Reservoir	Daisy Lake (Cheakamus Dam)	Moderate	High	High	A	HA
10142	Clear-water	Flood	Millar River	Moderate	High	High	A	HA
10141 / 10666 / 10664	Clear-water	Flood	Alta Creek	Moderate	High	High	A	HA

10190	Clear-water	Flood	Cheakamus River	Moderate	High	High	A	HA, RA. MA
10137	Clear-water	Flood	Whistler Creek	Moderate	High	High	A	HA
10470	Clear-water	Flood	Stawamus River	Moderate	High	High	A	HA, RA, MA
1A, 1B, 1C (12185 / 12186 / 12187)	Volcanic	Volcanic	Mount Meager Volcanic Complex	Low to High	High to Very High	High to Very High	C	-
2A, 2B, 2C, 2D, 2E (12189 / 12190 / 12193 / 12191 / 12192)	Volcanic	Volcanic	Mount Garibaldi Volcanic Complex	Low to Moderate	High to Very High	High	C	-
3A, 3B, 3C (12195 / 12196 / 12194)	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.

7.2.1. Clear-water Floodplain Mapping

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 7-2 highlights examples of clear-water flood hazard areas considered high priority for consideration in risk management decision making (i.e., Gun Creek, Seton River, Cayoosh Creek, Fraser River at Lillooet, Fraser River at Pavillion, and possibly Rutherford Creek). Further details on proposed assessment methodology, including further hydraulic modelling, are provided in Appendix I.

For areas with existing detailed flood hazard mapping (Appendix D, Section D.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.

7.2.2. Reservoirs

Section 3.1 described 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 7-2 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 and the opportunity for greater flexibility for land use based on hazard or risk-based decision making. Appendix H provides further details on the impact line approach.

7.2.3. 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.

This regional study provides boundaries of steep creek geohazard areas and relies on existing detailed studies where available, such as: Brittannia Creek; Cheekeye River; Catiline Creek; and Bear, Whitecap and Spider Creeks at Seton Portage (Appendix A).

Steep creek geohazard maps would be created with similar objectives to clear-water flood hazard maps: to describe the threat of a steep creek flood hazard scenario at a given location based on its 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 its probability of occurrence.

Table 7-2 highlights examples of steep creek hazard areas considered high priority for consideration in risk management decision making. The list is not exhaustive, and the full list of inventoried steep creek fans should be reviewed when selecting sites for further work. The purpose of the steep creek flood hazard maps would be to support:

- Land use regulatory planning, including bylaw compliance and revisions
- Emergency planning and operations
- Flood risk management, including prevention and mitigation.

Further details on proposed assessment methodology are provided in Appendix I.

As noted in Section 7.1, gaps also remain in the inventory of geohazards within the SLRD that represent sources, controls, or triggers for flood and steep creek geohazards. One such example is the potential for LDOFs in the upper basins of steep creeks, which have the potential to generate higher magnitude flows than “typical” steep creek processes occurring on the creek. Table 7-3 lists the creeks that were identified as subject to high or very high LDOF potential as a flag for consideration in future studies.

Table 7-3. List of creeks identified as subject to high LDOF potential.

Hazard ID	Creek Name	LDOF Potential Rating
12016	Spider Creek	High
12031	Unnamed Creek (E460197, N5563284)	High
12157	Blackcomb Creek	High
12162	Rutherford Creek	High
12117	Miller Creek	High
12089	Rubble Creek	High
12149	Unnamed Creek (E483031, N5520806)	High
12180	Culliton Creek	High
12171	South Creek	Very High

7.2.4. 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 7-2 highlights examples of volcanic hazard areas considered high priority for consideration in risk management decision making. Table 7-1 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.

7.3. Long-Term Geohazard Risk Management

The results of this study 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 useful 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 can 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 7-1).

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.

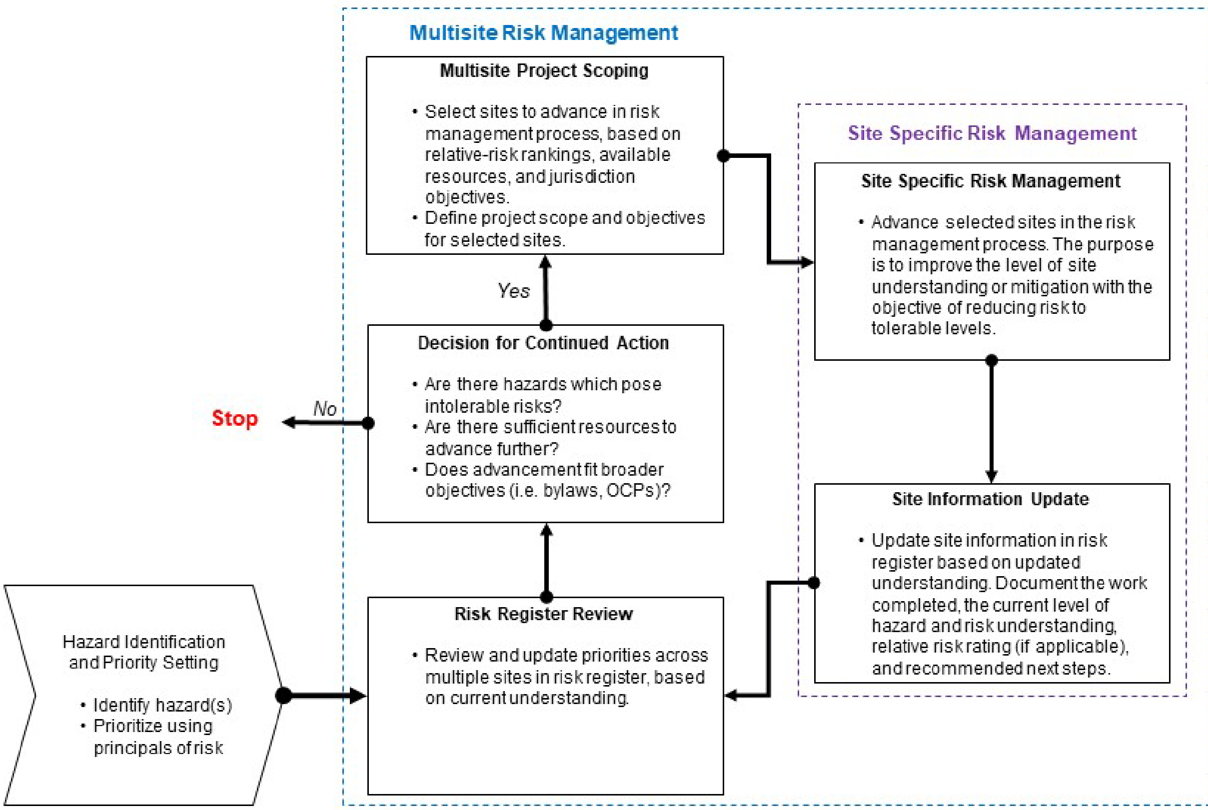


Figure 7-1. Schematic of multi-site risk management approach.

7.4. Geohazards Monitoring

Recommendation:

- Develop a path to design and implement geohazard monitoring and warning systems.

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 7-2 shows an example of 24-hour accumulated precipitation in southern British Columbia, reported via BGC's RNT[23]. 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 7-4). Figure 7-3 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.

[23] Results anticipated to soon be made available at finer resolution (1-3 km grid).

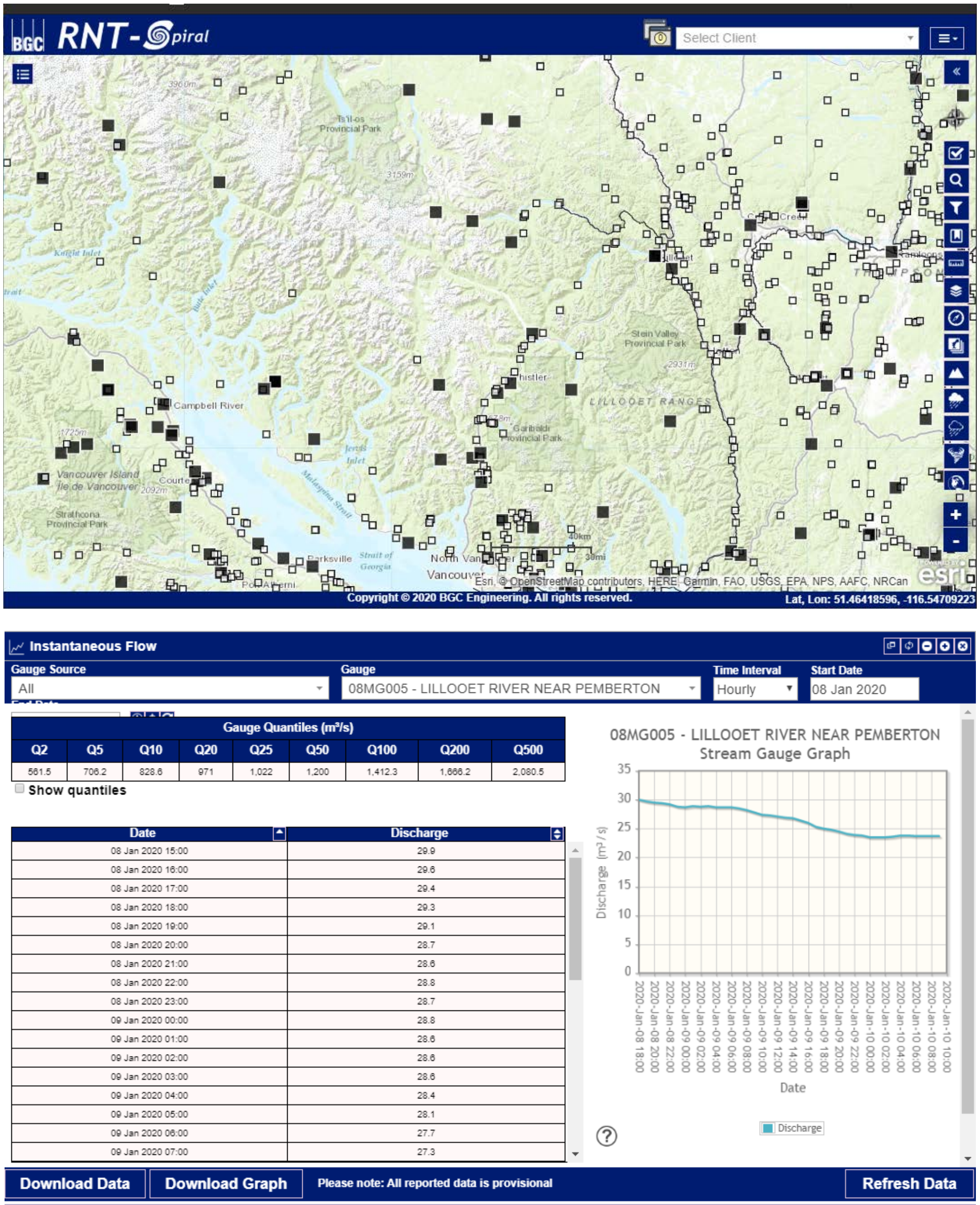


Figure 7-2. Screen capture of BGC RNT™ showing available real-time streamflow gauges in the District (solid black squares) and window showing real-time flows from WSC gauge 08MG005 – *Lillooet River near Pemberton*. Source: WSC (2020, via BGC RNT™).

Table 7-4. 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 7-3).

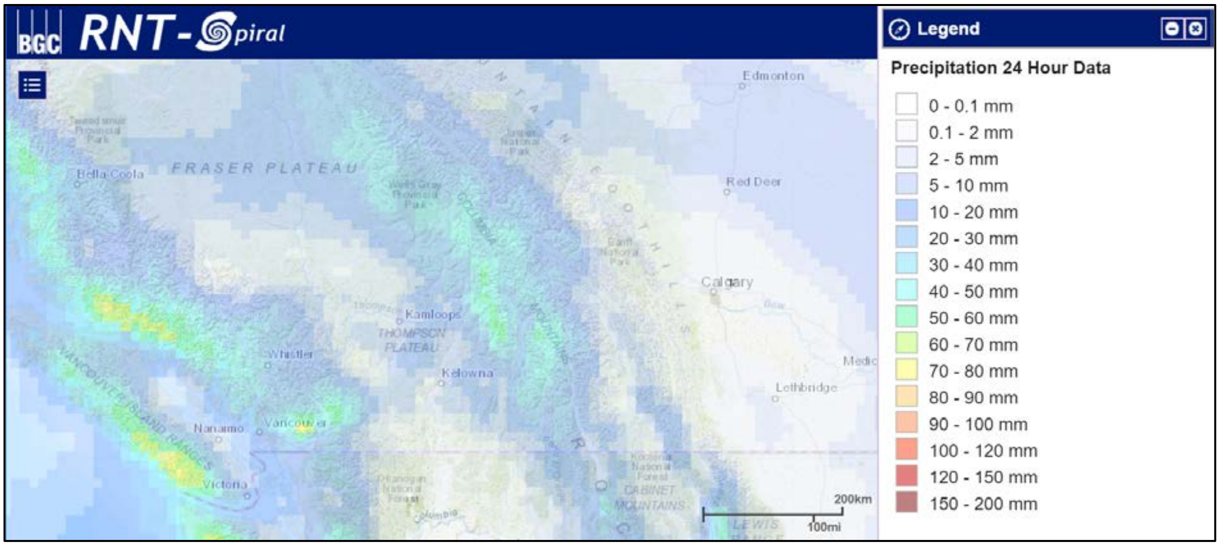


Figure 7-3. Example of 24-hour accumulated precipitation in southern British Columbia on November 3, 2018. Source: EC-MSC Canadian Precipitation Analysis (CaPA) (2018, via BGC RNT™).

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. Develop 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.

7.5. Policy Integration

Recommendations:

- Review Development Permit Areas (DPAs) within the SLRD, in light of the hazard extents identified in this study
- Review plans, policies and bylaws related to geohazards management
- 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).

7.5.1. 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.

7.5.2. 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. Application of study results to define DPAs should consider geohazard mapping uncertainties and the limitations listed in Appendices D-F.

7.6. 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.

7.6.1. Rationale

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 (EMBC, 2019), and is also the focus of 2019 UBCM Resolution B98: Resourcing A Collaborative System of Data Sharing in BC.

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.

7.7. Training and Stakeholder Communication

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.

7.7.1. Training

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.

8. CLOSURE

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

Yours sincerely,

BGC ENGINEERING INC.
per:

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

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APPENDIX A
DATA COMPILATION

Location				Project			Hazard Type			Reference
Name	River Basin	District	NTS ID	Project Title	Report? (Y/N)	Spatial information?	Flooding?	Landslide?	Steep Creek?	Citation
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. *Canadian Journal of Earth Science, 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. *Natural Hazards and Earth System Sciences, 12* (5), 1277-1294.
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 maping in the Resort Municipality of Whistler (File: 35100-30/119-4671) [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. Canadian Journal of Earth Sciences, 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 racharge in gullies. Geomorphology, 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. Canadian Geotechnical Journal, 29, 345-352.
M Creek	Howe Sound	SLRD	092G06	Meteorological antecedents to debris flow in southwestern British Columbia; some case studes	N			Y	Y	Church, M., & Miles, M.J. (1987). Meteorological antecedents to debris flow in southwestern British Colubia; some case studies. In J.E. Costa & G.F. Wieczorek (Eds), Debris flows/avalanches: process, recognitions and mitigation (pp. 63-79). Boulder, Colorado: Geological Society of America.
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.
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.

Location				Project			Hazard Type			Reference
Name	River Basin	District	NTS ID	Project Title	Report? (Y/N)	Spatial information?	Flooding?	Landslide?	Steep Creek?	Citation
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. Candaian 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.
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, 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 Squam	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.
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: Dyanmic 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 assesments for debris flows. In J.J. Clague and D. Stead (Eds.), Landslides: Types, mechanisms and modeling. Cambridge, UK: Cambridge University Press.
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.

Location				Project			Hazard Type			Reference
Name	River Basin	District	NTS ID	Project Title	Report? (Y/N)	Spatial information?	Flooding?	Landslide?	Steep Creek?	Citation
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 https://www.whistler.ca/sites/default/files/2016/Dec/related/21022/rmowfloodhazardspecificguide.pdf
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.
				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.
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.
				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 redevelopement. 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 B
CAMBIO COMMUNITIES

B.1. INTRODUCTION

B.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 – *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 and web service for prioritized geohazard areas). *Cambio* provides a platform to access the same results in a structure that supports decision making.

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

- Where are geohazards located and what are their characteristics?
- What community assets (elements at risk) are in these areas?
- What geohazard areas are ranked highest priority, from a geohazard risk perspective?

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

<u>Hazard information:</u>

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

<u>Exposure information:</u>

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

<u>Analysis tools:</u>

- Identification of assets in 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[1].

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.

B.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[2].

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.

B.2. NAVIGATION

Figure B.2-1 provides a screen shot of *Cambio* following user login and acceptance of terms and conditions. Section B.3 describes map controls and tools, including how to turn layers on and off for viewing. Section B.4 describes interactive features used to access and download information about geohazard areas.

On login, the map opens with all layers turned off. Click the layer list to choose which layers to view (See Section B.3).

[1] 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.

[2] 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.

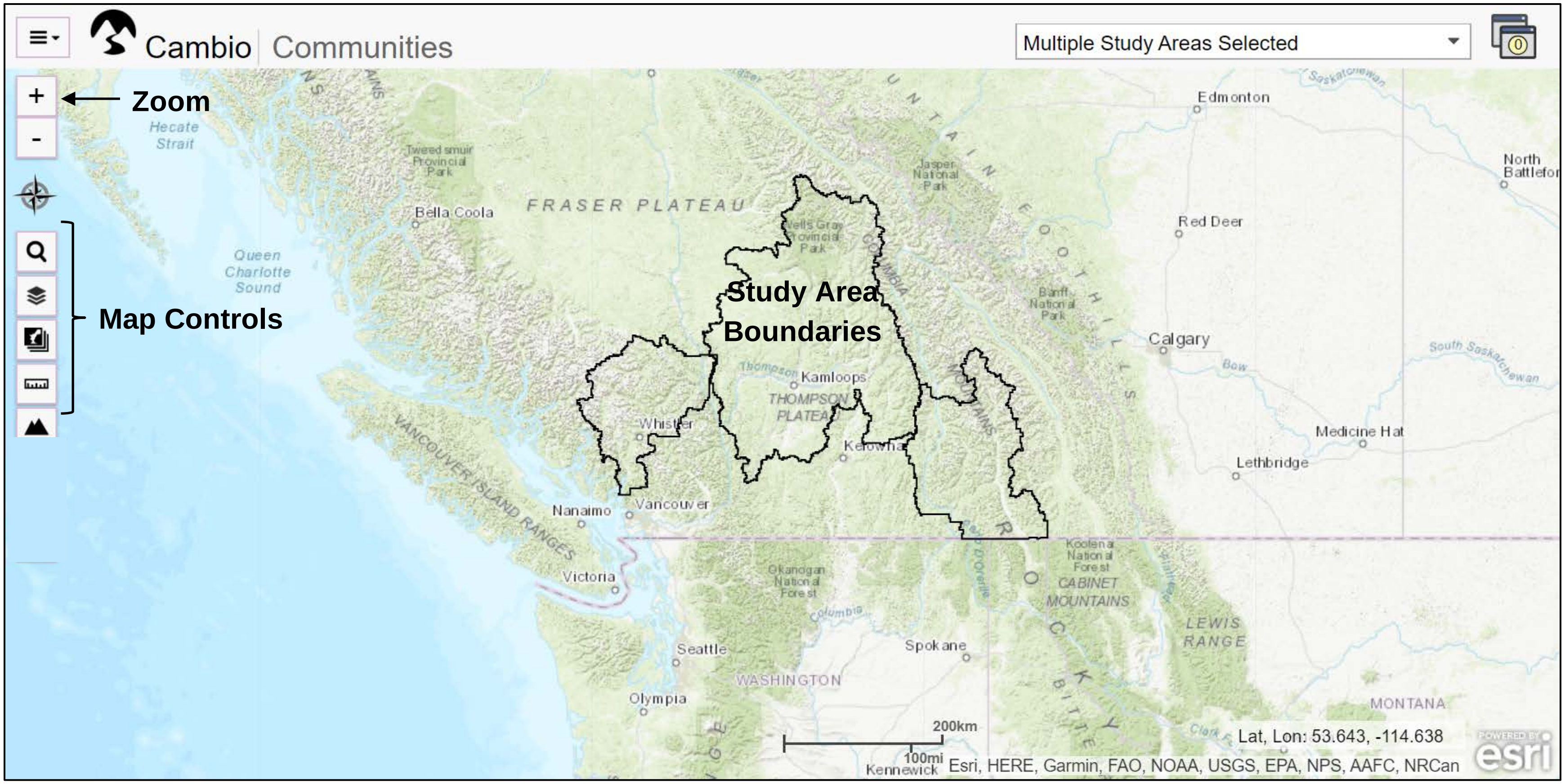

Figure B.2-1. Online map overview.

B.3. MAP CONTROLS

Figure B.2-1 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 B.3-1). Sections B.3.1 to B.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.

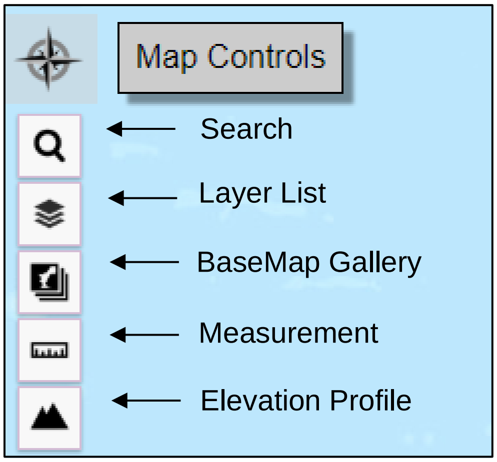

Figure B.3-1. Map controls and tools.

B.3.1. Search

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

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

B.3.2. Layer List

This control (Figure B.3-2) 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.

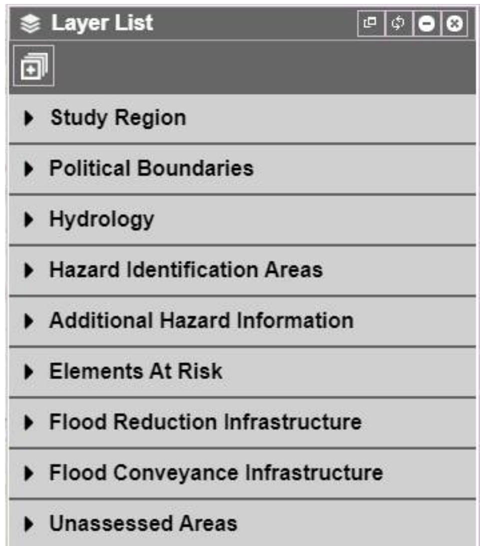

Figure B.3-2. Layers list.

B.3.3. Basemap Gallery

The basemap gallery allows the user to switch between eight 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.

B.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.

B.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 “ⓘ” 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.

B.4. GEOHAZARD INFORMATION

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

B.4.1. Geohazard Feature Display

Geohazard areas can be added to the map by selecting a given geohazard type under "Hazard Areas" in the layer list. Once selected, the geohazard areas can be colored by hazard type, 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).

Clicking on an individual geohazard feature reveals a popup window indicating the study area, hazard code (unique identifier), hazard name, and hazard type. At the bottom of the popup window are several options (Figure B.4-1). 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 "ⓘ" opens a sidebar with detailed information about the individual feature, as described in Section B.4.2.

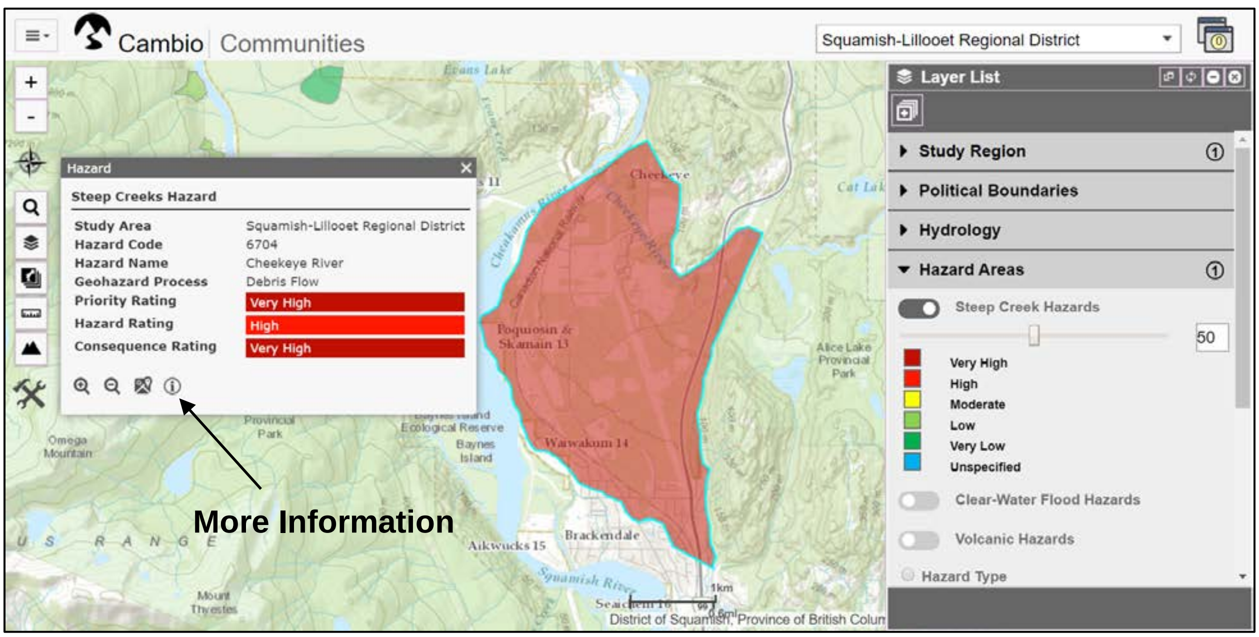

Figure B.4-1. Geohazard feature popup.

B.4.2. Geohazard Information Sidebars

Clicking a geohazard feature and then the "ⓘ" within the popup opens additional information in a sidebar on the right side of the screen (Figure B.4-2). Dropdown menus allow the user to view as much detail as required.

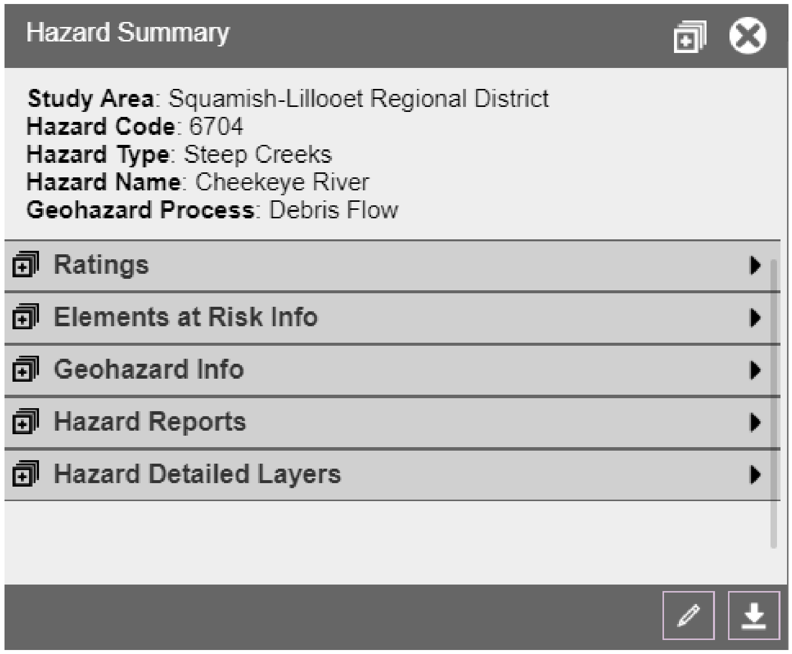

Figure B.4-2. Additional information sidebar.

Table B-1 summarizes the information displayed within the sidebar. In summary, clicking Ratings reveals the site Priority, 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 B-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).

B.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).

B.6. ADDITIONAL GEOHAZARD INFORMATION

B.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.

B.6.2. Imagery

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

B.6.3. River Network

In addition to geohazard areas, the river network displayed on the map (when set to viewable) is sourced from the National Hydro Network and published from BGC’s hydrological analysis application, River Network Tools™ (RNT). Clicking any stream segment will open a popup window indicating characteristics of that segment including Strahler stream order, approximate average gradient, and cumulative upstream catchment area (Figure B.6-1). 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.

