Large Scale Flood, Steep Creek, and Landslide-Dam Flood Risk Prioritization in British Columbia, Canada

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ABSTRACT
Mountainous areas of southern British Columbia, Canada, are subject to potentially damaging floods, debris flows, debris floods and landslide-dam floods that can result in property damage, loss of life, and the interruption of rail, highway, energy, and resource transportation corridors. Floods and steep creek geohazard events in 2017 and 2018 caused significant damages and loss of life that brought these issues to the forefront of public concern. We are completing flood, steep creek and landslide-dam flood risk prioritization studies for approximately 120,000 km^2 of southern British Columbia, with about 78,000 km^2 completed to date. While most creeks' headwaters are in largely undeveloped terrain, the main valley floodplains and lower reaches of steep creeks flow through areas containing over $30B in buildings and a network of roads, highways and utilities infrastructure. The assessment applied a consistent methodology to characterize geohazards and elements at risk, prioritized areas based on relative risk, and organized large volumes of geospatial data. Thus far, we have prioritized over 6,500 geohazard areas encompassing over 6,000 km^2. We present the study results on an interactive, searchable web application that supports long-term geohazard risk-informed development planning, bylaw enforcement, flood resiliency and emergency response planning.

ABSTRACT
Les régions montagneuses du sud de la Colombie-Britannique, au Canada, sont souvent affectées par des inondations, des laves torrentielles, des coulées hyper-concentrées, et des inondations à la suite de ruptures de barrage de glissements de terrain. Ces phénomènes naturels peuvent engendrer des dommages matériels, faire des victimes, et interrompre le trafic ferroviaire et routier et le transport de marchandises. Les inondations et glissement de terrain de 2017 et 2018 ont fait beaucoup de dégâts et des victimes, ce qui a fait réagir le public. Nous sommes sur le point de terminer des études de graduation du risque d'inondation, de laves torrentielles et de coulées hyper-concentrées sur un territoire d'environ 120,000 km^2 dans le sud de la Colombie-Britannique; 78,000 km^2 ont été étudiés pour le moment. Bien que les parties en amont des cours d'eau se trouvent généralement dans des régions non-développées, les plaines alluviales dans les vallées principales et le cours inférieur des rivières passent au travers de zones où se trouvent des bâtiments, et un réseau routier et ferroviaire représentant plus de 30 milliards de dollars. Notre évaluation s'est basée sur une méthode systématique de caractérisation des aléas et des éléments à risque, de classification en function du risque relatif, et de gestion de grandes quantités de données géospatiales. En tout, nous avons classifié plus de 6,500 aléas couvrant une superficie de plus de 6,000 km^2. Nous présentons les résultats de notre étude sur une application web interactive qui permet de planifier le développement, d'appliquer la loi, et de gérer les situations d'urgence et la prévention en matière d'inondation sur la base du risque à long terme.

1 INTRODUCTION

Mountainous areas of British Columbia (BC) are subject to geohazards resulting in property damage, loss of life, and the interruption of rail, highway, energy, and resource transportation corridors. Among the most frequent are a spectrum of clear-water flood and steep creek (debris floods and debris flows) geohazards. While such geohazards have historically occurred, events over the past five years have resulted in damages that have brought these issues to the forefront of public and political concern.

Representative examples of damaging events from the period 2012-2018 in southern BC include:

- Johnsons Landing debris avalanche and debris flow on July 12, 2012, 70 km northeast of Nelson, BC, which resulted in 4 fatalities.
- Flooding in the City of Grand Forks and neighboring areas of the Regional District of Kootenay-Boundary in May 2018, which resulted in property damages, economic losses, and issuance of evacuation orders to 1,600 homes.
- Debris floods at Sicamous and Hummingbird Creeks in June 2012, 20 km northeast of Salmon Arm, BC, which caused damage to several houses at Swansea Point and Two Mile. The debris flood at Sicamous Creek was the subject of a lawsuit with damages awarded in 2019.
- Flooding in Cache Creek in 2015, 2017, and 2018, which includes the flood-related fatality of the Cache Creek fire chief in 2017.
- Flooding in Cherry Creek south of Kamloops BC in 2017 and 2018.
- Robinson Creek debris flow, near Paradise Point, in May 2017, which led to one fatality and destroyed two houses.
- Debris flows in July and August 2018 that blocked Highways 1 and 97 in more than 40 places between Ashcroft and Clinton, BC. The debris flows were sourced from areas burnt by the 1,920 km^2 Elephant

Hill wildfire in 2017. The debris flows caused one fatality and several houses were affected by debris.

