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Semi-automated regional scale debris-flow and debris-flood susceptibility mapping based on digital elevation model metrics and Flow-R software

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Abstract

Regional scale debris-flow or debris-flood susceptibility mapping based on terrain analysis is limited by a high degree of effort and the availability of surface evidence for past events, which may be obfuscated by development or obscured by repeat erosion or debris inundation. This paper presents a semi-automated methodology for debris-flow and debris-flood susceptibility mapping at regional scale based on a combination of digital elevation model (DEM) metrics to identify potential source zones, and flow propagation simulations using the Flow-R code. The DEM metrics allow identification and preliminary, process-based classification of streams prone to debris flow and debris flood, respectively. Flow-R simulations are based on a combination of spreading and runout algorithms considering DEM topography and empirical runout parameters. The methodology was first tested in a region of the Canadian Rocky Mountains, where detailed debris-flood hazard assessments had been previously undertaken based on both field mapping and numerical modeling. It was then applied over two regions, with 22,000 km^2 and 55,000 km^2 areas, respectively, in central British Columbia, Canada. One important advantage of the presented methodology is the limited amount of data required to generate a preliminary susceptibility map over a large region. Once incorporated in a risk assessment framework, this map can be used to prioritize more detailed assessments. The methodology was also applied at a higher level of detail to an approximately 30 km long roadway corridor in Southwestern British Columbia. At the assessment level of this project, the methodology allowed generation of a susceptibility map which considered the cumulative contribution of several potential source zones within each debris-flow and debris-flood watershed. This map allowed risk-based prioritization and supported debris-flow risk reduction decision making.

Keywords: debris flow; debris flood; susceptibility mapping; digital elevation model; Flow-R; risk assessment

1. Introduction

Debris-flow and debris-flood susceptibility mapping based on terrain analysis is limited by the availability of surface evidence for past events, which may be obfuscated by development or obscured by progressive erosion or debris inundation. In addition, it can be limited by the relatively high level of effort to map large regions. To address these limitations, this paper presents a semi-automated methodology based on stream segments delineated from digital elevation models (DEMs), morphometric statistics on DEMs, and the Flow-R model ("Flow-R" refers to "Flow path assessment of gravitational hazards at a Regional scale") developed by Horton et al. (2008, 2013). This methodology allows identification, at a preliminary level of detail, of potential debris-flow or debris-flood hazard and modeling of their runout susceptibility over large study areas.

Using Flow-R, Horton et al. (2011) demonstrated the control of DEM topography on debris-flow propagation. Park et al. (2013) found good agreement between debris-flow paths predicted with Flow-R and an inventory of past events near Seoul, South Korea, despite the paucity of parameters for rheological properties and erosion rate required in the software. The software also provided reliable results within the framework of the development of a debris-flow susceptibility map at regional to national scale in Norway (Fisher et al., 2012). Blais-Stevens and Behnia (2016)

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undertook susceptibility mapping with Flow-R in northwestern Canada, and their results highlighted debris-flow potential in a number of channels that had not been previously documented. These results are consistent with the objective of susceptibility mapping, which is to consider the largest credible area affected by geohazard in the process of prioritizing future, more refined work. Further validation of the Flow-R software has been documented by Pastorello et al. (2017) and Kang and Lee (2018).

A few authors attempted to integrate Flow-R into preliminary hazard assessments, which typically require definition of landslide magnitude and frequency. Based on the assumption that larger debris-flow events are less frequent and able to travel for longer distances than smaller, more frequent ones (e.g., Corominas and Moya, 2008), Blahut et al. (2010) and Kappes et al. (2011) defined three magnitude-frequency runout scenarios corresponding to low, moderate and high hazard by means of different angles of reach (the angle of reach being one of Flow-R main input parameters; see also Corominas, 1996). Blahut et al. (2010) simulations were coupled with ratings for debris-flow hazard initiation probability.

