Quantifying debris-flow hazard and risk based on fan sector

Alex Strouth[1,2*], *Sophia* Zubrycky[2,3], and *Scott* McDougall[2]

[1]BGC Engineering Inc., Golden, Colorado, USA
[2]The University of British Columbia, Vancouver, British Columbia, Canada
[3]BGC Engineering Inc., Vancouver, British Columbia, Canada

Abstract. We show how a quantitative estimate of debris-flow hazard and risk can be derived simply from the position of infrastructure on the fan relative to the fan apex and the most likely flow path (e.g., active channel). Fan sectors and the spatial probability of impact in each sector are based on a fan-normalized heat map of debris-flow impacts derived from 146 mapped impact areas across 30 fans in southwestern British Columbia, Canada. As a proof-of-concept, we provide an example for annual life loss risk to an individual who occupies a home in various sectors of a debris-flow fan. The results are comparable to broad findings from quantitative risk assessments completed at 10 fans in British Columbia and Alberta, Canada with similar characteristics. The method presented here is a way to obtain a high-level quantitative risk estimate prior to a detailed site-specific assessment.

1 Introduction

Much of the information needed to characterize debris-flow hazard is recorded within, or can be derived from, the debris-flow fan. For example: frequency-magnitude relationships are recorded in fan stratigraphy and vegetation and can be estimated from the fan volume or area [1]; flow depths can be derived from fan stratigraphy; maximum travel distance is recorded by the fan boundary; and flow path and potential avulsion locations are controlled by the fan topography and channel position. We hypothesize that quantitative estimates of debris-flow hazard and risk, such as impact probability, impact intensity, vulnerability, and life loss probability, can be derived simply from the position of infrastructure on the fan relative to the fan apex and the most likely flow path (e.g., active channel).

Although debris-flow hazard and risk assessments are revolving more and more around numerical models (at least in our region of North America), empirical datasets that characterize debris-flow fans will always be needed to inform selection of input parameters and to validate model results. In fact, for many risk management situations, empirical-statistical analysis of the fan landform is a sufficient and efficient method for reaching a well-informed decision. Therefore, we are researching how to use simple characteristics of a fan to directly inform estimates of debris-flow hazard and risk. In this paper, we will:

1. Introduce the concept of “fan-normalized space” and demonstrate how it can be used to compare spatial hazard and risk trends across fans.
2. Introduce a method to quantify life-loss risk to houses based on their relative location on a fan.
3. Compare the results to quantitative risk assessments completed in British Columbia and Alberta, Canada.

2 Fan-Normalized Space

Zubrycky et al. [2] present a method to extract and visualize spatial impacts of debris flows on fans using a “fan-normalized space”. The method uses a circular measurement grid centred on the fan apex and normalized by the maximum down-fan length and maximum cross-fan arc length (Fig. 1). The fan-normalized space normalizes a location on the fan surface based on its position down-fan and cross-fan.

The maximum fan dimensions are interpreted to be the statistical upper bound of runout from the fan’s formative debris flows. Zones of increasing radii represent mobility down-fan. Arc length offsets represent lateral shifts across the fan relative to the previous debris-flow path. Previous debris-flow paths are often, but not always, represented by the current channel position.

Impact areas plotted in fan-normalized space highlight the typical runout distance and location and extent of avulsion impacts relative to the fan boundary. Multiple impact area plots can be combined for a fan or a group of fans to create a composite spatial impact heat map. Zubrycky et al. [2] created a composite spatial impact heat map for 146 impact areas across 30 debris-flow fans in southwest British Columbia, Canada (Fig. 2). The heat maps capture regional frequency–

* Corresponding author: astrouth@bgcengineering.ca

magnitude distributions, mobility behaviours, and avulsion behaviours specific to fans in the study area. These heat maps highlight areas on the fan that are most susceptible to debris-flow impact, without differentiation between debris-flow magnitude, flow thickness, composition, or speed.

Although we have not done so yet, other observations and estimates could also be plotted in fan-normalized space, such as deposit thickness, flow velocity, and vulnerability of buildings, infrastructure, and people. Trends in these data could be used to inform assessments of debris-flow hazard and risk to infrastructure and people, based on the relative location of these elements to the fan boundaries and previous debris-flow path.

For fans in a similar environment, and when paired with geomorphic interpretation and judgement, these observations can support quantitative estimates of debris-flow hazard in several ways. The heat map (Fig. 2) provides an estimate of susceptibility to debris flow impact for various fan sectors. This information supports qualitative and quantitative hazard assessments and debris-flow hazard mapping. With one additional step, a quantitative estimate of spatial impact probability can be derived by multiplying the susceptibility value by the average annual probability of a debris flow reaching the fan apex. Although the fan boundary is an imperfect normalizer (e.g., in the case of truncated fans), the fan landform and main channel can be identified reasonably consistently for the purpose of forecasting.