Since 1880, at least nineteen landslides dammed rivers and subsequent flooding events have also been documented within the Canadian Cordillera (Clague & Evans, 1994). Three of those events occurred between 1880 and 1921 on the Thompson River south of Ashcroft, BC, resulting in property damages and 15 fatalities near Spences Bridge in 1905.

Despite the high frequency of damaging geohazard events in BC, province-wide assessment of clear-water flood, steep creek, or landslide-dam flood geohazard risk has not yet been completed. Gaps in the completeness, consistency, and detail of knowledge about geohazards, exposure, vulnerability and risk create challenges for policy, legislation and risk management for local, provincial, and First Nations governments (Abbot and Chapman, 2018).

In this study we systematically characterized clear-water flood and steep creek (i.e., debris flow and debris flood) geohazards and elements at risk across about 120,000 km^2 of southern BC, and prioritized geohazard areas using a risk management framework (Figure 1). About 78,000 km^2 has been assessed to date. Within the 55,000 km^2 Thompson River Watershed we also completed screening level assessment of landslide-dam flood geohazards on major watercourses.

The study results will support implementation and possible updates to plans, policies and bylaws related to land use management, emergency management and flood resiliency planning, and will support decisions to undertake further assessment of higher priority areas.

In this paper we summarize the study approach and recommendations to further improve geohazard risk-informed development planning, bylaw enforcement, flood resiliency and emergency response planning.

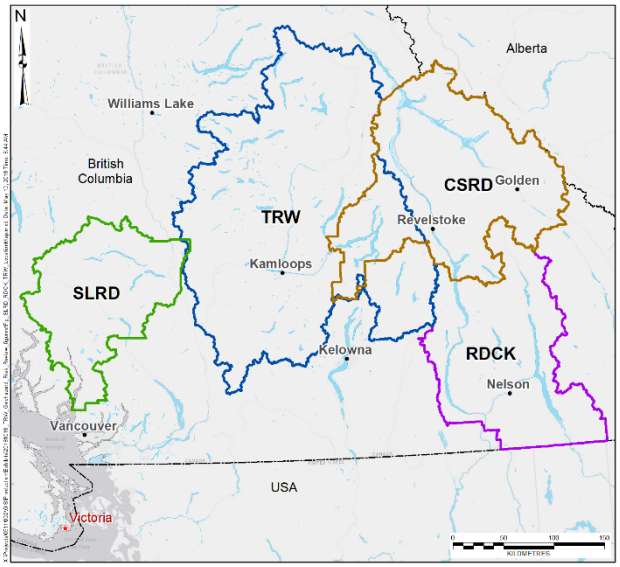

Figure 1. Geohazard risk prioritization study areas, including the Regional District of Central Kootenay (RDCK), Squamish-Lillooet Regional District (SLRD), Thompson River watershed (TRW), and Columbia-Shuswap Regional District (CSRD).

1.1 Study Area

1.1.1 Administration

We assessed developed portions of the Regional District of Central Kootenay (RDCK), and the Districts of North Okanagan, Thompson Nicola, Columbia Shuswap, and Cariboo where they fall within the 55,000 km^2 Thompson River watershed (TRW). Ongoing work also includes the Squamish Lillooet Regional District (SLRD) and the Columbia Basin portion of the Columbia Shuswap Regional District (CSRD). These regions have over $30 billion in building improvements (BC Assessment, 2018) and are traversed by lifelines that include the Trans-Canada Highway, Canadian National and Canadian Pacific Railways, and the Trans Mountain pipeline. The RDCK and CSRD are also part of a trans-national watershed, with flow regulation governed under the Columbia River Treaty.

1.1.2 Physiography

The study regions are diverse, encompassing interior mountain ranges, highlands, a dissected and semi-arid plateau, heavily glaciated mountain ranges, and a coastal fjord at the town of Squamish.

