BGC

COLD SPRING CREEK FAN DEBRIS-FLOW

Quantitative Risk Assessment

FINAL
March 12, 2021

BGC Project No.:
1572008

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

EXECUTIVE SUMMARY

Debris-flow hazards result in risks to people and infrastructure located on Cold Spring Creek fan in the Regional District of East Kootenay (RDEK), BC. This work follows a detailed hazard assessment by BGC Engineering Inc. (BGC) (September 25, 2020) and aims to inform proposed mitigation works at and upstream of the Cold Spring Creek fan apex.

This report documents the baseline and mitigated debris-flow risk assessment. It supports risk reduction decision making by estimating life-loss risk from Cold Spring Creek debris flows. Secondary hazards, including flooding and bank erosion, are described but not quantified because loss of life risks associated with these hazards were deemed low in relation to risk tolerance limits for existing development.

The objective of the assessment is to estimate baseline and mitigated debris-flow risk and compare it to individual and group risk tolerance thresholds used by other jurisdictions in BC. Individual risk is an estimate of the annual probability of death due to a debris flow for the individual most at risk in each building. Group risk is an estimate of the potential number of fatalities that could occur in the specified debris-flow scenarios. Individual and group life loss risk were assessed only for occupants in buildings.

This risk assessment is based on geohazard scenarios. These scenarios were developed in the hazard analysis and include representative events that could credibly result in life-loss. The risks contributed by individual geohazard scenarios were summed to obtain estimates of the total risk of life-loss across all debris-flow scenarios.

For debris flows, the scenarios cover a range of return periods from 100 to > 1000 years, each representing events with a certain frequency, volume, and discharge.

A range of return periods and associated debris volumes were modelled numerically using FLO-2D to capture the range of potential debris-flow runout extents and impact intensities. The probability of each debris flow volume class was developed from a previously established frequency-magnitude relationship (BGC, September 25, 2020), and flow mobility probabilities were assigned based on some calibration of known and reconstructed events paired with professional judgement. BGC delineated areas with approximately similar life loss risk structured into levels > 10^{-3} (> 1000 Micromorts), 10^{-3} to 10^{-4} (>100 Micromorts) 10^{-4} to 10^{-5} (>10 Micromorts) and < 10^{-5} (<10 Micromorts). Transitions from one risk zone to another were purposely blurred to avoid the illusion of exactness that cannot be achieved given the uncertainties underlying the analytical methods. New standard buildings constructed within these zones will likely share similar risk values, unless they are constructed well above grade and are protected from debris-flow impact.

Life loss risk was calculated for each geohazard scenario by estimating the probability that the scenario occurs (scenario probability), impacts a building (spatial impact probability) when a person is present (temporal probability), with a destructive intensity resulting in loss of life (vulnerability). The scenario risk estimates were summed to determine the probability of a fatality at each building (individual risk), and the cumulative probability of expected fatalities for all buildings (group risk).

Using the risk tolerance criteria for life-loss referenced by other local governments in British Columbia (e.g., the District of North Vancouver, District of Squamish and Cowichan Valley Regional District) BGC identified that debris-flow individual and group risk are unacceptable for existing development on Cold Spring Creek fan. For the unmitigated base case, 86 parcels within existing development have intolerable individual risk (>1:10,000). Figure E-1 shows the results of the group risk assessment. Assessment of the specific debris-flow scenario results suggests that risk management strategies should focus on reducing risk from debris flows that range in size up to 64,000 to 96,000 m^3 total volume (100 to > 1000 return periods).

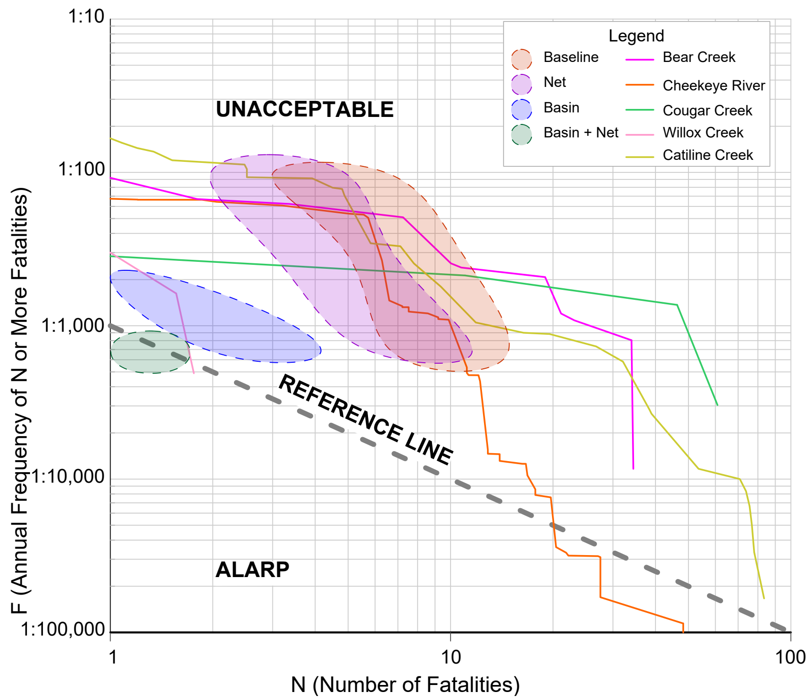

Figure E-1. Results of the group risk assessment for existing and proposed development, compared to group risk tolerance criteria used elsewhere in BC.

BGC also assessed economic losses associated with the different debris-flow scenarios for the unmitigated and mitigated cases. Those losses only pertain to building damage. They do not include building content, business losses and reconstruction costs of infrastructure, all of which would raise the total economic loss potential. Economic losses are summarized in Table E-1.

Both the life loss and economic risk estimates are similar to the highest developments on alluvial fans for which QRAs have been conducted in BC and Alberta. Therefore, a comprehensive debris-flow risk management plan including structural mitigation is warranted on Cold Spring Creek.

Table E-1. Economic losses for the different return periods for existing development and present occupancy. Ranges exemplify possible contents losses. Annualized losses are presented in brackets. All figures are rounded.

Return Period (years)	Expected Range of Economic Loss from Building Impact in Millions			
	Base Case	Debris Net	Debris Basin	Net and Basin
100 to 300	$20 to $30	$17 to $26	-	-
300 to 1000	$23 to $35	$21 to $32	$6 to $9	-
>1000	$29 to $44	$27 to $41	$15 to $23	$11 to $17
	Annualized Losses from Building Impact in Thousands			
100 to 300	$131 to $197	$113 to $170		
300 to 1000	$54 to $81	$48 to $72	$14 to $21	
>1000	$19 to $29	$18 to $27	$10 to $15	$7 to $11

TABLE OF REVISIONS

DATE	REV	REMARKS
March 4, 2021	DRAFT	Draft to McElhanney and RDEK for comment.
March 12, 2021	FINAL	Final incorporating RDEK comments.

LIMITATIONS

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1. INTRODUCTION

1.1. Project Overview

The community of Fairmont Hot Springs in the Regional District of East Kootenay (RDEK), BC is located on two coalescing fans. Alluvial fans are largely formed by catastrophic events in the form of debris floods and debris flows, which are events that exit the confines of the existing channel and deposit debris. Debris, over time, builds up and defines landforms known as alluvial fans.

While debris-floods (a flood with substantial sediment load) lead to economic losses, debris-flows (a fluid form of landslide) result in economic and life loss risks on Cold Spring Creek fan. Debris floods have, over the past 10 years or so, been relatively frequent with one occurring, on average, every 3 years. Debris flows are much rarer on Cold Springs Creek with no recorded event since the Fairmont Hot Springs community was built in the 1970s. A destructive debris flow, which, did not lead to fatalities, occurred on the adjacent Fairmont Creek in the summer of 2012.

Since debris floods do not result in intensities on Cold Spring Creek fan that are likely to threaten human life, they were not included in this risk assessments. Debris-flood hazard was described and quantified by BGC Engineering Inc. (BGC) in their September 2020 hazard report.

The RDEK needs to determine if debris flow risk to residents of Cold Spring Creek fan is tolerable, and if not, how much debris-flow protection is needed to bring risk to tolerable levels. This assessment will aid in that decision. Specifically, it helps to identify what volume of debris ought to be retained to render debris-flow risk tolerable. Given that the RDEK has not developed or legislated levels of tolerable life loss risk, this work evaluates risk by comparison to jurisdictions in Canada who have.

The following mitigation measures are presently being considered pending receipt of funding and integration of the results of this report in the final choice of mitigation measures:

- A debris basin with a capacity of approximately 65,000 m^3 (pending funding)
- A debris net in the lower Cold Spring Creek canyon with a capacity of approximately 10,000 m^3 (funding obtained)
- A combination of debris basin and debris net (funding pending for the debris basin).

In addition, BGC understands that a hydro-meteorological (weather-based) debris-flow warning system is being contemplated by the RDEK. Such a system, once tested and implemented, would warn residents of impending debris floods or debris flows and may be combined with evacuations for specified hazard zones. This may be an interim measure until such time as structural mitigation has been implemented or a permanent measure to manage residual risk.

RDEK retained BGC to carry out a debris-flow risk assessment and mitigation design. BGC's (October 16, 2020) proposal was approved by the RDEK in November 2020.

BGC is carrying out this work under a sub-consultant contract with McElhanney Ltd. (McElhanney) under terms and conditions of the agreement signed by BGC and McElhanney on September 18, 2020.

1.2. Report Objectives and Scope

This report documents BGC's baseline and mitigated debris-flow life loss risk assessment for the Cold Spring Creek fan. The term "baseline" refers to assessment of debris-flow risk, given the current creek conditions with an absence of mitigation. "Mitigated" refers to the risk condition after proposed engineered structures have been constructed. "Consultation Zone" defines the largest credible area that could be affected by Cold Spring Creek debris flows and associated hazards, and refers to the area assessed for debris-flow life loss risk (Drawing 01). "Secondary hazards" are defined as those that occur because of debris flows on Cold Springs Creek. Debris floods were not included in this assessment as they do not pose a credible life loss risk and have not led to significant property damage in the past.

The objectives of the study are:

- To estimate the risk of debris flows and associated hazards resulting in loss of life for persons occupying buildings and to evaluate risk estimates against tolerance thresholds adopted by other jurisdictions in British Columbia (BC) to date (summarized in the Draft Engineers and Geoscientists of BC (EGBC) Guidelines for Landslide Assessment in BC). The RDEK has not yet established life loss risk tolerance thresholds.
- Secondly, economic risks were estimated for the different return period classes and for different mitigation options.

To complete risk assessment and evaluation objectives, BGC completed the following scope:

- Assessment and evaluation of life-loss risks from debris flows. This included estimating the population that could be exposed to each potential geohazard scenario, then estimating life-loss based on the severity of impact that was estimated using numerical modeling of debris flow scenarios.
- Estimate of economic risk considering impacts to buildings and parcels. Parcel values were obtained from BC Assessment. Like for life loss, economic loss was based the severity of impact that was estimated using numerical modeling of debris flow scenarios.

This scope is associated with the following limitations:

- This risk assessment does not consider risk to people outside of buildings.
- The economic risk assessment does not quantify business losses or damage to infrastructure such as roads.
- It does not assess conventional riverine flooding on Columbia River.
- It does not assess other geohazard types on Cold Spring Creek including landslides or debris floods. It does not assess debris flows on Fairmont Creek or other side channels discharging onto Cold Spring Creek fan.
- It does not include rock avalanches in the Cold Spring Creek watershed that may evolve into debris flows or dam Cold Spring Creek.
- Estimated risk is based on current understanding of Cold Spring Creek debris flows, and current conditions on the fan. This assessment may need to be updated following major debris floods and debris flows on the Cold Spring Creek fan, if there is additional development proposed, or total occupancy changes significantly.

- Estimated risk is based on existing development, as of 2020 as shown on Drawing 01.

Table 1-1 shows how the present risk assessment fits into the overall risk management framework. The portions treated in this report are highlighted with a red box.

Table 1-1. Risk management framework.

Risk Management Stage			
Hazard Assessment (steps 1–2); Exposure Assessment (steps 1–3); Risk Analysis (steps 1–4); Risk Assessment (steps 1–5); Risk Management Options Assessment (steps 1–6); Risk Reduction (steps 1–7)	**Risk Communication and Stakeholder Consultation** Informing stakeholders about the impact assessment process	**1. Project Initiation** a. Define objectives b. Define the study area and level of detail c. Define roles of the client, regulator, stakeholders, and Qualified Registered Professional (QRP) d. Identify elements at risk and 'key' consequences to be considered for risk estimation. e. Define basic framework of risk scenarios.	**Monitoring and Review** Ongoing review of risk scenarios and risk management process
		2. Hazard Analysis a. Identify the hazard processes, characterize the hazard in terms of factors such as mechanism, causal factors, and trigger factors; estimate frequency and magnitude; and estimate the extent and intensity of hazard scenarios. b. Define geohazard scenarios. c. Assess if additional work is warranted.	
		3. Exposure Analysis a. Identify and map elements at risk b. Characterize elements at risk with parameters that can be used to estimate potential losses. c. Identify elements at risk exposed to each hazard scenario; and attribute each with the associated hazard intensity.	
		4. Risk Estimation a. Estimate loss for each hazard scenario. b. Generate risk or loss curves and summary statistics.	
		5. Risk Evaluation a. Compare the estimated risk or losses against tolerance criteria b. Prioritize risks for risk control and monitoring	
		6. Options Analysis a. Identify options to reduce risks to levels considered tolerable by the client or governing jurisdiction b. Select option(s) with the greatest risk reduction at least cost c. Estimate residual risk for preferred option(s)	
		7. Risk Reduction Implementation a. Implement chosen risk control options b. Define and document ongoing monitoring and maintenance requirements	

1.3. Project Background

Debris floods on Cold Spring Creek recur approximately every three years and have avulsed from the main channel and impacted portions of the fan area in the past (BGC, September 25, 2020). There has not been a recorded debris flow since development has occurred on Cold Spring Creek fan in the 1970s. Although there are no recorded fatalities from Cold Spring Creek debris floods or debris flows, the hazard posed to development on Cold Spring Creek fan has been recognized and studied in 2015 (Clarke Geoscience and EBA Tetratech) and 2020 (BGC). Frequent small volume debris floods, and clearwater floods largely remain within the Cold Spring Creek channel and are a hazard to adjacent residential and commercial buildings, recreational facilities, roads and culverts. Larger volume debris flows are likely to avulse from Cold Spring Creek channel and will impact substantial portions of the existing development and Highway 93/95, as well as various infrastructure distributed across Cold Spring Creek fan (Drawing 01).

Mitigation measures aim to reduce risk to existing development to levels deemed tolerable by the RDEK, if affordable in terms of construction costs and costs associated with operation and maintenance. Various forms of debris-flow mitigation are conceivable, including a variety of structural protection measures (e.g., barriers, basins, berms), public education, monitoring and evacuation, building-specific protection, and land-use restrictions (e.g., designated floodways). At the present time, a funding application has been made for a large debris basin with outlet structure at a cost of approximately $10 million, a debris net in the lower Cold Spring Creek canyon at a cost of approximately $1.5 million or a combination of both measures. A decision on funding for the debris basin will be made in April of 2021. The RDEK does not have the funds to construct such basin should the funding application be unsuccessful. The purpose of the baseline and mitigated risk assessment is to inform the mitigation design.