This paper presents four case studies using Flow-R for both debris-flow and debris-flood susceptibility mapping. The first case reports on a pilot study comparing Flow-R simulation results with detailed analysis of debris flood undertaken with the software FLO-2D. In the second and third ones, Flow-R results are integrated into regional scale debris-flow and debris-flood risk prioritization assessments, whose objective are to prioritize future detailed assessment on alluvial fans with higher risk potential. Finally, the fourth case study shows a similar example at a refined level of detail, where Flow-R was used to prioritize mitigation work on selected segments of roadway on a series of alluvial fans.

2. Methodology

2.1. Definitions

The term “landslide susceptibility” was defined by Fell et al. (2008) as “a quantitative or qualitative assessment of the classification, volume (or area), and spatial distribution of landslides which exist or potentially may occur in an area”. Susceptibility may be used for characterization of landslide potential both at the source and within the impact zone. In the two first case studies described in this paper, the term is primarily used to describe areas susceptible to geohazard impact, and no effort was made to classify source zones according to their likelihood of generating landslides. In the third example, classification and weighting of debris-flow source zones was incorporated based on experience and knowledge of the study area.

The proposed methodology required two main steps. The first one is the identification of steep creek geohazard sources, and the second one consists in the estimation of geohazard propagation and runout susceptibility. In this study, steep creek geohazards include both debris flow and debris flood. Debris flow is defined as a very rapid to extremely rapid surging flow of saturated debris in a steep channel, with strong entrainment of material and water from the flow path (Hungr et al., 2014). Debris floods correspond to very rapid flows of water, heavily charged with debris, in steep channels; their peak discharge is comparable to that of water floods (Hungr et al., 2014).

2.2. Identification of debris-flow and debris-flood sources

In this study, stream segments, generated based on DEMs, are used as “proxy” for steep creek geohazard source zones. This approach was chosen in part because it is computationally efficient across large regions. The segments need to be classified to differentiate the ones most likely to generate debris flows from the ones most likely to generate debris floods. In the proposed methodology, process types are classified using geomorphometric parameters such as the Melton ratio and watershed length. The former corresponds to the ratio between watershed relief and the square root of watershed area (Melton, 1957). The latter is calculated as the total channel length upstream of a given stream segment to the stream segment farthest from the fan apex. These terrain parameters are a good screening level indicator of the propensity of a creek to dominantly produce debris floods or debris flows (Holm et al., 2016). It should be noted that there is a continuum between debris flow and debris flood, which depends on factors such as velocity, sediment concentration and channel slope angle. As such some steep creek processes may present behavior in between typical debris flow or debris flood. In addition, both processes can occur within the same watersheds and consequently alluvial fans may not be completely assigned to one single process type.

2.3. Steep creek geohazard propagation and runout susceptibility modeling

FLOW-R simulates propagation of debris flows and debris floods through a DEM. In this study, sections of the freely available Canadian Digital Elevation Model (CDEM) at 20 m resolution were used. This resolution was selected, because it was the highest resolution available which covered the entire study areas. Propagation is modelled using spreading algorithms and simple frictional laws. Both spreading algorithms and friction parameters need to be calibrated by back-analysis of past events or based on geomorphological observations (e.g., alluvial fans).

FLOW-R can generate the maximum susceptibility that passes through each cell of the DEM, or the sum of all susceptibilities passing through each cell. The former is calculated using the “quick” calculation method and is used to identify the area susceptible to landslide processes. The “quick” method propagates the highest source segment, and iteratively checks the remaining source zones to determine if a higher energy or susceptibility value will be modelled. The latter is calculated in FLOW-R using the “complete” method and can be used to identify areas of highest relative regional susceptibility. The complete method triggers propagation from every cell in the source segments and then calculates the sum of susceptibilities at each cell of the DEM. It should be noted that the sum of susceptibilities has no physical meaning; rather it can be used as a regional comparison between sites to determine areas with higher hazard potential. Debris-flow and debris-flood propagations were modelled separately.