The RDCK is located entirely within the Columbia Mountains physiographic region, which is a highly mountainous area west of the Rocky Mountain Trench (Holland, 1976). Glaciers and high relief mountains are found in the north, while more rounded mountains are found in the south. With the exception of Slocan Lake and River, major water bodies and watercourses – which comprise the Kootenay, Columbia and Duncan Rivers - are regulated by dams and hydroelectric facilities.

Similar to the RDCK, the CSRD is situated within mountainous terrain of the Shuswap Highlands, Columbia Mountains, Rocky Mountain Trench, and Western Continental Ranges (Demarchi, 2011). Glacially sculpted and high relief mountains are common across the district, with the highest relief occurring in the Rocky Mountains of the Continental Ranges. The largest water body is Kinabasket Lake, a regulated reservoir of the Columbia River system.

Physiography of the TRW is predominantly defined by the Thompson-Okanagan Plateau ecoregion, a semi-arid and flat to rolling upland that has been dissected by the North Thompson, South Thompson, Thompson, and Nicola Rivers (Demarchi, 2011). Bordering the plateau are rolling to mountainous highlands and rugged mountain ranges. Many of the mountain valleys contain large lakes, such as Shuswap, Mara, and Adams Lakes. Although the TRW contains over 400 dams on smaller watercourses, flows on major watercourses in the TRW are largely unregulated.

The SLRD is entirely within the rugged Eastern Pacific Ranges (Demarchi, 2011). The area is heavily glaciated and ranges from transitional wet mild coast climate near the City of Squamish to dry cold interior climates in the northeastern part of the District. Most rivers in the SLRD are unregulated, except dammed reservoirs generating hydroelectric power in the Bridge, Seton, and Cheakamus River watersheds.

The rugged topography of all study areas encourages development in areas of flatter topography, especially floodplains and alluvial fans. This provides a key study motivation in that it concentrates development in areas prone to clear-water floods and steep creek geohazards.

1.1.1 Stream Network

We considered streams mapped within River Network Tools™(RNT), a web-based application developed by BGC Engineering Inc. (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, 2016). We supplemented these data with 1:50,000-scale CanVec digital watercourse linework to represent lakes and reservoirs. The publicly available stream network is enhanced by manual review and algorithms within the RNT database to ensure the proper connectivity of the stream segments. Dam locations were represented using the inventory provided by the BC Ministry of Forests, Lands and Natural Resource Operations (MFLNRO, 2017).

2 GEOHAZARD ASSESSMENT

2.1 Geohazard Process Type

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 mapped alluvial fans. The analysis included review of airphoto or satellite imagery, and review of historical records if available.

We also assigned a predicted process type (flood, debris-flood or debris flow) to the entire river network based on a statistical analysis of Melton Ratio (watershed relief divided by the square root of watershed area) and stream length measured upstream of a given stream segment. 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., 2005; Jakob et al., 2015; Holm et al., 2016). Table 1 summarizes watershed characteristics used to differentiate between these processes.

Table 1. 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. Classifying every stream segment 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 is a landslide-inducing processes in a hanging valley near the fan apex. For the prioritized alluvial fans, the interpreted process type was informed by the statistical classification but primarily based on terrain analysis and records of previous events.

2.2 Clear-water Floods

2.2.1 Hazard Identification

Table 2 summarizes the various approaches used to identify and generate clear-water flood hazard areas. The approach selected for each hazard area leveraged existing data and its resolution. We identified hazards located on or adjacent to elements at risk and displayed the resulting geohazard areas on the web application developed for the study. Also shown on the web application were 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. We also inventoried locations of known dams, flood risk reduction infrastructure, and flood conveyance structures but did not assess their role in managing flood risk.

Table 2. Summary of clear-water flood identification approaches.