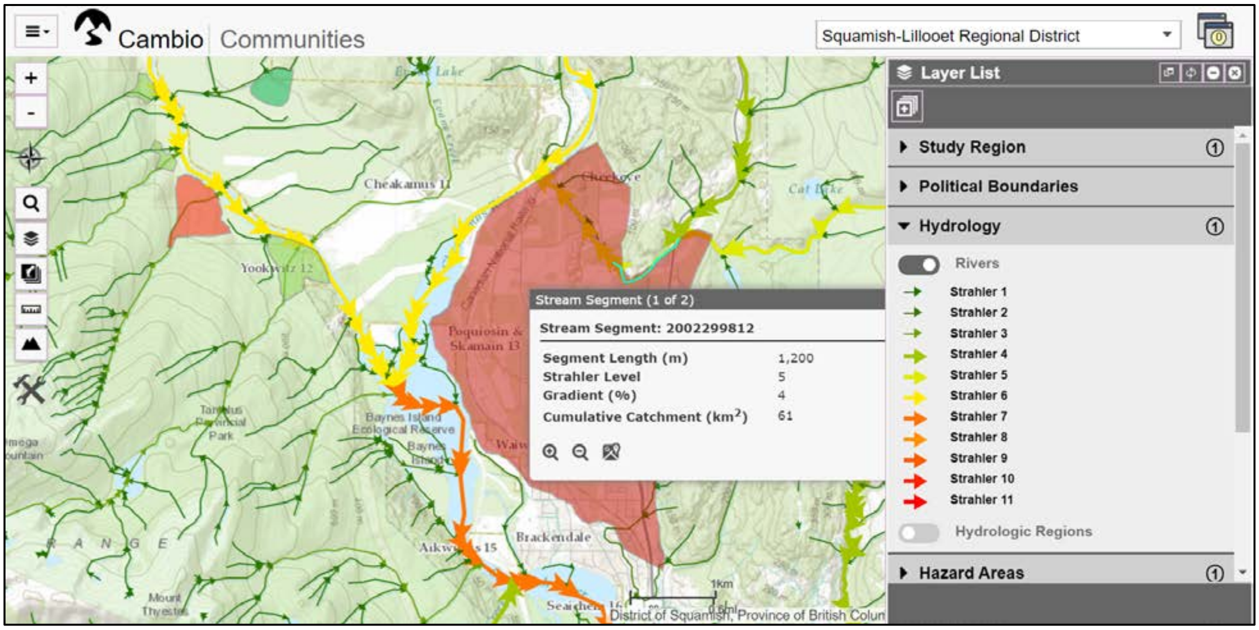

Figure B.6-1. Interactive Stream Network. The popup shows information for the stream segment highlighted in green.

B.6.4. Real-time Flow Gauges

Cambio also provides access to real-time[3] stream flow and lake level monitoring stations where existing. 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 B.6-2). The real time gauges are also colored on the map by their respective flow return period for the current reading date.

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

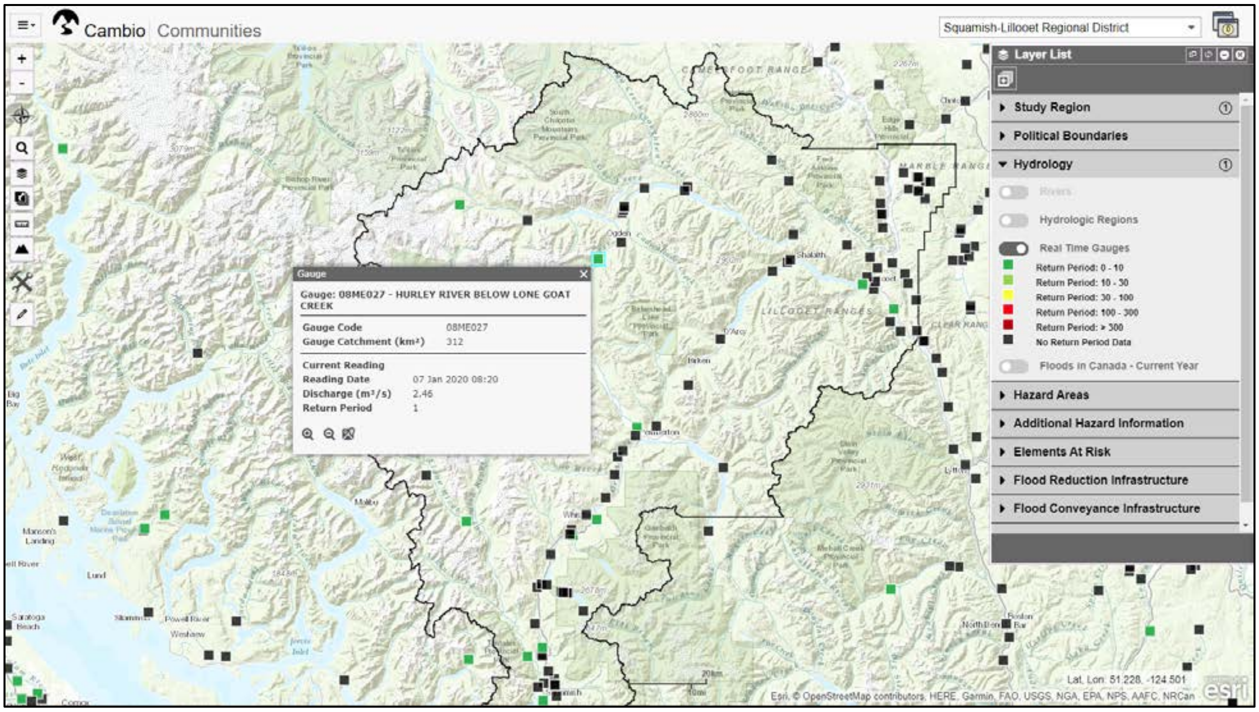

Figure B.6-2. Near real-time flow gauge. The popup shows gauge information including measured discharge and return period for a given reading date and time.

B.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[4] 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.

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

APPENDIX C
EXPOSURE ASSESSMENT

C.1. INTRODUCTION

This study assessed areas that both contained elements at risk and that were subject to geohazards. This appendix describes how elements at risk data were organized across the study area. Section 4.0 of the main report describes how weightings were assigned to these data as part of risk prioritization.

This appendix uses the following terms:

- **Asset** is anything of value, including both anthropogenic and natural assets. “Asset” does not imply any level of hazard exposure (i.e., assets may or may not be located in hazard areas).
- **Elements at risk** are assets located within geohazard areas and exposed to potential consequences of geohazard events.
- **Exposure model** is a type of data model describing the location and characteristics of elements at risk.

Table C-1 lists the elements at risk considered in this study. These data were organized in an ArcGIS SDE Geodatabase stored in Microsoft SQL Server. Software developed by BGC was used to automate queries to characterize elements at risk within hazard areas. This will allow updates to be efficiently performed in future. Sections C.2 to C.8 describe methods used to characterize elements at risk and lists gaps and uncertainties. Appendix A lists data sources.

The elements at risk listed in Table C-1 was compiled from public sources, local and district government input, and data available from the Integrated Cadastral Information Society (ICI Society, 2019)[1]. 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).

[1] Metadata stored with these data clarifies data sources and is available on request.

Table C-1. Elements at risk.

Element at Risk Type	Description	Category
People	Total population	<10
		10 – 100
		100 – 1,000
		1,000 – 10,000
		>10,000
Buildings Improvements	Total Improvement Value	<$100k
		$100k - $1M
		$1M - $10M
		$10M - $50M
		$50M - $100M
Critical Facilities	Presence of critical Facilities	Emergency Response Services
		Emergency Response Resources
		Utilities
		Communication
		Medical Facilities
		Transportation (excluding roads)
		Environmental
		Community
Businesses	Total annual revenue, or number of businesses where revenue data was not available.	<$100k annual revenue, or <2 businesses
		$100k - $1M annual revenue, or 2-4 businesses
		$1M - $10M annual revenue, or 5-10 businesses
		$10M - $50M annual revenue, or 11-50 businesses
		$50M - $100M annual revenue, or >50 businesses
		>$100M annual revenue, or >100 businesses
Lifelines	Road	Presence of any type
	Highway	0-10 vehicles/day (Class 7), or no data
		10-100 vehicles/day (Class 6)
		100-500 vehicles/day (Class)
		500-1000 vehicles/day (Class 4)
		> 1000 vehicles/day (Class <4)

Element at Risk Type	Description	Category
	Highway	Presence of any type
	Railway	
	Petroleum Infrastructure	
	Electrical Infrastructure	
	Communication Infrastructure	
	Water Infrastructure	
	Sanitary Infrastructure	
	Drainage Infrastructure	
Environmental Values	Active Agricultural Area	Presence of any type
	Fisheries	
	Species and Ecosystems at risk	

C.2. BUILDINGS (IMPROVEMENTS)

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) and 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 from 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 C-2 lists uncertainties associated with the use of BCA and cadastral data to assess the exposure of buildings development to geohazards.

Table C-2. Uncertainties related to building improvements and cadastral data.

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.
Cadastral Data Gaps	Areas outside provincial tax jurisdiction (i.e., First Nations Reserves) do not have BCA data are subject to higher uncertainty when characterizing the value of the built environment.	Incomplete information about the types and value of building improvements.
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	Parcels partially intersecting geohazard areas were conservatively assumed to be subject to those geohazards.	Possible over-estimation of hazard exposure

C.3. POPULATION

Population data was obtained from the 2016 Canada Census (2016) at a dissemination block[2] level of detail. 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.

2 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).

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.

C.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”, 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 C-3.

Table C-3. Critical facility descriptions.

Category	Example facilities in this category, based on Actual Use Value descriptions[1]
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[2]	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.

C.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 C-4 provides a more detailed breakdown of the utility classes shown in Table C-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 C-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
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

Id	Classified Type (BGC)	Description (ICI Society, 2019)	Position
31	Communication Infrastructure	Telcom Cable Line	Surface
32	Communication Infrastructure	Telcom Facility	Surface
34	Communication Infrastructure	Telcom Main	Surface
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

C.6. BUSINESS ACTIVITY

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 C-5 summarizes uncertainties associated with the data. In addition to the uncertainties listed in Table C-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 C-5. Business data uncertainties.

Type	Description	Implication
Revenue data	Revenue information was not available for all businesses.	Under-estimation of business impacts
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 impacts.

C.7. 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.

C.8. ENVIRONMENTAL VALUES

BGC included stream networks classed as fish bearing and areas classed as sensitive habitat in the risk prioritization.

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.

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).

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.

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APPENDIX D
HAZARD ASSESSMENT METHODS – CLEAR-WATER FLOODS

D.1. INTRODUCTION

D.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 D.1 provides background information and key terminology
- Section D.2 describes methods and data sources used to identify and characterize areas
- Section D.3 describes methods used to assign priority ratings.

This appendix entirely pertains to clear-water flood geohazards. Methods to identify and characterize elements at risk, steep-creek geohazards and volcanic geohazards are provided in Appendices C, E and F. The main report describes how geohazard and consequence ratings were combined to prioritize each geohazard area.

D.1.2. 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 D-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 D-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 D-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.

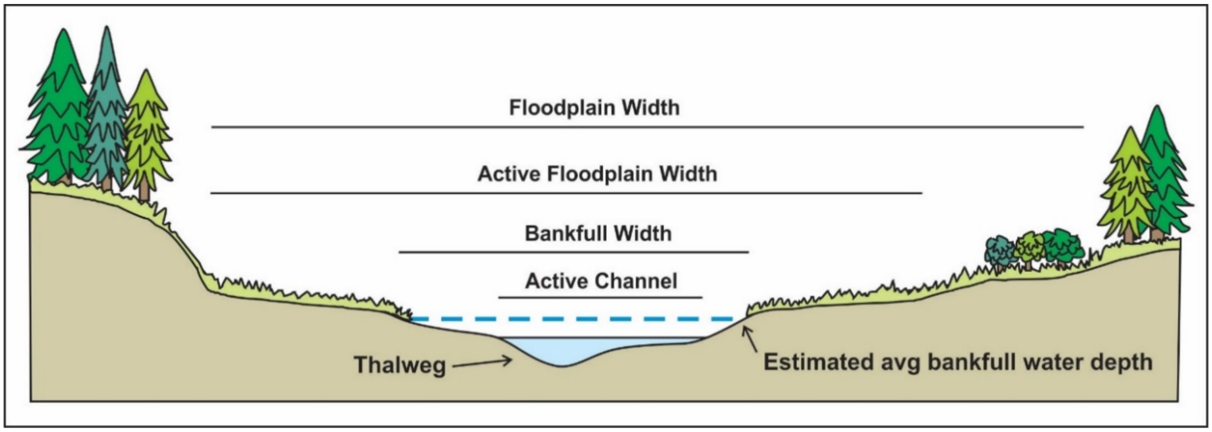

Figure D-2. Conceptual channel cross-section in a typical river valley.

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.

D.1.3. Terminology

This appendix refers to the following key definitions[1]:

- **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 1 in 200 chance of being exceeded in any year. AEP is increasingly replacing the use of the term ‘return period’ to describe flood recurrence intervals.
- **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.
- **Consequence:** damage or losses to an element-at-risk in the event of a specific hazard.
- **Flood Construction Level (FCL):** a designated flood level plus freeboard, or where a designated flood level cannot be determined, a specified height above a natural boundary, natural ground elevation, or any obstruction that could cause flooding.
- **Flood maps:** provide information on the hazards associated with defined flood events, such as water depth, velocity, and duration of flooding, and the probability of occurrence. These maps are used as a decision-making tool for local and regional governments during floods or for planning purposes.

[1] EGBC (2017, 2018).

- **Screening Level Flood Hazard Mapping:** delineation of flood lines and elevations on a base map, typically taking the form of flood lines on a map that show the area that will be covered by water, or the elevation that water would reach during a flood event. In this study, BGC deployed a regional scale approach for the identification of horizontal flooding extents as well as a coarse measurement of flood depths—this was done using a terrain-based flood hazard identification exercise using the Height-Above-Nearest-Drainage (HAND) approach, discussed in Section D.2.4. The approach employs the use of publicly available topographic data and hydrometric data from the Water Survey of Canada.
- **Flood mitigation**: measures that have the potential to reduce the risk associated with flooding. These measures can be broadly defined as structural such as flood protection infrastructure (e.g., dikes or diversions) or non-structural such as emergency response, resiliency and land-use planning.
- **Flood setback:** the required minimum distance from the natural boundary of a watercourse or waterbody to maintain a floodway and allow for potential bank erosion.
- **Risk**: a measure of the probability of a specific flood event occurring and the consequence
- **Steep-creek floods:** rapid flow of water and debris in a steep channel, often associated with avulsions and bank erosion and referred to as debris floods and debris flows.
- **Waterbody:** ponds, lakes and reservoirs.
- **Watercourse:** creeks, streams and rivers.

D.1.4. 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 D-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 D-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 D-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.

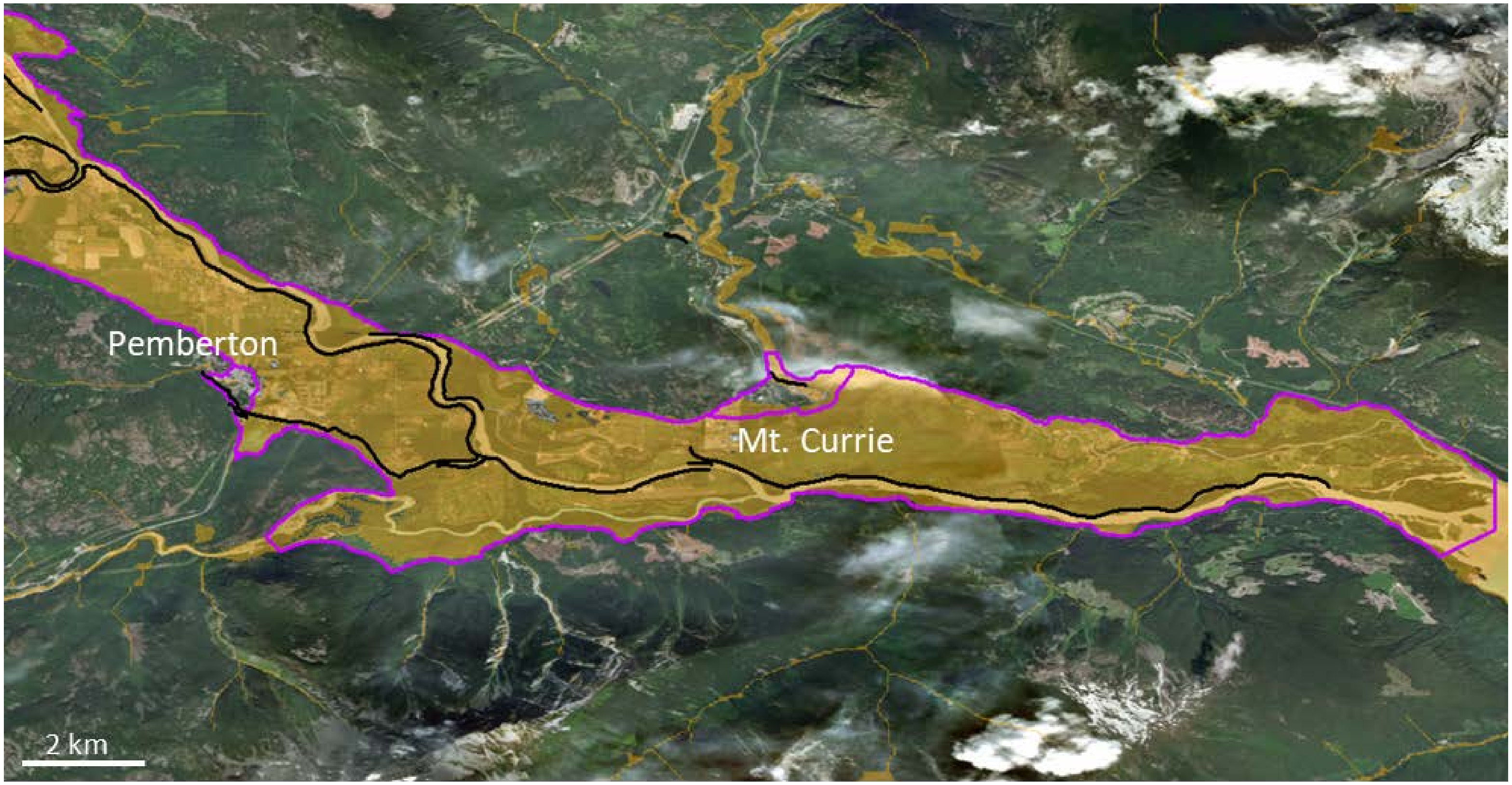

Figure D-3. Example spatial sources used to identify clear-water flood hazards in the SLRD including historical floodplain mapping (purple outlines) and predicted floodplain extents for streams and lakes without existing floodplain mapping (transparent orange areas). Locations of known flood protection 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.

D.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 D-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 E.

D.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 D-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 D-3). Additional details on the historical flood event inventory are provided in geospatial (GIS) layers delivered with this study.

Figure D-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).

D.2.2. Existing Floodplain Mapping

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

Site No.[1]	Watercourse (Area)	District	Approximate Floodplain Area (km^2)	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[2]	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 runout 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).

Site No.[1]	Watercourse (Area)	District	Approximate Floodplain Area (km^2)	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[2]	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.

Notes:

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

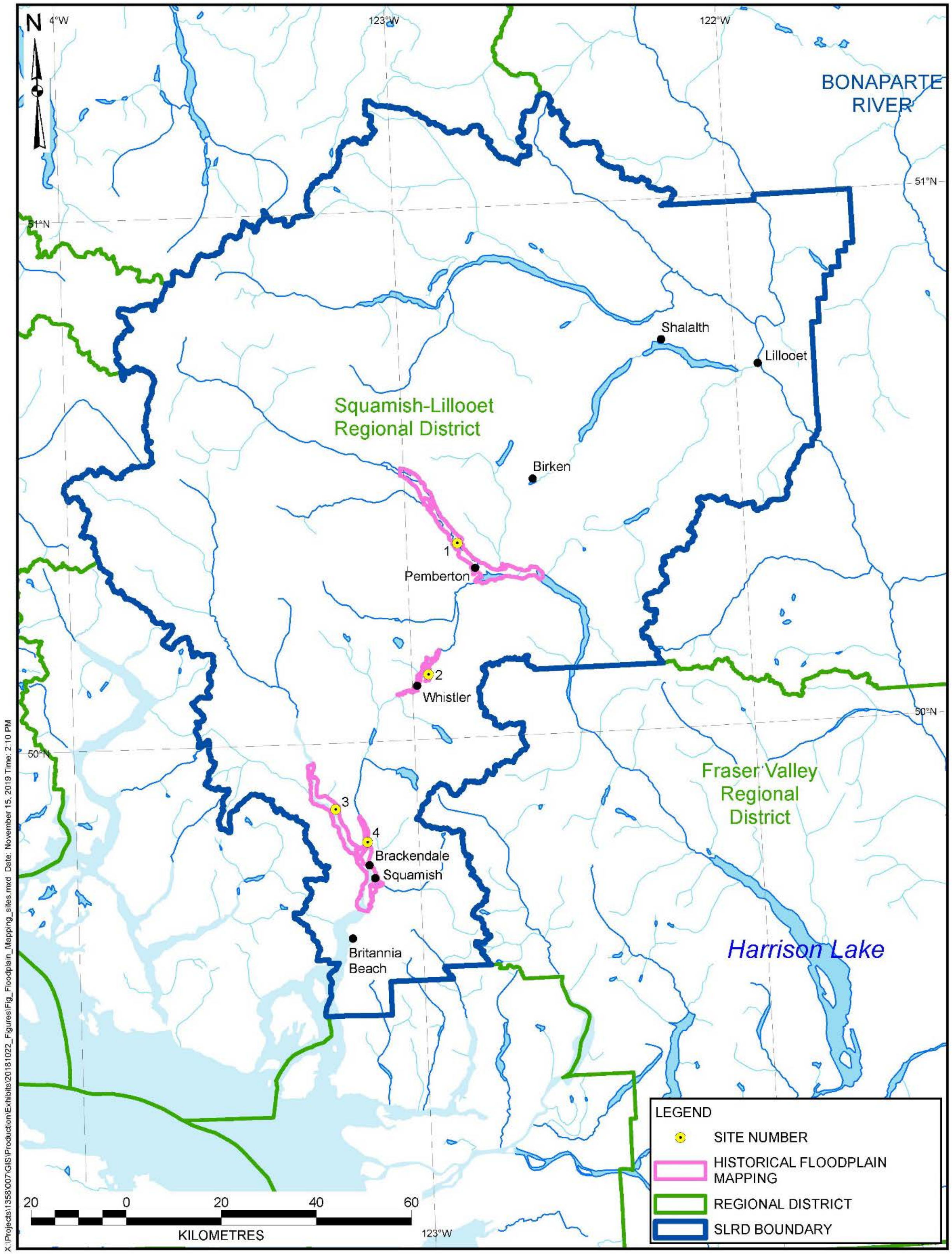

Figure D-5. Historical floodplain mapping in the SLRD.

D.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).

In addition, 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 Section D.2.2.2.

D.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.

D.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 horizonal 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 D-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

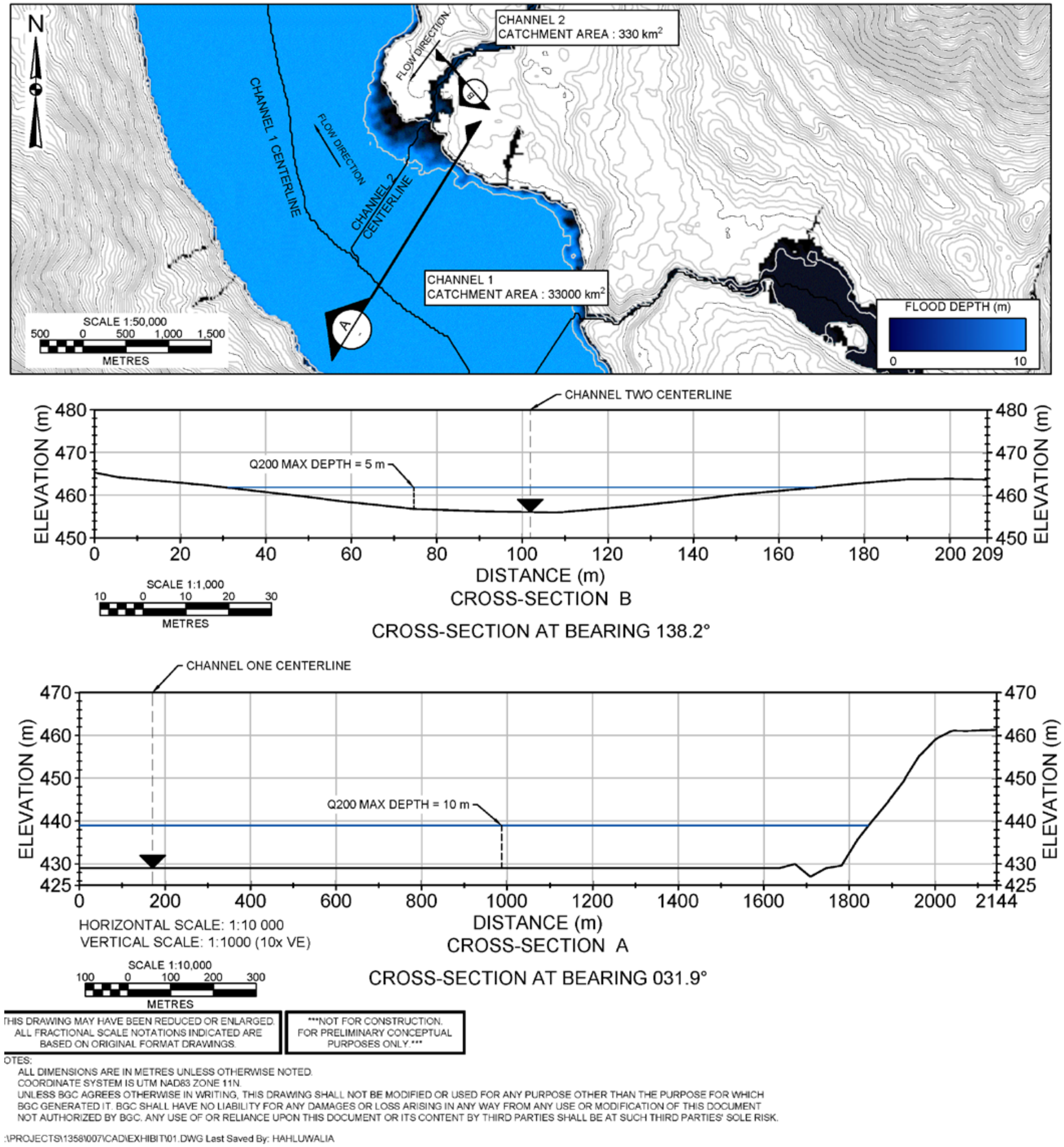

Figure D-6. Illustration of the HAND concept (Modified from Zheng et al., 2018).

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 D-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).

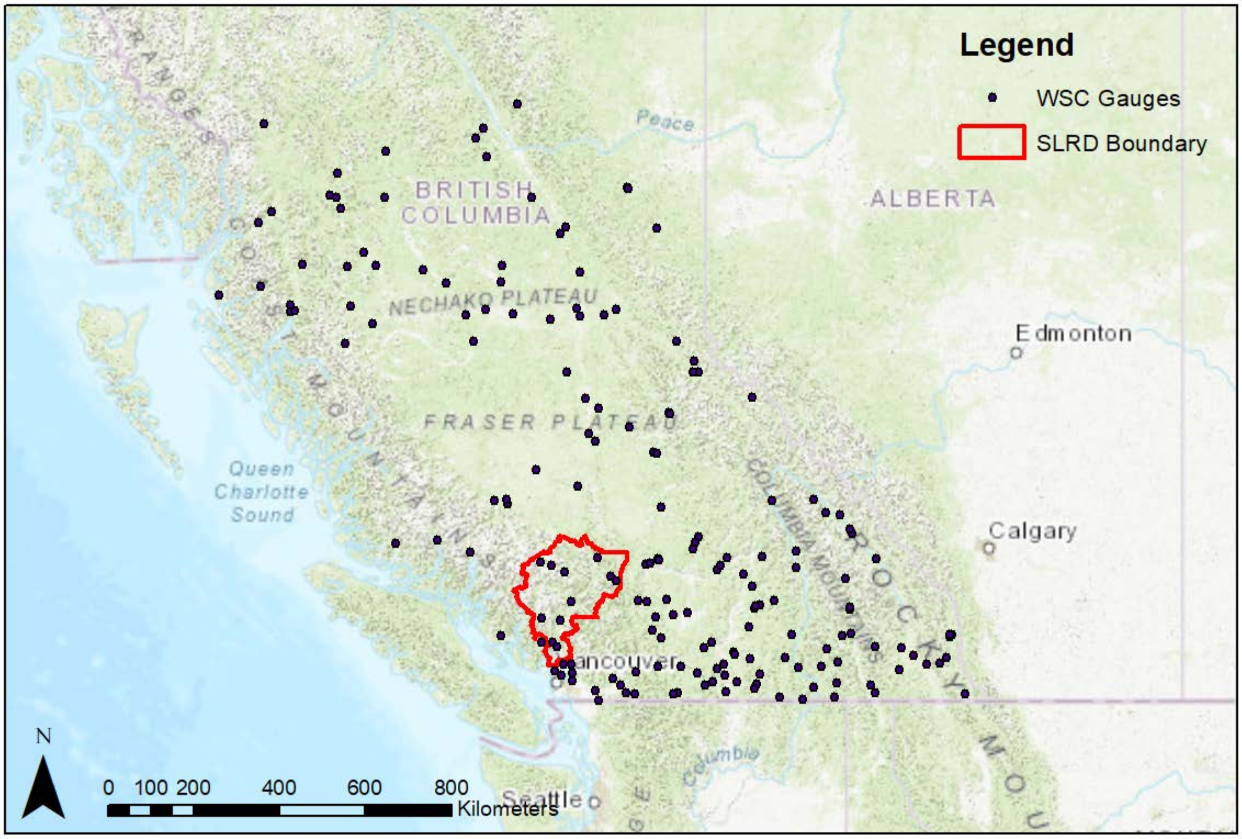

Figure D-7. Location of the 205 WSC hydrometric stations used in the analysis to extract the flood stage for the 200-year return period flood.

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 D-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 D-3.