3. Case Studies

3.1. Pilot Study: Canmore Area

We simulated an initial set of debris floods in the Canmore area, where a number of debris-flood fans had been previously studied at a detailed level (Jakob et al., 2017; Holm et al., 2018). Canmore is located in the Front Range of the Canadian Rocky Mountains, approximately 90 km west of Calgary. The objective was to compare Flow-R propagation results with detailed numerical modeling results. The detailed numerical modeling had been undertaken for a spectrum of debris-flood scenarios on each creek, using the software FLO-2D (2004) and provided estimates of flow depth within and beyond alluvial fans.

Calibration of Flow-R propagation parameters focused on attempting to reproduce the extent of debris-flood potential inundation of the worst-case scenario, corresponding to a 1000-3000-year return period event. The “quick” method was used for this purpose, as we were mostly interested in the maximum extent of potential inundation areas. The results were satisfying, as illustrated in Fig. 1, and provided confidence that Flow-R is able to delineate potential areas susceptible to debris flood at regional scale. Calibrated parameters in this pilot study are shown in Table 1. It should be noted that the FLO-2D model used a 10-m DEM resolution, while the DEM resolution used in Flow-R was 20 m.

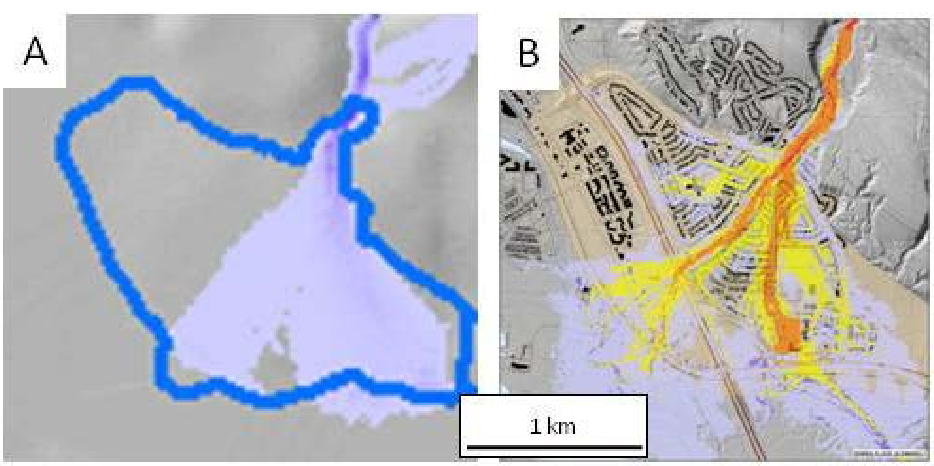

Fig. 1. Comparison between Flow-R propagation extent (A) and FLO-2D modeling results (B) at one of the alluvial fans of the Canmore area. The blue polygon in A and beige background in B outline a mapped alluvial fan. The purple color in B shows the extent of flow simulated with FLO-2D (yellow to red zone correspond to various flow impact intensities). The scenario shown in (B) is the largest modelled debris-flood scenario on this creek, corresponding to an estimated 1000-3000-year return period event.

Table 1. Calibrated debris-flood parameters used in Flow-R (Canmore)

Selection	Flow-R Parameter	Value
Directions algorithm	Holmgren (1994) modified	dh = 2, exponent = 1
Inertial algorithm	Weights	Gamma (2000) - Cosinus
Friction loss function	Travel angle	2-3°
Energy limitation	Velocity	< 15 m/s

Note that Flow-R could not model avulsions that are likely at culverts and bridges and which could send flow towards the western portion of the fan as shown on Fig. 1. Flow-R also cannot simulate bank erosion, channel scour and aggradation, all of which can affect flow behavior and thus risk. These limitations need to be considered in any site-specific application.

3.2. Regional scale assessments: Central British Columbia

The two case studies in Central British Columbia were part of regional scale steep creek geohazard risk prioritization studies. The study areas covered the entire Regional District of Central Kootenay (RDCK, 22,000 km^2) and the entire Thompson River Watershed (TRW, 55,000 km^2), British Columbia. The objective of the prioritization studies was to characterize and prioritize steep creek hazards that might impact developed properties. The studies focused on alluvial fans, as these are the landforms commonly occupied by elements at risk. Relative ratings of the likelihood that events occur and impact elements at risk were combined with consequence ratings to assign priority ratings to each fan. The results supported risk management decisions, policymaking, and prioritization of further assessment.