Approach	Application
Geohazard process type identification	Classification of each watercourse segment as dominantly subject to clear-water floods, debris floods, or debris flows.
Historical floodplain mapping	Identification of floodplain extents from publicly available historical mapping sources and estimates of flood depths across the floodplain.
Floodplain extent prediction for larger lakes and streams	Identification of low-lying adjacent areas using either a topographic elevation offset algorithm or a topographic analysis.
Screening-level hydraulic modelling for select locations	Identification of flood inundation extents and depths based on a digital elevation model and the output from the hydraulic model.
Lake level prediction	Statistical analysis of historical lake level records used to generate flood inundation extents and depths.
Proxy metrics for impounded reservoirs	Identification of potential inundation extents and depths resulting from extreme water levels.

2.2.2 Flood Frequency Analysis

RNT also contains hydrometric data collected from Water Survey of Canada (WSC) stations across Canada. We estimated flood discharge magnitudes and frequencies for a range of Annual Exceedance Probabilities (AEP) for each stream segment in the study area using algorithms based on a flood frequency analysis (FFA) approach.

2.2.3 Hazard Likelihood Estimation

Historical floodplain maps are typically based on the designated flood as represented by the 0.5% AEP event. For consistency, the same event likelihood was used to prioritize clear-water flood sites across the study areas.

2.2.4 Hazard Intensity Estimation

Hazard intensity describes the destructive potential of uncontrolled flows that could impact elements at risk. In a detailed assessment, it would be quantified by parameters such as flow depth and velocity. At a regional scale, these parameters are difficult to estimate because they are site-specific. At sites where estimates were not available based on previous analyses or hydraulic modelling completed for this study, we used proxies for flood depth such as peak discharge. Hazard intensity ratings were assigned to each site and used as input to consequence ratings. We applied hazard intensity ratings as input to a consequence rating, as described in Section 4.3.

2.3 Steep Creeks

2.3.1 Hazard Identification

Table 3 lists the approaches used to identify and rank steep creek geohazards. Together, these factors reflect an estimated likelihood that a geohazard process occurs and reaches areas with elements at risk with a certain level of intensity. We identified cadastral parcels of interest and inventoried and characterized alluvial fans located on or adjacent to these parcels.

Table 3. Summary of steep creek hazard identification and ranking approaches.

Approach	Application
Alluvial fan Inventory	Delineation of prioritized alluvial fans and interpretation of terrain characteristics used to assign geohazard ratings.
Geohazard process type identification	Classification of alluvial fans and streams as dominantly subject to clear-water floods, debris floods, or debris flows.
Hazard likelihood estimation	Screening level identification and estimate of geohazard likelihood for prioritized alluvial fans.
Impact likelihood estimation	Screening level estimate of impact likelihood for all steep creeks and used as basis to assign geohazard ratings to prioritized alluvial fans.
Intensity estimation	Screening level estimate of relative geohazard intensity (destructive potential) of debris flows or debris floods.

2.3.2 Alluvial Fan Inventory

The boundary of alluvial fans represents the steep creek geohazard areas prioritized in this study. We have mapped a total of 1,492 fans in the TRW and RDCK study areas, based on interpretation of available aerial and satellite imagery, lidar digital elevation model (DEM), and a review of previous reports and mapping.

2.3.3 Hazard Likelihood Estimation

We estimated hazard likelihood for each alluvial fan based on terrain interpretation, considering both basin 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 deposits and lobes on the fan, avulsion channels, and the type of vegetation. Basin and fan activity criteria were combined in a matrix to estimate relative hazard likelihood ratings.

2.3.4 Impact Likelihood Estimation

We estimated the relative likelihood that debris flows or debris floods will result in uncontrolled flows on fans, given the occurrence of a geohazard, using two methods: regional scale hazard susceptibility modelling and terrain interpretation. Both approaches were combined in a criteria matrix to assign impact likelihood ratings at a fan level of detail. We note that the actual likelihood of impact given a hazard occurrence will vary across a fan, depending on the location. However, given the large number and diversity of elements at risk, no ratings were assigned for individual elements, as would be completed for a detailed risk assessment.

In the numerical modelling method, we used a semi-automated approach based on the stream network and morphometric statistics to identify debris flow or debris flood hazards, and the Flow-R model developed by Horton et al. (2008, 2013) to model their runout potential. Every channel in the stream network classified as subject to debris flow or debris-flood geohazards was modelled using Flow-R and assigned a relative susceptibility (i.e., relative spatial occurrence) of runout potential (e.g., Figure 2; Sturzenegger et al., 2019). Terrain analyses then focused on identifying lack of channel confinement and evidence of channel avulsion on alluvial fans, where uncontrolled flow outside the active channel is assumed to have higher potential to impact elements at risk.