2. RISK ASSESSMENT FRAMEWORK

2.1. Introduction

Risk is a measure of the probability and severity of an adverse effect to health, property or the environment, and is estimated by the product of hazard probability (or likelihood) and consequences. By combining both hazard and consequence, risk assessments are a more powerful tool than designing for an arbitrary return period. For example, the efficacy of mitigating against a 500-year return period debris flow with $400,000 worth of assets and two weekend cabins are distinctly different than that of mitigating against an event of the same return period but with $40 million worth of assets and 300 people at risk. In the latter case, a substantially higher standard (i.e., larger, more robust mitigation structure) should apply. By systematically combining frequency (return period) and the respective consequences, risk assessments help to inform selection of an appropriate design event for mitigation structures that can vary based on the potential frequency of hazard and severity of consequence.

This risk assessment was completed at a parcel level of detail and was based on geohazard scenarios, which represent the spectrum of events that could credibly result in life-loss. A geohazard scenario is defined by return period and the type of mitigation considered in the numerical modelling. The risk assessment estimated the likelihood that geohazard scenarios will occur, impact building occupants in the Cold Spring Creek Consultation Zone, and potentially cause loss of life or economic losses.

To estimate life loss risk, it is necessary to understand:

• The frequency and magnitude of debris flows and secondary hazards	→	How often will they occur, and how big will they be?
• The likely impact extents and intensities of the hazards	→	What areas will be affected, and how damaging will the impact be?
• The distribution and characteristics of the exposed elements at risk	→	How many people live or work in the potentially affected development, and how much time do they spend in their homes, on average?
• The vulnerability of the elements at risk	→	If a house is impacted by a debris flow, how likely is it for the occupant to be killed?

This report answers each of these questions.

Once the hazards are identified and the key risk questions have been addressed, risk is calculated for individuals and groups.

Individual risk, also known as annual Probability of Death of an Individual, (PDI), evaluates the chance that a specific person will be killed by the hazard. This metric focuses on the person judged to be most at risk, corresponding to a person spending the greatest proportion of time at home, such as a young child, stay-at-home person, or an elderly person. For this assessment, individual risk is calculated as follows:

$$PDI_j = \sum_{i=1}^{n} P(H)_i P(S|H)_{i,j} P(T|S)_{i,j} V_{i,j} \qquad \text{Equation 2-1}$$

where:

- PDI_j is the PDI at a given parcel (j)
- $P(H)_i$ is the annual probability of a geohazard scenario (i)
- $P(S|H)_{i,j}$ is the spatial probability of impact of geohazard scenario (i) at a given parcel (j)
- $P(T|S)_{i,j}$ is the temporal probability of a person occupying a building at parcel (j)
- $V_{i,j}$ is the probability of fatality (vulnerability) given impact by the estimated hazard intensity[1].

Figure 2-1 is a simplified cartoon that explains the various terms.

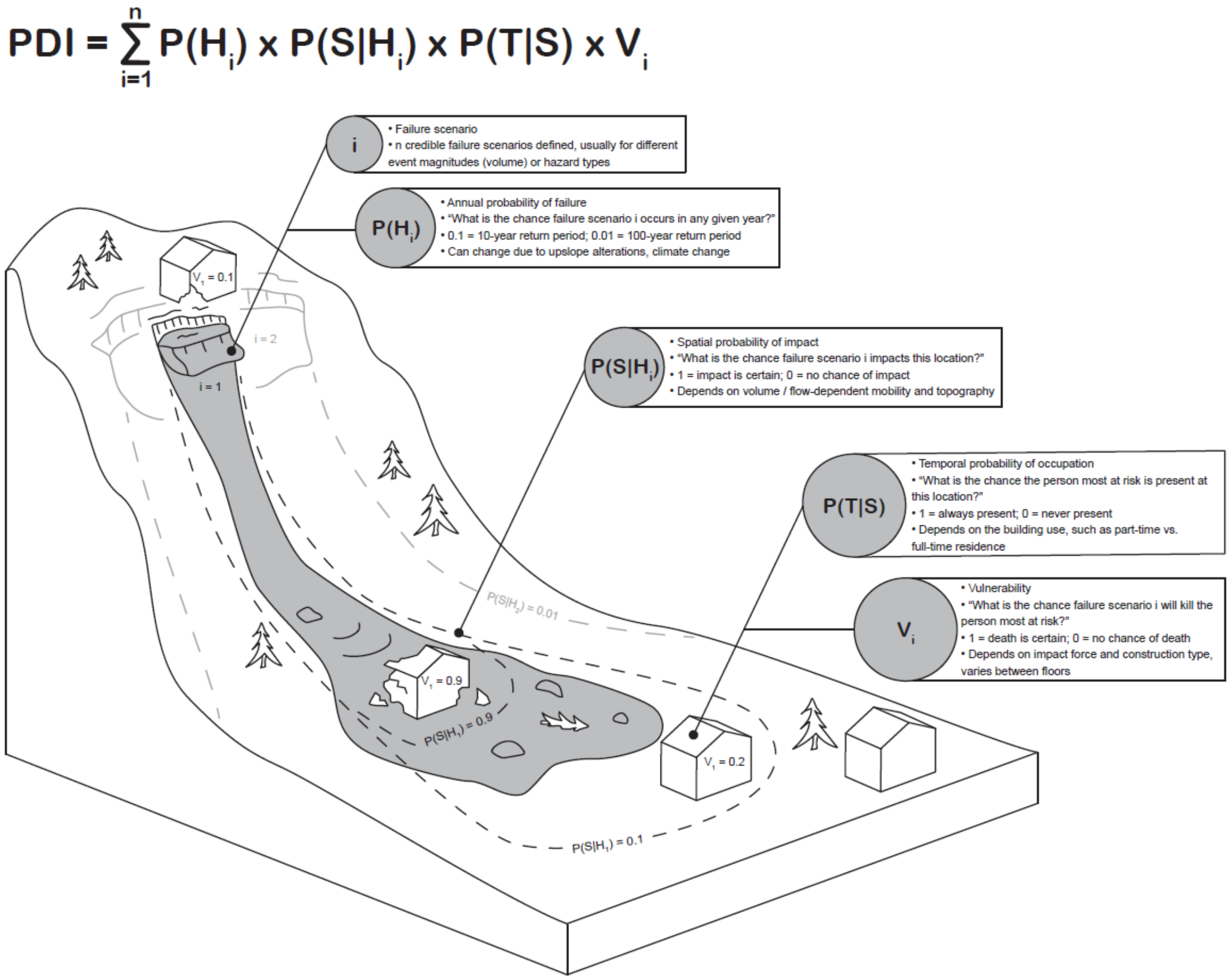


Figure 2-1. Sketch to illustrate the terms of the PDI risk equation. Artwork: BGC.

[1] Intensity refers to the destructive potential of an event (see Section 3.6).

Group risk, also known as societal risk, evaluates the number of people that could be killed by a debris-flow related hazard, considering all people located within the Consultation Zone.

Group risk is derived from f-N pairs where the annual probability of a given geohazard scenario, f_i, corresponds with an estimated number of fatalities, N_i defined as follows:

$$f_i = P(H)_i \qquad \text{Equation 2-2}$$

$$N_i = \sum_{j=1}^{m} P(S|H)_{i,j} P(T|S)_{i,j} V_{i,j} E_j \qquad \text{Equation 2-3}$$

where:

- $P(H)_i$, $P(S|H)_{i,j}$, $P(T|S)_{i,j}$, and $V_{i,j}$ are the same as defined in Equation 2-1; and
- E_j is the number of people exposed to the hazard in parcel (j).[2]

Section 3 provides more detailed descriptions of methods to estimate each variable in Equations 2-1 to 2-3.

2.2. Risk Evaluation

Although risk tolerance thresholds have not been adopted by RDEK to date, individual risk and group risk are compared in this report to thresholds adopted by other Canadian jurisdictions. Risk tolerance thresholds adopted by District of North Vancouver (2018), District of Squamish (2018), Town of Canmore (2016), and Cowichan Valley Regional District (2019) are defined as follows:

- Individual annual risk will be less than 1:10,000 (100 micromorts) for existing development and less than 1:10,000 + ALARP[3] ('As Low As Reasonably Practicable') for new development.
- Group annual risk tolerance will be based on the F-N plot[4]. Estimated societal risk, including risk to existing and proposed development, will fall at least within the ALARP zone.

The application of the term ALARP requires some discussion: To promote increased safety while adopting a relatively high and achievable risk tolerance threshold is to require that risks greater than the acceptable threshold are reduced to ALARP. The common definition of ALARP includes using best practices to manage risk and cost-benefit assessment to demonstrate that the cost of further risk reduction is *grossly disproportionate* to the benefit gained (HSE 2001). For landslide risk at existing development, best practices could include items such landslide hazard mapping, education of residents, development of emergency response and evacuation plans in conjunction

[2] There are 290 parcels within the Consultation Zone (i.e. all parcels affected by any future debris flow on the Cold Spring Creek fan)

[3] The District of North Vancouver uses 1:100,000 (10 Micromorts) risk for new developments.

[4] The horizontal axis represents the number of fatalities (N) and the vertical axis represents the cumulative annual probability of 'N' or more fatalities from all geohazard scenarios considered. Note that a capital *F* is used by convention to signify cumulative frequency; a lowercase *f* is used to indicate the frequency of individual geohazard scenarios.

with debris-flow early warning system, feasible structural mitigation measures, periodic review and change detection, and building-scale protection measures.

For new development, best practices may include avoidance or large-scale structural mitigation measures. Gross disproportion between mitigation costs and risk reduction benefits may be a reasonable requirement for a new development or where one party (who is willing to pay for mitigation) causes or transfers landslide risk to others. More commonly, however, a property owner at risk and the regulatory government have limited resources. In this case the concept of gross disproportion may be unachievable and can be counter-productive (see Strouth and McDougall 2020). In these scenarios, ALARP is achieved if best engineering and geoscience practices are followed and risk is reduced as far as achievable with the available resources.

The F-N plot is useful for evaluating safety and comparing risk to risk tolerance criteria, because it aggregates the scenarios that affect a given area. However, the F-N plot is difficult to understand and interpret, because it does not provide information about the source of the risk. For example, unacceptable risk could result from a single high frequency scenario, or multiple lower frequency scenarios. This is clarified in the text in the results section.

Figure 2-2 shows how the traditional FN curve applied by GEO (1998) has been re-interpreted by BGC as a more effective communication tool.

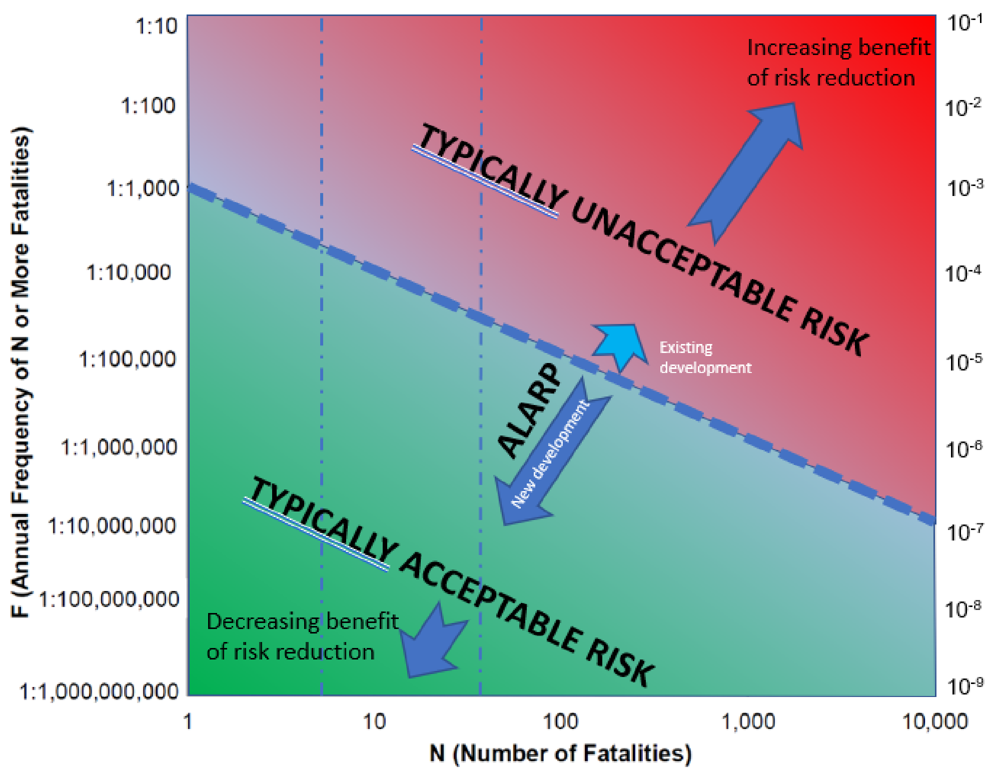


Figure 2-2. FN curve as applied to illustrate results from a group risk assessment. The lower horizontal axis shows the number of expected fatalities given the cumulative life loss risks for all scenarios. The two vertical axes show the frequency of fatalities, expressed in different mathematical notations. The further data plot to the top right corner, the less acceptable the risk and the greater the risk reduction benefit.

Figure 2-3 further clarifies the relationship of Micromorts and the odds per year and to contextualize these thresholds (Strouth and McDougall 2021).

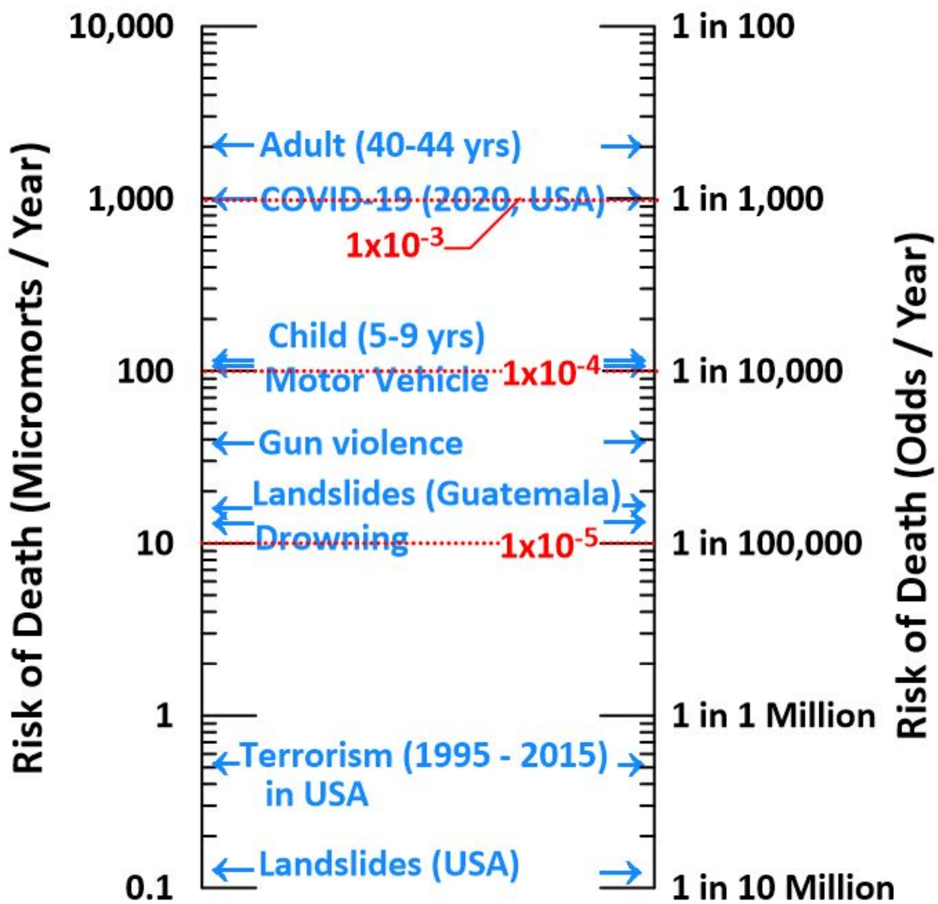


Figure 2-3. Risk of death in micromorts (left) and odds (right) for several populations, causes, and activities, estimated from annual deaths divided by total population in the USA (in 2017), except where Guatemala and COVID-19 are noted (CDC, 2020; Kockanek, Murphy, Xu & Arias, 2019; Sepulveda and Petley, 2015). Dashed red lines ($1x10^{-3}$, $1x10^{-4}$ and$1x10^{-5}$) are common individual life-loss risk tolerance thresholds for landslides.