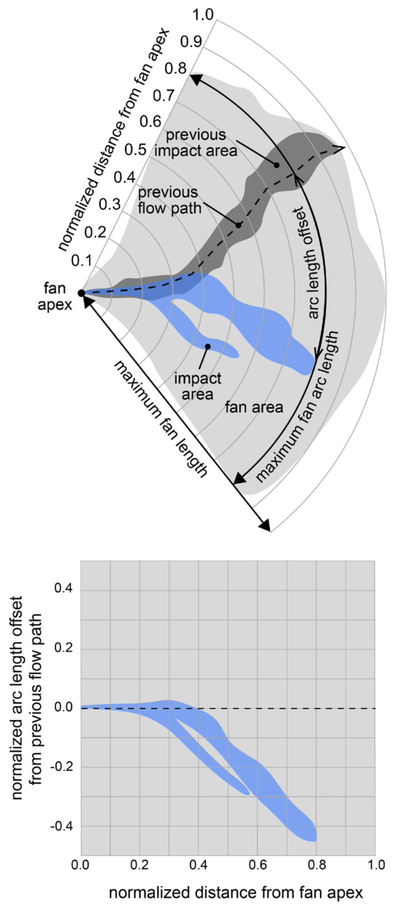

Fig. 1. Fan-normalized space for one impact area relative to the previous flow path.

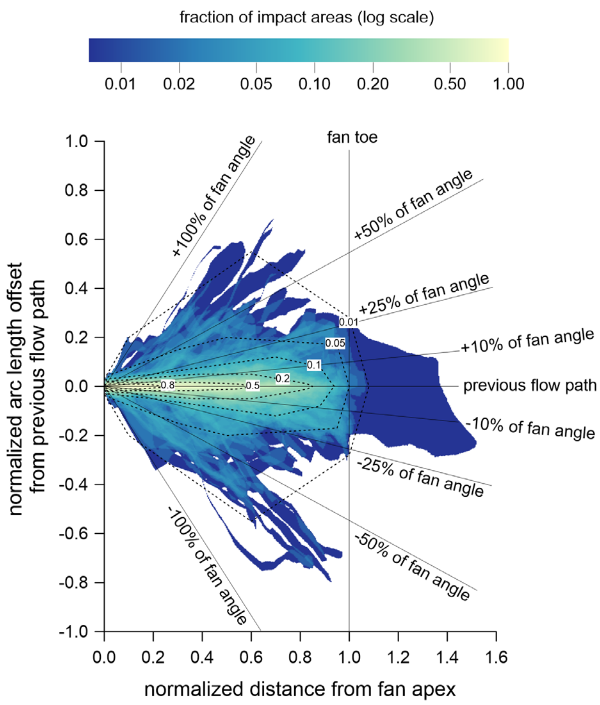

Fig. 2. Spatial impact heat map at 30 debris-flow fans in British Columbia, Canada [2]. Dashed lines are interpreted isolines of spatial impact frequency.

3 Estimated Risk by Fan Sector

We hypothesize that life-loss and direct damage risk related to debris flows could be estimated quantitatively based on the location of elements at risk in fan-normalized space. As a proof-of-concept, we provide an example for annual life loss risk (**R**) to an individual who occupies a home on a debris-flow fan, which is the product of [3]:

- **H**: Annual probability of a debris flow reaching the fan.
- **S:** Conditional probability that the home is reached by the debris flow.
- **T:** Conditional probability that the person is home when the debris flow occurs.
- **V:** Conditional probability that the person is killed if they are impacted by the debris flow (i.e., vulnerability).

H and **T** are independent of the home's location on the fan. **H** can be approximated based on the historical and vegetation record. In southwest British Columbia, many fans the authors have studied experience debris flows at a frequency in the range of 10 to 100 years. **T** can be approximated by the amount of time that the person most at risk spends at home. In the absence of other information, we assumed this value to be 70% to 80%.

S is a function of the home's location on the fan. We partitioned the fan into sectors to simplify selection of an **S** value (Fig. 3) and estimated ranges of **S** directly from the spatial impact heat map (Table 1).