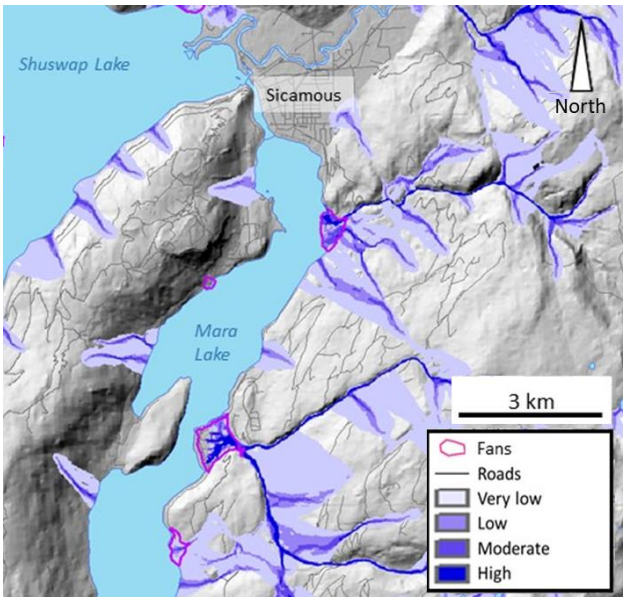

Figure 2. Debris flood hazard source and propagation susceptibility map for a section of the study area, showing the spatial distribution of the four different susceptibility classes.

2.3.5 Hazard Intensity Estimation

Peak discharge for clearwater flood fans was calculated using FFA, as outlined above. Debris flood peak discharge was estimated as twice the peak discharge of a clearwater flood in the same creek to account for sediment bulking and outburst flood effects (Jakob and Jordan, 2001).

In a detailed steep creek analysis, debris flow destructive potential is characterized based on intensity, which is quantified by parameters such as flow depth and velocity. Given that the Flow-R modelling method did not provide these data, debris flow peak discharge was estimated using a regional, statistically based approach. Like clear-water floods and debris floods, debris flows follow a frequency magnitude (F-M) relationship, where larger events with greater volumes and discharge occur more rarely. F-M relationships for debris flows are difficult and time-consuming 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. However, when several reliable F-M curves have been assembled, regional relations can be developed and applied as preliminary assessments to watersheds with limited data.

In this assessment, we used fan area-normalized F-M curves developed by Jakob et al. (2016) from creeks in southwestern British Columbia and Bow Valley, Alberta that have received detailed geohazard investigations. For each prioritized alluvial fan, an approximate event volume was calculated from the fan area and utilized to estimate the peak debris flow discharge using empirical relationships.

2.4 Landslide-dam Floods

A landslide-dam flood 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 downstream release of the impounded water following dam failure. This part of the study was limited to landslide-dam flood hazards along the Thompson River and its main tributaries within the TRW.

2.4.1 Hazard Identification

We considered the following questions when identifying watercourses prone to landslide-dam flood hazards in the TRW: (1) What types of landslides are likely to cause landslide dams?; (2) What sections of TRW watercourses are more likely to be blocked by a landslide dam?; and (3) What are the possible extents for upstream and downstream landslide-dam flooding?

Within the TRW most types and styles of landslide are possible, but not all are likely to create landslide dams. Using guidance from Clague and Evans (1994), who previously studied landslide-dam floods in western Canada, we considered rapid to extremely rapid (Varnes, 1978) landslides having volumes of $5x10^5$ m^3 or larger, and which occur from failures in bedrock slopes and dissected Quaternary valley fills as most likely to form landslide dams. The TRW is characterized by highly variable geologic and topographic conditions. This variability results in additional variability in landslide-dam flood geohazard conditions across the region and along individual watercourses. To identify unique segments of roughly uniform hazard and consequence at a scale appropriate for this study, we split watercourses into 146 shorter segments of relatively uniform conditions relevant to landslide dam formation.