Flow-R modelling focused on one component of the prioritization studies, the assignment of impact likelihood ratings. An impact likelihood rating was assigned to each fan of the study areas considering the relative spatial likelihood that geohazard events result in uncontrolled flows that could impact elements at risk. Uncontrolled flows were assumed to result from avulsions, whose potential depends of characteristics such as channel confinement and surface evidence for previous avulsions. Flow-R propagation parameters were calibrated based on typical parameters from the literature, experience with calibrated case studies (e.g., Section 3.1), and using the extent of mapped alluvial fans within the study areas. Table 2 and Table 3 show the calibrated debris-flow and debris-flood parameters, respectively, for the RDCK case study.

Table 2. Calibrated debris-flow parameters used in Flow-R for the RDCK assessment.

Selection	Flow-R Parameter	Value
Directions algorithm	Holmgren (1994) modified	dh = 2, exponent = 1
Inertial algorithm	Weights	Gamma (2000)
Friction loss function	Travel angle	5°
Energy limitation	Velocity	< 15 m/s

Table 3. Calibrated debris-flood parameters used in Flow-R for the RDCK assessment.

Selection	Flow-R Parameter	Value
Directions algorithm	Holmgren (1994) modified	dh = 2, exponent = 1
Inertial algorithm	Weights	Cosinus
Friction loss function	Travel angle	4°
Energy limitation	Velocity	< 15 m/s

The Flow-R “complete” method with sum of susceptibilities was used. The summed susceptibility values followed a negative exponential distribution (Fig. 2). They were classified into zones of very low, low, moderate, and high relative susceptibility based on comparison to fans with the clearest evidence of the extent of previous events, including avulsion channels and deposits visible on LiDAR imagery. Zones of the DEM with summed susceptibility values lower than a threshold corresponding to the 70th percentile were attributed ‘very low’ regional susceptibility (i.e., ‘very low’ susceptibility include the majority of areas covered by Flow-R simulations). Zones of ‘low’ regional susceptibility were defined between the 70th and 85th percentile (the 85th percentile corresponding approximately to the mean susceptibility value); ‘moderate’ and ‘high’ susceptibility were defined between the 85th and 95th percentile, and greater than the 95th percentile, respectively (Fig. 2). Portions of alluvial fans not encompassed by susceptibility modelling were interpreted as having “very low” regional susceptibility where modern fan morphometry encouraged flow away from the unaffected area, or not affected by debris flows/floods where deep channel incision indicated paleofans.

Because the study objective was to compare relative risk at a fan level of detail, the analysis did not include estimation of spatial impact likelihood for individual elements at risk on a fan. However, average impact likelihood ratings were assigned to compare fans, based on the proportion of each mapped fan area covered by moderate and high Flow-R susceptibilities. The initial impact likelihood ratings (based on the Flow-R “complete” method with sum of susceptibilities) were adjusted to consider avulsion susceptibility or recorded evidence, as Flow-R susceptibility modeling does not account for recent activity on the fans. Although impact likelihood ratings were assigned only to mapped alluvial fans, Flow-R simulations extending beyond the fan boundary were also considered when evaluating sites for potential future assessment. Impact likelihood ratings were verified based on both geomorphic mapping and records of past events.