3. HAZARD AND RISK ASSESSMENT METHODS

3.1. Introduction

This chapter describes the method and assumptions used to assess debris-flow life loss risk, and answers the following key questions:

- Which debris-flow scenarios are considered in the risk assessment?
- How often, on average, will those scenarios occur, and what will be their magnitude?
- How mobile are the flows and which areas will be affected by debris flows?
- What is the probability that a person is within a building in the debris-flow path when the debris flow occurs?
- What is the probability that life-loss occurs given impact to an occupied building?
- How many people could potentially be killed in each debris-flow scenario?
- What are the potential economic losses for variable debris flow magnitudes and mitigation scenarios?

3.2. Hazard Scenarios

Identification of debris-flow scenarios is the starting point for the risk assessment. These scenarios represent credible events that could result in life-loss. The event-set is not intended to represent all possible scenarios that could occur, but instead outlines a range of representative and relevant cases across the range of debris-flow frequencies and magnitudes considered in the assessment. Total risk was estimated by summing the risks associated with each event.

Identifying potential hazard scenarios requires understanding the range of potential event magnitudes which can affect the Cold Spring Creek fan. In this assessment, each scenario is a specific frequency-magnitude combination. Together, the scenarios are a representative sample of the possible range of events.

3.2.1. Frequency-Magnitude Relationship

The Cold Spring Creek frequency-magnitude relationship was established by BGC (BGC, September 25, 2020). It was constructed using an empirical method relating fan area to frequency-magnitude relationships, test pits, radiocarbon dating and dendrogeomorphology.

Hydrogeomorphic events (debris floods and debris flows) were postulated to occur as two distinct populations. The first population includes debris floods triggered by rainfall exceeding a critical shear stress[5] threshold in the channel bed (Church and Jakob, 2020) or in-channel or landslide-triggered mobilization of loose debris until a sediment concentration of approximately 50% or greater by volume is achieved which defines a debris flow, a liquid form of landslide. Figure 3-1shows the reconstructed and interpreted frequency-magnitude relationship for these populations.

[5] Shear stress is the force acting on the channel bed by the flowing water.

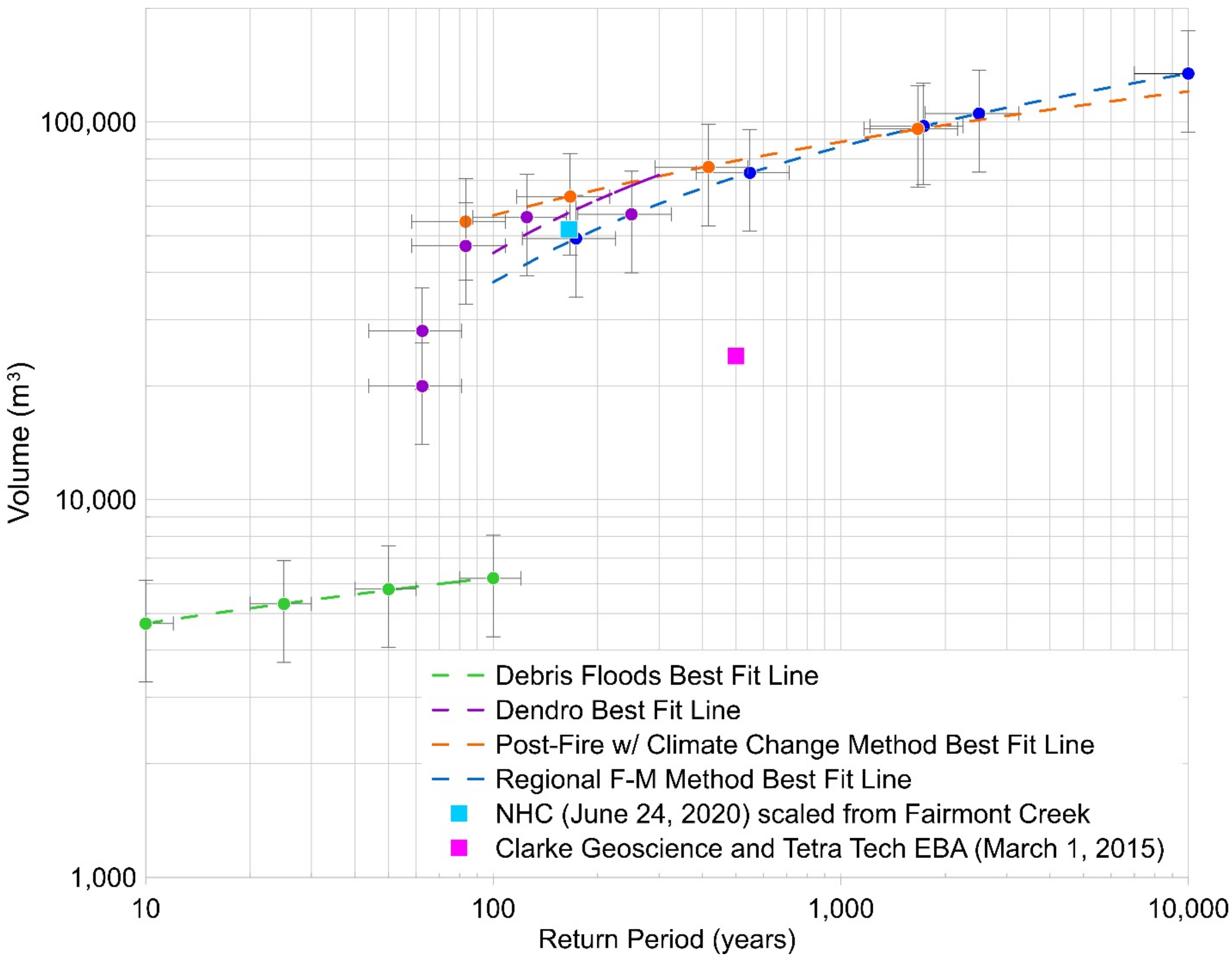


Figure 3-1. The frequency-volume methods considered reasonable for Cold Spring Creek. Best fit lines are trimmed at the 100-year return period as BGC considers debris flows below that return period are unlikely. The figure also shows the Clarke Geoscience and Tetra Tech EBA (March 1, 2015) F-M estimate as well as the recently updated (NHC, June 24, 2020) estimate for Fairmont Creek adjusted by watershed area. Error bars are based on judgement.

Figure 3-1 shows a wide range of hydrogeomorphic events that may occur on Cold Spring Creek. Debris floods are believed to occur only to approximately a return period of 100 years. Storms resulting in greater rainfall or rain-on-snow events are hypothesized to result in debris flows, rather than debris floods. To consider this range of events in a risk assessment, BGC subdivided the frequency-magnitude relationship into representative classes, where each class corresponds to an event magnitude and frequency, as shown in Table 3-1.

Table 3-1. Final frequency-magnitude numbers for debris floods and debris flows on Cold Spring Creek using a model ensemble.

Return Period (years)	Process	Debris Volume Best Estimate (m^3)	Peak Discharge (m^3/s)
3 to 10	Debris Flood	4,400	2.4
10 to 30	Debris Flood	4,800	3.8
30 to 100	Debris Flood	5,200	5.2
100 to 300	Debris Flow	63,500	210
300 to 1000	Debris Flow	76,000	260
>1000	Debris Flow	96,000	320

The frequency-magnitude relationship for Cold Spring Creek has been developed with data that span approximately 5,000 years, which is a period of substantial climatic and sediment supply fluctuations. This implies that some of those fluctuations are integrated in the frequency-magnitude relationship. The impact of future climate change on rock slide and rock avalanche frequency or magnitude is still somewhat speculative and BGC has not attempted to quantify these effects. In terms of mitigation, an adaptive approach can be chosen that allows mitigation upgrades should a significant change in debris flow frequency and magnitude be observed.

3.2.2. Debris-flow Avulsions

Avulsions affect which areas of the debris-flow fan will be impacted by a given event. Avulsions can be caused by obstructions that develop during a debris flow, for example, due to log jams, deposition of coarse boulder lobes and levees, or be caused by super-elevation in channel bends or flow height exceeding the banks. Avulsions were not explicitly addressed as the channel of Cold Spring Creek on the fan is poorly confined with respect to expected debris flow discharges (i.e., the channel does not have the capacity to convey any debris flows). Avulsions from the main channel are expected to occur at or upstream of the fan apex for all return periods, which has been verified by BGC's numerical modelling (BGC, September 25, 2020).

3.2.3. Debris-Flow Mobility

The mobility of a debris flow affects how far the flow will travel and therefore which areas of the fan it will impact. More mobile flows are associated with higher water contents, high fines contents or lower viscosities, so will run farther than lower mobility flows which typically have higher sediment concentrations, a highly frictional bouldery or organic debris front, or lesser fines content. Also, long-duration multiple-surge debris flows run further than a single-surge debris flow with similar grain size distribution. Detailed fan observations did not find indications for highly variable runout behaviour. In absence of observed flows on Cold Spring Creek, BGC calibrated the rheology on the 2012 debris flow on Fairmont Creek who shares similar watershed and geological characteristics.

3.3. Hazard Scenario Probability, P(H)

Hazard scenario probability defines the annual probability that a debris flow will occur on Cold Spring Creek with a certain magnitude and flow-mobility. It addresses the question, "What is the probability that, in any given year, a certain debris-flow will occur and affect the modelled fan sector?". Event probability describes the probability a debris flow of a given magnitude occurs. The event probabilities for each debris-flow scenario are shown in Table 3-2.

Table 3-2. Event probabilities for debris floods and debris flows on Cold Spring Creek.

Return Period (years)	Annual Probability $P(H_i)$	% exceedance probability in 50 years	Process
3 to 10	0.23	~ 100	Debris Flood
10 to 30	0.067	81 to 99	Debris Flood
30 to 100	0.023	39 to 81	Debris Flood
100 to 300	0.0067	15 to 39	Debris Flow
300 to 1000	0.0023	5 to 15	Debris Flow
> 1000	0.00067	> 5	Debris Flow

3.4. Spatial Impact Probability, P(S|H)

Spatial probability of impact considers the hazard extents in relation to the location of elements at risk. It addresses the question, "given that a debris-flood or debris-flow scenario occurs with a certain magnitude and flow-mobility, what is the probability a given building is impacted?". To assess spatial impact probability, each debris-flow scenario was modelled using the flood routing software FLO-2D (FLO-2D, 2017). Parcels impacted by the modelled flow were assigned $P(S|H) = 0.9$ for individual life loss risk calculations and $P(S|H) = 1$ for group risk calculations, and parcels that were not impacted were assigned $P(S|H) = 0$.

BGC selected this approach because it provides an approximation of the scenario impact extent such that total fatalities can be estimated for use in group risk calculations. However, the spatial impact probabilities likely overestimate risk at parcels that are shown to be impacted and underestimate risk at non-impacted parcels, because of uncertainty related to the numerical modelling results. To overcome this issue, an interpreted individual risk map was derived to account for parcel-scale uncertainties.

The following section summarizes details of the numerical modelling, including modelling background and inputs.

3.4.1. FLO-2D Model Background

Cold Spring Creek debris-flow modelling was completed using FLO-2D, a two-dimensional, volume conservation hydrodynamic model. FLO-2D was selected for modelling Cold Spring Creek events because it is suitable for modelling debris flows in that it allows simulation of an equivalent fluid (i.e., one with much higher viscosity than water) (Worni et al., 2012; Caballero and Capra, 2014).

In FLO-2D, flow progression is controlled by topography and flow resistance. The governing equations include the continuity equation and the two-dimensional equation of motion (dynamic wave momentum equation). The two-dimensional representation of the motion equation is defined using a finite difference grid system and is solved by computing average flow velocity across a grid element boundary one direction at a time with eight potential flow directions. Pressure, friction, convection, and local acceleration components in the momentum equation are retained.

FLO-2D uses a quadratic rheological model to control flow behaviour, when the mud flow module is used, such as for modelling debris flows at Cold Spring Creek. Details on model setup can be found in BGC (September 25, 2020).

3.4.2. Intersection with Elements at Risk Information

Spatial impact probability, flow depth, and flow velocity values were assigned to land parcels within the Consultation Zone based on the intersect between parcels and FLO-2D model results. The objective was to relate the debris-flow modelling results to elements at risk information such that debris-flow risk could be estimated. For existing development, risk was estimated at the parcel scale, which is the smallest spatial administrative division available to represent titled lots in RDEK.

As complete and accurate building footprint data were not available, and the Cold Spring Creek fan has a relatively small population, modelled intensities were overlayed with parcel boundaries and intensities were manually interpreted and assigned to each parcel for each scenario to represent intensities impacting a building at each parcel. Parcel data was obtained from BC Land Title and Survey (2018). Building footprint data displayed on Drawings 01 and 02 are publicly available from Microsoft Bing but has not been verified for completeness and accuracy.

3.5. Temporal Probability of Impact, P(T|S)

Temporal probability considers the proportion of time occupants spend within buildings, and address the question, “what is the chance a person is inside a building when a debris flow occurs?”.

BGC assumed that temporal probability varies between parcels depending on the parcel’s primary use. For example, the amount of time occupants spend within a home is likely higher than the amount of time occupants spend in school or at work. Therefore, temporal probability of impact was assigned to parcels based on their main primary use defined by BC Assessment (BC Assessment, 2020), and according to assumptions in Table 3-3.

Table 3-3. Temporal Impact Probability Assumptions

Primary Use Type	Occupation Rate Assumption	Temporal Probability of Impact
Commercial stores, offices, restaurants and other services	Occupied during business hours, assumed at be 40 hours per week on average.	0.25
Residential buildings	Occupied about 50% of the time on average. A more conservative value of 90% is used for estimation of individual risk, corresponding to a person spending the greatest proportion of time at home, such as a young child, stay-at-home person, or an elderly person.	0.5 (group risk) 0.9 (individual risk)

3.6. Vulnerability (V)

Vulnerability is defined as the probability of a fatality given a building is impacted in the hazard scenario. For life loss it addresses the question, “what is the chance of fatality for persons within buildings, given the building is impacted?”.

Table 3-4 shows the criteria used to estimate the vulnerability of persons within buildings to debris-flow impact as an indirect consequence of building damage. These criteria are based on the debris-flow intensity index (Jakob, Stein, & Ulmi, 2011), which describes the severity of the debris-flow impact at any location in the model domain. It is calculated as:

$$\mathrm{I_{DF}} = \mathrm{d} \times \mathrm{v}^2 \qquad \text{Equation 3-1}$$

where d is flow depth (m) and v is flow velocity (m/s). The debris-flow intensity index has also been referred to as momentum flux given the units of m^3/s^2 (Prieto et al., 2018).

Intensity was estimated at each grid cell based on the depth and velocity extracted from FLO-2D model results. Vulnerability was mapped to each parcel intensity using best estimate criteria in Table 3-4.