2.4.2 Hazard Likelihood

Geohazard likelihood is the estimated likelihood that landslides occur and result in landslide dams somewhere in the river segment. Landslide dam formation and subsequent outbreak flood potential are complex and highly uncertain processes that integrate multiple factors that may or may not result in landslide-dam related flooding. We address two questions to estimate hazard likelihood at a regional level of detail:

- Within a given stream segment, how likely is it that a potentially dam-forming landslide occurs?
- Given that such a landslide occurs, what is the likelihood that it forms a dam?

We address these questions by assigning ratings for the likelihood that a landslide will happen (a “Landslide Activity Likelihood Rating”) and – if it happens – form a dam capable of causing upstream and downstream flooding (a “Landslide-Dam Formation Likelihood rating”). Landslide activity likelihood corresponds to the historic frequency and average annual probability of landslides at a scale large enough to form a dam. Landslide-dam formation considers the likelihood that a landslide dam will form, and flooding will occur.

2.4.3 Impact Likelihood Estimation

Landslide-dam floods can have far-reaching effects both upstream and downstream from a dam location. Impact likelihood estimates the proportion of a landslide-dam flood area expected to be impacted for a given landslide-dam flood. For downstream flooding, we considered clear-water flood extents 10 km beyond the downstream limit of a river segment. While the downstream limit of flood propagation is highly uncertain and may exceed 10 km, this distance captured sufficient elements at risk to reasonably compare areas from the perspective of hazard exposure.

For upstream flooding caused by impoundment, we considered clear-water flood extents for a distance that was based on an average river gradient and landslide dam height of 10 m at the upstream end of the segment. The 10 m dam height was chosen following review of recorded landslide dam events and is based on the reported estimates of landslide-dam lake depths; thus, they may represent minimum heights. While historic landslide dams have exceeded 10 m, note that the 10 m height is measured at the upstream limit of the watercourse. A higher dam would be required further downstream, to achieve the same limit of upstream flood impoundment.

2.5 Effects of Climate Change

We developed simplified evaluation methodologies based on readily available data at the regional scale to differentiate relative effects of climate change between hazard sites. For clear-water floods, regional, relative differences in hydro-climatic characteristics were used to characterize the relative sensitivity of flood hazard areas to changes in the timing and intensity of freshet floods, in response to region-wide projected declines in snowpack depth due to climate change. For steep creeks, we characterized watersheds as either sediment supply-limited or sediment supply-unlimited pertaining to the availability of readily available sediment for transport by debris flows and debris floods.

3 EXPOSURE ASSESSMENT

We systematically compiled an inventory of elements at risk and developed software to automate their identification in geohazard areas. Table 4 lists the types of elements at risk considered in the study. For each element at risk, we assigned weightings to compare overall hazard exposure between geohazard areas. The ratings were based on stakeholder input with reference to the response goals of the BC Emergency Management System (BCEMS) (Government of BC, 2016). BCEMS goals are ordered by priority as follows:

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

Table 4. Elements at risk.

Element at Risk	Basis for Weightings
People	Census (2016) Population
Buildings	Building Improvement Value
Critical Facilities	Facility types
Businesses	Business presence or total annual revenue
Lifelines	Roads, railways, pipelines, electrical and communication infrastructure; water, sanitary and drainage infrastructure
Environmental values	Presence of active agricultural areas, fisheries, species and ecosystems at risk

4 RISK PRIORITIZATION

4.1 Overview

The prioritization framework used in this study was based on three questions addressing the relative contribution of hazard, exposure, and vulnerability to risk priority:

- What is the relative chance that geohazards will occur and impact areas with elements at risk (hazard)?
- What types and relative value of elements at risk are exposed to hazard (exposure)?
- Given impact, what is the relative potential for damage or loss (vulnerability)?

The combination of exposure and vulnerability represents consequences, and all three components together represent risk. We estimated each component separately and then combined them to form a priority rating for a given site. This three-part approach facilitates risk management planning and policy implementation in that it is relatively simple while still identifying each factor contributing to risk.

The 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. We applied the same approach across the range of assessed geohazard types, where the methods to estimate input values for the risk matrices were specific to each hazard type. Higher ratings generally reflect a higher estimated likelihood that more destructive flows will impact more extensive development. At the same time, the results are aggregate ratings that support, but do not replace, more detailed risk assessment and risk reduction planning.