We hypothesize that **V** could also be approximated based on fan sector because debris flows decelerate from a peak velocity near the fan apex to a stop before the distal fan margin. Therefore, it follows that impact intensity, building damage state, and probability of death are at a maximum near the fan apex and at a minimum in fan sectors that are on the distal fan, far from the channel. Since a similar heat map to Fig. 2 for **V** is not available, we estimated ranges of debris flow depths and velocities for the fan sectors typical of granular debris flows we have studied in southwest British Columbia. We then related the intensity (in terms of depth x velocity^2) to building damage class using methods from Jakob et al. [4] and estimated ranges of **V** for each building damage class (Table 2).

Using average values for **S**, **T**, and **V**, we calculate **R** to an individual who occupies a home on a fan with an average debris-flow frequency of 100 years (Table 3). In this region of Canada, individual life loss risks that are greater than 100 micromorts per year (i.e., 1 in 10,000 per year) are often considered to be intolerable for existing developments [3]. Therefore, Table 3 suggests, as a rule of thumb, that in the absence of mitigation, houses near the fan apex and near the channel will generally have intolerable life loss risk. Houses on the distal and mid fan far from the channel will generally have tolerable life loss risk.

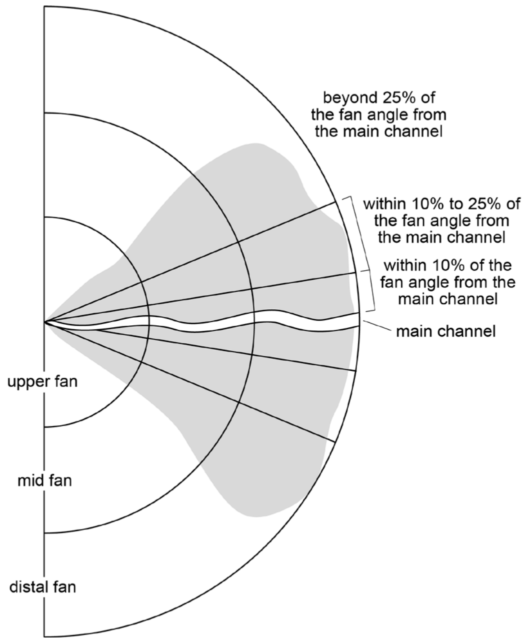

Fig. 3. Fan sectors used in the risk calculation.

Table 1. Estimated range of **S** for fan sectors based on data from 30 fans in southwestern British Columbia, Canada [2].

	Upper Fan	Mid Fan	Distal Fan
Main channel	0.8-1	0.5-0.8	0.05-0.5
Within 10% of the fan angle from the main channel	0.5-0.8	0.2-0.5	0.05-0.3
Within 10% to 25% of the fan angle from the active channel	0.1-0.5	0.1-0.2	0.01-0.1
Beyond 25% of the fan angle from the active channel	0-0.1	0-0.05	0-0.01

Table 2. Assumed range of flow parameters to inform selection of **V** based on debris flow intensity and damage class [4]. Depth [m], Velocity [ms^{-1}], Intensity [m^{3}s^{-2}].

	Near main channel	On fan, outside of main channel area
Upper Fan	Depth: 3-5 Velocity: 7-10 Intensity: 150-500 Damage class: Complete destruction **V**: 0.9	Depth: 1-3 Velocity: 5-7 Intensity: 25-150 Damage class: Major structural damage to complete destruction **V**: 0.5-0.9
Mid Fan	Depth: 1-3 Velocity: 5-7 Intensity: 25-150 Damage class: Major structural damage to complete destruction **V**: 0.5-0.9	Depth: 0.5-2 Velocity: 2-5 Intensity: 2-50 Damage class: Some to major structural damage **V**: 0.1-0.5
Distal Fan	Depth: 0.5-2 Velocity: 2-5 Intensity: 2-50 Damage class: Some to major structural damage **V**: 0.1-0.5	Depth: 0.1-1 Velocity: 1-3 Intensity: 0.1-10 Damage class: Some sedimentation to some structural damage **V**: 0.01-0.1

Table 3. Estimated annual life loss risk (**R**) in micromorts based on fan sector to an individual who occupies a home on a debris-flow fan with an average debris-flow frequency of 100 years. 1 micromort = odds of 1 in 1,000,000 per year [3].