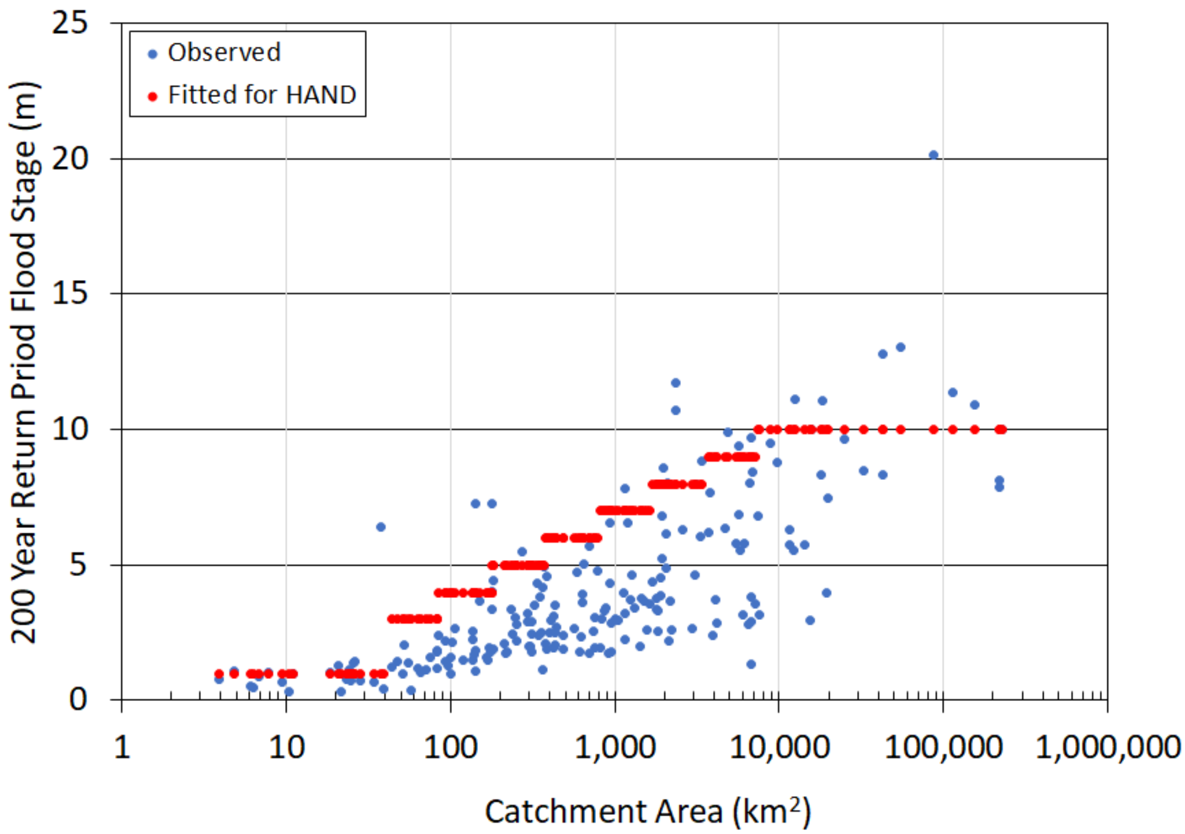

Figure D-8. **200-year return period flood stage versus catchment area for 205 WSC hydrometric gauging stations in southern BC. Red dots represent the curve fitted to observed values to relate catchment area to flood stage for estimating HAND flood depths.**

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

Catchment Area Categories		Maximum Estimated Flood Depth (m)
Lower Bound (km^2)	Upper Bound (km^2)	
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 in 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 D-6 illustrates this concept; here there are two watercourses; one with a total catchment area of 330 km^2 the other 33,000 km^2. The maximum HAND (based on the information in Table D-3) for the former is 5 m and 10 m for the latter.

The results from HAND mapping was compared to existing detailed floodplain mapping in the SLRD (Figure D-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.

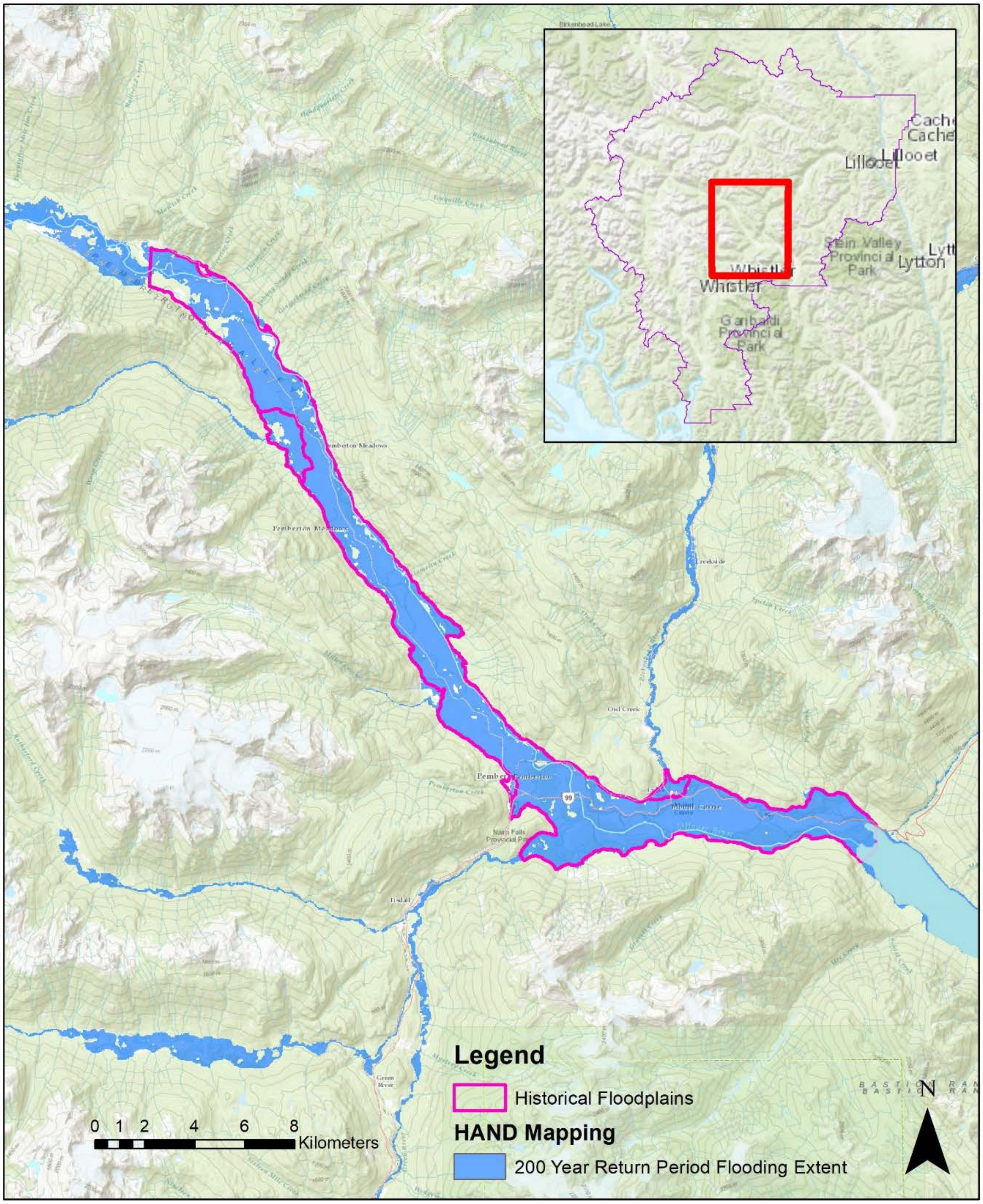

Figure D-9. Comparison between the historical floodplain mapping and the 200-year return period flooding extents based on the HAND mapping for the Lillooet River.

D.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.

D.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 D-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 D-4 (two of which have been breached or decommissioned at Britannia Creek, the site of the former Britannia Mine).

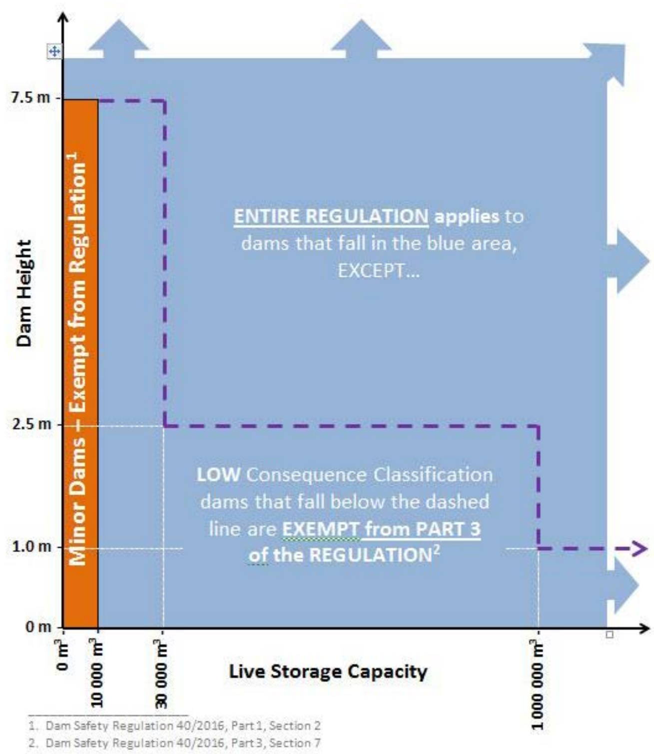

Figure D-10. Dam height (m) versus dam live storage capacity (m^3) as defined by the *Dam Safety Regulation*, BC Reg 40/2016, which along with the dam failure consequence classification determines which portion of the Regulation applies to the dam.

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 D-4 and Figure D-11.

Table D-4. List of dams located within the SLRD.

Dam Name	Owner	Dam Type	Ht (m)	Failure Consequence Category[1]	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	Cayoose Creek Power Lp	Concrete gravity	8.7	High	Active	Cayoosh Creek
Lower Mamquam Dam	Atlantic Power (Coastal Rivers) Corporate	Concrete gravity	3.4	Significant	Active	Mamquam River
Loch Lomond	Greater Vancouver Water District	Other	5.8	Significant	Active	Loch Lomond

Dam Name	Owner	Dam Type	Ht (m)	Failure Consequence Category[1]	Status	Waterbody
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.

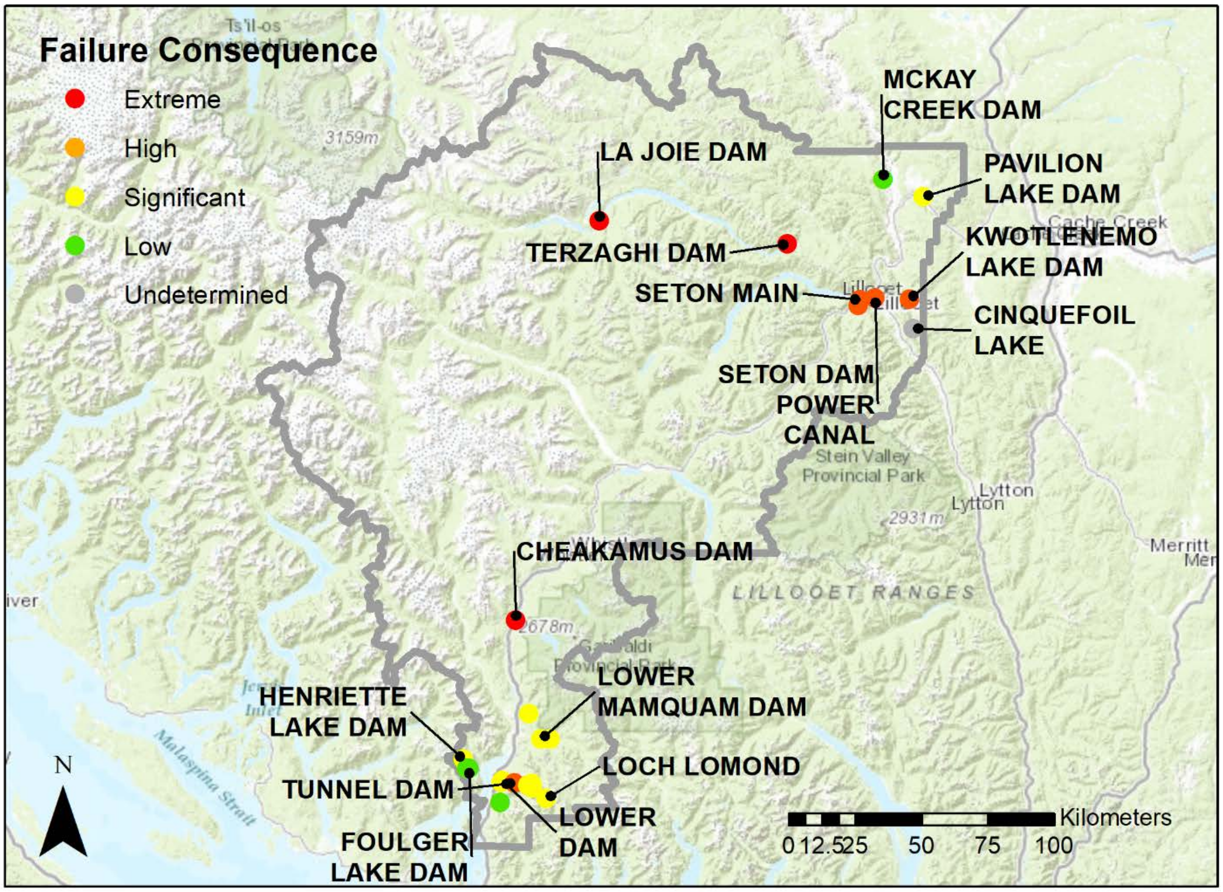

Figure D-11. Map showing the location of the dams located within the SLRD and their associated failure consequence classification.

D.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.

D.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.

D.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 (≥ 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.

D.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.

D.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 as summarized in Table D-5.

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

Geohazard Likelihood	AEP Range (%)(1)	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).

D.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 these two factors were determined.

D.3.2.1. Hazard Exposure (Elements at Risk)

Elements at risk are things of value that could be exposed to damage or loss due to geohazard impact (geohazard exposure). This study assessed areas that both contained elements at risk and that were subject to geohazards. As such, identifying elements at risk was required to both define the areas to be assessed and to assign consequence ratings as part of risk prioritization.

Section 3.0 of the main study report provides a complete list of elements at risk that were assessed in the study and the relative weightings applied to elements.

D.3.2.2. Hazard Intensity

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 D.2.4) to only include areas within the 200-year floodplain. Table D-6 shows the hazard intensity classes for clear-water hazard areas. The flood depth thresholds shown in Table D-6 are criteria developed from the HAND modelling and are conservatively high but provide a relative ranking of hazard areas. As well, the flood depths to 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 D-6. 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 E
HAZARD ASSESSMENT METHODS – STEEP CREEKS

E.1. INTRODUCTION

E.1.1. Objectives

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

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

Section 5.4 of the main report describes how geohazard and consequence ratings were used as inputs to prioritize geohazard areas. Section 6 of the main report describes how study results are delivered, including prioritized geohazard areas and supporting information.

E.1.2. What Are Steep Creek Geohazards?

Steep creeks (here-in defined as having channel gradients steeper than 3°, or 5%) are typically subject to a spectrum of sediment transport processes ranging from clear-water floods to debris floods to hyper-concentrated flows to debris flows, in order of increasing sediment concentration. They can be referred to collectively as hydrogeomorphic[1] processes because water and sediment (in suspension and bedload) are being transported. Depending on process and severity, hydrogeomorphic processes can cause local landscape changes.

These processes are continuous in space and time, with floods transitioning into debris floods upon exceedance of critical bed shear stress thresholds to mobilize most grains of the surface bedload layer. At high fines concentrations, hyperconcentrated flows develop. Debris flows are typically triggered by side slope landslides or progressive bulking with erodible sediment, a process observed specifically after wildfires at moderate to high burn severity. Dilution of a debris flow through partial sediment deposition on lower gradients (less than approximately <15°) channels and tributary injection of water can lead to a transition towards hyper-concentrated flows and debris floods and eventually floods. Some steep creeks can be classified as hybrids, implying variable hydrogeomorphic processes at different return periods.

Figure E-1 summarizes the different hydrogeomorphic processes by their appearance in plan form, velocity and sediment concentration.

[1] Hydrogeomorphology is an interdisciplinary science that focuses on the interaction and linkage of hydrologic processes with landforms or earth materials and the interaction of geomorphic processes with surface and subsurface water in temporal and spatial dimensions (Sidle & Onda, 2004).

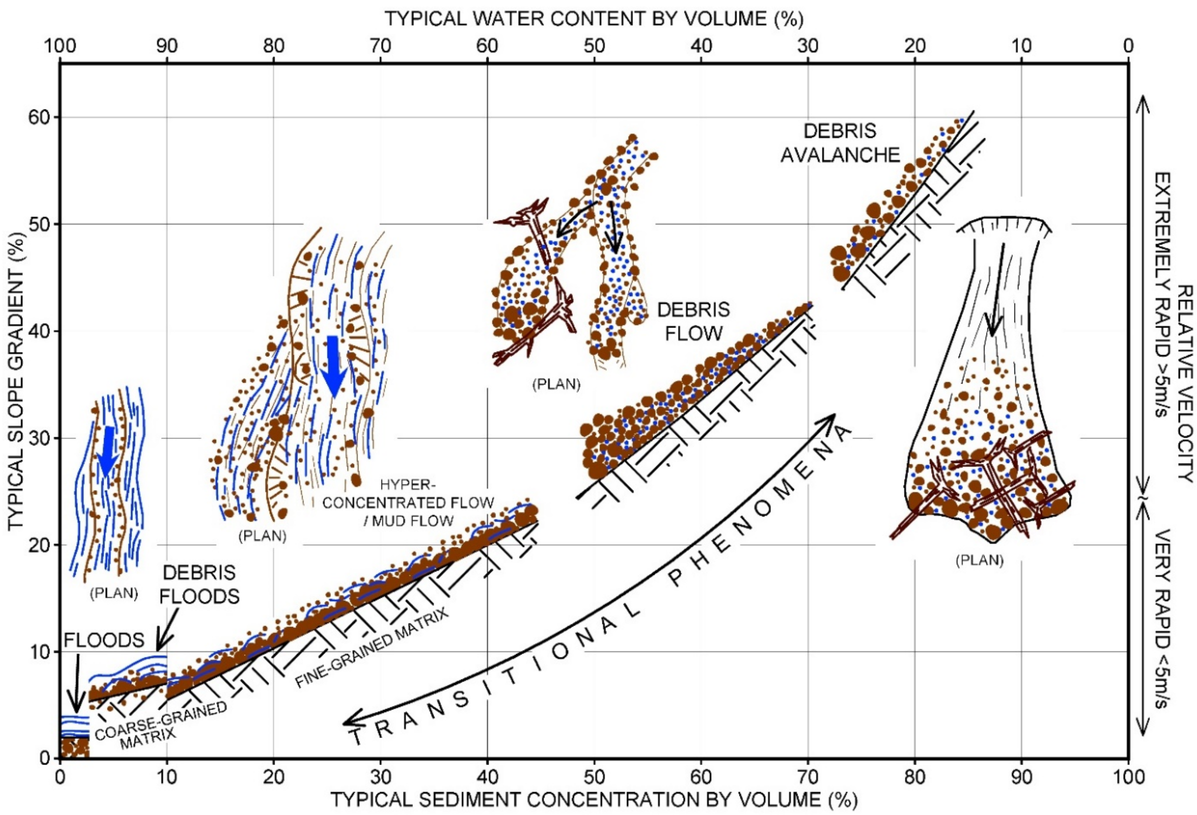

Figure E-1. Hydrogeomorphic process classification by sediment concentration, slope velocity and planform appearance.

E.1.2.1. 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 E-2 provides a typical example of a steep creek in the SLRD. Every watershed and fan is unique in the type and intensity of mass movement and fluvial processes, and the hazard and risk profile associated with such processes. Figure E-3 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.

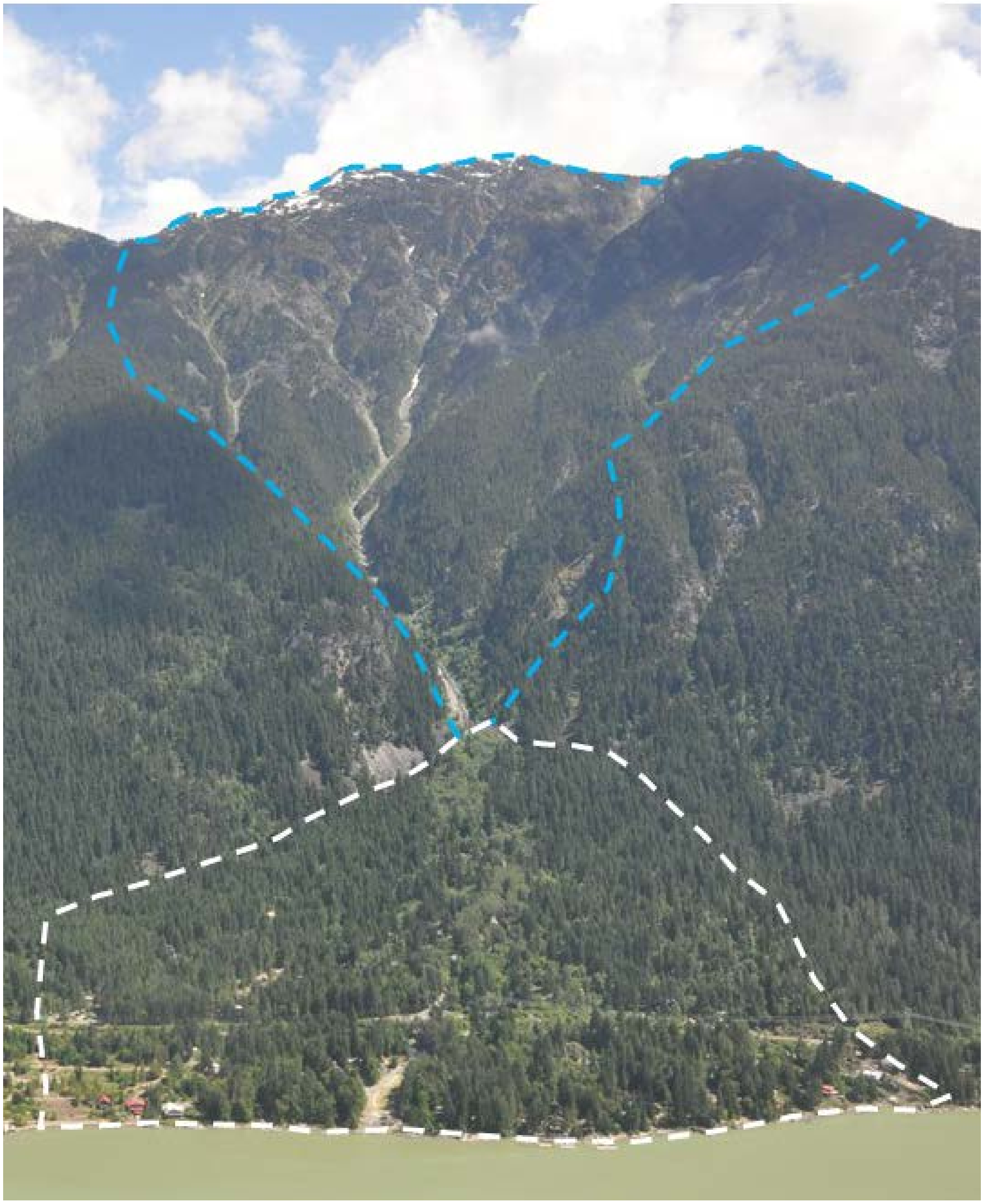

Figure E-2. A typical steep creek watershed and fan (Catiline Creek) located near Pemberton in the SLRD, with Lillooet Lake in the foreground. The approximate watershed and fan boundary are outlined in blue and white, respectively. Photo: BGC, taken on June 17, 2014.

Figure E-3. 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.

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 E-4).

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, which can fail catastrophically. In these scenarios, a debris flood may be initiated in the channel that travels further than the original landslide.

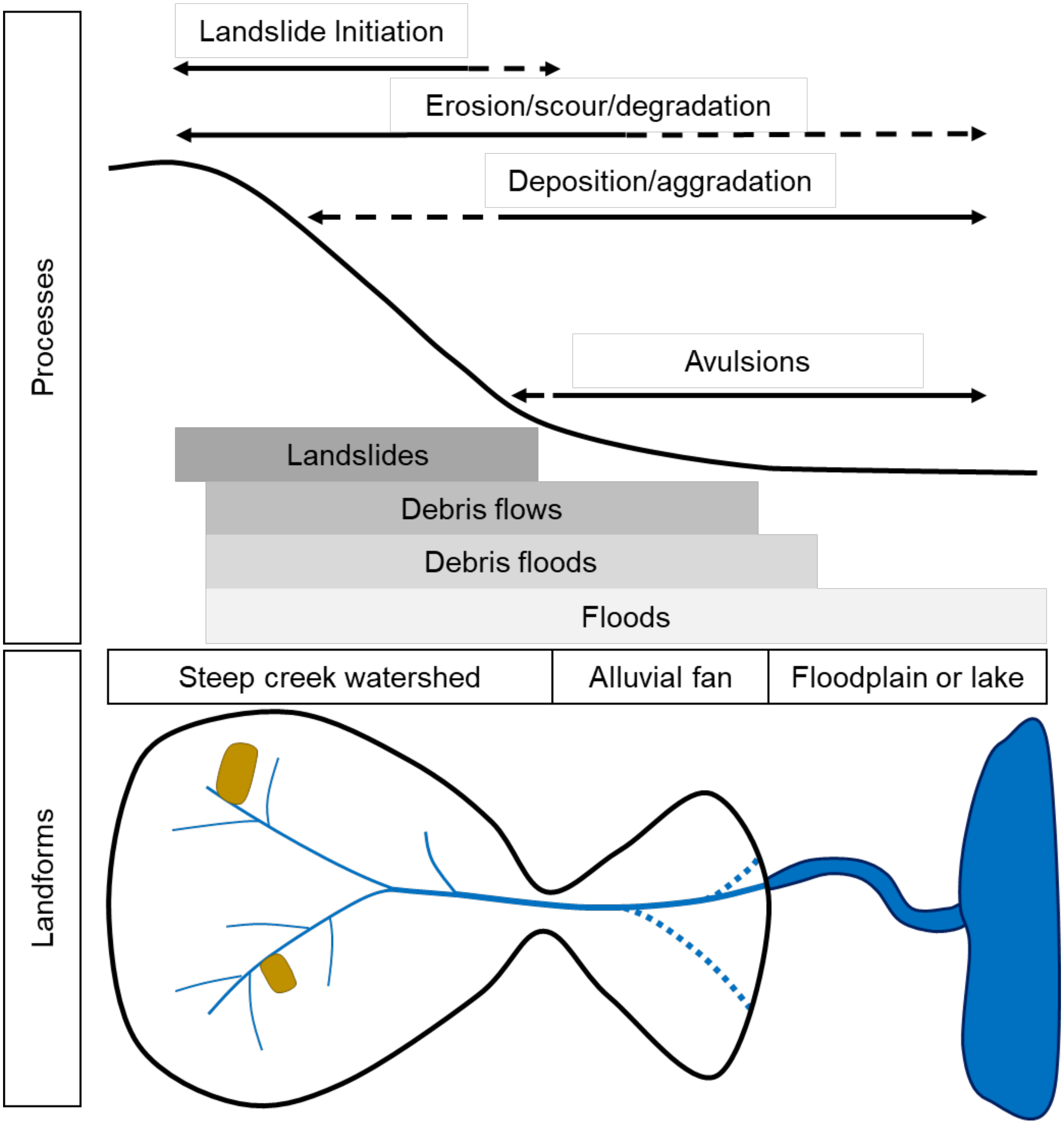

Figure E-4. Schematic diagram of a steep creek watershed system that shows the principal zones of distinctive processes and sediment behaviour. The alluvial fan is thought of as the long-term storage landform with a time scale of thousands to tens of thousands of years. Sketch developed by BGC from concepts 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. Identification of the inflection point, that is where erosion switches to deposition, is important for assessments of proposed or existing buried linear infrastructure (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). 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). Paleofans were not included in the fan inventory.

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 (Lovgreen, 2018). 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 E-5).