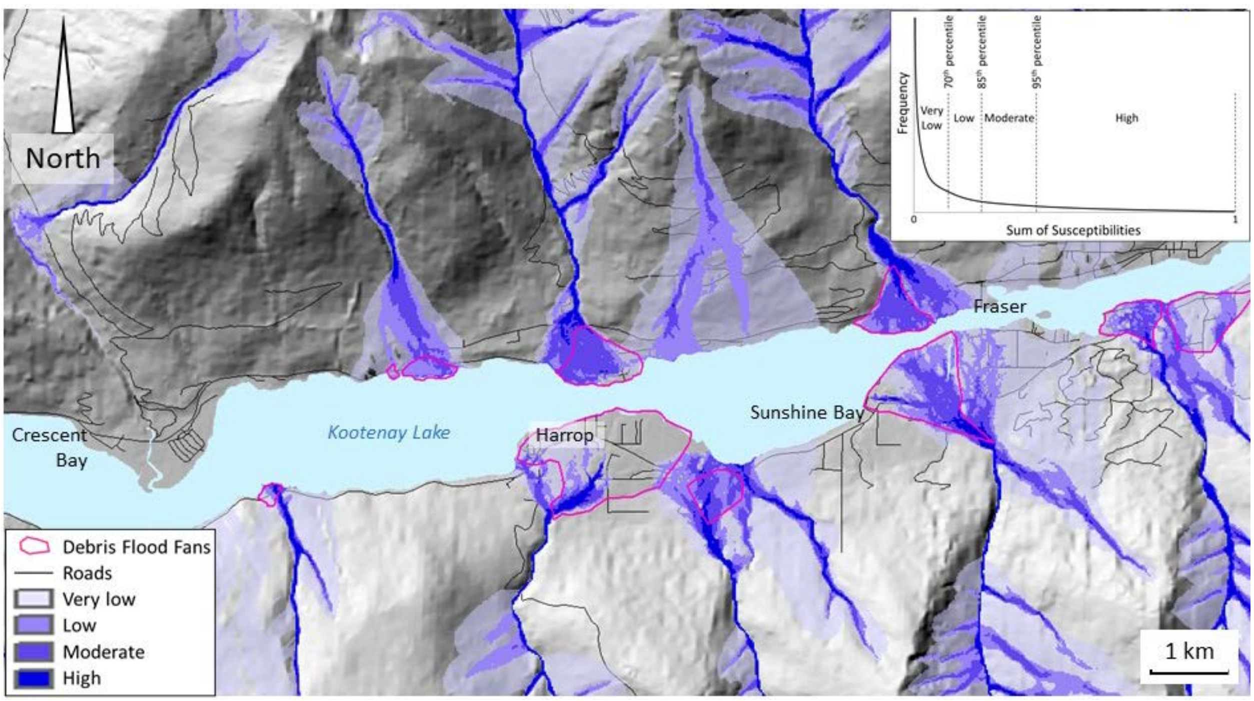

Fig. 2. Debris-flood susceptibility map for a section of the RDCK study area showing the spatial distribution of very low, low, moderate and high susceptibility. The inset figure shows a sketch illustrating the negative exponential distribution of summed susceptibilities and the percentiles used to define zones of very low, low, moderate and high susceptibility.

3.3. Refined regional scale assessment: roadway corridor in southwestern British Columbia

This study aimed to risk-prioritize creeks subject to both debris flows and debris floods along a 30 km long roadway corridor is southwestern British Columbia. The goal of creek prioritization was to facilitate objective and science-based allocation of resources for mitigation along a roadway located at the toe of steep creeks, without requiring detailed and costly hazard frequency-magnitude analysis and scenario modelling at each creek. Debris-flow and debris-flood hazards were categorized based on both relative frequency of initiation (rating of source areas) and their susceptibility to impact and cover the roadway.

FLOW-R was used to develop susceptibility zones within each fan of the entire study area, allowing comparison of relative susceptibility throughout the corridor. For this purpose, the “complete” method with sum of susceptibilities was used after calibration of propagation parameters. The summed susceptibility values were classified into areas of low, moderate, and high susceptibility in a similar manner as described in Section 3.2. Areas within alluvial fans not inundated by Flow-R modelling represent inactive zones, considering the present-day morphometry of the DEM.

The results suggest that the methodology allows direct comparison of the relative debris-flow/debris-flood runout susceptibility for the alluvial fans within the study area. Areas of higher relative regional runout susceptibility corresponded to watersheds with higher susceptibility of the source zones (i.e., higher number of potential debris flows/floods that can reach an alluvial fan), as well as increased control of topographic features (i.e., incised channels or avulsion paths within alluvial fan). Fig. 3 compares the calculated susceptibility values with the extent of debris-flow deposits from past events. As explained in Section 2.3, the susceptibility values calculated in this study have no physical meaning, rather were used for comparison between sites within the roadway corridor to determine higher relative hazard potential.