4.2 Hazard Rating

Table 5 presents the qualitative geohazard rating matrix used in this study. It combines hazard and impact likelihood ratings to rate the potential for geohazard events to occur and – if they occur – to impact elements at risk. The two axes help clarify the source of hazard for later mitigation planning. For example, flood regulation can control hazard likelihood, whereas structural mitigation (i.e., dikes) can control impact likelihood.

Table 5. 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	Mod.	High	Very High

Geohazard 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 6 describes how hazard and impact likelihood were defined for each hazard type. Table 7 lists the frequency and return period ranges used to assign hazard likelihood categories.

Table 6. Definitions of hazard likelihood and impact likelihood for the geohazard types assessed.

Factor	Geohazard Type	Definition
Hazard likelihood	Steep creeks	Likelihood of a steep-creek event large enough to impact elements at risk on an alluvial fan.
	Clear-water floods	0.5% AEP (200-year) flood
Impact likelihood	Steep creeks	Estimated likelihood of an uncontrolled flow reaching elements at risk, given that a steep-creek event occurs.
	Clear-water floods	Assumed impact likelihood of High within the flood extent, given occurrence of the 0.5% AEP (200-year) flood.

Table 7. Annual Exceedance Probability (AEP) ranges and representative categories.

Geohazard Likelihood	AEP Range	AEP	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

4.3 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) (UNISDR, 2015).

The same principles apply to this study, but with some simplification that reflects the level of detail of assessment. We assign consequence ratings that compare the relative, overall potential for loss between hazard areas, given hazard impact with a certain intensity (destructive potential). 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. Specifically, we assign consequence ratings by combining two factors rating the exposure of elements at risk (exposure rating) to destructive flows (vulnerability rating).

4.3.1 Exposure Rating

We used the following steps to assign a hazard exposure rating to each area as a proxy for the relative value of elements exposed to hazard:

1. Identify the presence of elements at risk.
2. Calculate their value and weight according to the categories listed in Table 4.
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 (Table 8).

Table 8. Exposure rating

Hazard Exposure Rating	Criteria
Very High	Greater than 95th percentile
High	Between 80th and 95th percentile
Moderate	Between 60th and 80th percentile
Low	Between 20th and 60th percentile
Very Low	Smaller 20th percentile

4.3.2 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. We 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.

4.3.3 Consequence Rating

Table 9 displays the matrix used to combine hazard exposure and intensity ratings and 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 9. 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	Mod.	High	Very High

4.4 Priority Rating

Table 10 displays the matrix used to prioritize geohazard areas based on the geohazard (Table 5) and consequence (Table 9) ratings.

Table 10. Priority rating

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	Mod.	High	Very High

We note that the geohazard areas prioritized are not all the same areal extent. This means that – all else being equal – larger areas may rank as higher priority because they contain more elements at risk. We 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, jurisdiction/ community continuity, future detailed study funding considerations, and study efficiencies.

5 RESULTS

We provide geohazard area mapping and prioritization on an interactive web application showing the following information:

1. Baseline geohazard, hydrologic and topographic features (e.g., DEM, watershed boundaries, and stream lines).
2. Geohazard exposure information (elements at risk)
3. Prioritized flood and steep creek hazard areas. Clicking on a hazard area reveals geohazard, consequence, and priority ratings, and supporting information.
4. Previous reports, linked for download, where available.