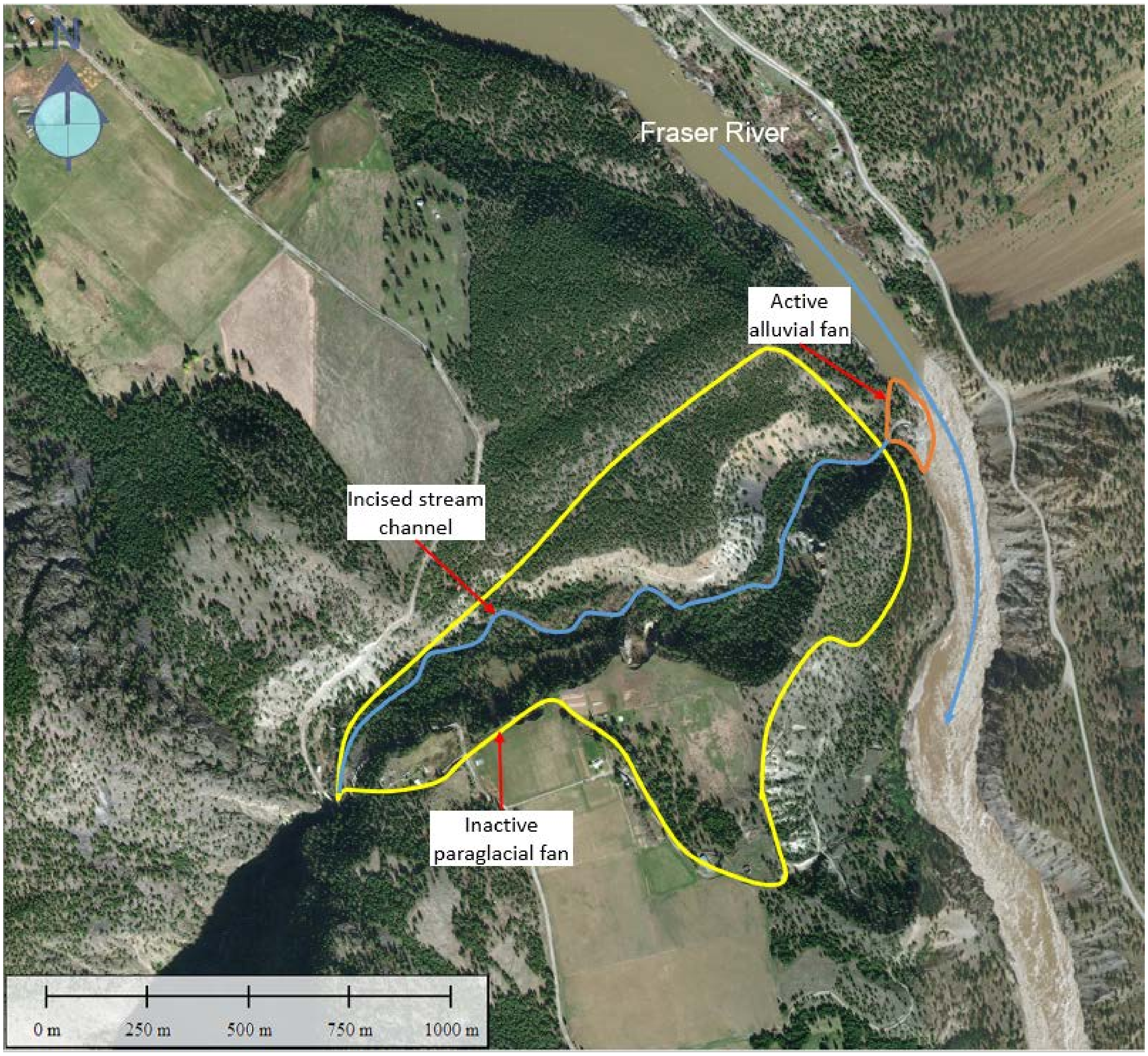

Figure E-5. Example of an inactive paraglacial fan and active alluvial fan on Texas Creek, near Lillooet. The distinction of the paraglacial fan being classified as an inactive paleofan is due to the incised stream channel. The inactive paraglacial fan and active alluvial fan delineated in this example are for illustration only and are not part of the inventory.

E.1.2.2. 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. Liquefaction occurs shortly after the onset of landsliding due to turbulent mixing of water and sediment, and the slurry begins to flow downstream. Post-fire debris flows are a special case where the lack of vegetation and root strength can lead to abundant rilling and gullying that deliver sediment to the main channel where mixing leads to the formation of debris flows. In those cases, no single source or sudden liquefaction is required to initiate or maintain debris-flow mechanics.

Sediment bulking is the process by which rapidly flowing water entrains bed and bank materials either through erosion or preferential "plucking" until sediment saturation is reached (often at 60-70% sediment concentration by volume). At this time, further sediment entrainment may still occur through bank undercutting and transitional deposition of debris, with a zero-net change in sediment concentration. Bulking may be limited to partial channel substrate mobilization of the top gravel layer, or – in the case of debris flows – may entail entrainment of the entire loose channel debris. Scour to bedrock in the transport zone is expected in the latter case.

Unlike debris avalanches, which travel on unconfined slopes, 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. Debris-flow physics are highly complex and video recordings of events in progress have demonstrated that no unique rheology can describe the range of observed mechanical behavior (Iverson, 1997). 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. Debris-flow deposits remain saturated for some time after deposition but become rigid once seepage and desiccation have removed pore water.

Coarse granular debris flows require a channel gradient of at least 27% (15^{o}) for transport over significant distances (Takahashi, 1991) and have volumetric sediment concentrations in excess of 50%. Between the main surges a fluid slurry with a hyperconcentration (>10%) of suspended fines occurs. Transport is possible at gradients as low as 20% (11^{o})[2], although some type of momentum transfer from side-slope landslides is needed to sustain flow on those slopes. Debris flows may continue to run out onto lower gradients even as they lose momentum and drain: the higher the fine grained (especially clay) sediment content, and hence the slower the sediment-water mixture will lose its pore water, the lower the ultimate stopping angle. The clay fraction is the most important textural control on debris-flow mobility. The surface gradient of a debris-flow fan approximates the stopping angle for flows issuing from the drainage basin.

2 For volcanic debris-flows (see Section E.1.2.3), transport can occur at even lower gradients.

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 and 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 hyperconcentrated flow phase that is characterized by lower volumetric sediment concentrations. The most severe damage results from direct impact of large clasts or coarse woody debris against structures that are not designed for the impact forces. Even where the supporting walls of buildings may be able to withstand the loads associated with debris flows, building windows and doors are crushed and debris may enter the building, leading to extensive damage to the interior of the structure (Jakob et al., 2012). Similarly, linear infrastructure such as roads and railways are subject to complete destruction. On medial and distal fan sections (the lower 1/3 to 2/3), debris flows tend to deposit their sediment rather than scour. Therefore, exposure or rupture of buried infrastructure such as telecommunication lines or pipelines is rare. However, if a linear infrastructure is buried in the proximal fan portions that undergoes cycles of incision and infill, or in a recent debris deposit, it is likely that over time or during a significant runoff event, the tractive forces of water will erode through the debris until an equilibrium slope is achieved, and the infrastructure thereby becomes exposed or may rupture due to boulder impact or abrasion. This necessitates understanding the geomorphic state of the fans being traversed by a buried linear infrastructure.

Avulsions are likely in poorly confined channel sections and on the outside of channel bends where debris flows tend to superelevate. Sudden loss of confinement and decrease in channel slope cause debris flows to decelerate, drain their inter-granular water, and increase shearing resistance, which slow the advancing bouldery front and block the channel. The more fluid afterflow (hyperconcentrated flow) is then 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. These flow aberrations and varying rheological characteristics pose a challenge to numerical modelers seeking to create an equivalent fluid (Iverson, 2014).

E.1.2.3. Volcanic Debris Flows

Volcanic debris flows, also called lahars, are described in Appendix F. Because volcanic debris flows are expected to runout beyond alluvial fans, they are considered separately than steep creek geohazards. Further information on volcanic debris flows and the methodology used for prioritization are provided in Appendix F.

E.1.2.4. Debris Floods

Within the past thirty years the term ‘debris flood’ has come into use to describe severe floods involving exceptionally high rates of transport of coarse sediments, usually occurring in steep channels. It is favoured by geotechnical engineers and engineering geomorphologists who share responsibility to protect civil society and its infrastructure from such events. A recent authoritative review of landslide-like phenomena defines debris flood as “very rapid flow of water, heavily charged with debris, in a steep channel. Peak discharge is comparable to that of a water flood.” (Hungr et al., 2014: p.185). The text continues: “the stream bed may be destabilized causing massive movement of sediment. Such sediment movement (sometimes referred to as “live bed” or “carpet flow” by hydraulicians) can reach transport rates far exceeding normal bed load movement through rolling and saltation. However, the movement still relies on the tractive forces of water.” (*ibid.*) Accordingly, debris floods represent flood flows with high transport of gravel to boulder size material.

Bedload transport in gravel-bed channels has been characterized in three stages (Carling, 1988; Ashworth & Ferguson, 1989). In stage 1, fine material – typically sand – overpasses a static bed or is mobilized by winnowing from an otherwise static bed. The force of the flowing water is insufficient to mobilize the local bed material. In stage 2, local bed material is entrained and redeposited at low rates. Individual clasts are mobilized from the bed surface independently of other entraining events (except when movement of a relatively large clast liberates much finer material that was lying in its shadow). Most of the bed remains stable. In stage 3, the entire bed becomes mobile and activity may extend to a depth of two or three median grain sizes below the surface as the result of momentum transfer by grain-grain collisions. A debris flood is specifically a case of stage 3 transport.

Debris floods are rare because stage 3 transport is rare in gravel-bed channels. In such channels, where bed and banks are constituted of similar material, the banks are more readily eroded than the bed so that the channel widens, with consequent reduction in flow depths, until it is just able to transport the incoming bed material load at rates near the threshold for transport (Parker, 1978). The Shields ratio – the dimensionless representation of the shear stress exerted by the flow on the bed – remains near the threshold value. Debris floods occur when this condition is exceeded. Steep mountain channels in which the width remains limited because the banks consist of rock or other non-erodible material are prone to debris-flood occurrence. Similarly, large and relatively steep channels carrying extraordinary (100-year return period or greated) are prone to debris-flood occurrence. Such floods are distinctly two-phase flows, with ‘clear water’ or water with a substantial suspended sediment load, overlying a slurry-like flow containing a high concentration of bed material, the finest fractions of which may be episodically suspended.

Debris floods typically occur on creeks with channel gradients between 5 and 30% (3 and 17^o) 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. Bank erosion and excessive amounts of bedload 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 larger than the D_{50}. 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. This is of particular relevance where a pipeline or telecommunication line is to be buried. Maximum scour during a debris flood may be much deeper than what is viewed and measured during a field visit.

Church & Jakob (2020) developed a three-fold typology for debris floods. This is summarized in Table E-1 and is still being developed. Identifying the correct debris-flood type is key in preparing for numerical modeling and hazard assessments. Type 2 is the typical debris-flood type referred to in this prioritization study. Type 1 is considered in clear-water flood on fan process described in Section E.1.2.5, due to similar regional scale characteristics. Type 3 is considered in the landslide dam outbreak flood (LDOF) parameter presented in Section E.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 (2005a) on the basis of 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.

Table E-1. Debris-flood classification based on Church & Jakob (2020).

Term	Definition	Typical sediment concentration by volume (%)	Typical Q_{max} factor compared to calc. clear-water	Physical Characteristics	Typical impacts	Typical return period range (years)
Type 1	Rainfall/snowmelt generated through exceedance of critical shear stress threshold when more than 1SD of the surface bed grains are being mobilized. While not a fixed threshold, the 1SD bed surface grains are a reasonable proxy for major channel shifts.	< 5	1.02 to 1.2 (depending on the proximity of major debris sources to the fan apex as well as organic debris loading)	Steep fans (1 to 10%), shallow but wide active floodplain widespread boulder carpets, clast to matrix-supported sediment facies, subrounded to rounded stones, some imbrication, disturbed riparian vegetation, frequent fan avulsions	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	>10
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) but depending highly on the proximity to the fan apex.	As for Type 1 but rarely clast-supported and with higher matrix sediment concentration. Stones subangular to angular, boulder carpets on fans often display sharp edges	Widespread bank instability, avulsions, substantial bed aggradation particularly on fans, blocked culverts, scoured bridge abutments, damaged buried infrastructure on fans	>50
Type 3	Outbreak flood in channels with insufficient steepness for debris-flow generation. Critical shear stress for debris-flood initiation exceeded abruptly due to sharp hydrograph associated with the outbreak flood. All Ds mobilized in channel bed and non-cohesive banks	< 10 (except immediately downstream of the outbreak)	up to 100 depending on size of dam and distance to dam failure, Q_{max} should be calculated by combination of dam breach analyses and flood routing	Presence or deduction of landforms that could lead to eventual outbreak floods, Watershed channel reaches with distinct trimlines in case of past events. pronounced superelevation in channel bends, even aged vegetation on large segments of the fan, high fines content in matrix, sometimes inverse grading	Vast bank erosion, avulsions, substantial bed degradation along channels and aggradation on fans, destroyed culverts, outflanked or overwhelmed bridges, damaged buried infrastructure on channels and fans	>100 (can be singular events in the case of a moraine dam or glacial breach)

E.1.2.5. Clear-water Floods on Alluvial Fans

Clear-water floods are defined in Appendix D 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". In Appendix D, clear-water flood hazard is estimated based on: historical and 3rd-party floodplain maps, historical events, existing hydraulic studies, coastal flood hazard extent, and HAND (Height Above Nearest Drainage) modeling. Further information on clear-water floods and the methodology used for prioritization are provided in Appendix D.

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, avulsion mechanism and LDOFs, and they are discussed in Section E.3.2.

E.1.3. Climate Change

E.1.3.1. Background

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.

Regional climate change projections indicate that there will be an increase in winter rainfall (PCIC, 2012), an increase in the hourly intensity of extreme rainfall and increase in frequency of events (Prein et al., 2017). Changes to short duration (one hour and less) rainfall intensities are particularly relevant for post-fire situations in debris-flow generating watersheds. Within the year to a few years after a wildfire affecting large portions of a given watershed, short duration and high intensity rainfall events are much more likely to trigger debris flows or debris floods, than prior to a wildfire event.

Steep creek basins can be generally categorized as being either:

- 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; or,
- 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.

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

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

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). In the case of wildfires, the impact on debris supply is greatest immediately after the wildfire, with its impact diminishing over time as vegetation regrows (see Section E.3.1.3). Wildfires are known to both increase the sediment supply and lower the precipitation threshold for steep creek events to occur.

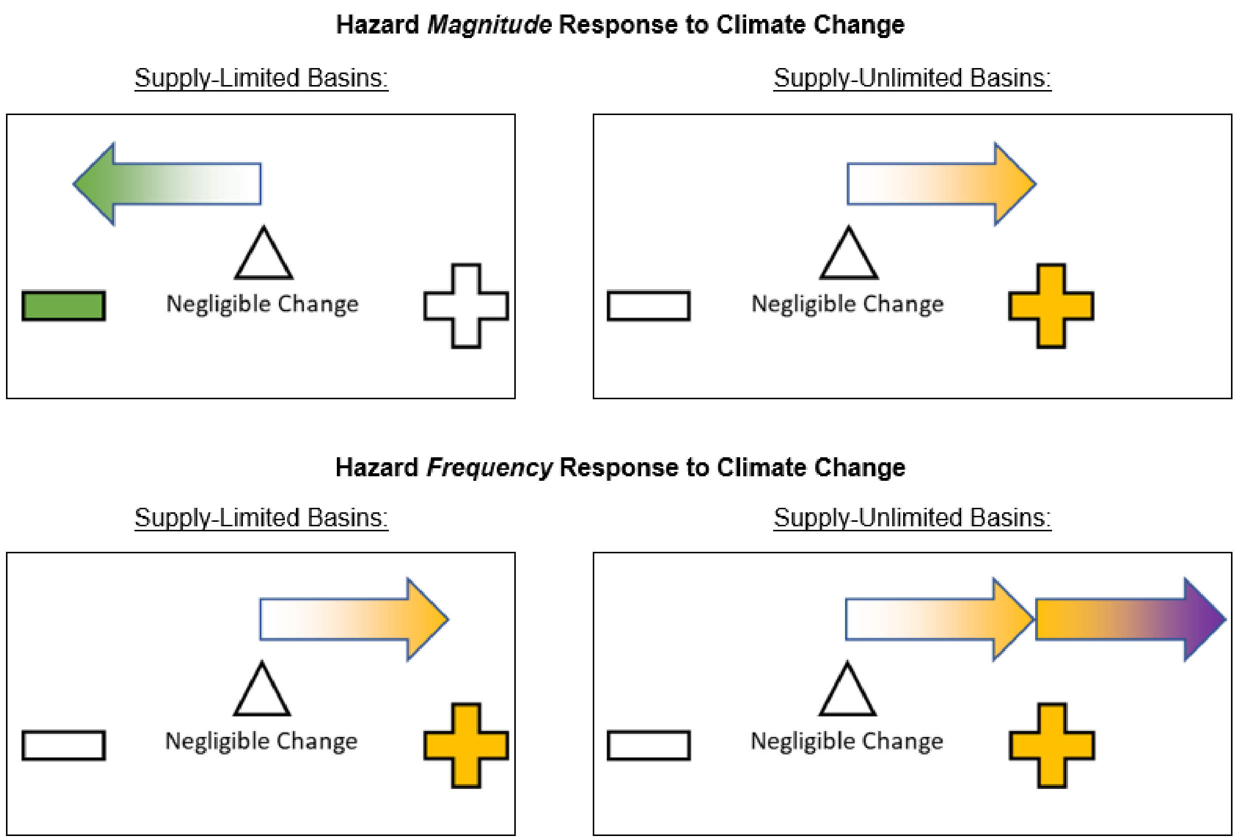

Figure E-6. Steep creek hazard sensitivity to climate change – supply-limited and supply unlimited basins.

E.1.3.2. Climate Change Adjustment in Steep Creek Geohazard Assessment

Planning decisions based on hazard maps can have implications for half a century or longer. As such, climate change is considered in steep creek hazard characterization by applying climate change adjusted estimates of peak discharge as inputs for hazard intensity ratings (Section E.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 prioritization study, because the adjustment would be applied to all geohazard areas, and therefore would not have any effect on the relative prioritization.

E.1.4. Workflow

The workflow for the steep creek geohazard assessment and risk prioritization includes three main phases: hazard identification, geohazard rating, and consequence rating. Figure E-7 summarizes the parameters used in each phase. The methods and criteria used to estimate each parameters are detailed in Sections E.2, E.3 and E.4.

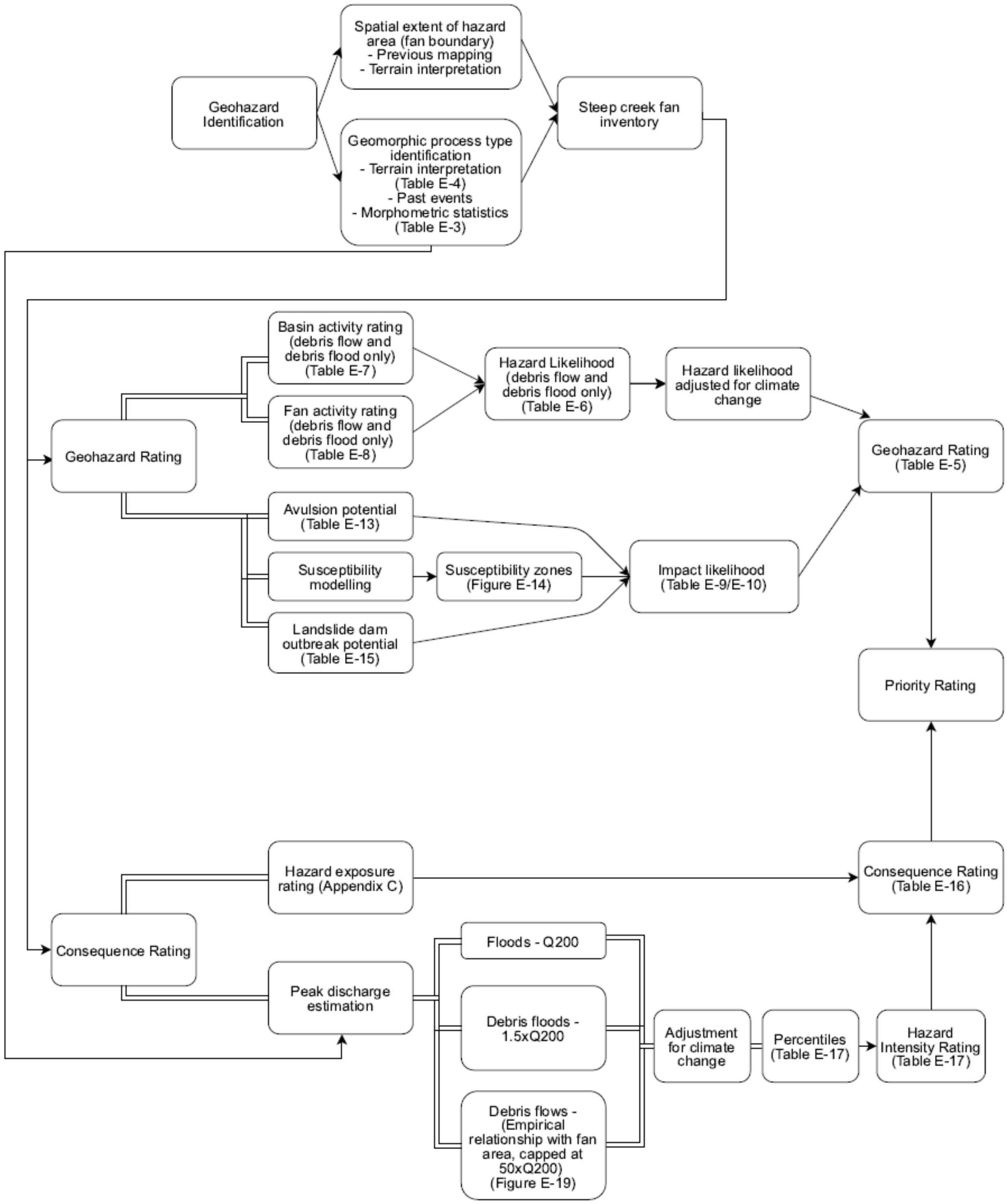

Figure E-7. Workflow for steep creek geohazard assessment and risk prioritization.

E.2. STEEP CREEK GEOHAZARD IDENTIFICATION

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 1.4).

The boundaries of alluvial fans define the steep creek geohazard areas prioritized in this study. 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, classified and used for both susceptibility modeling (impact likelihood rating, in Section E.3.2) and peak discharge estimation (intensity rating, in Section E.4).

E.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 limited coverage of lidar Digital Elevation Models (DEM). At sites where lidar DEMs were not available, low resolution (approximately 25 m)[3] Canadian Digital Elevation Model (CDEM) terrain models, aerial photographs, and satellite imagery available within ArcGIS were used for terrain interpretation. A total of 201 developed 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 E-8). 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 and characteristics 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. Specific 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 fan inventory 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[4]. 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 E.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

[3] 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).

[4] Most of the alluvial fans mapped in this study represent the accumulation of sediment over the Holocene period (since about 11,000 years BP).

not contain a mapped fan, are shown on *Cambio* for reference but are not otherwise characterized or prioritized.

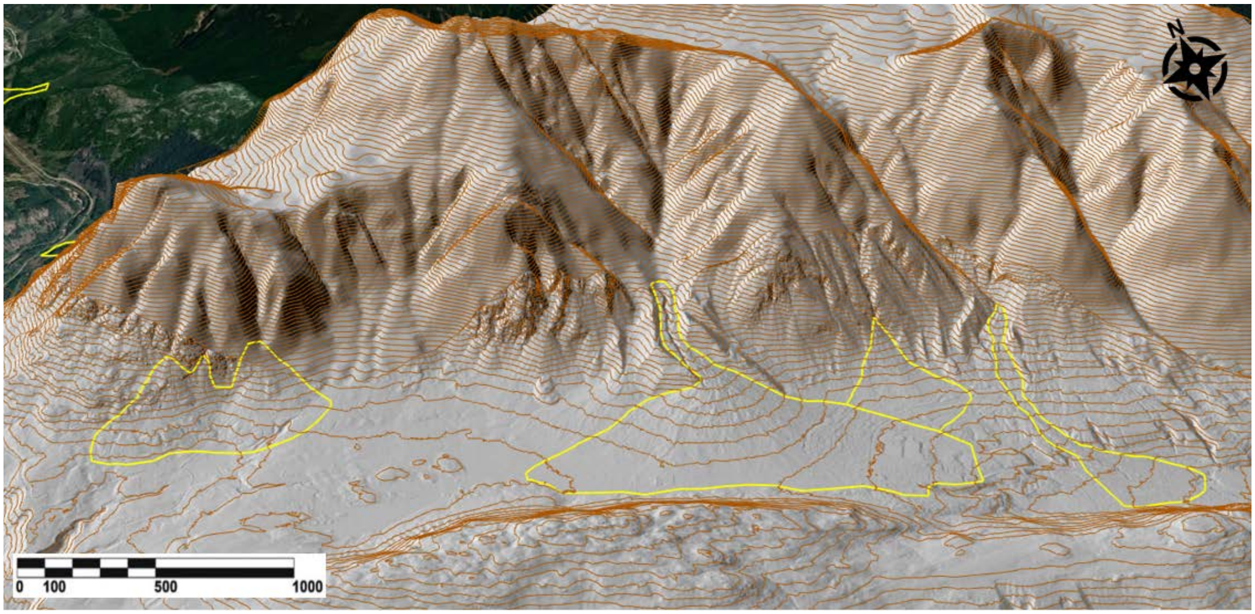

Figure E-8. Example of oblique lidar hillshade and 20 m contours showing alluvial fans at the base of an unnamed mountain north of the Village of Pemberton. lidar DEM provided by NDMP.

E.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 the 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., Squamish River), while Strahler order 3 and lower streams are typically smaller, headwater streams (e.g., Fitzsimmons Creek). An illustration of Strahler stream order classification is shown in Figure E-9 and described conceptually for the SLRD in Table E-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 Ministry of Forests, Lands and Natural Resource Operations (MFLNRO, 2017a).

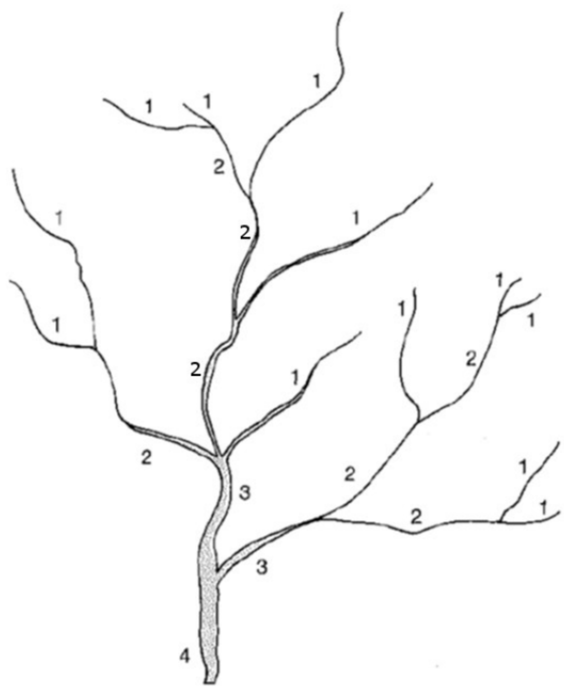

Figure E-9. Illustration showing Strahler stream order (Montgomery, 1990).

Table E-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.	2	Squamish River, Lillooet River, Bridge River, Fraser River

E.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 morphometric statistical approach was applied to every stream segment in the entire study area, including both developed and undeveloped areas. For the mapped geohazard areas, the morphometric statistical approach was considered alongside terrain interpretations. 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.

E.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[5] and watershed length[6] 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).

[5] Melton ratio is watershed relief divided by the square root of watershed area (Melton, 1957).
[6] Stream network length is the total channel length upstream of a given stream segment to the stream segment farthest from the fan apex.

2. Apply class boundaries to predict process types for all stream segments in the study area, regardless of whether they intersect fans.

Figure E-10 plots the study area creeks with respect to Melton Ratio and watershed length[7]. 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 E-3 lists class boundaries used to define process types on each segment of each creek within the SLRD, based on recommendations from previous studies in BC (Holm et al., 2016).

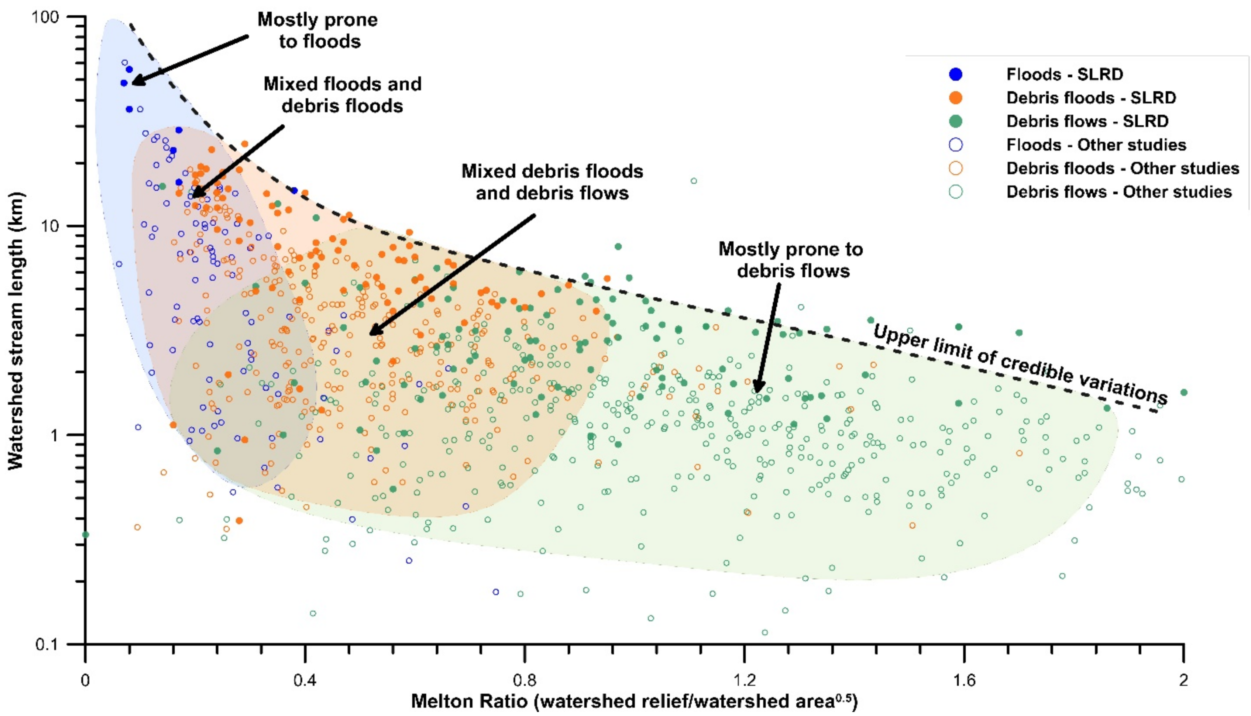

Figure E-10. Steep creek processes in the SLRD as a function of Melton Ratio and stream length. Process boundaries are derived from this study and additional fans in Alberta and BC (Holm et el., 2016, Lau, 2017).