Table 3-4. Debris-flow vulnerability criteria for persons within buildings. The most frequently occurring intensity class is outlined in orange.

Hazard Intensity Index (m^3/s^2)	Building Damage	Description	Life loss vulnerability (%)		
			Lower Bound	Best Estimate	Upper Bound
≤ 1	Minor	Slow flowing shallow and deep water with little or no debris. High likelihood of water damage, but structural damage is unlikely.	~0	~0	~0
1 to 3	Moderate	Mostly slow flow with minor debris. High likelihood of sedimentation and water damage. Potentially dangerous to people in buildings, or in areas with higher water depths.	0.01	0.02	0.04
3 to 10	Major	Potentially fast flowing but mostly shallow water with debris. Moderate likelihood of building damage and high likelihood of major sediment and/or water damage. Potentially dangerous to people on the first floor or in the basement of buildings without elevated concrete footings	0.05	0.2	0.4
10 to 30	Extensive	Fast flowing water and debris. High likelihood of structural building damage and severe sediment and water damage. Dangerous to people on the first floor or in the basement of buildings.	0.2	0.4	0.6
30 to 100	Severe	Fast flowing debris. High likelihood of severe structural building damage and severe sediment damage. Very dangerous to people in buildings irrespective of floor.	0.4	0.6	0.8
> 100	Complete Destruction	Very fast flowing debris. Very high likelihood of complete building destruction for unreinforced and reinforced buildings, and extreme sediment damage. A person in the building will almost certainly be killed.	0.8	0.9	1

Note: These vulnerability criteria were selected based on expert judgement paired with findings from a global literature review summarized by Jakob et al. 2012. It is also based on comparisons with mortality associated with dam outbreak floods in the United States (Appendix A). Research is ongoing to further improve confidence in vulnerability estimates.

3.7. Exposure Assessment (E)

Exposure is defined as the population within the Consultation Zone that could be impacted in a debris flood or debris flow. BGC did not differentiate between floors or the specific construction types. This includes persons located within areas that a debris flow could travel, such as those located on the first floor of buildings.

Estimating exposure includes first estimating the population-at-risk (PAR), which is defined as the total population within Consultation Zone buildings, then adjusting PAR for the proportion of people who could be within the potential path of a geohazard.

Persons outside buildings within the Consultation Zone are not considered in this assessment, as risk tolerance criteria adopted in other Canadian jurisdictions apply to risk to people within buildings.

3.7.1. Population-at-Risk in Existing Development

PAR in existing development is estimated using the following data sources:

- ParcelMap BC Parcel Fabric, which defines the spatial layout of titled parcels and surveyed provincial Crown land parcels in the district (BC Land Title and Survey, 2018).
- BC Assessment Data for properties in the consultation zone, obtained in December 2020. These data define the primary use of all properties within consultation zone parcels (BC Assessment, 2020).

This study assumes that the population between properties varies depending on its primary use. For example, more people are expected to occupy a multifamily dwelling compared to a single-family home. PAR in existing development is therefore estimated by:

- Assigning population counts to properties based on primary use type according to rules in Table 3-5
- Summing at-risk property populations for each parcel.

Primary use type for each building was assumed to be single family dwelling if BC Assessment information was unavailable. Populations for each building were assigned using the workflow listed above.

Table 3-5. PAR assumptions for parcel primary use in existing development

Primary Use	Occupancy[1]
Residential	2.2
Commercial	3.5

Note:

1. Property occupancy for residential use was determined from 2016 national census data. Property occupancy for commercial use was estimated from average employee counts for businesses across BC of similar description. Occupancy for commercial assumes 1 customer for every 4 staff.

3.8. Group Life-Loss Analysis

A life-loss analysis was carried out to estimate the number of fatalities that could occur in each of the three debris-flow scenarios for the unmitigated base case and the three mitigation options presently being contemplated by the RDEK. This was accomplished by using the interpreted intensities from the individual life loss risk analysis to estimate vulnerability of the population at each parcel. Then the potential fatalities for each parcel was estimated and summed for each debris-flow scenario. The number of fatalities for each parcel was calculated according to Equation 2-3.

3.9. Economic Risks

BGC estimated economic risk due to impacts of debris-flows on the Cold Spring Creek fan using total parcel values that include building and land values from the BC Assessment data (2020).

The same interpreted intensity values from the hazard modelling were used to assess the building vulnerability at each parcel using the criteria shown in Table 3-6. Economic risk was then estimated using Equation 3-1, where the hazard probability ($P(H)$) was the same for each scenario as for life-loss risk, the temporal probability ($P(T|H)$) equals 1 as buildings are always present, and the spatial probability ($P(S|H)$) was estimated as 1 for parcels that were impacted and 0 for non-impacted parcels.

$$Economic\ Risk_j = \sum_{i=1}^{n} P(H)_i P(S|H)_{i,j} P(T|S)_{i,j}\, V_{i,j} E_{,j} \qquad \text{Equation 3-2}$$

The estimate of economic risk in this assessment does not include business losses, damage to building contents or damage to infrastructure such as roads or culverts.

Table 3-6. Debris-flow vulnerability criteria for building damage. The most frequently occurring intensity class is outlined in orange.

Hazard Intensity Index (m^3/s^2)	Building Damage	Description	Building Damage vulnerability (%)
≤ 1	Minor	Slow flowing shallow and deep water with little or no debris. High likelihood of water damage, but structural damage is unlikely.	0.15
1 to 10	Major	Potentially fast flowing but mostly shallow water with debris. Moderate likelihood of building damage and high likelihood of major sediment and/or water damage. Potentially dangerous to people on the first floor or in the basement of buildings without elevated concrete footings	0.5
10 to 100	Severe	Fast flowing debris. High likelihood of severe structural building damage and severe sediment damage. Very dangerous to people in buildings irrespective of floor.	0.8
> 100	Complete Destruction	Very fast flowing debris. Very high likelihood of complete building destruction for unreinforced and reinforced buildings, and extreme sediment damage. A person in the building will almost certainly be killed.	1

Note: These vulnerability criteria were selected based on informed judgement and review of global literature summarized in Jakob, Stein and Ulmi (2012).

4. ASSESSMENT OF SECONDARY RISKS

4.1. Introduction

BGC identified potential secondary hazards that could occur because of a Cold Spring Creek debris flow or debris flood. We differentiate between the base case (unmitigated) and mitigated scenarios.

4.1.1. Base Case

- Interaction with tributary debris flow. During fieldwork in the summer of 2020, BGC identified a secondary fan north of Cold Spring Creek. It drains a minor watershed, but it has a disproportionally large fan, the reason of which is unknown. Should a debris flow occur on this fan, it may interact with that of Cold Spring Creek fan leading to some local deflection. BGC interprets this type of interaction a low probability event. It has not been included in the risk estimates.
- Blocking of culverts on the fan. This is considered almost certain for those culverts affected by debris flows. In BGC's numerical debris-flow model culverts were therefore assumed to be blocked and the results that inform the risk assessment are therefore considered realistic.
- Cold Spring Creek reservoir dam failure. BGC did not attempt to estimate or quantify the possibility of a failure of the Cold Spring Creek reservoir. A dam failure analysis had previously been conducted by Kerr Wood Leidal Associates Ltd. (December 29, 2014). Given that the volume of water released from the reservoir (1,200 m^3) is small relative to the lowest of the three considered debris flow scenarios (65,000 m^3), a reservoir rupture is believed to be indistinguishable from debris-flow impact alone.

4.1.2. Mitigated Case

In the mitigated case, for debris flows fully contained by the proposed debris basin and/or by the debris net for debris floods. However, it is possible that sediment starvation in Cold Spring Creek downstream of the debris net will lead to scour (channel bed erosion) that may destabilize banks where unprotected. Debris starvation would also lead to substantial entrainment downstream of the debris net which may, in the short-term (years to perhaps decades) lead to an increase in sediment recruitment downstream of the net. Over time, the channel downstream of the proposed basin would self-armor due to the differential transport of finer sediments downstream and the coarse ones remaining behind. The issue of scour, compared to direct debris-flow impact, is considered of lesser importance.

5. RISK ASSESSMENT RESULTS

5.1. Numerical Model Results

The numerical model results from the unmitigated base case can be found in BGC (September 25, 2020).

The following qualitative observations can be made from the model results. For the purpose of this summary, we differentiate between the upper and lower fan with the limiting line being Highway 93A/95.

- Impacts to Existing Development on the upper fan – some buildings near the fan apex are projected to be impacted by intensities between 10 and 30 m^3/s^2 at return periods over 100 years[6]. Figure 5-1 A and B provides examples for impact damage expected in this range from Montecito, California. This corresponds to flow depths of up to 4 m in the channel and up to 2 m on much of the upper fan surface. Flow intensities in the channel itself may exceed 30 m^3/s^2 for debris flows. The majority of buildings on the upper fan would be impacted with intensities between 3 and 10 m^3/s^2. At these intensities, there is a significant risk of structural damage and the possibility of building collapse. Notably, most fatalities that occurred in 2018 in Montecito, California occurred at intensities between 3 and 10 m^3/s^2 (Kean et al., 2019). An example of damage associated with this intensity is shown in Figure 5-2. Even if a debris flow does not crush a building, it can ingress through doors or windows and thus injure or kill people inside.

[6] Note that flow velocities have not been confirmed through modeling at Montecito. They were based on comparisons with tsunami fragility curves (Kean pers. comm., March 1, 2021)

Figure 5-1. Damage by the January 9, 2018 debris flow at Montecito, California of homes impacted with an approximate impact index of > 10 m^3/s^2. Flow depth appears to have been approximately 2 to 3 m. Photo: Courtesy Jason Kean, United States Geological Survey.

Figure 5-2. Damage by the January 9, 2018 debris flow at Montecito, California at a home impacted with an approximate impact index of 3 to 10 m^3/s^2. Flow depth appears to have been approximately 1.5 m. Photo: Courtesy Jason Kean, United States Geological Survey

- Impacts to Existing Development on the lower fan – The distribution of flow intensities is strongly dependent on building locations on the lower fan. Modelling suggests that the highest intensities are encountered on the northern lower fan limited to the north and south by glacio-lacustrine terraces (see BGC, September 25, 2020). Intensities ranging between 3 and 10 m^3/s^2 at return periods of 100 to 300-years only occur in narrow (< 15 m) areas where the debris is channelized, most of the remainder of affected areas has intensities of less than 3 m^3/s^2. These would likely result in damage unlikely to lead to building collapse as seen in Figure 5-3, again for Montecito, California. In that particular situation, mud and rocks entering through windows and particularly upstream facing doors could still result in fatalities as people may be pinned against walls.

Figure 5-3. Damage by the January 9 Montecito debris flow, California at a home impacted with an approximate impact index of < 3 m^3/s^2 and a flow depth of approximately 1.2 to 1.5 m. Image: Courtesy Jason Kean, United States Geological Survey.

Intensities change substantially on the lower fan with higher return periods. For return periods greater than approximately 300 years, flows begin to concentrate on the northern side of the fan against the glaciofluvial terraces where intensities can reach up to 30 m^3/s^2 due to this channelization which causes flow depth and velocities to increase.

5.2. Risk Analysis Results

This section summarizes the risk assessment results. As described in Section 2.1, life-loss risk is estimated separately for individuals and groups. The results presented are the combined annual risk from all debris-flow scenarios, given that some parcels may be impacted by more than one scenario. Drawings 01 and 02 present the individual risk results spatially for scenarios 1b and 4b, respectively.

The scenarios shown in Table 5-1 were considered in the risk assessment. For individual risk, only full occupancy scenarios were considered as it is challenging to quantify risk for the present occupancy as it is unknown which buildings have full-time occupants compared to buildings used primarily as vacation properties.

Table 5-1. Debris flow scenarios considered for the quantitative risk assessment.

Scenario	Occupancy[1]	Mitigation
1a	Present Occupancy	Unmitigated
1b	Full Occupancy	Unmitigated
2a	Present Occupancy	Debris Net Only
2b	Full Occupancy	Debris Net Only
3a	Present Occupancy	Debris Basin Only
3b	Full Occupancy	Debris Basin Only
4a	Present Occupancy	Debris Net and Basin
4b	Full Occupancy	Debris Net and Basin

Note:

1. Occupancy considers the proportion of the residents on the Cold Spring Creek fan that reside there year-round, versus parcels that are used as vacation properties. The current proportion of year-round residents is approximately 43% (email from Kara Zandbergen, personal communication, January 5, 2021).

The rational for differentiating between present occupancy and full-time occupancy is the realization that, over time, more and more people (often retirees) may choose to make their vacation home their full-time residency. BGC's analysis does not account for densification, either by adding new homes or replacing single family homes with multi-family buildings.

5.2.1. Individual Risk

Individual risk was estimated for existing development areas on the fan. Table 5-2 summarizes the results for all scenarios.

Table 5-2. Number of buildings exceeding the 10^{-3} and 10^{-4} risk tolerance threshold.

Scenario	Debris Flow Scenario						Total Risk (All Scenarios Combined)	
	100 to 300		300 to 1000		>1000			
Thresholds	$>10^{-3}$	$>10^{-4}$	$>10^{-3}$	$>10^{-4}$	$>10^{-3}$	$>10^{-4}$	$>10^{-3}$	$>10^{-4}$
1b - FO	36	91	0	72	0	84	36	108
2b - FO	22	77	0	38	0	64	22	94
3b - FO	0	0	0	3	0	17	0	18
4b - FO	0	0	0	0	0	10	0	10

The results from the analysis demonstrated that:

- PDI risk values are up to 14 times higher than risk commonly tolerated for existing development in BC (annual risk of death greater than 1 in 10,000 or 10^{-4}; EGBC, 2021).
- For the unmitigated (base case) scenario, the average return period for one loss of life is 22 years. Should all existing homes be occupied full-time, this value would decrease to 10. Note that this is a statistical figure and does not mean that there is a debris flow every 22 years resulting in one fatality. Debris flows on Cold Spring Creek are rare (> 100-year return period) and will likely lead to more than one fatality.

These findings gain further meaning when compared to other locations in British Columbia (BC) and Alberta (AB) where detailed individual risk assessments have been conducted. Some of those are summarized in Table 5-3.

Table 5-3. Summary of individual risk results from some alluvial fans in BC and Alberta.

Fan, Nearest Town	No. of parcels in consultation zone	$>10^{-3}$	10^{-3} to 10^{-4}	% of parcels at > 10^{-4} risk
Cold Spring Creek, Fairmont Hot Springs	170	5	81	51
Cheekeye River, Squamish	~500	6	12	3
Willox Creek, McBride	10	3	2	50
Catiline Creek, Pemberton	180	18	58	42
Bear Creek, Seton Portage	110	11	32	39
Cougar Creek, Canmore	1170	4	184	16

5.2.2. Group Risk

Group risk is an estimate of the probability and number of people killed by debris flow scenarios.

Table 5-4 provides estimated fatalities for each return period scenario. Figure 5-4 shows the so-called FN curve which plots the number of fatalities (N) against the probability of N or more fatalities (F) (see Section 3.8). The graph is separated into two broad zones split by a reference line that has often been used in other jurisdictions to delineate between what is declared as unacceptable and what can be considered tolerable. Risk is considered as “Tolerable” if it can be reduced to ALARP as described in Section 2.2.