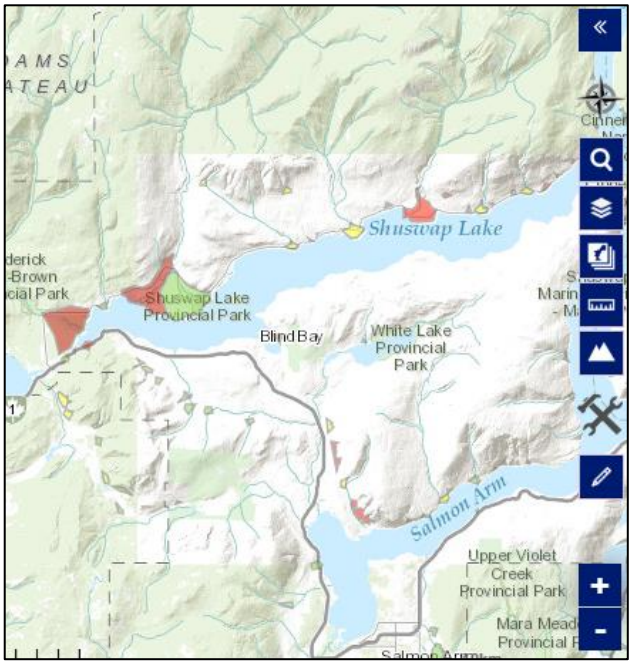

Figure 3. Screen capture of the web application displaying study results, showing prioritized steep creek fans.

Within the RDCK and TRW study areas, we prioritized 6,652 geohazard areas (Table 10) encompassing about 6,500 km^2 (approximately 7%) of the completed study areas in the RDCK and TRW. Table 10 does not include ongoing work in the SLRD or CSRD study areas.

Table 10. Number of prioritized geohazard areas

Geohazard Type	Priority Level					Grand Total
	VH	H	M	L	VL	
Clear-Water Floods		371	623	4,032	0	5,026
Landslide-Dam Floods		23	57	52	14	146
Steep Creeks	10	114	336	744	276	1,480
Grand Total (Count)	10	508	1,016	4,828	290	6,652
Grand Total (%)	0.2	7.6	15.3	72.6	4.4	100

6 CONCLUSIONS

We apply a consistent methodology to characterize geohazards and elements at risk, prioritize areas based on relative risk, and organize large volumes of earth sciences and asset data across about 120,000 km^2 of southern British Columbia, with about 78,000 km^2 assessed to date. We present the study results on an interactive, searchable web application that supports long-term geohazard risk-informed development planning, bylaw enforcement, flood resiliency and emergency response planning.

This study lays a foundation for a potentially province-wide evaluation of geohazard risks that facilitates transparent and fair allocation of limited funding to reduce geohazard risk the highest risk sites. As development pressures and climate change conspire to increase risk to human life and infrastructure, tools supporting provincial or national scale geohazard risk management are increasingly needed to reduce catastrophic loss.

Although the results provide a basis for large area geohazard prioritization, we emphasize there are additional factors for risk management and policy making that were not considered in this study. For example, other factors include the level of risk reduction achieved by existing structural mitigation (dikes), comparison of the risk reduction benefit to the cost of new or upgraded flood risk reduction measures, types of losses not considered (i.e. intangibles), and the level of flood resiliency in different areas.

We identified gaps and opportunities to improve the understanding of geohazards; geohazard exposure (i.e., the built environment); and the characterization of existing flood protection measures. We also identified opportunities to improve geohazard information management and integrate risk-informed decision making into policy. Table 11 summarizes recommendations we put forward for consideration by government agencies. Implementing these recommendations would be greatly facilitated by provincial support to take advantage of efficiencies of scale.

Table 11. Recommendations

Type	Recommendation Summary
Data Gaps	• Resolve data gaps related to baseline topographic, bathymetric and stream network data; geohazard sources, controls, and triggers; geohazard frequency- magnitude relationships, characteristics of flood protection measures and flood conveyance infrastructure, and hazard exposure (elements at risk).
Further Geohazards Assessments	• Complete more detailed assessments for areas identified in this study as top priority.
Geohazards Monitoring	• Add real-time stream flow and precipitation monitoring functions to geohazard web applications, to support emergency monitoring. • Develop criteria for hydroclimatic alert systems informing emergency response. • Develop capacity for the automated delivery of alerts and supporting information informing emergency response.
Policy, Plans, and Bylaw Integration	• Review Development Permit Areas (DPAs) considering the geohazard areas defined in 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. • Develop a maintenance plan to keep study results up to date as part of ongoing support for bylaw enforcement, asset management, and emergency response planning.
Training and Stakeholder Communication	• Provide training to stakeholders who may rely on study results, tools and data services. • Work with communities in the prioritized geohazard areas to develop flood resiliency plans informed by stakeholder engagement.

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