[7] 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.

Table E-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 where 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 apply to hanging valleys, where the lower channel sharply steepens below a gentle upper basin.
- Finally, as explained in Section E.1.2, 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. Such events are commonly referred to as hyperconcentrated flows (Pierson, 2005b). Similarly, not every debris flood shows the same characteristics (see Section E.1.2.4).

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) would result in higher confidence. Therefore, BGC manually interpreted the dominant fan-forming process types for the prioritized geohazard areas (Section E.2.3.2).

E.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.

Table E-4 summarizes the characteristics used to differentiate hydrogeomorphic processes on fans from imagery and field evidence.

Table E-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	• Steep (>15°) average watershed channel gradient and typically small (< 3 km^2) watersheds with high relief • Frequent sediment sources in upper watershed (rockfalls, debris avalanches, etc.) • Inconsistent breaks in tree canopy on fan along stream channel.	• Moderately steep (3-15°) average watershed channel gradient, medium to large watersheds with moderate to high relief • Sediment sources in upper watershed (rockfalls, debris avalanches, etc.) • Consistent break in tree canopy on fan along stream channel.	• Low (<3°) average watershed channel gradient, medium to large watersheds with moderate to low relief. • Wide channels • Large gap in tree canopy along stream channel. • Overbank deposits
lidar	• Fan gradient > 5° • Levees along channel margin • U-shaped channels • (Boulder) lobes on fan surface • Tongue-shaped boulder carpets • Sharp deposit boundaries	• Fan gradient 2-10° • No levees along channel • Potential lobes on fan surface • Paired terraces	• Fan gradient < 5° • Wide channels • Lack of lobes and levees along channel margin
Field	• Matrix-supported deposits common, clast-supported rarely • Inversely graded deposits • No imbrication in deposits • Levees along channel margins • U-shaped channels • Boulder lobes on surface • Impact scars on trees • Adventitious roots • Buried tree trunks	• Clast-supported deposits • Normally graded deposits • Imbricated channel deposits (moderate frequency) • Potential lobes on surface • Paired terraces • Impact scars on trees • Adventitious[8] roots • Buried tree trunks • Boulder carpets • Deposition of bedload up to water surface elevation	• Clast-supported deposits • Normally graded deposits • Imbricated channel deposits (common frequency) • Wide, shallow deposits • Wide and shallow channels • Evidence of multiple tree stand ages along stream channel.

E.3. GEOHAZARD RATING

BGC assigned geohazard ratings that considered the following two factors:

1. Geohazard likelihood: What is the likelihood of steep creek geohazard events large enough to potentially impact elements at risk[9] (Section E.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 E.3.2)?

8 Adventitious roots are roots arising in abnormal places
9 Elements at risk are defined as assets exposed to potential consequences of geohazard events (see Section 4 of the main report, and Appendix C).

These two factors were combined in the qualitative geohazard rating matrix shown in Table E-5 to prioritize each geohazard area. Sections E.3.1 and E.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, aerial photography, satellite imagery, recorded events (Section 2.7 of the main report) and past assessments (Appendix A).

Table E-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
Impact Likelihood	**Very Low**	**Low**	**Moderate**	**High**	**Very High**

E.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[10]. The correlation between geohazard likelihood and frequency is consistent with Table 5-3 of the main report.

E.3.1.1. Geohazard Likelihood Rating

Geohazard likelihood ratings were 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 E-6) for each prioritized geohazard area, as discussed in the section below.

[10] While a single geohazard likelihood rating was assigned for prioritization (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 E-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

E.3.1.2. Geohazard Likelihood Criteria

Table E-7 and Table E-8 summarize the criteria used to rate basin activity and fan activity, respectively. Figure E-11 and Figure E-12 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 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 E-7 and Table E-8 are not applicable for clear-water floods.

Table E-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	• Minimal sediment sources. • Supply limited watershed.	• Negligible sediment sources in or along channel or in tributaries.	• Absence of landslide scars or erodible terrain. • Basin is treed. • Several rounded slopes.
Low	• Identifiable sediment sources, but most show limited evidence of activity or connectivity. • Supply limited watershed	• Minimal sediment sources in or along channel and any existing channel material is not easily mobilized (e.g. dense till, partially bedrock controlled).	• Some exposed soil or rock occurs. • Absence of fresh landslide scars or debris below exposed terrain. • Absence of channel deposits. • Basin and channel are mostly treed
Moderate	• Active sediment sources, but the material is not easily mobilized AND is not connected to the main channel or fan. • Supply limited or unlimited watershed.	• Sediment sources are present in or along channel. • Channel material is not easily mobilized (e.g., dense till, partially bedrock controlled) • Tributaries with identifiable sediment sources (e.g. debris-flow tributaries) typically stall before reaching main channel. • Main channel often has variable width.	• Sediment sources are present on slopes (e.g., presence of landslide scars in soil or rock). • Source material or in channel deposits are not easily mobilized (e.g., coarse, angular colluvium, dense till, or partially bedrock controlled). • Landslide deposits typically stall before the main channel.
High	• Active sediment sources, but the material is either not easily mobilized, or not clearly connected to the main channel or fan. • Supply unlimited watershed	• Numerous, actively producing source areas along main channel and tributaries (i.e., debris slides, debris avalanches, raveling in lacustrine, glaciofluvial, or morainal sediments); • Evidence of temporary sediment storage along main channel.	• Numerous, actively producing source areas on slopes or in channel. • Channel is choked with debris, but the material is not easily entrained (e.g., coarse angular colluvium) • 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).
Very High	• Active sediment sources that could be easily mobilized and are well connected to the main channel or fan. • Supply unlimited watershed	• Numerous, actively producing source areas along main channel and tributaries (i.e., debris slides, debris avalanches, raveling in lacustrine, glaciofluvial, or morainal sediments); • Source material could be easily entrained. • Tributaries with identifiable sediment sources (e.g., debris-flow tributaries) deposit straight into main channel.	• Numerous, actively producing source areas on slopes or in channel. • Channel choked with debris. • Easily entrained source materials along channels (e.g., talus, glacial deposits, volcanics)

Table E-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[1,2]	Return Period	Number of Recorded Events[4]	Fan Observations: Debris-flood dominated creeks	Fan Observations: Debris-flow dominated creeks
Very Low	500 year	None	• Vegetated mainstem. • No distinguishable debris-flood related landforms. • Uniform tree canopy of mature forest.	• No observable mainstem. • No distinguishable debris-flow related landforms. • Uniform tree canopy of mature forest.
Low[3]	200 year	None	• Partially vegetated mainstem. • Muted channels or over bank deposits (most likely only visible in lidar). • Uniform tree canopy of mature forest.	• Vegetated mainstem. • Muted channels, lobes or levees (most likely only visible in lidar). • Uniform tree canopy of mature forest.
Moderate	50 year	0 to 1	• Unvegetated mainstem. • Channels and over bank deposits are visible in lidar, but potentially not in imagery. • Persistently includes swaths of mixed deciduous or conifer trees in riparian zone.	• Partially vegetated mainstem; • Channels, lobes or levees are visible in lidar, but potentially not in imagery. • Persistently includes swaths of mixed deciduous or coniferous trees associated with debris-flow landforms.
High	20 year	1 to 2	• Unvegetated mainstem; • Channels and over bank deposits are visible in imagery and lidar. • Persistently includes variable tree stand ages in riparian zone. • Regenerative vegetation and exposed sediment along channel. • Undersized channel in comparison with active floodplain width. • Partially vegetated bank erosion scars.	• Partially vegetated mainstem. • Channels, lobes or levees are visible in imagery and lidar. • Persistently includes swaths of regenerative (<10 year) or immature (<50 year) forest, potential areas of bare sediment.
Very High	5 year	8 (or at least two in the past 10 years where records are not available over a longer period)	• Unvegetated mainstem; • Channels and over bank deposits are visible in imagery and lidar. • Persistently includes areas of pioneer vegetation in riparian zone. • Fresh deposits are visible. • Undersized channel in comparison with active floodplain width. • Fresh bank erosion scars along mainstem.	• Fresh deposits are visible. • Channels, lobes or levees are visible in imagery and lidar. • Persistently includes swaths of bare sediment or low (<2 year) pioneer vegetation.
Cannot determine[3]	n/a	n/a	• Anthropogenic modifications across most of fan, and no evidence of past events in air photo record.	

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 E-11. 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 (Imagery: DigitalGlobe, 2014).

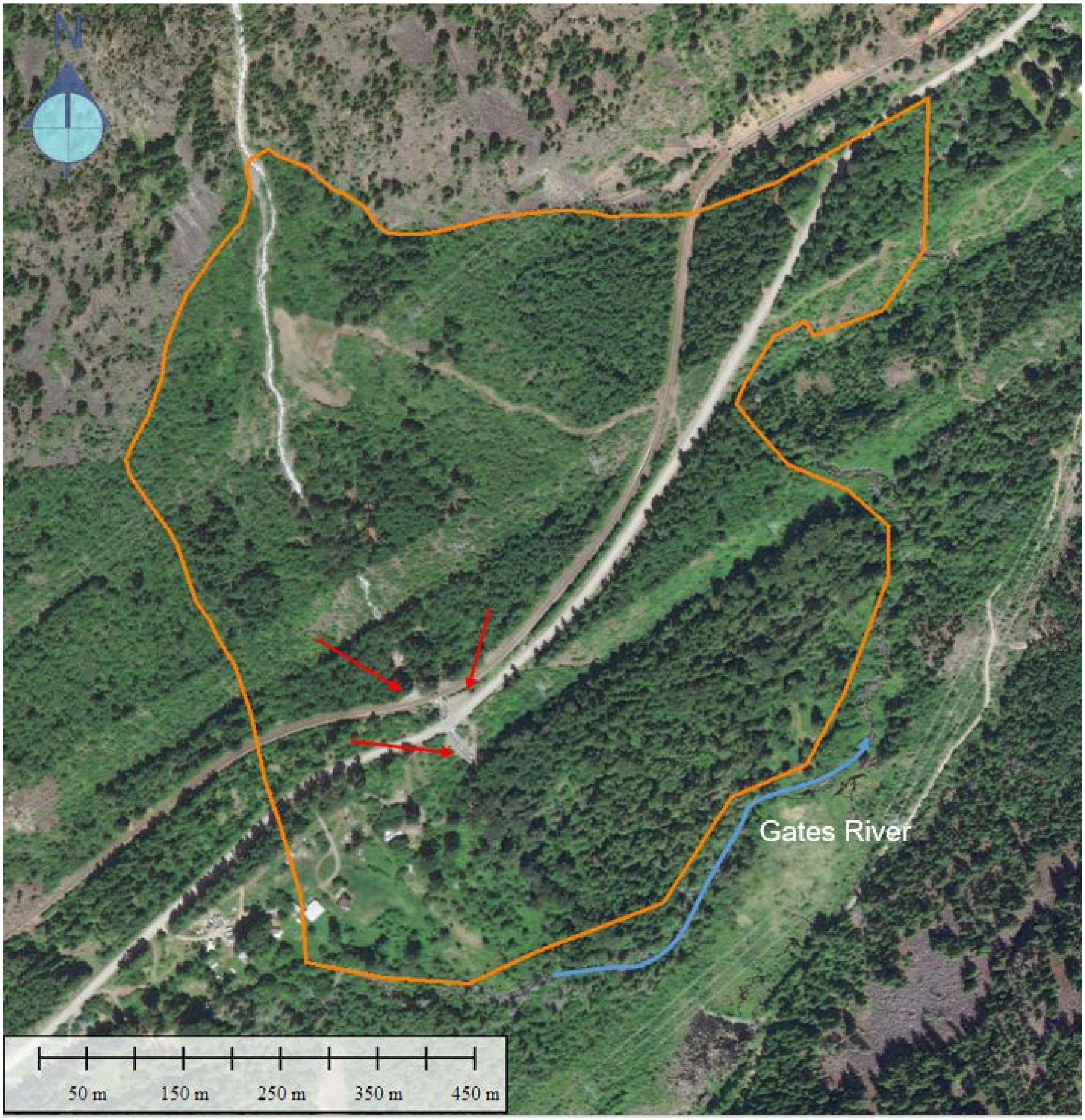

Figure E-12. Example of evidence (red arrows) for a recent (2015) debris-flow deposit on Neff Creek, located north of Pemberton. The approximate alluvial fan boundary is shown in orange (Imagery: DigitalGlobe, 2015).

E.3.1.3. Wildfires

Wildfires in steep mountainous terrain are often followed by a temporary period of increased geohazard activity. This period is most pronounced within the first three to five years after the fire (Cannon & Gartner, 2005; DeGraff et al., 2015). After about three to five years, vegetation can 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 & Helvey, 1976; Sidle, 1991; 2005). This second period of heightened debris-flow activity is rare.

Detailed post-wildfire geohazard assessment is outside the scope of work. Therefore, BGC assigned basin activity ratings based on current observations at the time of the assessment. Information on the occurrence of wildfires in the watershed (based on data from Ministry of Forests, Lands, Natural Resources Operations and Rural Development[11]) is shown for informational purposes in *Cambio*. Future wildfire activity could change the potential basin activity rating by one or more categories, and all ratings should be re-visited following the occurrence of a wildfire.

E.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 prioritization, 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.

E.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 E.3.2.2 and E.3.2.3), which was then complemented by observations on avulsion activity (Section E.3.2.4) and the potential for a LDOF (Section E.3.2.5). Previous assessments and event records were referenced where available. The methods described in this section are applicable for regional-scale assessment.

[11] https://catalogue.data.gov.bc.ca/dataset/fire-perimeters-historical; https://catalogue.data.gov.bc.ca/dataset/fire-locations-current (accessed in December 9, 2019)

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 E-13). 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 E-9.

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 E-10; Appendix D). 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 E.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 the LDOF potential rating was "moderate"; and by a factor of 2 if it was "high' or "very high" (Section E.3.2.5). This adjustment serves to flag fans where there is a possibility of major flooding events associated with potential LDOF events.

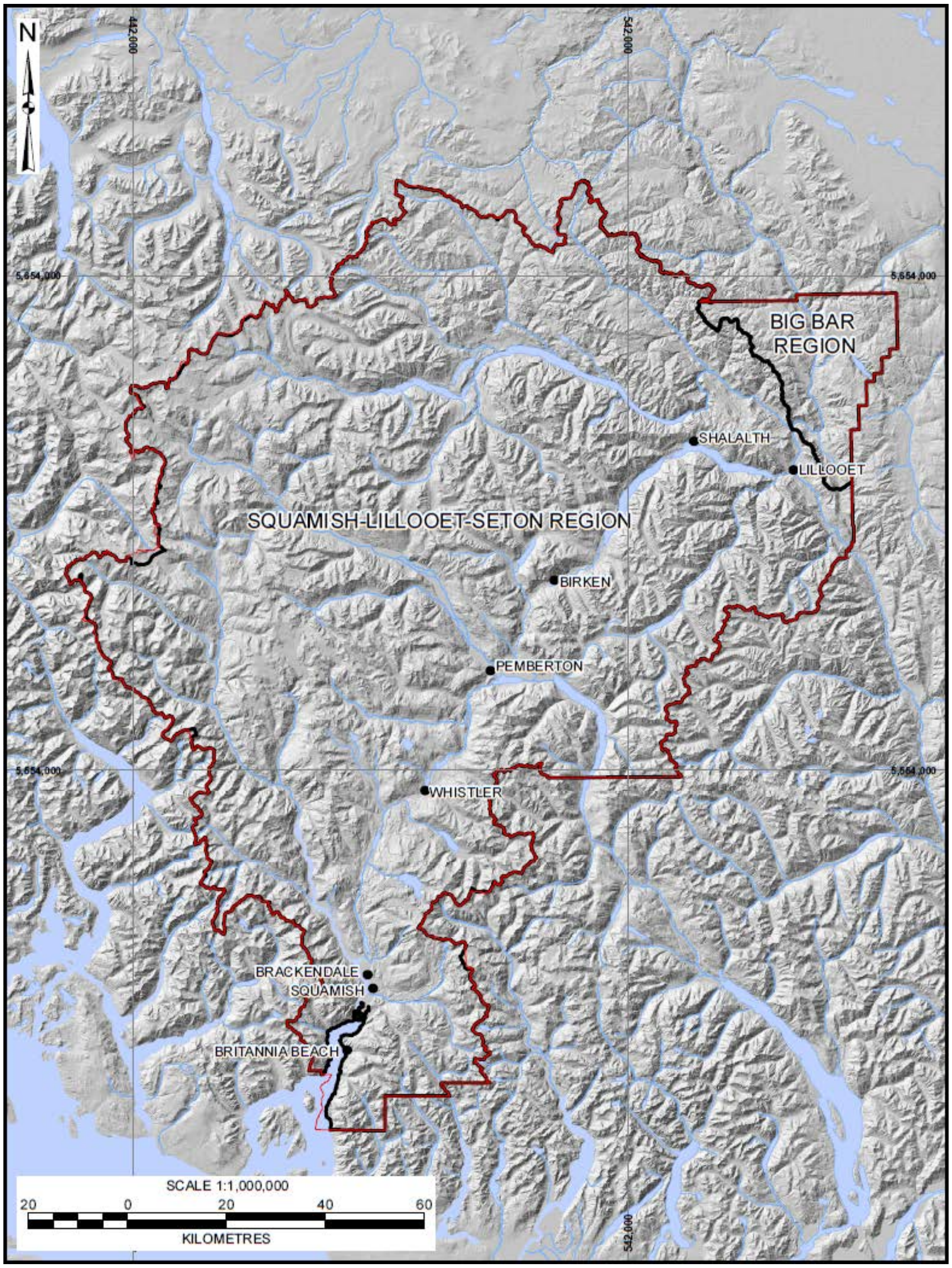

Figure E-13. Regions used during calibration of the susceptibility model, overlaid on the Canadian Digital Elevation Model (CDEM).

Table E-9. 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[1]	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 the LDOF potential criteria are “moderate”; and by a factor of 2 if they are “high’ or “very high”.

Table E-10. Summary of criteria used for impact likelihood rating for clear-water floods on fans.

Impact Likelihood Rating[1]	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 the LDOF potential criteria are “moderate”; and by a factor of 2 if they are “high’ or “very high”.

E.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 E.2.2 and E.2.3.1), and the Flow-R model[12] 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 E.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 E.2.2 and E.2.3.1. Both spreading

[12] "Flow-R" refers to "Flow path assessment of gravitational hazards at a Regional scale". See http://www.flow-r.org

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), Catiline 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 E.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 (Section 2.7 of the main report).

Table E-11 and Table E-12 show Flow-R calibrated parameters for debris flows and debris floods, respectively. The debris-flow and debris-flood scenarios are modelled separately.

Table E-11. 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 E-12. 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 E-14). 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 70th 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 70th and 85th percentile (the 85th percentile corresponding approximately to the mean susceptibility value); ‘moderate’ and ‘high’ susceptibility were defined between the 85th and 95th percentile, and greater than the 95th 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).

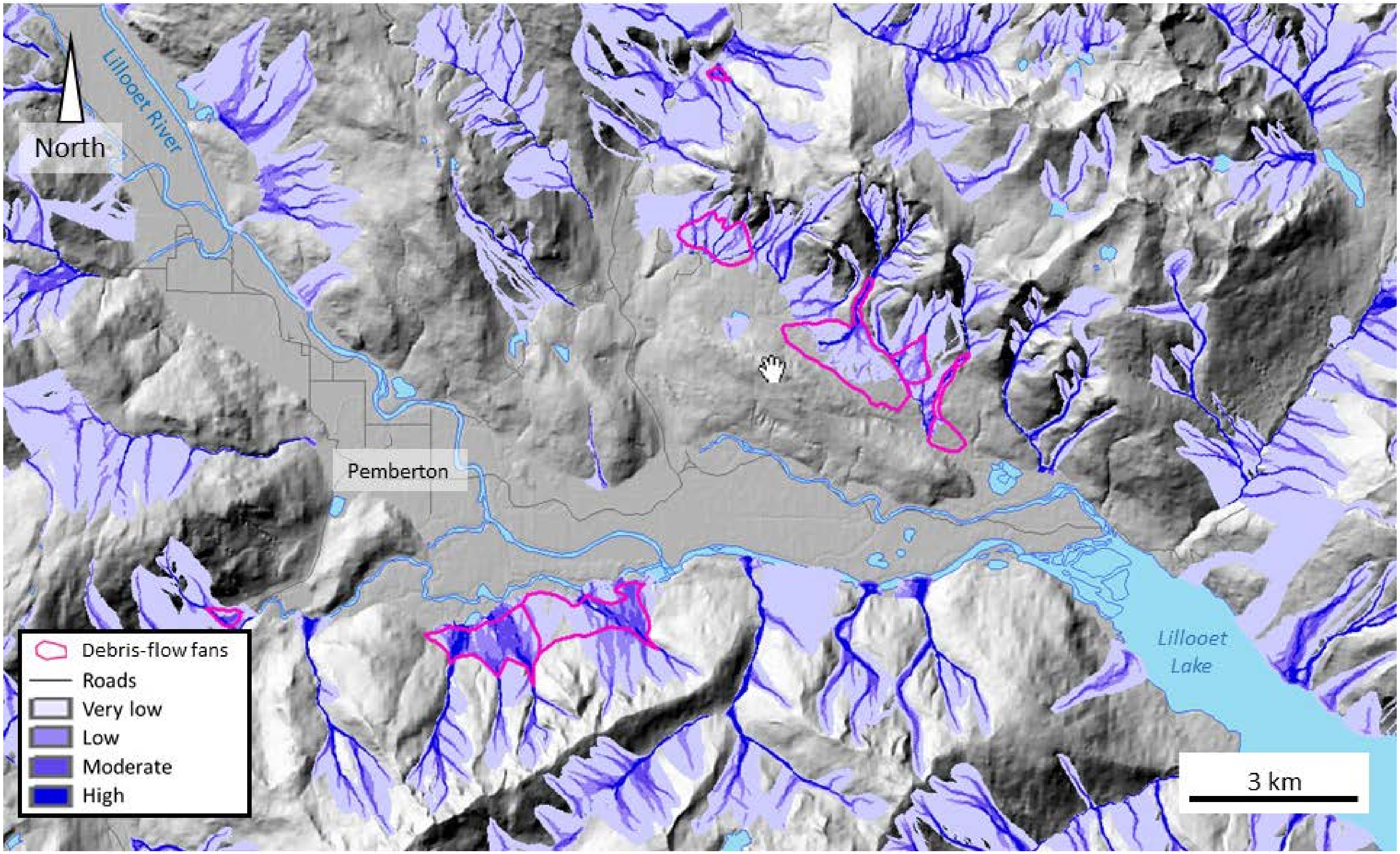

Figure E-14. Debris-flow susceptibility map for a section of the study area showing the spatial distribution of the four different susceptibility classes and developed debris-flow fans.

E.3.2.3. Clear-water Flood Susceptibility

Section D.2.4 of Appendix D (Clear-water Hazard Assessment Methodology) 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.

E.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 vegetation and the presence of relict channels, lobes and deposits on the fan surface (Table E-13; Figure E-15). These features are usually detectable on lidar hillshades; interpretations are less certain for areas without lidar 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).

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-water body interface. As such, these fans typically exhibit characteristics of a “Very High” or “High” rating, as long as 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 does not need to be upgraded.

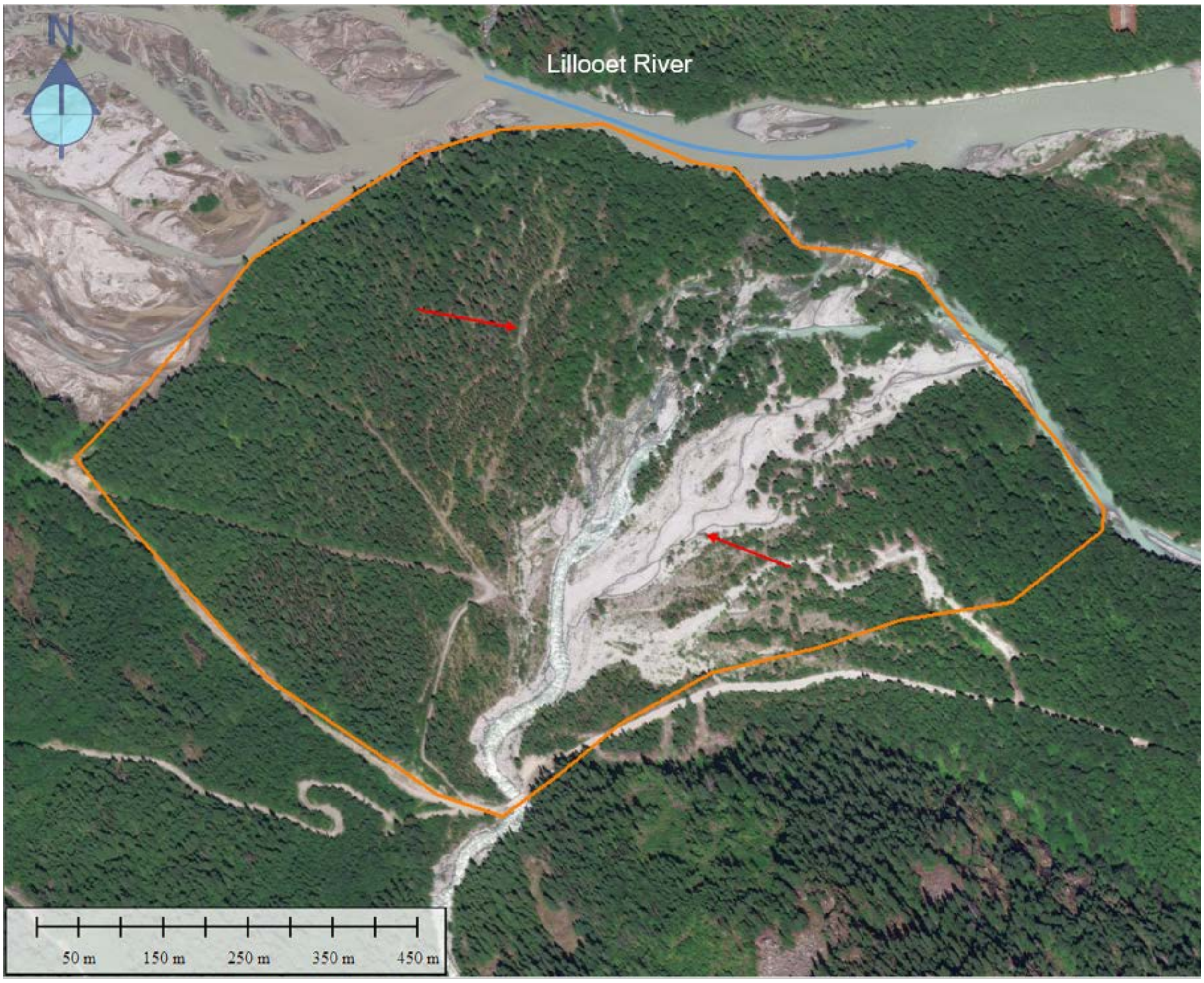

Figure E-15. Example of high evidence for previous avulsion on South Creek, located west of Pemberton. The approximate fan boundary is shown in orange.

Table E-13. Evidence of previous avulsions criteria. These criteria refer to the frequency of events avulsing on the fan, as opposed to Table E-8, which refers to the frequency of events reaching the fan regardless of avulsing or not.

Surface Evidence of Previous Avulsions[1]	Representative Return Period (years)	Number of Recorded Events[2]	Description	Characteristic Observations[3]
Very Low	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.
Low[1]	200	None	Historical channels visible with lidar but they are muted and vegetated and not discernable on satellite imagery.	Vegetated fan with consistent, mature stand age. Muted historical channels visible in if available. lidar
Moderate	50	0 to 1	Historical channels on fan surface are visible in lidar 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.
High	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., debris-flow levees) as described in the fan activity rating.
Very High	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 exist.	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.

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 generate an avulsion. BGC characterized the most likely avulsion mechanism that could occur at each prioritized geohazard area (Table E-14). At the regional scale of the study, these mechanisms were not used in the attribution of evidence for previous avulsion rating; however, natural landform obstruction and channel plugging are implicitly accounted for in the susceptibility model described in Section E.3.2.2 or evidence for previous avulsion detailed in Table E-13.

Table E-14. Avulsion mechanism description.

Avulsion Mechanism	Description
Bridge crossing	Forestry, highway, railway bridges on the main channel of fan
Culvert crossing	Culvert used to contain the flow on the main channel
Natural landform obstruction	Places where flow could leave the main channel (e.g., sharp bend in main channel)
Channel plugging	This usually occurs when debris flows stall and create a lobe front, forcing the remaining flows to go around the stalled or slow-moving boulder lobe. The evidence of channel plugging is typically avulsion channels and lobes across the fan in several channels. This type of avulsion typically occurs at the inflection point of the fan. The presence of a channel inflection point can be observed as a change from entrenched channel to unconfined channel, drastic change in grain size as debris flows are deposited, or a sudden change in average channel gradient.
None	no identifiable landform or anthropogenic feature that could enhance avulsions (i.e., very high or high channel confinement rating).

E.3.2.5. Landslide Dam Outbreak Flood 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 E-16; Bovis & Jakob, 2000; Guthrie et al., 2012). In this assessment, LDOF potential is expected to be a factor potentially increasing the potential for avulsion; therefore, it is considered in the impact likelihood rating (see Section E.3.2.1). However, LDOFs are a distinct population of events from the “typical” debris flows and debris floods defined in Section E.3.1. Therefore, this rating serves as a flag for consideration of more specific analyses to address this type of geohazard.