Table 5-4 shows that the unmitigated base case may result in as little as 3 fatalities for the 100 to 300-year return period event, and up to 14 for the > 1000-year return period event. These numbers diminish with the degree of mitigation effort. For a net and basin, the numbers reduce to a range of zero to 2. With some mitigation optimization, the expected range of fatalities can be reduced to zero as long as the majority of the debris flow sediment is being contained by the mitigation measures. The fatality figures reported in Table 5-4 are a likely range in fatalities symbolizing the uncertainty inherent in the estimate. Lower or greater numbers are possible but are less likely according to BGC’s analysis. The numbers should primarily be used for comparison and to demonstrate the effects of mitigation.

Table 5-4. Summary of Group Risk Results only for present development occupancy. Estimated ranges are presented in brackets to avoid the illusion of certainty. Ranges are only presented for numbers greater than 1.

Return Period (years)	Expected Range of Fatalities			
	Base Case	Debris Net	Debris Basin	Net and Basin
100 to 300	3-6	2-5	0	0
300 to 1000	5-11	3-6	1	0
>1000	7-14	6-11	2-4	0-2

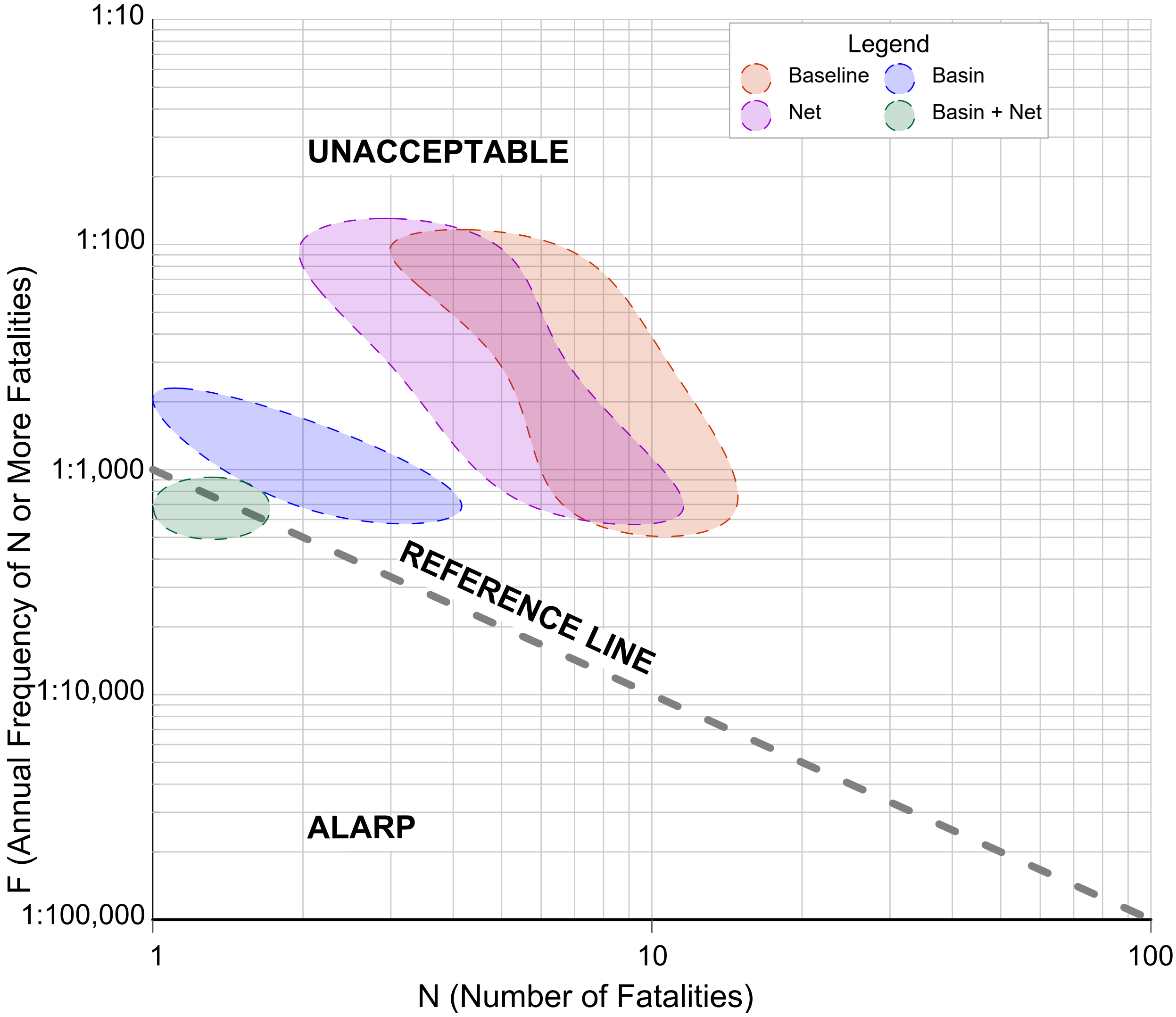


Figure 5-4. Detailed group risk analysis for the four risk scenarios considering present occupancy.

The group risk analysis and especially the interpretation of Figure 5-5 provides the following key results:

- Group risk for existing development in the unmitigated case is well above the reference line separating unacceptable risk from tolerable. This result alone is a strong argument that mitigation on Cold Spring Creek fan is important and justifiable from a life loss risk perspective.

- There is a substantial risk difference between existing occupancy and full occupancy. There appears to be a tendency in BC that historically part-time use rural communities are increasingly occupied by retirees or people who choose to work remotely. Hence it is conceivable that over time, the community of Fairmont Hot Springs will also be mostly full-time residency.
- The construction of a debris flow net will reduce risk, but will not reduce risk to near or below the reference line for either full-time occupancy or part-time occupancy.
- The construction of the debris basin of 65,000 m^3 capacity, presently envisioned by BGC and McElhanney for the RDEK ARDM funding submission, will substantially reduce risk albeit still above the reference line.
- The debris basin in conjunction with the debris net will achieve the greatest risk reduction benefit with only the > 1000-year return period events potentially overtopping the basin resulting in a risk that is close to the reference line.

Similar to individual risk, BGC compared group risk for a number of well-studied fans in other jurisdictions. This is summarized in Figure 5-5. The figure demonstrates that for existing development and accounting for present occupancy, Cold Spring Creek plots as one of the most dangerous (i.e., highest group risk) fans that BGC has studied in BC and Alberta. Highest group risk, in this context, is defined as the maximum orthogonal distance of the plotted curve from the reference line.

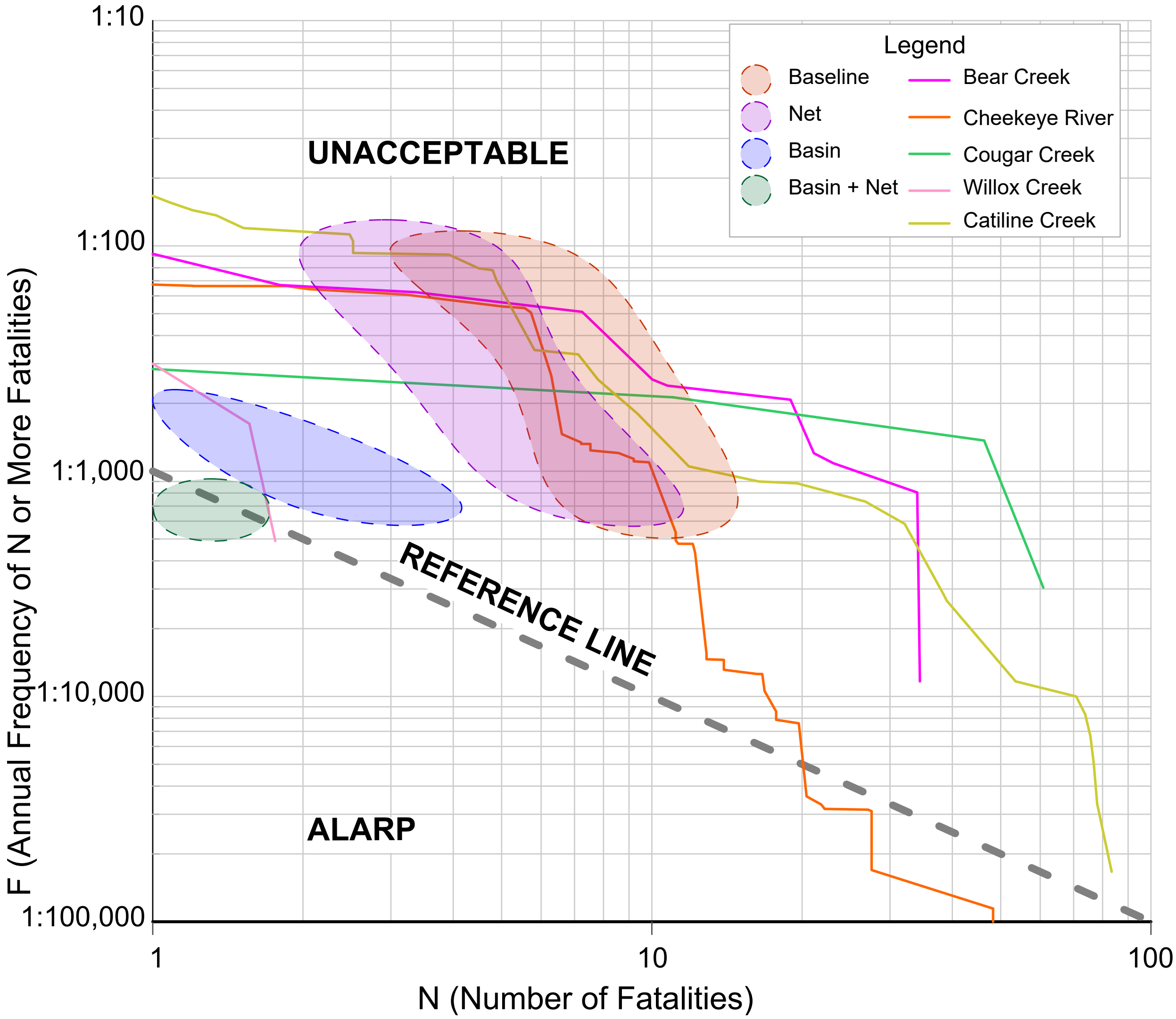


Figure 5-5. Comparison of detailed group risk analysis for Cold Spring Creek with other assessed steep creeks across BC (Cheekeye River, Squamish, Willox Creek, McBride, Catiline Creek, SLRD, Bear Creek, SLRD, Cougar Creek, Canmore, AB).

In summary, Cold Spring Creek fan and its development can be classified as a high-risk location compared to other studies that BGC has conducted in various parts of BC and in the Canmore, Alberta, area. Severe life loss could be expected in case of a debris flow in absence of evacuation.

5.2.3. Economic Risks

Economic risks can be used as another important driver in risk-based decisions. While economic risks are typically more important in situation where life loss risk is low (for example, slow moving landslides or landslides that affect infrastructure without causing harm to people), there is value in examining them. The methods to determine economic risks have been described in Section 3.9. This section provides the results from the analysis. Those losses only pertain to building damage and exclude building content, business losses and reconstruction costs of infrastructure, all of which would raise the total economic loss potential by at least 50%. This is captured by reporting a value range in Table 5-5.

Table 5-5 and Figure 5-6 shows the economic risk for specific hazard scenarios.

Table 5-5. Economic losses for the different return periods for existing development and present occupancy. Note that this does not include calculations of contents which could add as much as 50%. All figures are rounded.

Return Period (years)	Expected Range of Economic Loss from Building Impact in Millions			
	Base Case	Debris Net	Debris Basin	Net and Basin
100 to 300	$20 to $30	$17 to $26	-	-
300 to 1000	$23 to $35	$21 to $32	$6 to $9	-
>1000	$29 to $44	$27 to $41	$15 to $23	$11 to $17
	Annualized Losses from Building Impact in Thousands			
100 to 300	$131 to $197	$113 to $170		
300 to 1000	$54 to $81	$48 to $72	$14 to $21	
>1000	$19 to $29	$18 to $27	$10 to $15	$7 to $11

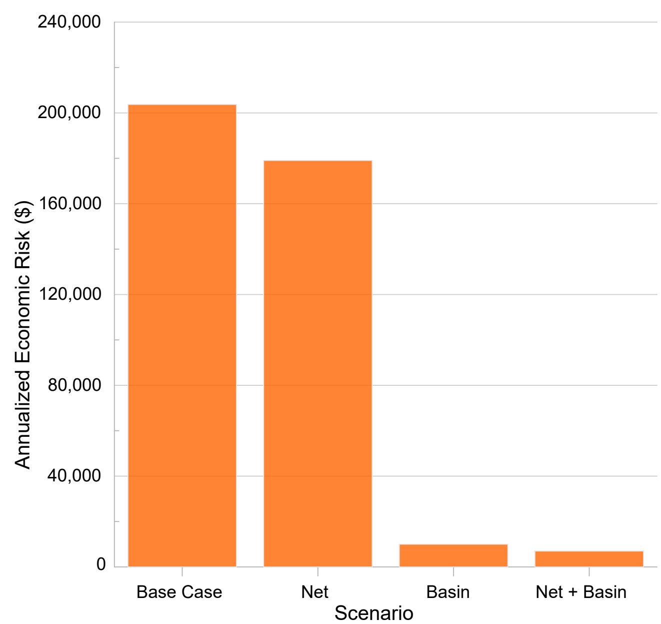


Figure 5-6. Plot comparing estimate of annualized economic risk for the four different scenarios.

Table 5-5 and Figure 5-6 illustrate that economic losses would be greatly reduced for the debris basin and net and basin options (or a larger basin). Table 5-5 also demonstrates that the annualized economic losses are highest for the lowest return period class. This means that even if life loss risk cannot be reduced below levels typically considered as tolerable by mitigating against the largest event, there is still strong economic incentive to reduce risk for at least the 100- to 300-year return period event.

6. DISCUSSION

6.1. Alternative Measures of Risk

Few jurisdictions in BC mandate quantitative risk assessments and have set life safety risk tolerance criteria. The RDEK belongs to a majority of districts and municipalities who do not have such requirements or risk-based policy. Therefore, it is useful to compare the findings of this study with other measures to evaluate risk. One of those is a semi-quantitative approach that has been used widely by the petroleum, chemical and mining industries amongst others. It is called “semi”-quantitative because the actual risk is not associated with numerical values. The event encounter probability and consequences, however, are quantified to some degree.

Similar to the QRA conducted herein, the geohazard semi-quantitative risk assessment (SQRA) involves identification of geohazards and estimation of the likelihood that a geohazard event will occur, impact an element at risk, and cause some magnitude and type of damage or loss. The principal steps in this semi-quantitative risk assessment are:

1. Identification of geohazard scenarios.
2. Estimation of the likelihood that a geohazard scenario will result in some undesirable outcome in the consequence categories of human safety and economics, while others such as social and cultural, intangibles (human suffering), and environmental can be added for completeness.
3. Estimation of these consequences.
4. Combine the likelihood of unwanted outcome and its consequences to arrive at a risk classification ranging from Very Low to Very High.

Risk estimates considered in this report represent the present case (i.e., consider the existing conditions).

6.1.1. Methods

Figure 6-1 shows the risk evaluation matrix used to combine likelihood of unwanted outcome (left hand column) and consequence assessment (lowermost 6 rows) to determine a risk rating for steep creek hazards (coloured centre portion of the matrix). The probability of the undesirable outcome and the severity of the consequence define an intersection point in the matrix that ranks the risk scenario from “Very Low” to “Very High”. The risk ranking of all categories can then be used to prioritize risks for comparison of potential risk reduction measures.