Risk (R) (micromorts)	Upper Fan	Mid Fan	Distal Fan
Main channel	6,100	3,400	600
Within 10% of the fan angle from the main channel	3,400	800	70
Within 10% to 25% of the fan angle from the active channel	1,600	300	20
Beyond 25% of the fan angle from the active channel	300	60	2

Quantitative risk assessments (QRAs) carried out by BGC Engineering Inc. (BGC) during the last decade also suggest there is a relationship between the fan sector and quantitative risk value. From a review of QRAs completed at 10 fans located in British Columbia and Alberta, Canada (characteristics summarized in Table 4), we found **R** tends to be:

- >1,000 micromorts (i.e., >1 in 1,000) per year near the fan apex and mid-fan near the channel.
- 100 to 1,000 micromorts (i.e., 1 in 10,000 to 1 in 1,000) per year in the distal fan near the channel.
- < 100 micromorts (i.e., <1 in 10,000) per year in the mid and distal fan far from the channel.

These risk values from the QRAs accord with the estimated risk by fan sector values presented in Table 3.

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Table 4. Typical characteristics of debris-flow fans where life loss risk was quantified by BGC.

Item	Description
Return period of debris flows large enough to cause life loss	10 to 100 years
Return period of largest debris flow considered in the risk estimate	1,000 to 3,000 years
Volume of debris flows considered	1,000 to 5,000,000 m^3
Building type	Wood frame, single family homes, without local debris flow impact protection

Fig. 4 is an example map of life loss risk that was created for one of these projects. It has several characteristics that are common to all the QRAs in that risk values are greatest near the fan apex and near the most likely flow path, and smallest on the distal fan far from the most likely flow path. In this case, the most likely flow path identified through numerical modelling is not the current stream channel. Engineering judgement is required when using the fan sector approach for risk estimation, such as selecting the most likely flow path (which may not be the main channel) and adjusting spatial probabilities (Table 1) based on topography.

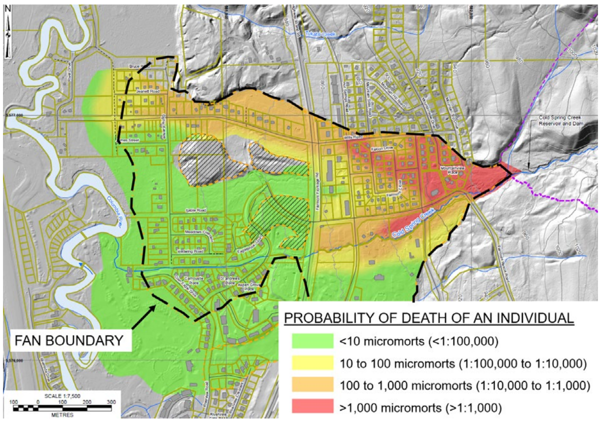

Fig. 4. Example life loss risk estimate map for individuals within homes at Cold Spring Creek, British Columbia [5].

4 Discussion

The heat map of spatial impact and estimated life loss risk by fan sector are specific to the region in which they were developed. Even within that region, they do not replace a detailed, site-specific risk assessment. Nevertheless, approximate estimates like these could have many uses, including for:

- Regional prioritization studies that attempt to identify the highest risk fans and quantify risk levels.
- Regional planning studies that attempt to identify the number of individuals at certain risk levels.
- Estimating total debris-flow risk across a large region, for example, to compare with historical records and to allow calibration of site-specific estimates.
- First order inferences at specific sites to guide preliminary decisions and for scoping more detailed assessments.

Although the estimates are highly approximate, they provide quantitative values that can be used to compare debris-flow risks to other hazards and to estimate the justifiable cost of risk reduction measures [6].

More research is needed to fully develop these tools, and we encourage others to collect and publish data from other world regions. Research needs include:

- Collecting flow intensity, vulnerability, and quantitative individual risk estimates from a variety of settings and plotting them in fan-normalized space.
- Identifying spatial patterns and relationships between fan and infrastructure characteristics and hazard and risk values.
- Developing heat maps in fan-normalized space, like Fig. 2, to illustrate the spatial patterns.

References

1. M. Jakob, E. Mark, S. McDougall, P. Friele, C.-A. Lau, & S. Bale. Earth Surf. Process. Landf. **45**, 12, 2954–2964 (2020)
2. S. Zubrycky, A. Mitchell, S. McDougall, A. Strouth, J.J. Clague, B. Menounos. Earth Surf. Process. Landf. **46,** 12, 2395-2413 (2022)
3. A. Strouth, S. McDougall. Landslides **19**, 4, 977-991 (2022)
4. M. Jakob, D. Stein, M. Ulmi. Natural Hazards, **60**, 2, 241-261 (2011)
5. BGC Engineering Inc., Cold Spring Creek Fan Debris Flow, Quantitative Risk Assessment. Final report for Regional District of East Kootenay, Canada, (2021)
6. A. Strouth, S. McDougall. Landslides **18**, 3, 1071-1085 (2021)