Table E-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).

Figure E-16. 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 E-15. Landslide dam outbreak flood potential criteria.

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

E.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 E-16 and further introduced in Sections E.4.2 and E.4.3.

Destructive potential is characterized based on intensity, which is usually quantified by parameters such as flow depth and velocity. 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 prioritization study, BGC used peak discharge as a proxy for flow intensity. The methods to estimate peak discharge are presented in Section E.4.1.

Table E-16. 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
Hazard Intensity Rating	**Very Low**	**Low**	**Moderate**	**High**	**Very High**

E.4.1. Peak Discharge Estimation

Clear-water flood, debris-flood, and debris-flow processes can differ widely in terms of peak discharge. The peak discharge of a debris flood is typically 1 to 1.2 times that of a clear-water flood in the same creek but could be much greater for debris-floods Types 2 and 3 (Table E-1). If the creek is subject to debris flows, the peak flow may be much higher (as much as 50 times) than the flood peak discharge (Jakob & Jordan, 2001). Figure E-17 shows a hypothetical cross-section of a steep creeks, including:

- Peak flow for the 2-year return period (Q_2)
- Peak flow for the 200-year return period flood (Q_{200})
- Peak flow for debris flood (Q_{max} debris flood)
- Peak flow for debris flow (Q_{max} debris flow).

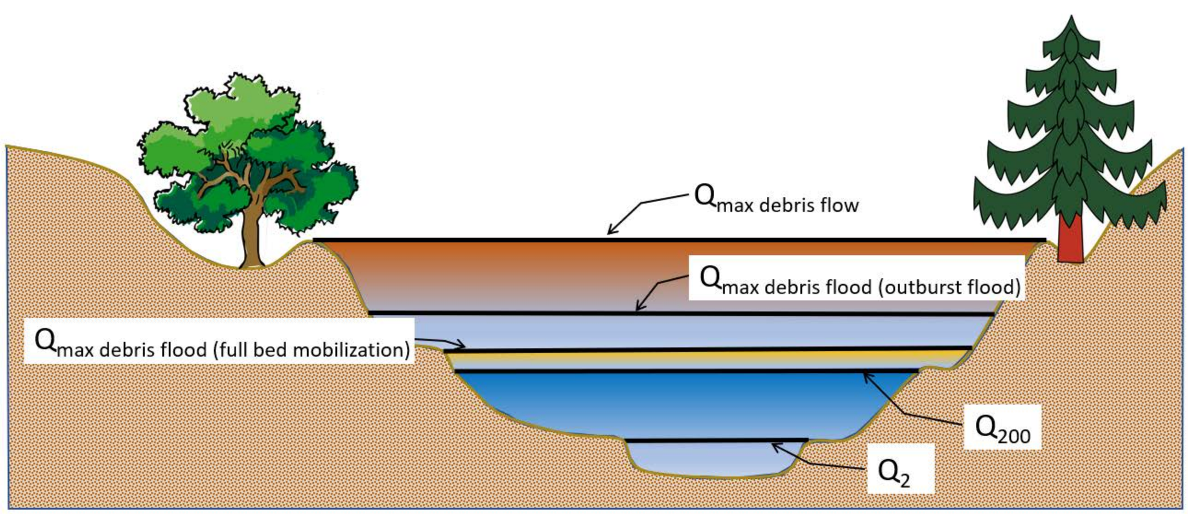

Figure E-17. Steep creek flood profile showing schematically peak flow levels for different events.

Due to the differences in peak discharges associated with each process type, the maximum peak discharge at the prioritized 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 projected climate change effect on steep creek geohazard magnitude (Section E.1.3), the peak discharge for fans associated with supply-limited basins was reduced by 10%[13], and the peak discharge for 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 process.

E.4.1.1. Clear-Water Floods

Flood frequency analysis (FFA) is used to estimate the flood discharge magnitudes and frequencies for multiple return periods (2-year up to the 1 in 200-year event) at a location along a watercourse. In the RNT presented in Section E.2.2, an FFA is automatically generated for each stream segment using information and data from hydrometric stations that are connected to the stream network. FFAs are based on either an analysis of several hydrometric stations with similar catchment and hydrological characteristics (regional analysis) or a prorated analysis, based on the catchment area, using a single station located on the same watercourse.

RNT contains hydrometric data collected from Water Survey of Canada (WSC) stations across Canada. A total of 88 WSC stations are located within the SLRD (EGBC, 2018). Of these stations, 17 are active and 71 are discontinued. Of the 17 active stations, 11 are also used for real-time flood monitoring (Figure E-18).

Screening-level flood discharge quantiles were generated based on the FFA approach for every stream segment intersecting the apex of an alluvial fan within the SLRD. Because RNT is applied as a screening level tool to predict flows over a large geographical area, the flow estimates have the following limitations:

- Gauges on regulated rivers (i.e., rivers where flows are controlled by a dam) are not used in the FFA; and flow regulation is not accounted for in watercourses with flow controlled by dams.
- Attenuation from the many lakes, wetlands and marshes in the SLRD may not be accounted for in the flow estimates. Peak flow values may be overestimated in catchments that contain these features. This factor can only be resolved via detailed rainfall/snowmelt-runoff modeling.
- Peak flow estimates do not account for potential outburst floods from ice jams, glacial or moraine-dammed lakes, beaver dams, landslide dams which may be of substantial magnitude in some locations.

[13] The 10% decrease/increase is based on judgment due to the lack of literature currently available on this topic.

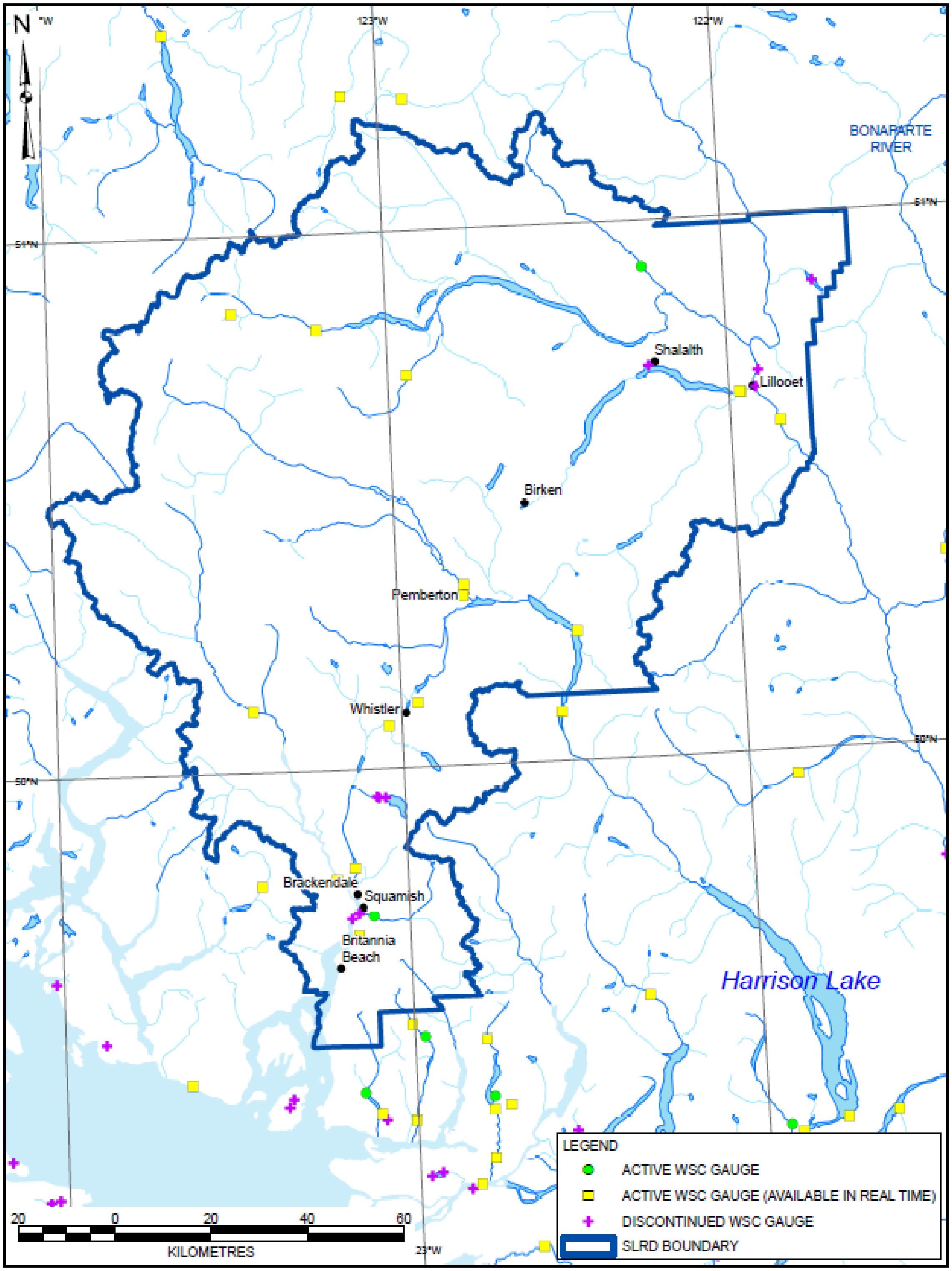

Figure E-18. WSC active and inactive gauges within the SLRD. Active stations are represented by a Green dot; Active stations that are also real-time monitoring stations are represented by a Yellow square; and Discontinued stations are represented by a Purple cross.

- The stream network dataset does not reflect recent changes to drainage alignments due to natural river migration or artificial alterations, which could impact calculated catchment areas and the selection of stream segments available for analysis.
- The stream network does not include stormwater infrastructure and drainage ditches.
- Regional FFAs typically under-estimate peak flows for smaller watersheds (< 25 km^2), as such catchments are rarely gauged and runoff processes are not necessarily scalable compared to larger catchments.

Implication of these uncertainties include under or overestimation of flow discharge at a given return period. They are not addressed further in this study and are not expected to affect relative priority rankings at the screening level of current study.

E.4.1.2. Debris Floods

Type 1 and 2 debris floods vary in discharge between 1.02 times to several times (see Table E-1) the corresponding clear-water flood discharge (Church & Jakob, 2020). At the regional scale of this prioritization 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 200-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 (LDOF) are addressed as a parameter in the geohazard impact likelihood rating (see Section E.3.2.5).

E.4.1.3. Debris Flows

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

- A regional frequency-magntiude (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, based on the fan area for each prioritized debris-flow fan.
- The hypothetical sediment volume of a 200-year return period debris-flow event was calculated from the site-specific F-M.
- The peak discharge of the hypothetical 200-year return period event was calculated from the event volume using empirical relationships.

Typically, F-M relationships for debris flows are difficult to compile 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, when several reliable F-M curves have been assembled, regional relations can be developed. 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. 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 E-19 shows the resulting normalized F-M curve for debris flows in southwestern British Columbia.

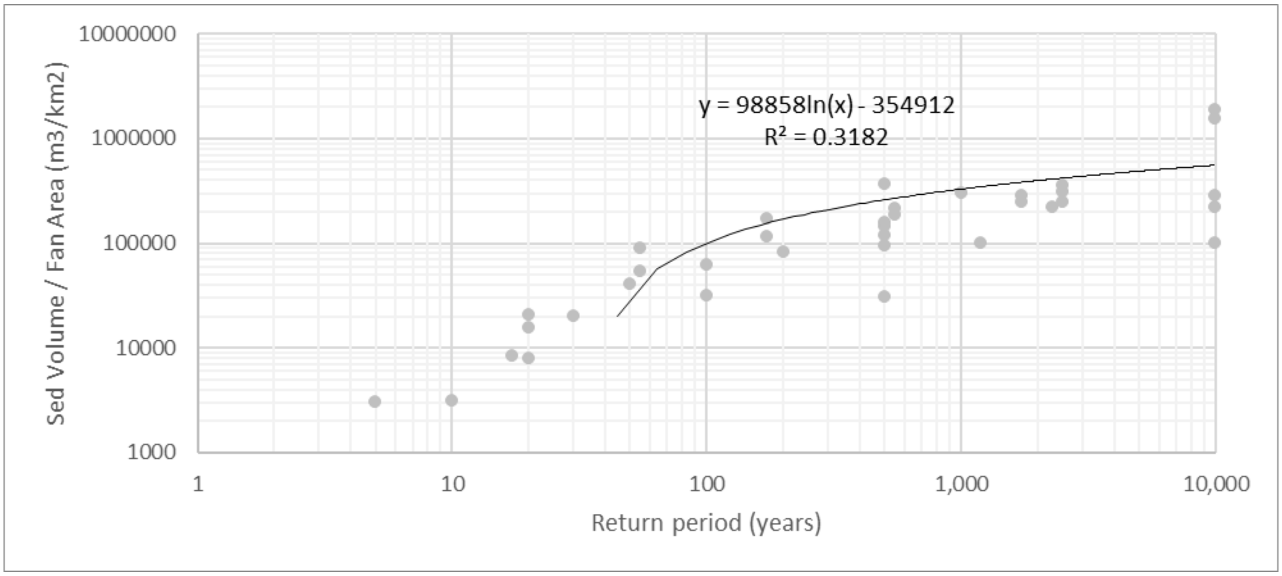

Figure E-19. F-M curve for debris flows in southwestern British Columbia using data from ten study creeks. Curves are truncated at the 40-year return period (Jakob et al., 2020).

The regional F-M relationship (Equation E-1), based on the best-fit line from Figure E-19 for the the detailed study[14] of sixteen creeks in southwestern BC, is then derived:

$$V_S = A_f[98858\ln(\mathrm{T}) - 354{,}912] \quad \text{[Eq. E-1]}$$

Using this equation, BGC predicted sediment volumes (V_s) for each prioritized geohazard area within SLRD using the fan area (A_f) and an average return period (T) of 200 years. This equation was used for comparative analysis amongst prioritized geohazard area in this study.

Having determined sediment volume, three published empirical relations for granular debris flows were considered to estimate peak discharge on each debris-flow creek. These relations are as follows:

[14] BGC, March 28, 2013; July 30, 2014; January 22, 2015; January 31, 2017; May 31, 2017; June 2018; April 6, 2018; Cordilleran Geoscience, 2008 and 2015; Clague et al., 2003; and Michael Cullen Geotechnical Ltd. & Cordilleran Geoscience, 2015.

$$M = 13 * Q^{1.33}$$ (Mizuyama et al., 1992) [Eq. E-2]

$$M = 28 * Q^{1.11}$$ (Jakob and Bovis, 1996) [Eq. E-3]

$$M = (10 * Q)^{6/5}$$ (Rickenmann, 1999) [Eq. E-4]

where M is the debris-flow volume in m^3 and Q is peak discharge in m^3/s. The above equations are solved iteratively for Q using the sediment volumes (M) derived using Equation C-1. The average of the calculated peak discharge is reported for each creek in *Cambio*. It should be noted that debris-flow peak discharge estimates using this method may result in overestimation of peak discharge. To address this issue, BGC assumed that debris-flow peak discharge could not exceed the peak discharge of a clear-water flood in the same creek by more than 50 times.

E.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 E.4.1 were analyzed statistically and integrated into the intensity rating system, where Very Low to Very High classes are defined using percentiles (Table E-17).

Table E-17. Summary of criteria used for intensity rating. The percentage criteria related to peak discharge estimates at all study fans.

Hazard Intensity Rating	Criterion
Very Low	< 20th percentile
Low	20th to 50th percentile
Moderate	50th to 80th percentile
High	80th to 95th percentile
Very High	95th to 100th percentile

E.4.3. Hazard Exposure Rating

The hazard exposure rating for each prioritized 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 C.

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APPENDIX F
HAZARD ASSESSMENT METHODS – VOLCANIC HAZARDS

F.1. INTRODUCTION

F.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.

As noted in Section 3.3.1 of the Main Report, 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 F-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.

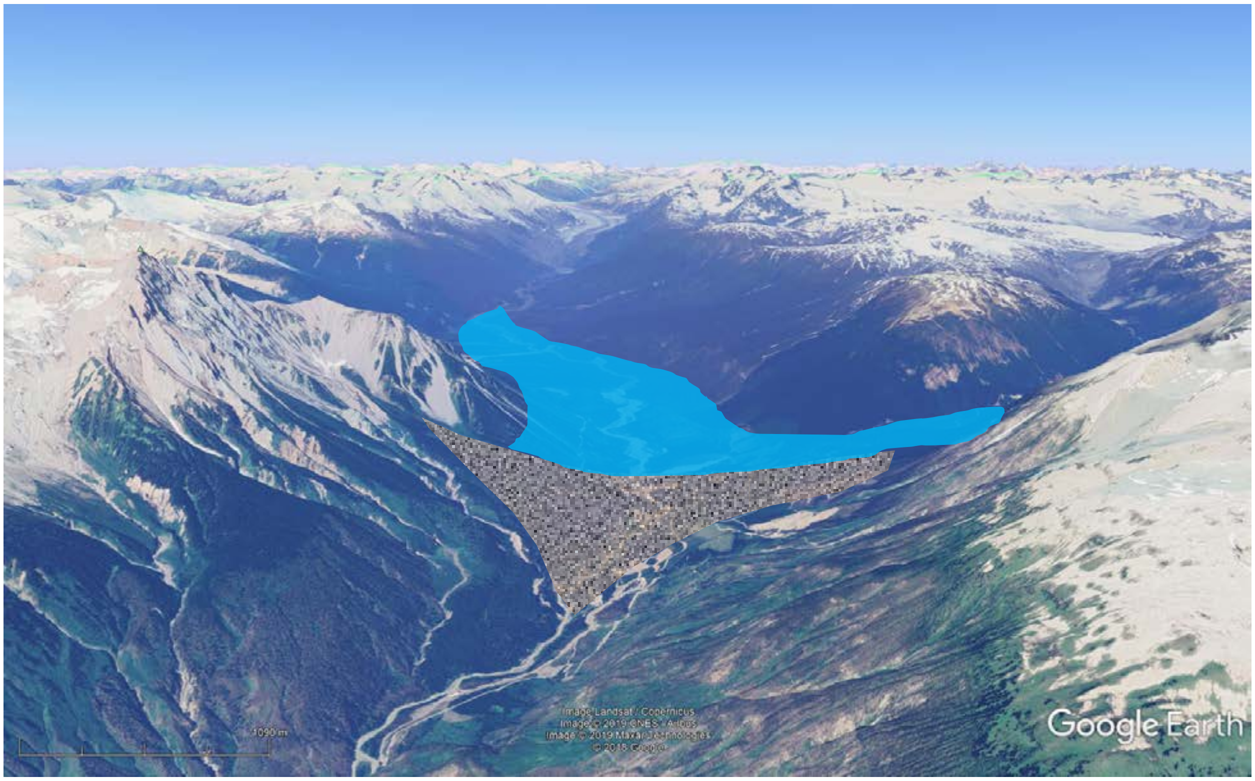

Figure F-1. Upper Lillooet River Valley with Plinth Peak on the left. The sketched outline shows a past landslide dam and the possible extent of a rock avalanche from the north flanks of Plinth Peak.

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^3 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.

F.1.2. Data Sources

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

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

Reference	Use in this study	Applicable Hazard Scenario (Section F.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[1] (CDEM)
- Lidar data provided to BGC by the SLRD.

Flood Mapping Polygons

- Clear-water flood hazard areas prioritized by BGC, as described in Section 4.1 and Appendix D.
- 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.

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

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

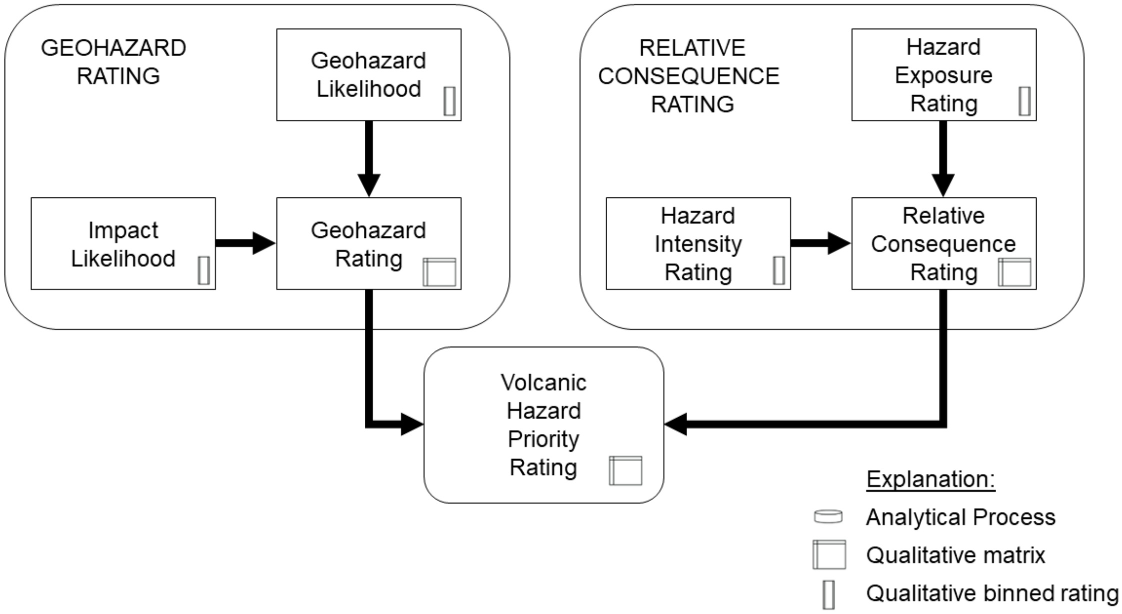

Figure F-2. Volcanic hazard analysis workflow. Geohazard rating and relative consequence rating elements are described in Appendix F (this text).

F.3. VOLCANIC HAZARD SCENARIOS

Table F-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 F.2 and are shown on *Cambio*, the web application displaying the results of this study. 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 F-2. Volcanic hazard scenarios.

Hazard Scenario	Description
Mount Meager Volcanic Complex	
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.
Mount Garibaldi Volcanic Complex	
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.
Mount Cayley Volcanic Complex	
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 F-1.

Once runout distance was estimated, geohazard extent was approximated from the hazard extents developed for clear-water floods (Appendix D) 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.

F.4. GEOHAZARD RATING

Table F-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 F-1.

Table F-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
Impact Likelihood (estimated chance of occurrence)	Very Low (< 5%)	Low (5 to 33%)	Moderate (33 to 66%)	High (66 to 95%)	Very High (>95%)

F.5. CONSEQUENCE RATING

Table F-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 C.

Hazard intensity ratings were applied as averages to each prioritized geohazard area, using judgement with reference to the data sources summarized in Table F-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 F-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
Hazard Intensity	Very Low	Low	Moderate	High	Very High
I_{DF}	< 0.1	0.1 to 1	1 to 10	10 to 100	> 100

REFERENCES

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 Squamish District, Ministry of Forests, Lands, and Natural Resource Operations.

Jakob, M., Stein, D., & Ulmi, M. (2012). Vulnerability of buildings to debris flow impact. *Natural Hazards, 60(2),* 241-261. https://doi.org/10.1007/s11069-011-0007-2

Major, J. J., Pierson, T. C., & Scott, K. M. (2005). Debris flows at Mount St. Helens, Washington, USA. In M. Jakob & O. Hungr (Eds.), *Debris-flow Hazards and Related Phenomena* (pp. 685-732). Chichester, UK: Praxis Publishing Ltd.

Northwest Hydraulic Consultants (NHC). (2018, November 26). *Flood Hazard Mapping and Risk Assessment – Upper Squamish* [Report]. Prepared for Squamish – Lillooet Regional District.

Roberti, G., Ward, B., van Wyk de Vries, B., Falorni, G., Menounos, B., Friele, P., Williams-Jones, G., Clague, J.J., Perotti, G., Giardino, M., Baldeon, G. & Freschi, S. (2018) Landslides and glacier retreat at Mt. Meager volcano: Hazard and risk challenges. In: Proceedings of the 7th Canadian Geohazards Conference: Engineering Resiliency in a Changing Climate.

Simpson, K. A., Stasiuk, M., Shimamura, K., Clague, J. J., & Friele, P. (2006). *Canadian Journal of Earth Science, 43,* 679-689. https://doi.org/ 10.1139/E06-026.

APPENDIX G
RISK ASSESSMENT INFORMATION TEMPLATE (RAIT)

Public Safety Canada | Sécurité publique Canada
Ottawa, Canada
K1A 0P8

National Disaster Mitigation Program (NDMP)
Risk Assessment Information Template

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: • Speed of onset and duration of event; • Level and type of damaged caused; • Insurable and non-insurable losses; and • Other details, as appropriate.	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.

Risk Event Identification and Overview	
Provide a qualitative description of the defined geographic area, including: • Watershed/community/region name(s); • Province/Territory; • Area type (i.e., city, township, watershed, organization, etc.); • Population size; • Population variances (e.g., significant change in population between summer and winter months); • Main economic areas of interest; • Special consideration areas (e.g., historical, cultural and natural resource areas); and an • Estimate of the annual operating budget of the area.	Catiline Creek is located within a 4 km^2 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.
Methodolgies, processes and analyses	
Provide the year in which the following processes/analyses were last completed and state the methodology(ies) used: • Hazard identification; • Vulnerability analysis; • Likelihood assessment; • Impact assessment; • Risk assessment; • Resiliency assessment; and/or • Climate change impact and/or adaptation assessment. Note: It is recognized that many of the processes/analyses mentioned above may be included within one methodology.	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. 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.

Hazard Mapping

To complete this section:

- 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.
- 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.
- Identify where and how flood hazards may affect the defined geographic area.
- Identify the mapped areas that are most likely to be impacted by the identified flood hazard.

Map(s)/photograph(s) can also be used, where appropriate, to visually represent the information/prioritization being provided as part of this template.

Hazard identification and prioritization

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.	Debris flow, rock avalanche.
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	
Description of risk event, including risk statement and cause(s) of the event	
Provide a baseline description of the risk event, including: • Risk statement; • Context of the risk event; • Nature and scale of the risk event; • Lead-up to the risk event, including underlying cause and trigger/stimulus of the risk event; and • Any factors that could affect future events. Note: The description entered here must be plausible in that factual information would support such a risk event.	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 occuring 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.

Location	
Provide details regarding the area impacted by the risk event such as: • Province(s)/territory(ies); • Region(s) or watershed(s); • Municipality(ies); • Community(ies); and so on.	Province: BC Region: Squamish-Lillooet Regional District, Electoral Area C Watershed: Catiline Creek Community: Lillooet Lake Estates
Natural environment considerations	
Document relevant physical or environmental characteristics of the defined geographic area.	Catiline Creek is located within a 4 km^2 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 m3 could occur.
Meteorological conditions	
Identify the relevant meteorological conditions that may influence the outcome of the risk event.	Debris flow events on Catiline Creek are primarily triggered by high precipitation events. These may regional or highly localized and may occur any time between Spring and Fall inclusive.

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: • Population density; • Vulnerable populations (identify these on the hazard map from step 7); • Degree of urbanization; • Key local infrastructure in the defined geographic area; • Economic and political considerations; and • Other elements, as deemed pertinent to the defined geographic area.	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.

Asset inventory	
Identify the asset inventory of the defined geographic area, including: • Critical assets; • Cultural or historical assets; • Commercial assets; and • Other area assets, as applicable to the defined geographic area. Key asset-related information should also be provided, including: • Location on the hazard map (from step 7); • Size; • Structure replacement cost; • Content value; • Displacement costs; • Importance rating and rationale; • Vulnerability rating and reason; and • Average daily cost to operate. A total estimated value of physical assets in the area should also be provided.	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 >3000 years, with high vulnerability to loss of life.

Other assumptions, variability and/or relevant information	
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.	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.

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.

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.	
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.	5
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.	

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)			

		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	

	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)			

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	

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	

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)			

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)			

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	

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.

Key Information Sources	
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. Clearly identify unclassified and classified information.	BGC Engineering Inc. (2015, January 22). Catiline Creek Debris-Flow Hazard and Risk Assessment [Report]. Prepared for Squamish-Lillooet Regional District.

Description of the risk analysis team	
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.	Kris Holm, M.Sc., P.Geo. Mr. Holm is a Principal Geoscientist with over 20 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. Matthias Jakob, Ph.D., P.Geo. Dr. Jakob's expertise revolves primarily around steep creek processes and risk management but extends to landslide and flood risk management for a broad range of private and government clients. He has authored some 40 peer reviewed journal papers and a total of over one hundred technical papers in journals, conference proceedings and books. He is adjunct professor at the Geography and Earth and Ocean Science departments at the University of British Columbia where he teaches courses in applied geomorphology.

APPENDIX H
RESULTS SPREADSHEET
(PROVIDED SEPARATELY IN EXCEL FORMAT)

APPENDIX I
RECOMMENDATIONS – DETAILED STUDIES

I.1. INTRODUCTION

Section 8.0 of the Main Document made the following recommendations

- *Complete detailed clear-water floodplain mapping for the areas identified by SLRD or stakeholders as top priority, following review of this assessment.*
- *Complete detailed steep creek geohazards assessments for areas identified by or stakeholders as top priority, following review of this assessment.*

This appendix provides additional detail on recommended assessment approaches. BGC recommends that any new geohazards assessments and mapping be integrated into the current regional study and used to update the geohazard ratings.