The following text provides an example: A specific debris-flow scenario has a probability of 0.01 (1% annual exceedance probability). It thus falls into the “moderate” or “unlikely” category (given that the 0.01 is at the class boundary). One may wish to choose the “moderate” and “unlikely” likelihood classification as it is at a class boundary. Evaluating the Safety, Economic, Social & Cultural and Intangible consequences, one finds “severe” to “catastrophic” consequences, while the environmental consequences are believed to be low. Combining the “severe” and “catastrophic” consequence rating with the “moderate” or “unlikely” likelihood rating, yield an overall “high” to “very high” risk.

BGC

Flood Risk Evaluation

Risk Evaluation and Response

VH	Very High	Risk is imminent and could happen at any time irrespective of particular triggers; risk reduction ought to be developed and implemented as soon as practical.
H	High	Risk is likely considered unacceptable; long-term risk reduction plan ought to be developed and implemented in a reasonable time frame.
M	Moderate	Risk may be tolerable; more detailed review may be required and risk reduced to As Low As Reasonably Practicable (ALARP) based on available funding.
L	Low	Risk is considered tolerable; continue to monitor
VL	Very Low	Risk is considered broadly acceptable; no further review or risk reduction required

Likelihood Descriptions and Indices

Likelihood of Undesirable Outcome (P_H * $P_{S:H}$)

Description	Probability Range	Chance of occurrence in a lifetime (80 yrs) (%)	1	2	3	4	5	6
Very Likely	>0.9	100	M	H	H	VH	VH	VH
Likely	0.1 to 0.9	100	L	M	H	H	VH	VH
Moderate	0.01 to 0.1	55 to 100	L	L	M	H	H	VH
Unlikely	0.001 to 0.01	8 to 55	VL	L	L	M	H	H
Very Unlikely	0.0001 to 0.001	1 to 8	VL	VL	L	L	M	H

Consequence Descriptions and Indices

Indices	1 Negligible (Very Low)	2 Minor (Low)	3 Moderate	4 Major (High)	5 Severe (Very High)	6 Catastrophic
Safety	Minor public impact	Minor injury	Major injuries	Single fatality	Multiple fatalities (< 10)	Multiple fatalities (>10)
Economic	Negligible; no business interruption; <$1,000	Some asset loss; <$10,000 damages	Serious asset loss; loss of access for one day; <$100,000	Major asset loss and loss of access for one week; <$1M	Severe asset loss; up to 1 month access loss; <$10M	Catastrophic asset loss; >1 month access interruption; >$10M
Social & Cultural	Negligible impact	Slight impact; recoverable within days	Moderate impact, recoverable within weeks	Recoverable within months	Long-term (years) loss of social and cultural values	Complete loss of significant social and cultural values
Intangibles (personal suffering)	Negligible impact	Slight impact; recoverable within days	Moderate impact, recoverable within weeks	Personal hardship usually recoverable within months	Leaves significant personal hardship for years	Irreparable personal hardship
Environmental	Negligible impact	Slight impact; recoverable within days	Moderate impact; recoverable within weeks/months	Major impact; recoverable within months/years	Some species loss; restoration could take years	Irreparable species loss

Figure 6-1. BGC's semi-quantitative risk matrix for geohazard risk assessments.

The risk matrix provided in Figure 6-1 is also known as Multi-Criteria Analysis (MCA). Relative to a cost-benefit analysis (CBA), the main merit of MCA is that it explicitly considers project impacts that are not easily assigned monetary values, and which are often referred to as "intangibles" in CBA. Therefore, MCA can account for social, cultural, and environmental impacts of geohazard risk reduction projects. A drawback of this method is that the consequence ratings for some categories are subjective. The top five rows of Figure 6-1 guide possible responses by the RDEK to each risk level but depend on the District's risk tolerance criteria.

BGC considered the same geohazard scenarios as for the QRA described earlier in this report which inform the left-hand side of Figure 6-1 and the same life loss and economic consequences which inform the bottom five rows of Figure 6-1. The other consequences (intangibles, social-cultural and environmental) were estimated to the best of BGC's knowledge. Environmental risks are probably relatively minor as Cold Spring Creek is only fish-bearing in the lower reaches (downstream of Highway 93/97) to the best of BGC's knowledge.

6.1.2. Risk Evaluation and Response

The end goal of the risk matrix is to quantify the risks as shown in the top five rows in Figure 6-1. These descriptions are assigned to the likelihood of an event occurring and the resulting consequence. Responses start from Very Low (VL) in which risk is acceptable and no further review or risk reduction is required. Very Low risks can therefore be ignored by decision makers. Low (L) risks are generally considered to be tolerable, but if resources become available, it may make sense to reduce those risks further. Moderate (M) risks may be considered tolerable, but a detailed review is considered necessary to ascertain tolerability and, if resources allow, reduce risk to Low. High (H) risk is considered unacceptable and a risk reduction plan should be devised and implemented within approximately five years. Finally, Very High (VH) risk is considered unacceptable in the short term and immediate risk reduction is required with a long-term risk reduction plan. The response categories are suggestions and are not based on legislation but have been widely used by various industries (oil and gas, mining, hazardous waste, chemical).

Table 6-1. SQRA of existing conditions for Cold Spring Creek. The upper non-shaded values relate to the consequence category while the lower values relate to risk.

	Base Case		Debris Net		Debris Basin		Debris Basin & Net	
Probability	**Unlikely (0.01 to 0.001)**	**Very Unlikely (>0.001)**	**Unlikely (0.01 to 0.001)**	**Very Unlikely (>0.001)**	**Unlikely (0.01 to 0.001)**	**Very Unlikely (>0.001)**	**Unlikely (0.01 to 0.001)**	**Very Unlikely (>0.001)**
Consequence	**Risk Rating**							
Safety	Catast.	Catast.	Severe	Catast.	Major	Severe	Moderate	Severe
	High	High	High	High	Moderate	Moderate	Low	Moderate
Economic	Catast.	Catast.	Catast.	Catast.	Severe	Catast.	Moderate	Catast.
	High	High	High	High	High	High	Low	High
Social & Cultural	Severe	Severe	Severe	Severe	Major	Major	Major	Major
	High	Moderate	High	Moderate	Moderate	Low	Moderate	Low
Intangibles	Severe	Severe	Severe	Severe	Severe	Severe	Minor	Severe
	High	Moderate	High	Moderate	High	Moderate	Low	Moderate
Environmental	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
	Low	Low	Low	Low	Low	Low	Low	Low

The semi-quantitative risk assessment demonstrates that, overall, economic risks rank the highest, followed by intangibles, safety and social/cultural, which are closely related. It also demonstrates that the benefits of a debris net are negligible compared to the debris basin or a combination of debris basin and net. The reason for this is, unlike for the QRA, the life loss categories are in orders of magnitude and there is no difference in risk evaluation between 2 and 10 people.

The semi-quantitative risk assessment therefore supports the results of the QRA (Section 5) for both life loss and economic loss consequences.

6.2. Mitigation Implications

The QRA shows that the overall debris-flow risk is unacceptable for existing development. Lowering group risk to a tolerable level (i.e., below the reference line in Figure 5-4) requires mitigating against the > 1000-year return period scenario because it plots above the reference line. For PDI risks 10 houses exceed the risk value of 10^{-4} with the debris net and basin for the > 1000-year return period debris flow (Drawing 02). This indicates that, while the combined basin and net mitigation provides substantial overall risk reduction, additional measures may be warranted. These could be specific to houses that are still exceeding the risk value of 10^{-4},debris basin optimization to increase debris storage capacity, or a real-time warning system in connection with emergency management plans.

This finding suggests that risk management strategies should ideally aim to retain most of the > 1000-year return period debris flow, i.e. up to 96,000 m^3 total volume. “Most”, because some overflow could be tolerated as it would not result in intolerable life loss potential and could be managed through additional downstream measures such as berms and ditches. The recommended design event for the mitigation system is informed by this analysis but ultimately depends on the available funds for mitigation and successful design optimization.

6.3. Uncertainty

Parameters in the risk equation are subject to various uncertainties. This section discusses the influence of these uncertainties on the BGC risk assessment results.

6.3.1. Hazard Scenarios

The hazard scenarios used herein are associated with uncertainty that relate to debris-flow probability and the flow mobility probability, with the former being likely the more pertinent one. A doubling in return period for the highest frequency event will half the risk. Event probability has been deciphered using a model ensemble (BGC, September 25, 2020). Further refinements could only be achieved by a more rigorous test trenching program. This, however, is hampered by budgetary constraints and challenges with trenching in a developed community. Given that BGC has relied in their analysis on several lines of evidence, there is reasonable confidence that the frequency-magnitude relationship is adequate to inform mitigation design.

Flow mobility could be further refined by assuming more viscous (low-mobility) and less viscous (high mobility) flows. In a risk framework this would require assigning a probability of either flow mobility occurring, for which there is no basis. Therefore, BGC (September 25, 2020) chose a single mobility that appears to reflect field evidence (i.e., simulates the distribution of debris flow sediments on the fan) and was calibrated using the 2012 debris flow event on Fairmont Creek.

BGC also chose to not integrate avulsion scenarios in their analysis because the channel is poorly defined and of much lower capacity than the peak discharge associated with debris flows. This means that avulsions will occur upstream of the fan apex and the developed portions. This implies that specific avulsion scenarios are unimportant compared to cases where a deep channel feeds through a fan as is the case for portions of the Fairmont Creek fan complex.

Secondary effects of debris flows are possible that have not been analysed specifically. For example, it is conceivable that during a debris flow that reaches the lower fan east of Oglivey Ave. and north of Wills Road, the debris flow may undercut the glaciolacustrine terraces and create slumps that may, in some cases affect homes. Similarly, neither the numerical modelling nor this risk assessment accounts for floods, debris floods or possibly debris flows discharging from a usually dry gully at the north end of Mountain Top Drive as this was outside the scope of this work.

6.3.2. Spatial Impact Probability

Debris-flow processes depend on several local factors such as topography, geologic and geomorphological conditions, and hydrodynamic interactions that influence the path that a debris flow follows. Debris-flow modelling in this assessment is completed for 4 m x 4 m grid cells, so micro-scale (< 4 m horizontal scale) variation in these factors are not captured. For example, if someone had built a narrow wall across their property, especially after lidar data were obtained, this would not be captured in the numerical modelling, but could make a substantial difference in how the debris flow would behave. In addition, although numerical modelling is sophisticated, existing tools are limited in their ability to model erosion, deposition, multi-phase behaviour and flow surges in space and time.

BGC did not add so-called area reduction factors (ARFs) to the model. ARFs mean that existing homes are added to the model and the flows would be deflected by buildings. BGC chose not to add this functionality as it is unclear which buildings would be destroyed and which ones may suffer limited damage and deflect debris. This degree of granularity is not warranted in cases where it is unclear to which degree a building may survive debris impact.

Fan avulsions can occur through either debris-flow surges stalling and deflecting following debris, or by log jams, vehicle pile-ups, damaged or undamaged homes obstructing flows. Furthermore, debris may run into currently unpredicted areas should a highway be washed out and water and debris find a new channel. Including all such scenarios would vastly increase the modelling effort and increase the sophistication of risk modelling. In BGC's considerable experience, adding degrees of model scenario complexity has little bearing on the main risk assessment outcomes and the extra effort is rarely warranted. In addition, it will not be possible to capture all possible debris-flow outcomes.

To account for these limitations, BGC has interpreted the model results for the composite hazard map shown in BGC (September 25, 2020).

6.3.3. Temporal Probability of Impact

Temporal probability of impact depends on several factors that influence the likelihood of a person being present in a building at any given time. This includes factors such as the time of day, how a building is used (e.g., a weekend vacation property or year-round use dwelling), or the day-to-day patterns of specific building users.

When considering individual risk, BGC accounted for these uncertainties by assuming a temporal impact probability of 90% for persons in all residential units and used average temporal occupancy lengths for various business types assuming a 40-hour work week. Therefore, the PDI risk calculations are conservative. If, for example, a property is used only for the summer months (June, July, August), then the actual risk is one forth compared to full-time use. If the same property is only used on weekends during the summer (~13 weekends or 26 days out of the year) then the actual risk is only 1/14th compared to the full-time risk. It should be noted, however, that occupancy is not static. Many rural communities in BC, have over time transitioned from mostly part-time vacation properties to full-time retirement homes, a trend that is continuing. In that, the risk map (Drawing 01) which contours individual risk should not be used a policy tool for individual properties as it pertains to development permit applications. In those cases, the actual parcel-specific PDI will have to be calculated that accounts for the present and/or proposed occupancy.

When considering group risk, all buildings within the Consultation Zone are considered simultaneously (i.e., >100 parcels). BGC therefore assumes that average temporal occupancy lengths are a reasonable proxy for temporal impact probability at Consultation Zone scale, as individual differences between parcels will have a cancellation effect. For residential buildings, BGC assumed they are occupied 50% of the time when estimating group risk. For commercial parcels, BGC used generalized opening hours (e.g., offices are open from 9 am to 5 pm, Monday to Friday).

6.3.4. Vulnerability

Vulnerability criteria assumes mortality is an indirect result of building damage that results from debris-flow impact. Uncertainties pertain to human behaviour and differences in a building's capacity to resist debris-flow, flood, or bank erosion-related damage. This includes factors such as building type, existence and height of reinforced concrete foundations, construction quality, and construction materials.

Since data about building characteristics or human behavior are not available, all buildings and persons were considered to have similar vulnerability. This simplified approach reflects the level of detail of hazard and building structure information available. However, BGC recognizes there is likely large differences in buildings conditions across the Consultation Zone.

BGC's methodology assumes specific intensity class boundaries (1-3, 3-10, 10-30, >30 m^3/s^2) for debris flow intensity. Minor flow changes (for example, base case vs. debris net) can switch the vulnerability to a lower class. This effect is particularly noticeable if, for example, a parcel intensity drops from 3.5 to 2.7 m^3/s^2. Since vulnerability is one order of magnitude less for the 1-3 m^3/s^2 class compared to the higher class, this has a strong effect on the risk results. BGC sample-checked this and noticed that this is the case for the debris net modelling runs. This effect would largely disappear if the intensity class boundaries were either larger (1 to 10, 10 to 50 etc.), or smaller (<2, 2 to 4, 4 to 6 etc.). To compensate for this effect, BGC provided ranges rather than precise figures.

6.3.5. Exposed Population

Uncertainties in exposed population depend on assumptions related to estimating the population-at-risk, and the proportion of that population that would be impacted in a debris-flow scenario. When considering the population-at-risk, the main source of uncertainty pertains to how many people live or work within buildings. When considering exposed population, sources of uncertainty mainly pertain to people's location within a building (i.e., first floor or second or basement, or on the side of the impact vs. the opposing side).

BGC estimated life loss risk by assuming the building populations will be similar to average conditions determined from census data or BC business data (Section 3.7) and assumed people are evenly distributed through buildings. Multiple floors were not accounted for in buildings.

At the individual parcel scale, such assumptions might over- or underestimate risk. However, considering exposed population is only applicable to group risk estimates that are carried out at the Consultation Zone scale (i.e., >100 parcels), over- or underestimation of population at individual parcels are assumed to have a cancellation effect. As such, the average exposed population is considered a reasonably proxy.

6.3.6. Numerical Risk Values

Given the above uncertainties, the ultimate risk values (i.e., the product of all the individual risk terms as shown in Equation 2-1) can vary. The degree of variation will depend on each building, especially for buildings located at the transitions between PDI risk bins and the fringes of the risk map (Drawings 01 and 02). Therefore, applying a single confidence bound in percent would not be appropriate. PDI risk variation also varies depending if an avulsion occurs upstream which may reduce or increase risk for a specific property and on the probability of such avulsion. BGC did not evaluate forced avulsions for reasons outlined in Section 6.2.1.