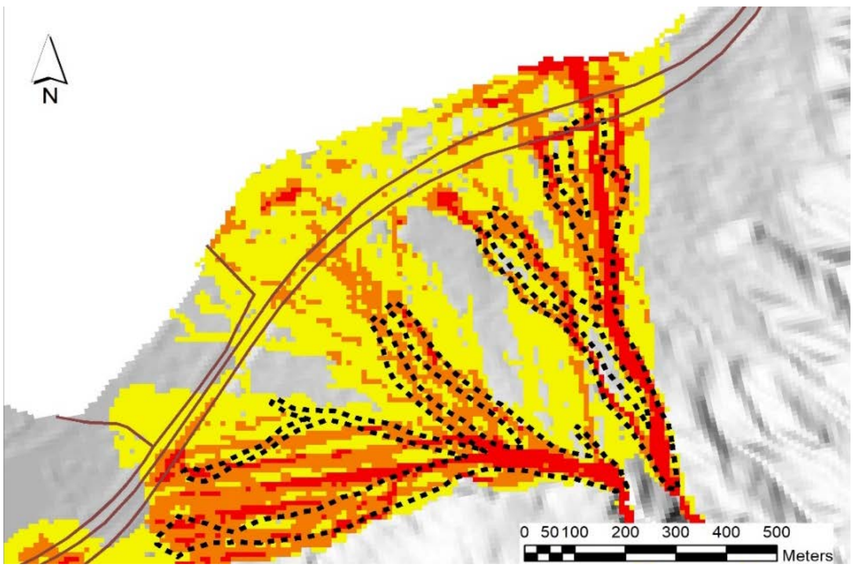

Fig. 3. Map comparing the extent of recent debris-flow deposits (black, dashed lines) on an alluvial fan of the roadway corridor with the results of Flow-R modeled susceptibility, where yellow = low susceptibility, orange = moderate susceptibility, and red = high susceptibility. The alignment of the roadway is shown with brown lines.

4. Discussion

This paper presents a semi-automated methodology for debris-flow and debris-flood susceptibility mapping at regional scale, which combines GIS-based identification of geohazard sources with geohazard propagation modeled using the software Flow-R. Four case studies show that modeled susceptibility includes areas inundated by known debris-flow or debris-flood events and match active alluvial fan boundaries. This provides a basis to evaluate relative hazards in cases where detailed frequency-magnitude analyses and scenario modelling is not feasible.

4.1. Semi-automated steep creek geohazard source identification

Steep creek geohazard source zones were identified as stream segments automatically generated from DEMs. It is possible that stream segments were not generated for very small watersheds. At the scale of the regional studies, we consider that very small watersheds are unlikely to represent a significant steep creek geohazard risk. Another potential limitation of using stream segments as source zones is that steep creek geohazards rarely initiate exactly in stream channels and are more commonly triggered by landslides initiating on channel side slopes. Consequently, defining debris-flow source zones based on stream segments should be considered an empirically-based proxy for actual source areas, because it can be efficiently completed and calibrated for large regions. This simplification does not affect propagation results significantly.

The methodology for source identification applied to the Canmore, RDCK and TRW case studies answered the question, "given debris-flow/flood occurrence, what is the runout/spreading?". Watersheds can exist where debris-flow source zones are mapped but no actual debris source exists (e.g., bare rock channels with insufficient sediment supply), or where limited source areas result in lower runout susceptibility. This simplification was necessary due to the limited data concerning sediment availability at regional scale. For more refined studies, such as the roadway case study, where more detailed information was available about steep creek source zones, rating of source segments can be integrated.