I.2. CLEAR-WATER FLOODPLAINS

I.2.1. 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. In summary, this level of effort includes the following components:

- Review Lidar and historical imagery to identify features such as historical channels
- Review of stakeholder input
- Site visit and qualitative assessment of flood hazards, including documentation of existing flood and erosion protection
- Bank erosion quantitative assessment using historical air photographs
- Watershed-scale land use change consideration
- Climate change predictions for precipitation and runoff as inputs to hydraulic modelling
- Hydraulic modelling with possible dike breach scenarios, where applicable
- Flood hazard inundation maps for 200-year and possibly 500 to 1,000-year flood event.

I.2.2. Suggested Work Plan

Table I-1 lists recommended tasks for each area to be mapped. Each task is described in the sections which follow. BGC notes that tasks will differ in detail for individual areas.

Table I-1. Recommended clear-water floodplain mapping work plan.

Activities	Tasks	Deliverables/Products	Resources
Data Compilation	Survey and Base Data Collection	Base inputs for hazard analyses and study integration such as historical air photographs, regional geology maps and land use coverage maps	• 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
Analysis	Hydrology and Climate Change Assessment	Hydrologic inputs for hydraulic modelling including climate-change adjusted precipitation and runoff inputs	• 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

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. The survey 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.

Additional items that require compilation from available sources beyond the information collected in this current regional study include:

- 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).

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 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.

I.3. RESERVOIRS

High and/or fluctuating lake levels on regulated lakes can result in geohazards such as the following:

- Flood inundation
- Shoreline erosion
- Impact by landslides and associated landslide-generated impulse waves
- Groundwater mounding
- Wind- and boat-generated waves
- Storm surge.

Impacts from such events are manifested through a chain of events where the hazard occurs, impacts an element at risk, and causes something of value to suffer a loss. Losses can be measured, for example, as the number of causalities (e.g., displaced persons, injured persons, fatalities), economic value (e.g., capital cost, or life cycle cost), time (e.g., days, weeks, months or years of schedule delay, or of loss of use of some asset or functionality), or ecological value.

Where additional reservoir geohazard and risk assessment is considered in these areas, BGC suggests using an 'impact line' approach, which is based on guidelines provided by the International Commission on Large Dams (ICOLD, 2002). 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 and the opportunity for greater flexibility for land use based on hazard or risk-based decision making.

Figure I-1 provides a schematic illustration of flooding, erosion, stability, and landslide-generated wave impact lines. Each are described further below.

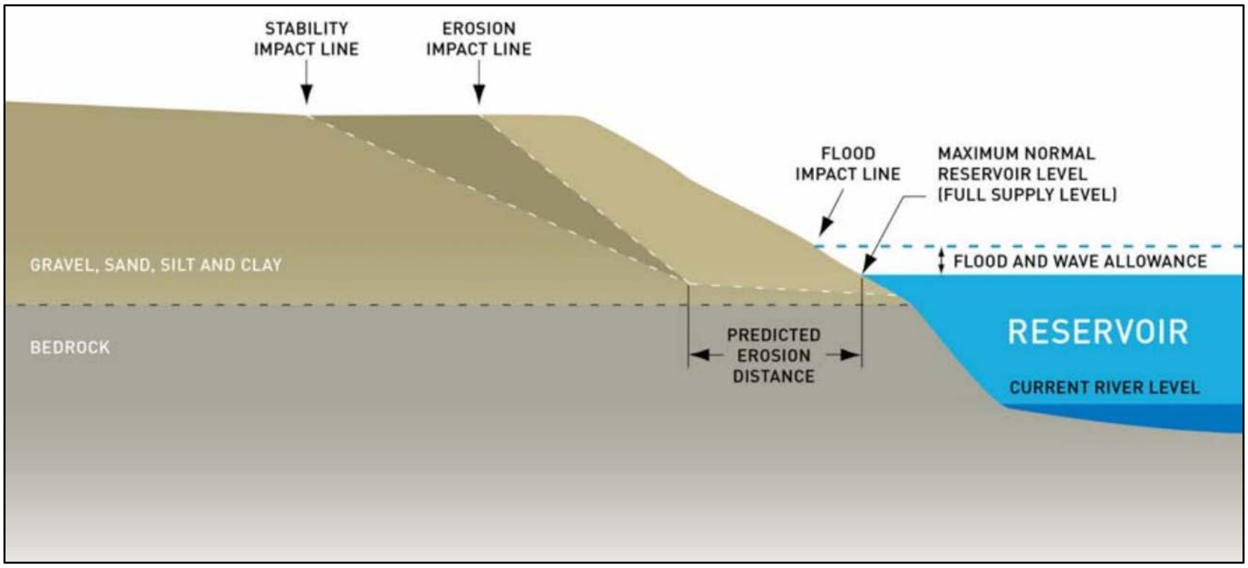

Figure I-1. Schematic illustration of the Flood, Erosion, and Stability Impact Lines for a typical low bank (top graphic) and high bank (lower graphic) slope (adapted from McDougall et al., 2015).

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. They provide an upper envelope on each of the various contributing factors listed above, or for all of them simultaneously. The current study presented in this report presents a flood impact line that includes floods only (surface and basement impacts). An expanded impact assessment framework could include these other sources of inundation.

The *Erosion Impact Line* is the boundary beyond which the top of the slope adjacent to the reservoir would not be expected to regress due to erosion caused by the impoundment and operation of the reservoir over a defined period (e.g., 100 years). It considers both predicted shoreline erosion and the formation of a slope above the reservoir shoreline using appropriate eroded (short term, steep) slope angles for the geological units present around the shoreline.

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.

The *Landslide-Generated Wave Impact Line* is not shown on Figure I-1 and may not be appropriate for all areas. It shows a boundary line where it can be determined that waves triggered by landslides entering a reservoir (landslide-generated waves) could temporarily inundate 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.

I.4. STEEP CREEKS

I.4.1. Approach and Overview

As per EGBC Guidelines for Legislated Flood Assessments in BC (2018), BGC suggests that "Class 3" Flood Hazard Assessments for Debris Floods or Debris Flows be completed for the prioritized steep creek flood hazard sites. A Class 3 assessment is semi-quantitative, in that steep creek flood hazards are described using both empirically derived values, as well as limited computation of site-specific parameters (e.g., magnitude or velocity).

The objective of the assessment is to generate hazard maps for each fan. 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[1] portions of the alluvial fan and areas potentially susceptible to avulsion or bank erosion during the specified steep creek flood hazard return periods.
- 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.

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

- 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.

I.4.2. Recommended Work Plan

Table I-2 lists tasks suggested for each steep-creek hazard study area. Each task is 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 I-2. Suggested steep-creek hazard mapping work plan for each steep-creek hazard area.

Activities	Tasks	Deliverables/Products	Resources
Data Compilation	Base Data Collection	• Base inputs for hazard analyses and study integration.	• Qualified Professional • District staff • Provincial staff
	Asset and Elements at Risk Inventory Update	• Base inputs for hazard analyses and study integration.	• Qualified Professional • District staff
Analysis	Steep Creek hazard characterization and analysis (desktop and field)	• Field observations to inform hazard analyses and modelling (surface observations and test pits) • Field review of any existing structural protection structures (engineered or non-engineered) • Regional F-M relationships • Hydrologic inputs for hazard modelling.	• Qualified Professional
	Climate Change Assessment	• Qualitative description of anticipated changes to F-M under climate change scenarios	• Qualified Professional
	Hazard Modelling	• Model outputs showing flow intensity (flow extent, flow depth and velocity), that form the basis for hazard mapping	• Qualified Professional
	Channel Stability Investigation	• Geomorphological inputs for flood hazard maps. • Bank erosion and set-back analysis	• Qualified Professional
	Study Integration	• Integration of new hazard mapping results with previous study.	• Qualified Professional • District staff
Final Deliverables	Hazard Map Production	• Steep creek hazard maps.	• Qualified Professional • District staff
	Reporting and Data Services	• Description of methods, results, and limitations, and data and web services for dissemination of study results.	• Qualified Professional • District staff

Data Compilation

The base data collection would include compiling all relevant site data relating to steep creek flood hazards. These data would be used as base inputs for the steep creek flood hazard mapping. 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.

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.

<u>Numerical Modelling</u>

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.

<u>Additional Considerations</u>

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.

REFERENCES

Engineers & Geoscientists British Columbia (EGBC) (2018, August 28). *Legislated Flood Assessment in a Changing Climate in BC, Version 2.1*. Professional Practice Guidelines.

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van Dijk, M., Kleihans, M.G., Postma, G., & Kraal, E. (2012). Contrasting morphodynamics in alluvial fans and fan deltas: effects of the downstream boundary. *Sedimentology,* 59(7), 2125-2145.

APPENDIX J
GEOHAZARDS EVENT INVENTORY

Year	Month	Type of Hazard	Location	Source	Description of Event
1855-1856	September- March	Landslide	Daisy Lake, Rubble Creek	Moore and Mathews (1978)	A rock cliff collapsed, releasing water from a lava dammed lake and depositing debris for 4.6 km along Rubble Creek valley. Tiered deposits indicate debris came in surges.
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.
1906	September	Outburst Flood - Natural Impoundment	Sea to Sky, Britannia Beach, Britannia Creek	Septer (2007)	A logjam on Brittania Creek caused it to shift course at the apex of its fan. At the upper end of Brittania Beach flats, the creek was blocked by debris and diverted down the center of the flat. Employees of the Brittania Company were at work on September 9, blasting the obstruction and causing it to avulse onto the floodplain when the rush of water came.
1907		Debris Flow	Seton Portage, Bear Creek	BGC (2018, April 6)	Portage River was completely blocked by a huge slide originating from Bear Creek watershed. Lillooet residents, noting a drop in the levels of Seton Lake and the creeks, went up by boat to investigate. The Seton Portage River was completely blocked by a huge slide and its waters flowing back to Anderson Lake. The spring freshet soon broke through the slide and a new river channel was formed.
1915	March	Landslide	Sea to Sky, Britannia Beach, Jane Creek	Blais-Stevens and Hungr (2008)	Canada's second worst landslide disaster (after the Frank Slide) occurred when 200, 000 m^3 of rock and ice avalanched into Jane mining camp. 54 people were killed.
1919	November	Watercourse Flood	Pemberton, Lillooet River	Septer (2007)	Baker Road, Bossomworth and Lillooet River bridges were carried away as the Lillooet rose following heavy rain event. The northern area was described as a "vast sea" in which many cattle were drowned.
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
1921	October	Outburst Flood - Natural Impoundment	Sea to Sky, Britannia Beach, Britannia Creek	Eisbacher (1983)	Log jams created in Britannia Creek from human activity were made worse during heavy rainfall. One burst releasing a deluge of boulder debris and uprooted trees, destroying buildings and killing 37 people.
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.
1931	October	Debris Flow	Mount Meager, Devastator Creek	Jordan (1994)	Devastator Creek experienced a huge debris flow which travelled the full length of Meager Creek valley. Multiple surges were seen and they entered and partially blocked the Lillooet River.
1931	October	Debris Flow/Debris Flood	Mount Meager, Devastator Creek, Lillooet River	Jordan (1994)	Devastator Creek experienced a huge debris flow which travelled the full length of Meager Creek valley. The Lillooet River was partially blocked by surges of debris flow.
1932	December	Watercourse Flood	Squamish, Howe Sound	District of Squamish (2014)	The ocean topped the sea dike and flooded downtown Squamish
1933	December	Watercourse Flood	Sea to Sky, Britannia Beach, Britannia Creek	Septer (2007)	Britannia Beach was swept clean and a new high tide level was marked by storm surging.
1937	October	Watercourse Flood	Cheakamus River Valley, Cheekye River	Septer (2007)	A railway bridge was pushed out of alignment and flooded by the Cheekye river, isolating Brackendale between 2 lost bridges.
1937	October	Watercourse Flood	Squamish, Mamquam River, Cheekey River	Septer (2007)	A railway bridge was pushed out of alignment and flooded by the Mamquam river, isolating Brackendale between 2 lost bridges.
1940	September-November	Watercourse Flood	Pemberton, Lillooet River	NHC (November 22, 2018)	The valley was flooded in the fall of 1940 when a poorly constructed dike breached. The flooding covered the entire valley, impacting buildings, livestock and vegetation.
1940	October	Watercourse Flood	Gold Bridge , Bridge River	Septer (2007)	Bridge River waters reached the highest marks ever recorded to date. Road communications with a number of large gold mines in the Bridge River district was cut when bridges washed away. The road was out until October 25. One motorist was killed on a flood damaged road near Gold Bridge.
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.

Year	Month	Type of Hazard	Location	Source	Description of Event
1945	June	Watercourse Flood	Pemberton, Lillooet River	Septer (2007)	Warm weather and melting snow caused the Lillooet River to go on a new rampage. It overflowed highways and isolated farms and areas in the foothills. Roads were under 1 m of water.
1947		Landslide	Mount Meager, Devastator Creek	Septer (2007)	A landslide in Devastator Creek was revealed by aerial photographs in 1947, which show fresh landslide debris on the surface of Devastation Glacier, which has its source on the west side of the valley directly opposite the 1975 landslide. The debris shows no distortion from glacial movement and its volume is estimated to be in the order of 2-4 Mm^3. It travelled a distance of 1500 m on Devastation Glacier but didn't extend past its toe.
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	August	Landslide	Lillooet,	Septer (2007)	A passenger train was delayed by a mudslide across the tracks above Lillooet.
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.
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.
1955	November	Debris Flow/Debris Flood	Lillooet,	Septer (2007)	Heavy rains caused washouts and slides on the rail line between Shalalth and Lillooet, cancelling the passenger train. The line was cleared late on November 5th.
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.

Year	Month	Type of Hazard	Location	Source	Description of Event
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	August	Debris Flow	Cheakamus River Valley, Cheekye River	Eisbacher (1983), Jones (1959)	Following a sudden rainstorm, thousands of yards of tuff breccia debris and logs rushed down the Cheekeye River and built a 4.5 m high dam across the Cheakamus River. Eye witnesses say that the mudflow moved at 8 km/h near the mouth of the Cheekeye River, flowed for several minutes and appeared to be about 3 m high. According to accounts by local inhabitants, an even larger flow occurred about 30 years prior to 1958.
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.
1955-1965		Watercourse Flood	Sea to Sky, Daisy Creek	Thurber (April 1983)	Flooding on Daisy Creek washed out the BC railway trestle bridge.
1960-1965		Debris Flow/Debris Flood	Sea to Sky, Porteau Cove, Kallahne Creek	Thurber (April 1983)	Highway culvert plugged and washed out the road, similar to what happened in 1981.
1961	January	Landslide	Pemberton, Lillooet,	Septer (2007)	Three days of torrential rain caused slides on the rail line between Pemberton and Lillooet.
1963	July	Debris Flow	Squamish River Valley, Dusty Creek, Turbid Creek	Clague and Souther (1982)	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.
1963	December	Watercourse Flood	Sea to Sky, Britannia Beach, Britannia Creek	Thurber (April 1983), Septer (2007)	Seven families were evacuated, and the highway washed out by flooding on Britannia Creek. This was the fourth flood in three years.
1964	March- May	Debris Flow	Seton Portage, Bear Creek	BGC (2018, April 6)	In early spring of 1964, a debris flow occurred on Bear Creek. The event was triggered by rain on snow. According to a resident the debris stopped approximately 200 yards above the church in Necait, travelled over to the upper house and travelled all the way to the road at the RV park.
1964	June	Debris Flood/Flood	Seton Lake,	Septer (2007)	Heavy rains caused slides and washouts on the rail line around Lillooet. A mountain stream, which empties in to Seton Lake, cut the line 21 km south of Lillooet (Puck Creek?). A number of roads in the area were also washed out and the rainfall was the heaviest in recorded memory for that area.
1965	April	Landslide	Fountain,	Septer (2007)	A 6 m section of a wall of rock above an old washout gave way. Some children had been climbing the washout debris and the falling rock killed one child and injured three others.
1967	November	Debris Flood/Flood	Sea to Sky, Britannia Beach, Britannia Creek	Septer (2007)	Floodwaters swept away the water main supplying the town when Britannia Creek spilled over its banks and cut a new channel down the mountain. The flood impacted several homes and the townsite was covered with 0.15 m of mud. At one point, 0.6 m of water covered Highway 99.
1967	December	Outburst Flood - Manmade Structure	Squamish, Howe Sound	District of Squamish (2014)	The sea dike was overtopped and flooded downtown Squamish.
1968	January	Watercourse Flood	Tisdall,	Septer (2007)	A section of highway 99 between Whistler and Pemberton closed after 1 m of water flooded the road near Tisdall. On the outskirts of Pemberton, floodwaters caused the evacuation of the residents of two houses.
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.
1969	March	Debris Flow	Sea to Sky, Porteau Cove,	Septer (2007)	Heavy rains in the Porteau Cove area caused a debris slide on Highway 99. Some boulders measured up to 3 m high. As the rocks, mud and trees blocked the highway, a detour had to be built at Porteau.
1972		Debris Flood	Mount Meager, Capricorn Creek	Jordan (1994)	A 1973 air photo shows the fan of Capricorn Creek covered with recent debris. The date of 1972 is corroborated by dendrogeomorphology dating. The event is classified as a debris flood event due to the lack of obvious levees as well as other factors described in the source.
1972		Debris Flood/Flood	Sea to Sky, Deeks Creek	Jackson et al. (1985)	Flooding occurred on Deeks Creek that overtopped the BC Railway bridge but did not cause any major damage.
1975	July	Landslide	Mount Meager, Devastator Creek	Mokievsky-Zubok (1977)	A glacier-initiated land-ice slide occurred on the southwestern side of Devastation Glacier. An estimated 2.5×10^6 m^3 of ice and about 26×10^6 m^3 of debris descended 1150 m over 6.5 km and blocked Meager Creek, forming a small lake. The slide claimed the lives of four people on a sand bar at Meager Creek.
1975	October	Watercourse Flood	Pemberton, Lillooet River, Green River, Birkenhead River	Septer (2007)	Flooding on Birkenhead River washed out 3 km of track, a second washout occurred at the Green River. Highway 99 was washed out 11 km south of Pemberton forcing a closure of the highway. Lillooet River recorded the second highest measured flow (October 1984 was maximum recorded flow).

Year	Month	Type of Hazard	Location	Source	Description of Event
1975	November	Watercourse Flood	Cheakamus River Valley, Cheakamus River, Daiy Lake, Mamquam River, Cheaakamus 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	Pemberton, Lillooet River	Septer (2007)	The Lillooet River recorded the second highest measured flow for the 65-year period up to October 1984 with a discharge of 705 m^3/s at a gauge height of 5.15 m. The average Lillooet River discharge for the 65-year period up to October 1984 was 126 m^3/s.
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.
1976/1977		Debris Flood	Sea to Sky, Furry Creek	Thurber (1983)	The two bridges at Furry Creek were blocked with debris. The road was overtopped by the creek but the road was not washed out.
1977	December	Landslide	The Barrier,	Septer (2007)	On December 24, approximately 300,000 m^3 of rock fell from the near-vertical upper cliff face below Barrier Lake. The debris covered most of the springs at the foot of the talus. It involved a segment of the precipice some 200 m long, 200 m high and metres to perhaps tens of metres thick. Residents 3 km to the west reported hearing about midnight December 24 the noise caused by the rockfall. No local earthquake had been recorded at the time nor unusual weather conditions.
1980	December	Watercourse Flood	Pemberton, Lillooet River	Septer (2007), KWL (December 23, 2002)	One of three floods in Lillooet River Valley from 1980 to 1984 that caused the Ministry of Environment, Water Management Branch to issue a flood study for the area. The Lillooet River crested to within 0.1 m of the top of the dyke in four areas in Pemberton Valley Dyking District. Where the river overflowed its banks, it carried large amounts of wood debris onto agricultural land.
1980	December	Watercourse Flood	Pemberton, Ryan River	Septer (2007)	Ryan River broke through the dykes in 12 places. For a length of 4 km the water reached the top of the dyke, a frozen layer of snow on top of the dyke prevented the water from overflowing the dyke over the whole length.
1980	December	Watercourse Flood	Pemberton, Miller Creek	Septer (2007)	Two slides came down in the mountain area of Miller Creek. Floodwater carried the slide material down to the valley floor. It deposited in the creek bed, raising the bed to an elevation that sent water over the banks and into habited areas, flooding farmland and four houses. Floods damaged Miller Creek bridge in Pemberton Meadows.
1980	December	Watercourse Flood	Pemberton, Birkenhead River	Septer (2007)	The Birkenhead River overflowed its banks near a home, carrying vast quantities of gravel into agricultural land and containing large pools of water.
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.
1980	December	Watercourse Flood	Cheakamus River Valley, Culliton Creek	Eisbacher (1983), Septer (2007), VanDine (1984)	During an intense rainstorm, several thousand cubic metres of debris and logs were pushed against the upstream embankment of the highway by the swollen Culliton Creek. The culverts across the road were completely blocked and overflow carved a wide gash into the road bed. Judging from the stream gauge records of other torrents of similar size in this region maximum flood discharge during the storm amounted to about 30 times the mean rate of discharge for the month of December. The highway was relocated from the mouth of the gorge onto a bridge several tens of meters to the west.
1980	December	Debris Flood	Whistler, Nineteen Mile Creek, Twentyone Mile Creek, Fitzsimmons Creek	Eisbacher (1983), Septer (2007), RMOW (2016)	A two-day rainstorm along the snow-covered mountains was the trigger event for extensive debris floods. Near Whistler Village the freezing level rose to about 2000 m and snowmelt combined with more than 100 mm of rain to create sudden runoff which mobilized logs from clogged channel reaches along many creeks. Although the impact of most of the debris washed down by the swollen torrents was neutralized by dikes or deposited in natural or artificial depressions along the lower reaches, some damage was done to roadworks and bridges. The only way to travel north of Alpine Meadows on Highway 99 was by a stepladder across the rushing waters of Nineteen Mile Creek as volunteers had dug out this section of the highway in order to save the surrounding residences from being washed away by the floods.

Year	Month	Type of Hazard	Location	Source	Description of Event
1980	December	Debris Flood/Flood	Tisdall, Rutherford Creek	Eisbacher (1983), Septer (2007), RMOW (2016)	During the rainstorm, one abutment of the railroad bridge across Rutherford Creek was washed out, necessitating replacement of the whole structure. During the same storm there was a major shift of the braided Rutherford Creek channel between the bridge and Green River.
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	Debris Flood	Sea to Sky , Kallahne Creek	Thurber (1983)	Kallahne Creek blocked the highway culvert. The culvert and road washed out, and a great deal of material was deposited downstream of the highway.
1981	October	Debris Flow/Debris Flood	Sea to Sky , Furry Creek	Septer (2007)	Heavy rain triggered flooding and debris torrents were triggered in the mountains east of Howe Sound including Furry Creek. At Furry Creek, the bridge abutment fill washed out. The washout was attributed to high creek flows and debris jamming.
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	October	Watercourse Flood	Pemberton, Lillooet River	NHC (November 22, 2018), Septer (2007)	96 mm of rain fell in Pemberton in 48 hours. Flooding during this event had a slightly lower flow magnitude from the fall 1940 event. The Lillooet River overtopped its banks, washed out the airport access road, landing strip, newly constructed fence and deposited about 150 mm depth of silt over the entire area. Common damage resulted from scouring, bank and dyke erosion, channel changes, wood debris, bedload deposition, landslides and inundation.
1981	October	Watercourse Flood	Pemberton, Birkenhead River	Septer (2007)	High water washed out the Sam Jim Bridge over the Birkenhead River, isolating three families. The December 1980 flood had previously damaged this structure.
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.
1981	December	Watercourse Flood	Whistler, Whistler Creek	Hungr (1993)	Flooding on Whistler Creek remained confined to its regular channel but delivered several thousands of cubic meters of gravelly debris to the fan and caused flooding along Highway 99.
1982		Debris Flow/Debris Flood	Sea to Sky , Furry Creek	Eisbacher (1983)	During an intense rainstorm pulses of blocky-bouldery debris washed out the low highway bridge crossing the creek.
1984	January	Watercourse Flood	Pemberton, Lillooet River	Septer (2007)	Major ice movement occurred on the Lillooet River near Pemberton which resulted in removal of riprap river protection along a strip 1.8 m high and 975 m long.
1984	June	Debris Flow	Squamish River Valley, Avalanche Creek, Turbid Creek	Cruden and Lu (1992)	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	Debris Flow	Mount Meager, Hot Springs Creek	Jakob (1996), Septer (2007)	In October 1984, a large debris flow (estimated volume of 50,000 m^3) descended Hotsprings Creek and destroyed several vehicles parked at the Hotsprings Creek recreation site.
1984	October	Debris Flood/Flood	Whistler, Whistler Creek	Hungr (1993)	Flooding on Whistler Creek remained confined to its regular channel but delivered several thousands of cubic meters of gravelly debris to the fan and caused flooding along Highway 99.
1984	October	Debris Flow	Pemberton, Ryan River	Jordan (1994)	A channel that drains a small, steep basin at the mouth of Ryan River near Pemberton experienced a debris flow event in October 1984 as a result of the heavy rainstorm.
1984	October	Watercourse Flood	Squamish, Cheakamus River, Cheekeye River, Squamish River,	District of Squamish (2014)	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	Pemberton, Lillooet River, Miller Creek, Ryan River	Septer (2007)	Third highest flood on record at the time of the report. The flooding resulted in major damages to the dyking system, rail lines, roads, bridges and other infrastructure. Flood mapping for the area was updated after this event and published in September 1990. Dykes around the village broke in 15 places. The flooding on Lillooet River and its tributaries Ryan River and Miller Creek, forced evacuation of more than 300 people. Some people were trapped overnight on the upper floor of flooded buildings. Ryan River was over its banks carving new channels and spreading out over fields. The Village Council of Pemberton declared Pemberton a disaster area and requested aid from the provincial government. Floodwaters damaged 177 homes and their contents. On the Mount Currie Indian Reserve, the Lillooet River breached the dyke built in 1982 and 60 houses were surrounded by water. The valley's water system was plugged in several places by debris and while the sewage treatment plant was shut down, untreated sewage had flowed into the river.

Year	Month	Type of Hazard	Location	Source	Description of Event
1984	October	Watercourse Flood	Squamish, Squamish River	Hickin and Sichingabula (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.
1984	October	Watercourse Flood	Gold Bridge, Hurley River	Septer (2007)	Heavy rainfalls affected the Gold Bridge area where logs and debris accumulated in the Hurley River. The cost of some minor clean out was estimated at $5,000.
1984	October	Watercourse Flood	Cheakamus River Valley, Whistler, Cheakamus River, Fitzsimmons Creek	RMOW (2016)	Whistler received 127 mm of rain in 3 days causing major flooding. Flood damage in Whistler included: severe erosion of the Cheakamus River approximately 250 m above the municipal sewage treatment facility, resulting in migration of the Cheakamus River channel and loss of about 1 hectare of land. Large logjams completely blocked the Cheakamus River in its canyon section downstream of the treatment facility. In addition, debris flows in Fitzsimmons Creek washed-out two footbridges and minor accumulations of logs and debris were scattered over the reach from the Blackcomb Way Bridge to the Nancy Green Drive Bridge. Creek overflows were reported to have entered the day parking area. Damage was estimated $100,000.
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.
1986	March/April	Landslide	Mount Meager, Lillooet River	Evans (1987)	In March or April 1986, a rock avalanche occurred on the north peak of Mount Meager within the Mount Meager volcanic complex in the Coast Mountains of British Columbia. The rock avalanche travelled over a glacier surface in the upper part of its track. Some of the debris reached Lillooet River, nearly 2000 m below the upper part of the detachment zone, and temporarily blocked it.
1986	October	Debris Flow	Lillooet Lake, Catiline Creek	BGC (2015, January 22)	A debris flow initiated above the fan apex and below the intersection of the two main tributaries. The debris flow travelled down the channel, entraining additional material in the channel. The event affected a home on the fan. The event volume is estimated at 2,700 m^3.
1987	August	Debris Flow	Mount Meager, Boundary Creek	Jakob (1996), Jordan (1994)	A large debris flow descended Boundary Creek in August 1987 which diverted Meager Creek to the other side of its valley, possibly blocking the channel for a short period of time. Largest recorded debris flow during the last 15 years for this creek.
1987	August	Debris Flow	Mount Meager, Canyon Creek	Jordan (1994)	A debris flow in August 1987 occurred on the creek with a magnitude of about 10,000 m^3.
1987	August	Debris Flow	Lillooet Lake, Catiline Creek	BGC (2015, January 22)	A debris flow occurred on Catiline Creek as reported by residents but no written documentation for the event has been identified.
1988	September	Debris Flow	Mount Meager, Boundary Creek	Jordan (1994)	In September 1988, a second debris flow covered part of the Boundary Creek fan. The debris characteristics were like those of the previous event. The deposit volume is estimated at about 5000 m^3, although an unknown additional volume of the debris flowed off the fan into Meager Creek.
1988	September	Debris Flow	Mount Meager, No Good Creek	Jordan (1994)	In the 1987 to 1989 period, several relatively small debris flows occurred, which barely reached the mouth of the channel, and caused about a metre of total aggradation throughout its lowest kilometer. One of these events occurred on the same day as the 1988 event on Boundary Creek. Only about 100 m^3 deposited at the mouth of the channel, but most of the debris probably entered Meager Creek and was carried away
1989	October	Debris Flow	Sea to Sky, Britannia Beach, Britannia Creek	Septer (2007), Bland (1992)	A debris flood was caused on Britannia Creek by an intentional breach of Park Land Dam. The breach resulted in an estimated peak discharge of 255 m^3/s. While significant volumes of sediment were not deposited on the fan, the entire mainstem channel was disturbed, creating favourable conditions for sediment transport during subsequent peak flow events.
1989	November	Debris Flow	Mount Meager, Boundary Creek	Jordan (1994)	A third debris flow occurred in November 1989, with a deposit volume of about 25,000 m^3. This event happened during a rainstorm which caused high discharges which could have washed some debris volume away. The entire fan was covered by deposits, which were about twice as thick on average as those of the 1988 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	October	Debris Flow	Mount Meager, Canyon Creek	Jakob (1996), Jordan (1994), Septer (2007)	Canyon Creek produced a large debris flow in 1990 which destroyed a logging camp near the mouth of the creek. The flow deposited about 20,000 m^3. The one occupant of the camp escaped injury because he was warned by the loud noise of the approaching debris flow.
1990	October	Debris Flow	Mount Meager, No Good Creek	Jordan (1994)	In October 1990, a large debris flow removed all the accumulated material in the channel and deposited at least 10,000 m3 of debris at its mouth, briefly blocking off Meager Creek to a depth of several metres. The total volume of the event must have been considerably larger, since most of the debris was carried downstream by the river.
1990	November	Debris Flow	Mount Meager, Hot Springs Creek	Jordan (1994)	A debris flow occurred in late 1990 or early 1991 and covered about half the area of the 1984 debris flow deposit. The event probably took place during a major rainstorm in November 1990
1990	November	Watercourse Flood	Lillooet,	Septer (2007)	Flooding in the Lillooet area closed the Duffey Lake Road from Pemberton to Lillooet.