Therefore, should the RDEK decide to use a risk-based approach to decision making for development permit applications, a qualified professional (QP) would need to make a parcel-specific assessment of individual risk accounting for the various uncertainties including the vulnerability to the specific existing or proposed building.

6.4. Life-Loss Outside Buildings

This risk assessment only considers persons within buildings because the group risk tolerance criteria referenced by this project were developed for people within buildings. However, if a Cold Spring Creek debris flow occurs, it is likely that a proportion of the affected population would be outside buildings, (either on foot or in a vehicle), and some could be directly exposed to the debris flow.

People outside buildings would be substantially more vulnerable to debris-flow impact than those within buildings. When a debris flow impacts a building, the impact forces dissipate or are absorbed as the flow re-directs around the structure or the structure yields to impact, and life-loss is assumed to be mostly a result of building-damage. People outside buildings would be exposed to direct impact forces and could be crushed by moving debris, pinned against buildings, vehicles or trees or drown, and BGC expects mortality rates for such cases would be higher than for people indoors. Therefore, this study likely underestimates the number of fatalities for a given hazard scenario.

Estimating the number of persons outside of buildings who could be exposed to debris-flow scenarios is outside the scope of this study and is subject to considerable uncertainty. Estimates would depend on the specific behaviours of the local population, and how they use individual parcels through-out the year. BGC generally expects that an increase in population on Cold Spring Creek fan would likely increase the number of persons outdoors on average, and therefore an increase in group risk beyond what is quantified in this study. Any upstream structural debris flow mitigation would reduce risk also to people outside of buildings. Resilience and risk-reduction measures, such as public education of debris-flow hazards, and emergency planning and preparation could be considered to minimize increases in group risk.

6.5. Economic Exposure

This risk assessment did not consider all types of economic losses associated with Cold Spring Creek debris flows such as building contents losses, infrastructure damage or business losses, nor does it account for losses associated with frequent debris floods. The assessment is valuable for public communication and to justify mitigation spending. Including these factors could at least double the economic losses due to hazards from Cold Spring Creek.

6.6. Summary

Table 6-1 summarizes the various uncertainties associated with this risk assessment and the degree of confidence in the assumptions that were made.

Table 6-2. Summary of uncertainties, confidence and impacts on study results for the Cold Springs Creek risk assessment. Note that the impacts of the specific uncertainty sources can increase or decrease actual risk values for specific properties and for group risk.

Source of Uncertainty	Degree of Confidence	Anticipated Bearing on Risk Assessment Results
Hazard Scenarios	Moderate to High	Low to Moderate. Addition of more hazard scenarios will increase the sophistication of the outcome but not the principal results unless it can be demonstrated that the lowest return period for debris flows changes by a factor or more. Therefore, risk could increase or decrease.
Spatial Impact Probability	Moderate	Low to Moderate. Major unexpected avulsions can change the risk profile as well as artificial fan surface alterations and future debris floods and debris flows that change fan or channel topography. With forced avulsion scenarios, risk could decrease in some portions and increase in others, total risk will likely be similar or the same as shown.
Temporal Probability of Impact	Moderate	Low to Moderate (small, i.e., 10-20% changes in the time residents spend in their homes) have little bearing on the final risk estimates. For PDI calculations, BGC assumed full-time occupancy. If full-time occupancy materializes or if additional homes be constructed, group risk will increase proportionally.
Vulnerability	Low to Moderate	Moderate. There are still relatively few studies that have systematically examined how impact forces relate to building destruction and mortality. Vulnerabilities can oscillate substantially depending on where a person is during time of impact, how a building is impacted and what kind of structural supports it has, and if there are windows facing upslope. This degree of granularity cannot be resolved at the scale of this study. The results presented are best estimates.
Exposed Population	Moderate	Moderate. Data on the number of people in each home do not exist and fluctuate seasonally as well as every time a house is sold. However, PDI calculations only pertain to the person most at risk. For group risk calculations, the assumed number of 2.2 people per house appears to be an adequate average for most rural developments in BC. Given

Source of Uncertainty	Degree of Confidence	Anticipated Bearing on Risk Assessment Results
		that BGC assumed full-time occupancy for all properties in the PDI calculations, the PDI results are likely overestimated somewhat.
Life Loss Outside Buildings	Not considered	The number of people outside of buildings depends on the time of day, time of year and human behaviour (i.e., if they leave their homes for reasons of panic or curiosity). Given that it was not assessed by BGC, it implies an overall underestimate of total risk.
Economic Exposure	Low to Moderate	Market value of homes fluctuates, and business activity varies. Data on business activity can be obtained but the impacts from debris flows on business activity are difficult to assess. Building contents have not been accounted for. Given that various damages to infrastructure and business losses have not been considered in this economic risk assessment, BGC's analysis likely underestimates total economic risk.

BGC used ranges for group risk and economic risk throughout this assessment to avoid the illusion of precision. Similarly, figures demonstrating group risk (FN curves) have been equipped with risk zones, rather than a precise line to show uncertainty.

7. CONCLUDING REMARKS

The purpose of this assessment was to quantify the life loss and economic risk posed by debris flows to existing development on the Cold Spring Creek fan.

The results of the risk assessment demonstrated that approximately 86 properties exceed the commonly quoted 1:10,000 life loss risk tolerance threshold for individual risk at the current part-time occupancy. A 1:10,000 annual life-loss risk is similar to the risk of dying in a motor vehicle accident in BC. Importantly, of those 86 properties, 5 have a greater than 1:1,000 life loss risk (i.e., 10 times the risk of dying in a motor vehicle accident). Group (societal) risk for the fan is over one order of magnitude (i.e. 10 times) above those thresholds that are commonly quoted as separating tolerable from unacceptable risk.

Direct economic losses attributable to building impact can be significant ranging from \$20M for the 100 to 300-year return period debris flow to \$29M for the greater than 1000-year return period debris flow. Annualized losses range from approximately \$20,000 to \$130,000 for the same return period range. These estimates exclude building contents, business loss and infrastructure repairs.

The key qualitative findings of this risk assessment are:

- From a life loss perspective, risks on Cold Spring Creek fan are clearly unacceptable when compared to risk tolerance standards applied elsewhere in BC.
- Economic loss potential is very high compared to the various fans in BC and Alberta for which BGC or others have conducted quantitative risk assessments.
- A debris net in the lower Cold Spring Creek canyon alone would reduce debris-flow life loss and economic risk but risk would remain well above commonly applied risk tolerance thresholds.
- A debris-flow basin as currently proposed in the 2021 Adaptation, Resilience and Disaster Mitigation (ARDM) funding application would provide substantial risk reduction but would only reduce life loss risk to tolerable levels if combined with a debris net, or with a capacity that retains up to the 1000-year return period debris flow. Residual risk could be reduced by additional property-specific measures or an early warning system as well as resident education to influence human behaviour in case of debris-flow occurrence.

Quantitative risk assessments are based on various assumptions and errors in the frequency-magnitude analysis will propagate to the risk analysis. Since no debris flows have been observed on Cold Spring Creek in recent history (unlike at the adjacent Fairmont Creek in 2012), it is not possible to draw direct conclusions or calibrate risk with a known event. Therefore, the results presented herein should not be interpreted as precise. For this reason, BGC has presented the life loss risk assessment results as a credible range rather than fixed numbers.

The findings in this report are difficult to imagine because there have only been damaging debris floods with minor (nuisance) damage since the Fairmont Hot Springs community has been built in the mid 1970s. This may lead to the perception of relative safety because it is challenging to envision a wall of debris up to 3 m high rushing through the development with sufficient power to destroy homes. Unfortunately, global and BC experience has shown that even relatively inactive steep creeks can eventually produce destructive debris flows with substantial life loss and damage potential. Old debris-flow levees in the watershed, sedimentary stratigraphy and the numerous large boulders, strewn across the Fairmont Hot Springs community are without doubt a legacy of such events as is the very existence of the fan landform on which the community has been built. Figure 7-1 shows some examples of debris-flow impacts in unmitigated situations for fans in BC. These are meant to illustrate that those residents believed they were relatively safe because they had never witnessed debris flows since the developments had been constructed.

The comparison with other intensely studied creeks in BC and Alberta shows that Cold Spring Creek life loss risks rank amongst the highest. A question may emerge why the 2012 debris flow on Fairmont Creek (volume 65,000 m^3) did not result in fatalities, while a debris flow with the same magnitude on Cold Spring Creek is estimated to result in three to six fatalities (Table 5-4). The reason is likely that dense development occurs right up to the fan apex in the case of Cold Spring Creek, while Fairmont Creek is confined for a much longer reach due to the build-up of precipitates from the adjacent hot springs. Further downstream, development is fragmented by golf course fairways which reduces development density.

Nations like Austria, Switzerland, Italy, France, Japan or cities like Hong Kong have hundreds of thousands of mitigation works on their creeks to reduce debris-flow risks, yet all of BC has perhaps 50 to 100 of such structures, even though BC is 23 times larger than for example Switzerland. There are several reasons for this dichotomy: The above jurisdictions are much more densely developed (5 people per km^2 in BC, vs. 219 per km^2 in Switzerland) and thus a much larger population is potentially at risk. Secondly, the above-quoted locations have a much longer written history of damaging events due to the much longer permanent development history. Thirdly, the gross domestic product ($253 billion in BC vs. $ 893 billion in Switzerland for 2018), tax base and dedicated funds to reduce debris flow- and other landslide risks is much higher than in BC. Yet despite the much more developed steep creek mitigation infrastructure in those nations and places, deadly debris flow disasters still occur. There is little question that a creek like Cold Spring Creek would be mitigated in those jurisdictions.

This report emphasizes that debris-flow risk reduction through structural mitigation and/or a real-time warning system on Cold Spring Creek is critical to safeguard present and future residents and their properties on the fan from an eventual destructive and potentially deadly debris flow.

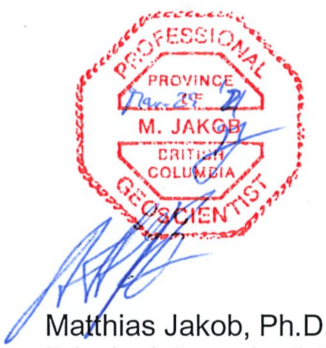
Figure 7-1. Deadly and/or high economic loss debris flow disasters in BC on previously unmitigated fans. Intensities have not been back-calculated but likely exceeded 10 m^3/s^2 in most instances.

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:



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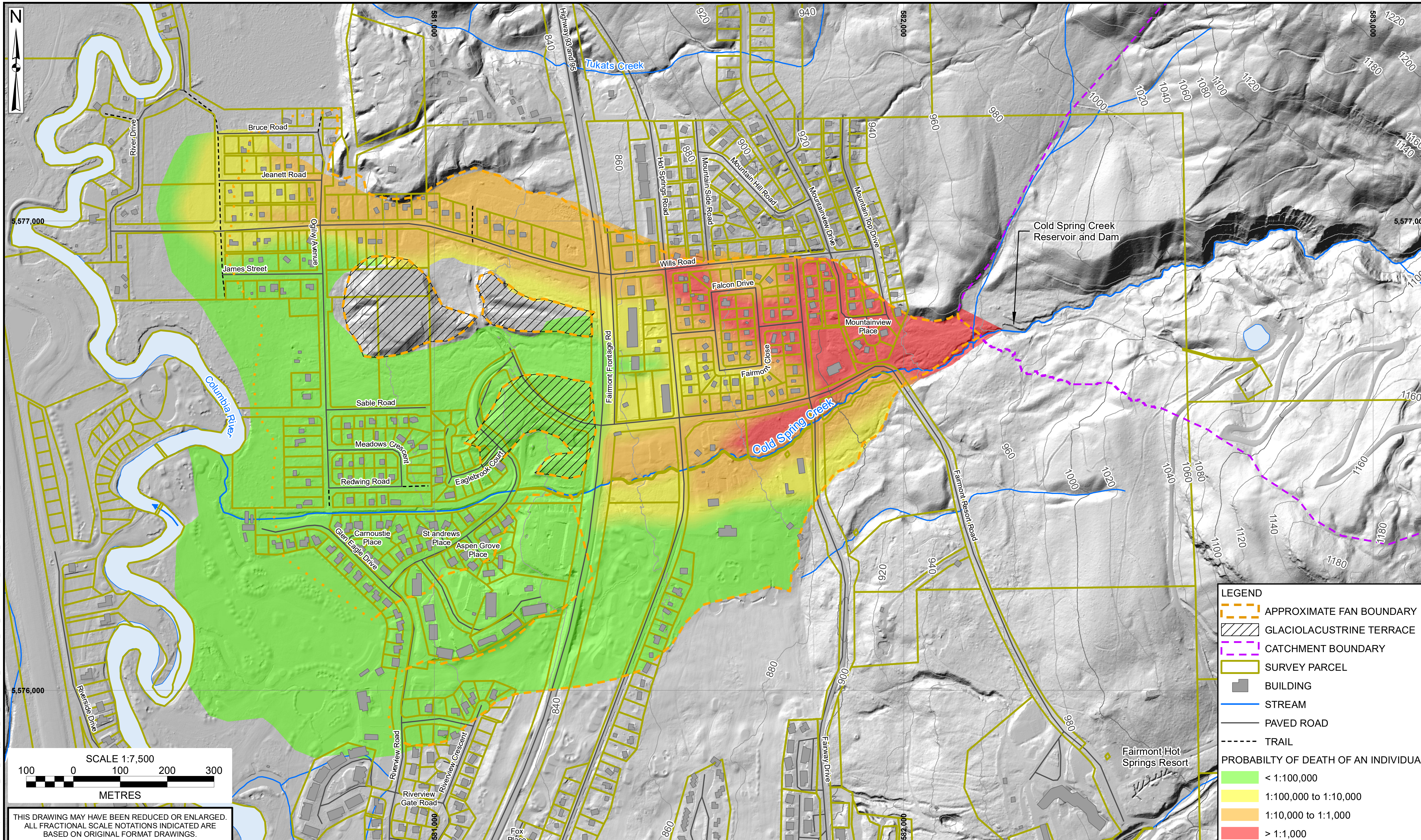
DRAWINGS



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

NOTES:
1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "COLD SPRING CREEK FAN DEBRIS-FLOW QUANTITATIVE RISK ASSESSMENT" AND DATED MARCH 2021.
3. LIDAR DATA PROVIDED BY REGIONAL DISTRICT OF EAST KOOTENAY, PREPARED ON SEPTEMBER 12, 2018. CONTOUR INTERVAL IS 10 m.
4. ROADS, STREAM AND WATERBODY DATA FROM CANVEC, AND COLD SPRING CREEK DIGITIZED BASED ON LIDAR DATED SEPTEMBER, 2018. BC ASSESSMENT DATA FROM ICI SOCIETY FTP SITE, DOWNLOADED AUGUST 7, 2018. BUILDING FOOTPRINT DATA FROM MICROSOFT BING.
5. THE FAN BOUNDARY AS DRAWN IS APPROXIMATE AND DELINEATES THE LANDFORM BASED ON LIDAR DATED SEPTEMBER, 2018. THE BOUNDARY SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DOES IT SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
6. COLOURS ARE SHOWING THE ANNUAL PROBABILITY OF DEATH OF AN INDIVIDUAL (PDI) ASSUMING FULL TIME, RESIDENTIAL OCCUPANCY DUE TO DEBRIS-FLOW HAZARD FROM COLD SPRING CREEK. NO OTHER GEOHAZARDS HAVE BEEN CONSIDERED IN THE RISK ASSESSMENT. BUILDINGS ONLY OCCUPIED PART TIME OR COMMERCIAL PROPERTIES MAY HAVE A LOWER PDI THAN INDICATED ON THE MAP.
7. THIS MAP REPRESENTS A SNAPSHOT IN TIME. FUTURE CHANGES (DEVELOPMENT, MITIGATION, GEOHAZARD EVENTS) MAY WARRANT THE RE-DRAWING OF CERTAIN AREAS.
8. PROJECTION IS NAD 1983 UTM ZONE 11N. VERTICAL DATUM IS CGVD2013.
9. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED OR USED FOR ANY PURPOSE OTHER THAN THE PURPOSE FOR WHICH BGC GENERATED IT. BGC SHALL HAVE NO LIABILITY FOR ANY DAMAGES OR LOSS ARISING IN ANY WAY FROM ANY USE OR MODIFICATION OF THIS DOCUMENT NOT AUTHORIZED BY BGC. ANY USE OF OR RELIANCE UPON THIS DOCUMENT OR ITS CONTENT BY THIRD PARTIES SHALL BE AT SUCH THIRD PARTIES' SOLE RISK.