The proposed semi-automated approach for steep creek process type classification (based on Melton ratio and watershed length) systematically identifies stream segments as debris-flow or debris-flood sources. In reality, steep creek processes may behave transitionally between debris flows and debris floods, and the two processes may occur alternatively on the same alluvial fan. In the proposed methodology, both debris-flow and debris-flood stream segments can exist within the same watershed and consequently, alluvial fans may be inundated by Flow-R simulations from both debris-flow and debris-flood segments. To account for this limitation, expert judgement was applied to classify each alluvial fan as the most likely process type.

4.2. Susceptibility mapping with Flow-R

Propagation parameters in Flow-R are empirical and require calibration. In the case studies presented in this paper, debris-flow and debris-flood propagation parameters were calibrated so that the extent of the simulations reproduces as closely as possible the extent of mapped alluvial fans. In terms of frequency-magnitude relationship, the susceptibility mapping corresponds to the affected fan areas of rare and large events, and in many cases the modelled extent could be viewed as the largest credible event.

The RDCK case study illustrates the applicability of susceptibility mapping at regional scale using Flow-R. It is important to note that for larger study areas (e.g., TRW case study), application of a single set of model parameters per process may not be appropriate; the study area may need to be subdivided into sub-regions based on their physiographic, geological and/or climatic conditions, and model parameters calibrated independently for each sub-region. It is also interesting to note that two of the studied watersheds in the Canmore area contain dams. Such watersheds can be expected to require specific model parameters for susceptibility mapping. This is consistent with previous work by Pastorello et al. (2017).

Calculation of the sum of susceptibilities in Flow-R allows subdivision of alluvial fans in zones with various susceptibility levels, as illustrated in Sections 3.2 and 3.3. In the case study presented in Section 3.3, this approach allows consideration of individual elements at risk within the fans of a studied region.

Flow-R propagation is controlled by present-day topography of alluvial fans, as provided by DEMs. The summed susceptibilities allow consideration of watershed size and associated cumulative potential source zones. In addition, if source zones are weighted (e.g., Section 3.3), modelled susceptibility accounts for initiation frequency implicitly and in a relative way. However, the software does not fully take into consideration evidence for past avulsions in the assessment of fan activity and potential for uncontrolled flows.

5. Perspective

The case studies presented in this paper illustrate a methodology for steep creek geohazard susceptibility mapping combining semi-automated identification of geohazard sources with propagation simulations modeled using the software Flow-R. The reported case studies are characterized by different assessment levels, depending on the scale of the study area and the degree of understanding and knowledge of steep creek geohazards. The following is an attempt to define three levels of detail for debris-flow/flood hazard incorporating the proposed methodology:

- High/screening level assessment: Flow-R simulations are run from stream segments using the "quick" method to generate susceptibility maps corresponding to the maximum expected extent of steep creek geohazards. These maps allow identification of locations where elements at risk intersect zones susceptible to debris-flow or debris-flood hazards.
- Regional scale assessment: in the RDCK and TRW case studies, Flow-R simulations are run from stream segments using the "complete" method to generate susceptibility maps corresponding to the maximum credible extent of steep creek geohazards, and allowing rating each fan using an impact likelihood value. Combined with estimates of hazard likelihood and potential consequences, the rating provides an objective, practical approach

to prioritize hundreds to thousands of steep creek fans across many thousands of square kilometers. It should be noted that impact likelihood ratings are for entire fans and therefore not estimates of spatial probability of impact for specific elements at risk, which would vary depending on their location on the fans.

- Refined regional scale assessment: in the roadway case study, a similar approach as in the RDCK and TRW case studies was used, but the relative susceptibility rating was used to identify zones of higher susceptibility within alluvial fans to prioritize allocation of funds for mitigation work. This is a first step towards estimation of the spatial probability of impact for specific elements at risk (sections of the roadway in this case). However, the approach does not replace quantitative estimates of the spatial probability of impact for specific element at risk, as would be completed in a detailed study. Since susceptibility modelling does not consider volume or flow peak discharge, it is not suited for detailed risk analyses or risk control design, which require numerical modeling of flow extent, depth and velocity for specific hazard scenarios.

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