Year	Month	Type of Hazard	Location	Source	Description of Event
1990	November	Watercourse Flood	Pemberton, Green River	Septer (2007)	High water on Green River damaged BC Hydro's 500-Kv powerline south of Pemberton. The river took out three transmission towers, one of which had the foundations washed from underneath. When it brought down 990 m of line a second tower buckled and a third was damaged.
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.
1990	November	Watercourse Flood	Whistler , Green Lake, Alta Lake	RMOW (2016)	Over a 4-day period Whistler received approximately 200 mm of rain. The storm was a high-intensity, long-duration rain-on-snow event and exceeded the 25-year records at Whistler. Flooding was reported in several low-lying areas of Whistler. High water level at Alta Lake was 639.25 m; Green Lake 634.74 m. Residents at Alta Lake stated that 1990/1991 were the highest water levels observed in 52 years. Residents at Green Lake stated that 1990/1991 were the highest water levels observed since 1956.
1991	August	Watercourse Flood	Pemberton, Ryan River, Green River, Lilooet River, Lilooet Lake	NHC (November 22, 2018)	During August of 1991, unusually heavy rains affected the Sea to Sky corridor. Lillooet Lake reached its highest level on record and water levels cut off the road leading to Duffey Lake cutting off access to the Village of Lillooet from the west. The Pemberton municipal airport was completely inundated, berms along the Lillooet River were eroded which flooded agricultural land. The dyke on Ryan River was overtopped, to save some of the agricultural land, the Pemberton Meadows road was purposely breached as culverts were inadequately sized for the flood waters. The high waters on Lillooet River backed up Green River. Water levels on Green River were high enough to overflow the bridge's access road. The existing earth berm of the right bank of the creek was breached in three locations.
1991	August	Landslide	Seton Lake, Bridge River, Carpenter Lake	Septer (2007)	Heavy rain caused mudslides, cutting rail and road links to Lillooet. The first slide occurred on the Duffey Lake Road, covering a 50 m stretch of the rail link about 7 km south of Lillooet in a 5 m pile of mud and rubble (Audrey Creek?). Two cars of a freight train were derailed by a second mudslide as the train sat waiting for the first slide to be cleared. Highway 12 between Lillooet and Lytton was closed because of mudslides. On August 21, the Ministry of Transportation and Highways reported the Duffey Lake Road to be in muddy and extremely rough conditions. The rainfall caused BC Hydro to spill the most water over top of the Carpenter Lake dam into the Bridge River since 1972.
1991	August	Debris Flow	Sea to Sky, Britannia Beach, Britannia Creek	Bland (1992), Septer (2007)	Landslides in the upper watershed of Britannia Creek transformed into debris flows that inundated the main community area. About 30 residents within the main alluvial fan area were evacuated as flood waters deposited gravel and debris to an average depth of 1 m over the fan area. A major channel avulsion occurred resulting in damage to sewer and water services. Based on post-event surveys, the total volume of debris deposited on the fan and in the channel was 30,000 m^3, with an unknown volume discharging into Howe Sound.
1991	August	Debris Flow	Seton Portage, Bear Creek	BGC (2017, January 31)	A debris flow occurred that reached the Seton River floodplain during record rainfalls in the region. Debris flow depth at the Harvey Lavigne house situated on the top of the truncated debris flow fan above the Seton River floodplain was recorded as 0.4 to 0.5 m and had a flow width ranging from 10 to 15 m. As the flow arrived on the Seton River floodplain it spread, thinned and filled depression with sand, silt and clay.
1991	August	Watercourse Flood	Lillooet Lake, Lillooet Lake, Lilooet River, Millar Creek, Ryan River	Septer (2007)	Significant flooding of agricultural land occurred when the dyke on Ryan River was overtopped. In addition, damage was caused to bank protection and dykes on Lillooet and Ryan rivers and Miller Creek. Lillooet River caused damage to the Pemberton airport and croplands in the floodplain area. Miller Creek spilled its banks. Agriculture Canada estimated that at least 50% of the valley's potato crop was lost. Emergency response personnel located over 200 people stranded by floodwaters on Lillooet Lake. 40 of those stranded were evacuated to Pemberton.
1991	August	Watercourse Flood	Pemberton, Lillooet River	Septer (2007)	Significant flooding of agricultural land occurred when the dyke on Ryan River was overtopped. In addition, damage was caused to bank protection and dykes on Lillooet and Ryan rivers and Miller Creek. Lillooet River caused damage to the Pemberton airport and croplands in the floodplain area. Miller Creek spilled its banks. Agriculture Canada estimated that at least 50% of the valley's potato crop was lost. Emergency response personnel located over 200 people stranded by floodwaters on Lillooet Lake. 40 of those stranded were evacuated to Pemberton.
1991	August	Debris Flow	Whistler, Fitzsimmons Creek	RMOW (2016), MoE (1995), Ward et al. (1991)	Severe flooding, erosion and debris flows on Fitzsimmons Creek caused major damage to bridges, rail lines and utility services. A major potential landslip was identified along Fitzsimmons Creek above the townsite. The most spectacular changes to the channel bed and floodplain occurred in the canyon reach. During the tail end of the flood, the creek eroded its own deposits, and within eight days the bed level had eroded to an elevation that was 4.5 m lower than the elevation in June 1991. Concerns existed about the stability of a logjam that existed about 100 m upstream of the Blackcomb Mountain pump station intake. The logjam was completely carried away and smothered by new bed material and debris. At the pump station immediately downstream of this reach, the creek bed had risen about 2.5 m during the flood. Within eight days of the flood, it fell to the same level that existed before the flood. Green Lake and Alta Lake both experienced highest water levels in 35 and 52 years respectively.

Year	Month	Type of Hazard	Location	Source	Description of Event
1991	August	Watercourse Flood	Cheakamus River Valley, Cheakamus River, Cheekye River	District of Squamish (2014), MoE (1995), Septer (2007)	Squamish recorded one-day rainfall with 103 mm. High flows in the Squamish, Cheakamus, Cheekeye, Mamquam and Stawamus rivers and in Culliton and Mashiter creeks caused limited flooding and considerable damage to rock riprap bank protection, roads and the water intake of Mashiter Creek. The dyke and revetment on the right bank of Stawamus River in Valleycliffe suffered damage to bank protection at several locations. Damage also occurred at Mamquam River opposite the golf course and at the Squamish River at Judd Slough, Culliton Creek and Cheakamus River. The widespread flooding forced the evacuation of many Upper Cheakamus residents. On the Cheakamus River, damages occurred to the abutments of the Bailey bridge on the road leading to Paradise Valley and the dyke at the upstream end of the North Vancouver Outdoor School was overtopped. The First Nations community of Cheekeye was completely flooded in several feet of water. The dyking for the first nations community was noted to be inadequate as the dyke was not high enough and the water just ran over it. 15 houses on IR 11 were flooded and the access road to Paradise Valley was washed out.
1991	August	Watercourse Flood	Cheakamus River Valley, Culliton Creek	Septer (2007)	The Culliton Creek Highway 99 bridge was almost lost because water was threatening to wash away the bridge.
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 riprapped, and the creek was redirected back to its original course.
1992	January	Watercourse Flood	Cheekamus River Valley, Cheakamus River, Cheekye River	Septer (2007)	Flooding occurred near the confluence of the Cheekeye and Cheakamus rivers. Debris left over from the massive flooding in August 1991 contributed to minor flooding of the Cheakamus. The force of the river spread it out and water was spread over the sides. According to public works assistant superintendent, damage could have been more widespread were it not for the high grade of the Paradise Valley Road, which held back much of the rising water. The build up on the road acted like a dam and allowed the water to bypass the first nations reserve's nearby subdivision and follow an old riverbed instead. As a safety precaution the subdivision was evacuated overnight.
1992	January	Watercourse Flood	Cheekamus River Valley, Cheakamus River, Cheekye River	Septer (2007)	Flooding occurred near the confluence of the Cheekeye and Cheakamus rivers. Debris left over from the massive flooding in August 1991 contributed to minor flooding of the Cheakamus. The force of the river spread it out and water was spread over the sides. According to public works assistant superintendent, damage could have been more widespread were it not for the high grade of the Paradise Valley Road, which held back much of the rising water. The build up on the road acted like a dam and allowed the water to bypass the first nations reserve's nearby subdivision and follow an old riverbed instead. As a safety precaution the subdivision was evacuated overnight.
1992	June	Outburst Flood - Manmade Structure	Sea to Sky, Furry Creek, Furry Creek	Septer (2007)	Tana Development Canada Ltd. successfully dismantled the Furry Creek dam, 2.2 km upstream from Highway 99. The structure was demolished by a blast from 74 charges, which removed 50 m from the dam's length. The Ministry of Environment's dam division had considered the structure susceptible to failure since it was cataloged 24 years prior. But an agreement with Anaconda Exploration of Canada Ltd., previous owners of the site, stipulated that the dam could remain because there was no development downstream. After Tanac purchased the property and began the next phase of its development, the dam was slated for demolition. The structure was holding back an estimated 20,000-30,000 m^3 of sand, gravel and wood debris, 8,000-10,000 m^3 of which was released in a 200 m surge when the dam was demolished. Depending on the amount of rainfall that will flush the material, it would probably take one to three years to make its way downstream. To act as a trench, through which the material was to flow, Tanac had removed 5,000 m^3 of gravel from the front of the Squamish highway bridge. The company would later dredge the trench until all the material worked its way out of the creek.
1992	October	Watercourse Flood	Mount Meager, Meager Creek	Septer (2007)	During high water, a washout on the Meager Creek Road stranded 14 vehicles with 20 people.
1992	October	Watercourse Flood	Pemberton, Ryan River	Septer (2007)	Flooding occurred in Pemberton after Ryan River breached a dyke. The airport and golf course flooded from the Green River side.
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		Debris Flow	Tisdall, No Law Creek	Jakob (1996)	A debris flow in 1993 stalled within several meters of the left bank of Rutherford Creek, indicating that larger and more mobile debris flows are capable of blocking Rutherford Creek.
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^3 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.
1997	May	Watercourse Flood	Lillooet, Seton River, Fraser River	Septer (2007)	The culvert that housed two pumps, part of Lillooet's secondary water system, washed down Seton River. The washout, caused by high water levels in the Fraser River and rain in Seton-Cahoosh headwaters, would cost $50,000 to repair.

Year	Month	Type of Hazard	Location	Source	Description of Event
1997	June	Lake Flood	Seton Lake, Seton River, Seton Lake, Anderson Lake	Septer (2007)	BC Hydro took action on a number of fronts to minimize the impacts of spring freshet's rising waters. On June 5, they opened the taps increasing the flow of the Seton River from a minimal 26 m^3/s to a maximum of 57 m^3/s. As of June 9, Seton Lake was only inches off full at 236.09 m but holding its own (Full pool is at 234.29 m). BC Hydro hoped to cope with the majority of the run-off through the Seton system in order to keep it from spilling into Bridge River. The Downton and Carpenter reservoirs still had a little leeway as the inflows continued to rise. However, as in previous years, the bottleneck occurred at the Seton end, where the canal and generating station cannot handle the volumes of water sometimes presented. When Seton Lake is full pool and Seton River is running at full spate, a spill at Terzaghi Dam becomes the only option.
1998	July	Debris Flow	Mount Meager , Capricorn Creek	Bovis and Jakob (2000)	During a period of high temperatures in upper Capricorn Creek, a large debris flow was triggered due to the failure of volcanic rock in the watershed. The debris flow deposited at the mouth of Capricorn Creek, where it enters Meager Creek, to create a landslide dam. The debris flow was followed by three days of hyperconcentrated flow surges. Within a few days of the formation of the landslide dam, a spillway notch had been cut that prevented catastrophic failure of the landslide dam. The debris flow travelled approximately 5.5 km down the length of Capricorn Creek.
1998	July	Debris Flow	Mount Meager , Meager Creek	Bovis and Jakob (2000)	During a period of high temperatures in upper Capricorn Creek, a large debris flow was triggered due to the failure of volcanic rock in the watershed. The debris flow deposited at the mouth of Capricorn Creek, where it enters Meager Creek, to create a landslide dam. The debris flow was followed by three days of hyperconcentrated flow surges. Within a few days of the formation of the landslide dam, a spillway notch had been cut that prevented catastrophic failure of the landslide dam. The debris flow travelled approximately 5.5 km down the length of Capricorn Creek.
1999	April	Watercourse Flood	Lillooet,	Septer (2007)	In the Lillooet area, heavy rain saturated the road and embankment at km 5 on Mission Mountain Road, causing the road to fail. Restoration cost was $71,000.
1999	May	Debris Flow	Lillooet, Dickey Creek	Septer (2007)	High water and a debris flow caused the washout of two culverts and roadway on Dickey Creek Road No. 40, 5 km west of Lillooet. A very heavy build-up of gravel occurred. The cost to remove a temporary bridge, backfill erosion, restore the creek channel, riprap banks and to replace the structure to new design standard was $350,000.
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.
1999	June	Debris Flow	Lillooet, Spray Creek	Septer (2007)	High water and a debris flow over the Texas Creek Road caused erosion and culvert damage at Spray Creek, McFee and Cat Creek. The costs to replace the culverts, riprap and road surfaces was $17,000, $7,800 and $2,000, respectively.
1999	June	Watercourse Flood	Moha, Hell Creek	Septer (2007)	High water levels in Hell Creek eroded upstream of a culvert on Carpenter Lake Road and filled in the culvert causing $2,500 restoration cost.
1999	June	Watercourse Flood	Carpenter Lake, Hog Creek	Septer (2007)	High water washed out the road surface and shoulders at culverts at km 10 on Marshall Creek Road in the Carpenter Lake area west of Lillooet, causing major erosion damage. Restoration cost was $17,000.
1999	June	Watercourse Flood	Mount Meager, Meager Creek	Septer (2007)	During spring runoff, Meager Creek Road washed out at the 11 km mark, temporarily leaving 40 persons in 18 vehicles stranded at the Forest Service recreation site.
1999	July	Watercourse Flood	Lillooet,	Septer (2007)	High water and debris flowed onto Highway 12 near Lillooet. The cost to restore ditches and basin was $9,000.
2003	October	Watercourse Flood	Squamish, Cheakamus River, Squamish River	District of Squamish (2014), Septer (2007)	Largest flood in 50 years (369 mm in 4 days) caused District evacuations and damaged the BC rail line. Dikes were not overtopped.
2003	October	Watercourse Flood	Tisdall, Rutherford Creek, Cheakamus River	RMOW (2016), Septer (2007)	During a 5-day period from October 16-20, Whistler received over 220 mm of rain. The unusually heavy rain produced record rain-on-snow peak flows. Floodwaters destroyed the Rutherford Creek Bridge, linking Whistler and Pemberton on Highway 99, resulting in the deaths of 5 people. In addition, floodwaters along the Cheakamus River near Cheakamus Canyon took out 200 m of pavement from Highway 99. Whistler was cut-off both to the north and south
2003	October	Lake Flood	Lillooet Lake, Lillooet River	Septer (2007)	A tropical storm combined with a Pacific front melted snow and precipitated up to 300 mm in Whistler area with precipitation levels decreasing through the mountains due to the rain shadow affect. The snow-melt and rain caused Lillooet Lake to raise 5 m, 3.3 m over normal maximum summer levels. Discharge in Lillooet River rose from 60 m3/s to a maximum of 1370 m3/s. This even caused flooding to more than 2 m above bank full stage in parts of the lower 14 km of the Lillooet River valley. The water level on Lillooet River rose 4.8 m and Pemberton was under water. During the flood event, nearly 800 people were forced from their homes in Squamish, Pemberton and Mount Currie.
2004	July	Debris Flow	Lillooet Lake, Catiline Creek	BGC (2015, January 22)	A debris flow initiated in the east tributary of the watershed. Local residents reported an intense rainstorm that likely triggered the event. Debris-flow deposits were observed at the FSR bridge with some debris flowing beneath the bridge to the lake. A small cabin on the left bank close to the FSR bridge had debris at its doorsteps but was not damaged.
2005	January	Watercourse Flood	Pemberton, Pemberton Creek	Septer (2007)	Pemberton Creek threatened to breach its banks as water rose 60 cm in three hours. Several housing complexes with hundreds of residents remained on evacuation notice due to the rising waters of Pemberton Creek.

Year	Month	Type of Hazard	Location	Source	Description of Event
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^3 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.
2007	March	Watercourse Flood	Carpenter Lake, Carpenter Lake	MoTI (2019)	A washout on highway 40, 68 km west of the junction with highway 99, reduced the highway to single lane alternating traffic.
2007	March	Debris Flow	Carpenter Lake, Carpenter Lake	MoTI (2019)	A mudslide on highway 40, 60 km west of the junction with highway 99, closed the highway for a few hours and then single lane alternating for the afternoon before completely re-opening.
2007	March	Watercourse Flood	Sea to Sky, Deeks Creek	MoTI (2019)	Flooding on highway 99, north of Deeks Creek pullout, 18 km north of junction with Marine Drive at Horseshoe Bay, was reported.
2007	April	Watercourse Flood	Carpenter Lake, Carpenter Lake	MoTI (2019)	A washout on highway 40, 53 km east of Gold Bridge, reduced traffic to single lane alternating traffic for 20 days.
2007	June	Watercourse Flood	Pemberton, Lillooet River	MoTI (2019)	Flooding on highway 99, 6 km north of Pemberton, reduced traffic to single lane alternating traffic for 2 days.
2007	July	Watercourse Flood	Pemberton, One Mile Creek	MoTI (2019)	Flooding on highway 99 in Pemberton reduced traffic to single lane alternating traffic for 5 days.
2007	December	Watercourse Flood	Pemberton, One Mile Creek	MoTI (2019)	Flooding on highway 99 at One Mile Creek in Pemberton closed the highway for a day.
2008	January	Watercourse Flood	Cayoosh Creek, Cayoosh Creek	MoTI (2019)	Flooding at Cayoosh Creek Bridge reduced highway 99 to single lane alternating traffic.
2008	March	Watercourse Flood	Carpenter Lake, Bighorn Creek	MoTI (2019)	A wash out on highway 40, 67 km west of junction with highway 99, reduced traffic to single lane alternating traffic for 3 days.
2008	May	Debris Flow	Moha, Bridge River	MoTI (2019)	A mud slide on highway 40, 65 km east of Gold Bridge, closed the highway in both directions for a day.
2008	May	Watercourse Flood	Pemberton, Lillooet River	MoTI (2019)	Flooding on highway 99, 1 km north of Pemberton, reduced traffic to single lane alternating traffic for 3 days.
2008	May	Watercourse Flood	Pemberton, Birkenhead River	MoTI (2019)	Flooding 8 km north of Pemberton on highway 99 reduced traffic to single lane alternating traffic for 5 days.
2008	June	Watercourse Flood	Pemberton, Birkenhead River	MoTI (2019)	Flooding 8.1 km north of Pemberton on highway 99 reduced traffic to single lane alternating traffic for 3 days.
2008	June	Debris Flow	Carpenter Lake, Carpenter Lake	MoTI (2019)	A mud slide on highway 40, 20 km west of Mission Dam, closed the highway for a day.
2008	July	Watercourse Flood	Pemberton, Birkenhead River	MoTI (2019)	Flooding 8 km north of Pemberton on highway 99 reduced traffic to single lane alternating traffic for a day.
2009	November	Watercourse Flood	Pemberton,	MoTI (2019)	Flooding on highway 99, 1 km south of Pemberton, was reported but did not affect traffic.
2009	December	Watercourse Flood	Sea to Sky, Porteau Cove,	MoTI (2019)	Flooding on highway 99, at Porteau Cove Provincial Park, was reported.
2010	August	Debris Flow	Mount Meager, Capricorn Creek	Guthrie et al. (2012)	A large volcanic rock avalanche on Mount Meager on August 6, 2010 transformed into a large debris flow that travelled down Capricorn Creek. Due to the large mass and velocity of the debris flow the deposit caused landslide dams on both Meager Creek and Lillooet River. The runout of the event was approximately 7 km from Mount Meager to the mouth of Capricorn Creek at Lillooet River. Downstream residents in Pemberton were evacuated until the landslide dam breached. Although there were no fatalities in this event the cost was estimated to be in the order of $10M.
2010	September	Debris Flow	Lillooet Lake, Catiline Creek	BGC (2015, January 22)	A debris flow initiated from the east side of the basin. Local high intensity rainfall was likely the trigger for the event. The initial debris-flow lobe remained confined, crossed the FSR and plugged the channel immediately downslope. At this point two smaller lobes avulsed to the north and south, each reaching Lillooet Lake. The debris buried a truck and travelled through the subdivision. The estimated volume is 15,000 to 20,000 m^3.
2011	March	Watercourse Flood	Squamish,	MoTI (2019)	Flooding on highway 99, 1 km south of Alice Lake Road, closed a lane on the highway.
2011	March	Debris Flow	Moha,	MoTI (2019)	A mud slide on highway 40, 42 km west of the junction with highway 99, closed the highway for the morning then reduced traffic to single lane alternating traffic for the afternoon before the debris was cleared.
2011	November	Watercourse Flood	Carpenter Lake, Cedar Creek	MoTI (2019)	A wash out on highway 40, at Cedar Creek, 64 km west of junction highway 99, reduced traffic to single lane alternating traffic for
2011	November	Watercourse Flood	Whistler,	MoTI (2019)	A wash out on highway 99, 10 km north of Whistler, closed a lane of the highway for up to 4 days.
2012	July	Debris Flow	Lillooet,	MoTI (2019)	A mud slide on highway 99, 23 km south of Lillooet. The mudslide reduced the highway to single lane alternating traffic.
2012	July	Debris Flow	Carpenter Lake,	MoTI (2019)	A mud slide on highway 40, 20 km west of Mission Dam, closed the highway for the morning.

Year	Month	Type of Hazard	Location	Source	Description of Event
2012	November	Debris Flow	Squamish River Valley, Turbid Creek	Aldous (2012)	A debris flow on Turbid Creek (known locally as Mud Creek) washed out the Squamish River FSR and stranded two vehicles on the far side of the creek unable to reach Squamish.
2013		Debris Flow	Seton Portage, Bear Creek	BGC (2017, January 31)	A debris-flow ran out across the fan surface but did not flow below the truncated fan surface above the Seton Portage floodplain. In the upper channel, some of the debris avulsed from the channel and was deposited across a wide area among the trees.
2013	May	Watercourse Flood	Pemberton, Birkenhead River	MoTI (2019)	Flooding was reported on highway 99, 11 km north of Pemberton, overnight on May 12th and was clear by the May 13th morning.
2013	August	Debris Flow	Lillooet Lake, Catiline Creek	BGC (2015, January 22)	A debris flow initiated from the east side of the watershed. The debris flow remained confined along the length of the channel to the debris basin immediately upstream of the FSR, filled the basin, deposited 4 to 5 m of debris on the FSR, and then continued down the channel. A large debris lobe was deposited on the south bank, plugging the channel at a footbridge crossing. The flow then avulsed north, overrunning the boat launch and reaching the beach. The north lobe swept over the driveway of an A-frame house, pushed the same pickup that was buried in 2010 into the lake and destroyed a boat rack full of boats. Several buildings along the creek corridor narrowly escaped being struck by debris. The volume is estimated to be 10,000 to 25,000 m3.
2013	September	Debris Flow	Lillooet,	MoTI (2019)	Mudslide on highway 12, 20 km south of junction with highway 99, closed both lanes for a day and required a geotechnical assessment.
2014	June	Watercourse Flood	Squamish River Valley, Turbid Creek	EMBC (June 9, 2014)	Turbid Creek (known locally as Mud Creek[BC1])[BC2] 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.
2014	December	Watercourse Flood	Whistler, Crabapple Creek	RMOW (2016)	194.5 mm of rain in 3 days lead to overland flooding in the Whistler Cay/Tapley's Farm area. On the afternoon of December 10, Crabapple Creek exceeded its bank near the Whistler Golf Course, water from the creek entered the basement of 2 residences. A family of four and two tenants living in the suite were evacuated.
2014	December	Debris Flow	Lillooet Lake,	MoTI (2019)	A mudslide on highway 99, 30 km south of Kane Creek Bridge, closed the highway in both directions.
2015	August	Debris Flow	Birken, Gates Lake, Unnamed Creek	EMBC (August 16, 2015)	On August 15, a major debris flow was triggered in an existing avalanche chute on the north side of Gates Lake. A gate and a boat launch/dock were impacted, and four homes were isolated beyond the debris flow.
2015	September	Debris Flow	Carpenter Lake,	MoTI (2019)	A mud slide on highway 40, 84 km west of the junction with highway 99, closed the highway for the morning.
2015	September	Debris Flow	Birken, Neff Creek	Lau (2017)	A debris flow on Neff Creek, that occurred during an atmospheric weather event in southwestern BC, knocked down powerlines, and buried a highway, railroad and two residences on the fan. Up to 12 m of scour occurred near the fan apex, adding volume to the event. The stream avulsed both east and west of the former channel upstream of the railway bridge.
2015	September	Debris Flow	Seton Portage, Bear Creek	BGC (2017, January 31)	A debris flow occurred during a storm that triggered abundant debris flows in the Pemberton to Seton corridor. The debris flow filled the upstream side of the berm then overtopped the berm, eroding an approximately 5 m wide section on its downslope side.
2015	September	Debris Flow	Lillooet,	MoTI (2019)	Mud slide 15 km south of Lillooet on highway 99 that closed highway for approximately 7 hours then reduced highway to single lane alternating traffic for 1 day.
2015	September	Debris Flow	Carpenter Lake,	MoTI (2019)	A mudslide on highway 40, 1 km west of Mission Dam, closed the highway for an hour.
2015	September	Debris Flow	Carpenter Lake,	MoTI (2019)	A mudslide on highway 40, 84 km west of the junction with highway 99, closed the highway for the day.
2015	September	Debris Flood	Seton Portage, Whitecap Creek	BGC (2018, April 6)	A debris flood and channel avulsion occurred on Whitecap Creek that isolated and damaged an access road, four residences and an office building. The avulsion occurred approximately 250 m upstream of the confluence of Portage River. Debris transported by Whitecap Creek deposited in Portage River resulting in complete blockage for approximately 170 m.
2016	April	Watercourse Flood	Seton Portage, Anderson Lake	SLRD (2016)	Unseasonably high temperatures initiated early freshet melt in the drainages feeding Anderson Lake. Anderson Lake was unusually high throughout the winter of 2015/2016 due to the impacts of a September 2015 debris flow on Seton River. Several large boulders were removed from the mouth of the Seton River at Seton Portage to improve water flow from Anderson Lake. Water levels were monitored, and sandbagging was coordinated to protect properties in Seton Portage at risk of flooding.
2016	July	Debris Flow	Carpenter Lake,	MoTI (2019)	A mud slide on highway 40, 83 km west of the junction with highway 99, closed the highway.
2016	July	Debris Flow	Seton Portage, Bear Creek	BGC (2017, January 31)	A debris flow occurred during a localized storm event in the Seton Portage area. The storm brought a total of 27 mm of rainfall, primarily occurring within a 12-hour window. The approximate volume of the debris that spilled over the berm in this event was 3800 m^3.
2016	November	Watercourse Flood	Pemberton, Lillooet River	NHC (November 22, 2018)	Pemberton Valley experienced a large flood in November 2016 (peak flow of 956 m^3/s at the gauge near Pemberton). While not as large as the 2003 flood, it still caused extensive flooding in unprotected areas of the valley.
2016	November	Debris Flood	Seton Portage, Whitecap Creek	BGC (2018, April 6)	A channel avulsion occurred on Whitecap Creek that damaged an access road and residence, and isolated the Tsal'alh office and campground. The avulsion occurred approximately 250 m upstream of the confluence with Portage River. The deposited material in Portage River blocked about 75% of the river.

Year	Month	Type of Hazard	Location	Source	Description of Event
2017	September	Debris Flow	Pavilion,	MoTI (2019)	Mud slide 30 km north of Lillooet on highway 99. The road was reduced to single lane alternating traffic for two hours.
2017	November	Debris Flow	Carpenter Lake,	MoTI (2019)	A mud slide on highway 40, 83 km west of the junction with highway 99, reduced the highway to single lane alternating traffic.
2018	April	Debris Flow	Lillooet,	MoTI (2019)	A mud slide on highway 99, 15 km north of Lillooet reduced traffic to single lane, alternating.
2018	August	Debris Flow	Carpenter Lake,	MoTI (2019)	A mud slide on highway 40, 70 km west of junction with highway 99, closed the road in both directions.
2019	September	Debris Flow	Squamish River Valley, Turbid Creek	n/a	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.