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APPROVED:	MJ

CLIENT: Regional District of East Kootenay

BGC

PROJECT: COLD SPRING CREEK FAN DEBRIS-FLOW QUANTITATIVE RISK ASSESSMENT

TITLE: BASELINE FULL TIME OCCUPANCY RISK MAP

PROJECT No.:	DWG No:
1572 008	01

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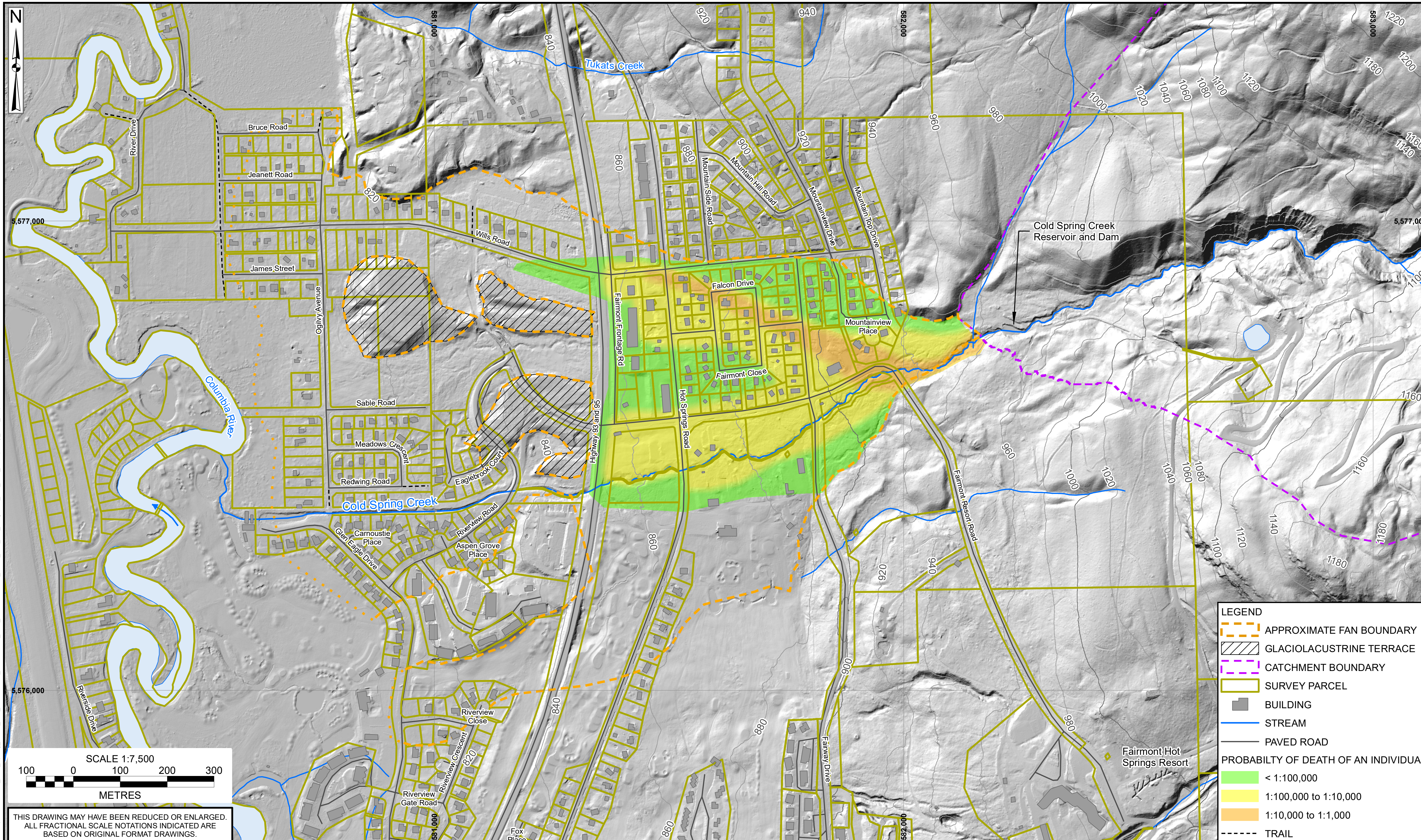

THIS DRAWING MAY HAVE BEEN REDUCED OR ENLARGED. ALL FRACTIONAL SCALE NOTATIONS INDICATED ARE BASED ON ORIGINAL FORMAT DRAWINGS.

NOTES:

1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "COLD SPRING CREEK FAN DEBRIS-FLOW QUANTITATIVE RISK ASSESSMENT" AND DATED MARCH 2021.
3. LIDAR DATA PROVIDED BY REGIONAL DISTRICT OF EAST KOOTENAY, PREPARED ON SEPTEMBER 12, 2018. CONTOUR INTERVAL IS 10 m.
4. ROADS, STREAM AND WATERBODY DATA FROM CANVEC, AND COLD SPRING CREEK DIGITIZED BASED ON LIDAR DATED SEPTEMBER, 2018. BC ASSESSMENT DATA FROM ICI SOCIETY FTP SITE, DOWNLOADED AUGUST 7, 2018. BUILDING FOOTPRINT DATA FROM MICROSOFT BING.
5. THE FAN BOUNDARY AS DRAWN IS APPROXIMATE AND DELINEATES THE LANDFORM BASED ON LIDAR DATED SEPTEMBER, 2018. THE BOUNDARY SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DOES IT SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
6. COLOURS ARE SHOWING THE ANNUAL PROBABILITY OF DEATH OF AN INDIVIDUAL (PDI) ASSUMING FULL TIME, RESIDENTIAL OCCUPANCY DUE TO DEBRIS-FLOW HAZARD FROM COLD SPRING CREEK. NO OTHER GEOHAZARDS HAVE BEEN CONSIDERED IN THE RISK ASSESSMENT. BUILDINGS ONLY OCCUPIED PART TIME OR COMMERCIAL PROPERTIES MAY HAVE A LOWER PDI THAN INDICATED ON THE MAP.
7. THIS MAP REPRESENTS THE RESIDUAL RISK AFTER INSTALLING DEBRIS NET AND DEBRIS BASIN MITIGATION AS PROPOSED AT THE TIME OF REPORTING. FUTURE CHANGES TO DESIGN OF EITHER MTIGIATION ELEMENT MAY WARRANT THE RE-DRAWING OF CERTAIN AREAS.
8. PROJECTION IS NAD 1983 UTM ZONE 11N. VERTICAL DATUM IS CGVD2013.
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REVIEW:	BCP
APPROVED:	MJ

CLIENT: Regional District of East Kootenay

BGC

PROJECT: COLD SPRING CREEK FAN DEBRIS-FLOW QUANTITATIVE RISK ASSESSMENT

TITLE: BASIN AND NET MITIGATION FULL TIME OCCUPANCY RISK MAP

PROJECT No.:	DWG No:
1572 008	02

APPENDIX A
VULNERABILITY CRITERIA VALIDATION

APPENDIX A – DEBRIS FLOW VULNERABILITY CRITERIA

Debris flow vulnerability is the probability of a fatality given an element at risk is impacted by a debris flow with certain severity. When considering debris flow life-loss risk assessment, it addresses the question, "what is the chance of fatality for persons within buildings, should the building be impacted?".

Table A-1 shows the vulnerability criteria used to estimate the probability of fatality for persons within buildings impacted by debris flows. This criterion is based on the debris-flow intensity index (Jakob et al., 2011), which describes the severity of the debris flow impact and represents the probability of fatality as an indirect consequence of building damage. Intensity is defined as:

$$I_{DF} = d \times v^2$$

where d is flow depth (m) and v is flow velocity (m/s). Intensity values can be estimated using a variety of techniques such as back analysis of field evidence, or through numerical modelling.

Table A-1. Debris flow vulnerability criteria for persons within buildings.

Hazard Intensity Index (m^3/s^2)	Life loss vulnerability (%)
≤ 1	~0
1 to 3[1]	0.02
3 to 10	0.2
10 to 30	0.4
30 to 100	0.6
> 100	0.9

Vulnerability criteria in Table A-1 have been developed through professional judgement informed, in part, by a global literature review conducted in 2011 (Jakob et al. 2011). However, there is still currently no systematic analysis of mortality from debris flows in literature from which the criteria can be compared. Ongoing work for the January 2018 debris flow at Montecito will shed some more light on this question.

To further check vulnerability criteria assumptions for reasonableness, these criteria were compared to cases where fatalities in dam outbreak floods were known (RCEM, 2015a). These cases were compiled by the U.S. Bureau of Reclamation for specific use in dam safety risk analysis (RCEM, 2015b). Cases are divided into those where downstream residents had little to no warning of the potential event, and cases where downstream residents had adequate warning for evacuation. Given debris flows are rapid on-set events where downstream residents would likely have insufficient time for evacuation, these cases represent an approximation of debris flow life-loss.

Figure A-1 shows a comparison of debris-flow vulnerability criteria to dam outbreak flood event case histories where downstream residents had little to no warning of the event. The debris-flow vulnerability criteria shown in Table A-1 depend on debris-flow intensity. However, the mortality rates compiled by the U.S. Bureau of Reclamation for dam outbreak floods are slightly different, as the product of flood depth times velocity (i.e. not the square of velocity). Vulnerability criteria were compared previously by BGC by:

- Modelling a single debris-flow run-out in FLO-2D, using methods and parameters representing a Cheekeye River debris flow with a 1,000 to 3,000-year return period (BGC, December 4, 2020).
- Estimating debris-flow intensity for each model grid cell, then estimating the corresponding debris-flow fatality rates using vulnerability criteria in Table A-1.
- Plotting the range of estimated debris flow fatality rates against dam outbreak flood cases, using corresponding depth x flow velocity values for each grid cell.

This comparison shows that debris-flow vulnerability criteria are in general agreement with the most severe dam outbreak flood cases. Debris flows typically have higher sediment concentrations than dam outbreak flood waves and are thus denser. This results in higher impact forces. Therefore, BGC expects debris-flow fatality rates to be near the upper limit of dam breach cases, and considers the criteria suitable for the Cold Spring Creek debris-flow risk assessment.

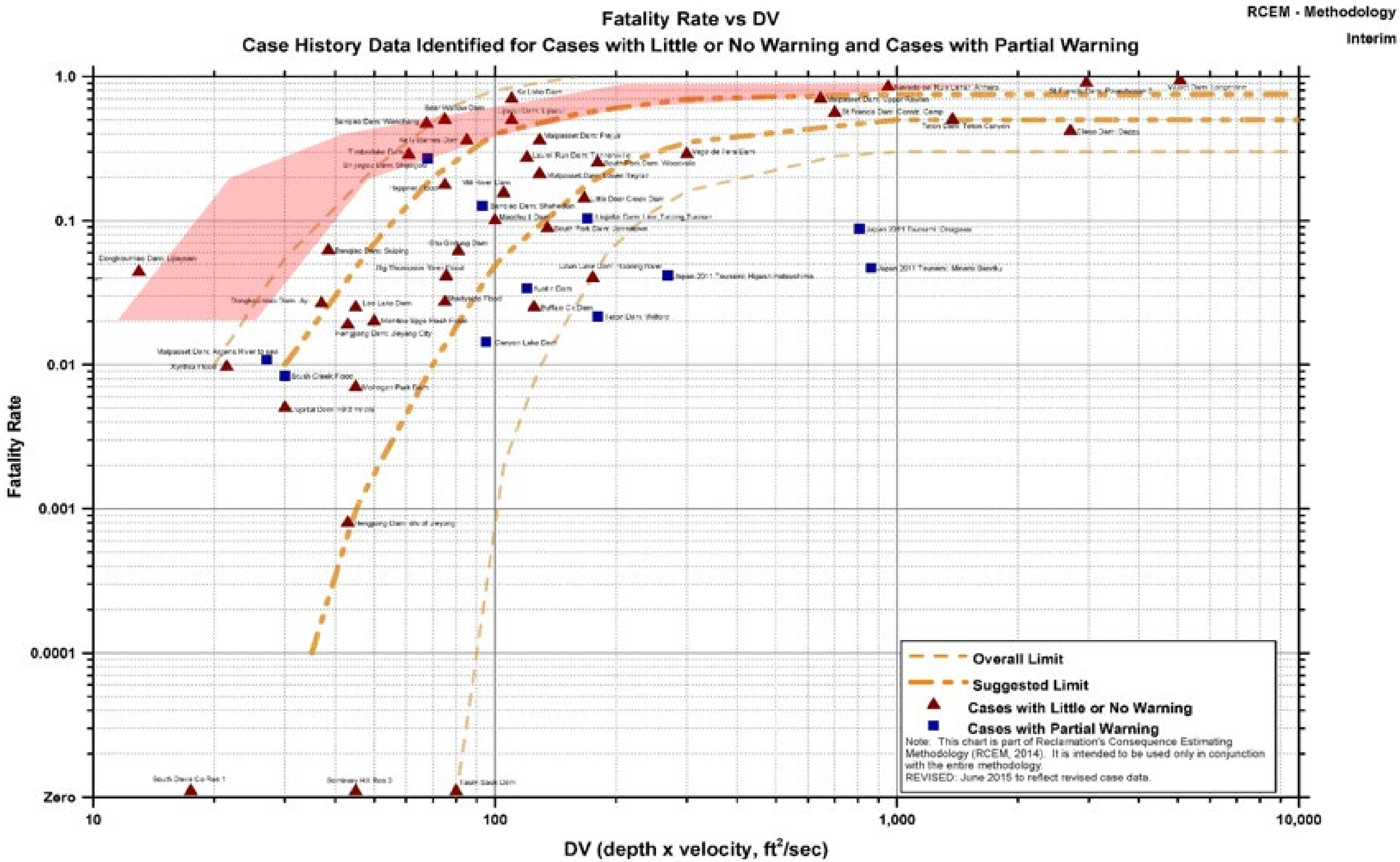

Figure 1 - Fatality Rate vs. DV - Case History Data Identified for Cases with Little or No Warning and Cases with Partial Warning

Figure A-1. Debris-flow mortality rates (red shading) estimated from a range of modelled debris-flow intensities, compared to mortality in historic dam outbreak floods with comparable intensity.

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U.S. Bureau of Reclamation (2015b). RCEM – Reclamation Consequence Estimating Methodology – guidelines for estimating life loss for Dam Safety Risk Analysis. U.S. Department of Interior, Bureau of Reclamation. July 2015.