Simulation of some debris flows in Klanawa watershed in Vancouver, British Columbia

GeoCalgary
2022 October 2-5
Reflection on Resources

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ABSTRACT
Debris flows are steep mountain hazards that may impact infrastructure, human life and environment considerable distance from their source. Runout simulation tools often require site-specific parameters that may be difficult to estimate or impractical to deploy at a regional scale. In contrast, models that do work regionally tend to provide limited data to the user. In this study, a relatively new agent-based simulation program called DebrisFlow Predictor was used to estimate the scour, deposition and volume of debris flows which occurred in a selected area of the Klanawa Watershed in Vancouver Island, British Columbia. This program employs a group of autonomous subroutines, or agents, that act on a digital elevation model (DEM) using a set of probabilistic rules for scour, deposition, path selection, and spreading behaviour. The advantages of this program are that it requires limited input, including DEM and user-defined initiation zones, and only modest computational power.

RÉSUMÉ
Les coulées de débris sont des risques liés aux montagnes escarpées qui peuvent avoir un impact sur les infrastructures, la vie humaine et l'environnement à une distance considérable de leur source. Les outils de simulation du ruissellement nécessitent souvent des paramètres spécifiques au site qui peuvent être difficiles à estimer ou peu pratiques à déployer à l'échelle régionale. En revanche, les modèles qui fonctionnent au niveau régional ont tendance à fournir des données limitées à l'utilisateur. Dans cette étude, un programme de simulation basé sur des agents relativement nouveau appelé DebrisFlow Predictor a été utilisé pour estimer l'affouillement, le dépôt et le volume des coulées de débris qui se sont produits dans une zone sélectionnée du bassin versant de Klanawa sur l'île de Vancouver, en Colombie-Britannique. Ce programme emploie un groupe de sous-programmes autonomes, ou agents, qui agissent sur un modèle numérique d'élévation (DEM) en utilisant un ensemble de règles probabilistes pour l'affouillement, le dépôt, la sélection de chemin et le comportement d'étalement. Les avantages de ce programme sont qu'il ne nécessite qu'un nombre limité d'entrées, y compris le MNE et les zones d'initiation définies par l'utilisateur, et une puissance de calcul modeste.

1 INTRODUCTION

Debris flow is the term given to a moving mass of loose mud, soil, rock and debris that travels extremely rapidly (velocities > 3 m/s and typically between 5 and 10 m/s) down steep slopes in mountainous regions. Often triggered by heavy rainfall, debris flows tend to impact infrastructure, communities, lives, and the environment considerable distance from the source. Though debris flow mechanics are well understood, modeling the complex dynamic behavior is complicated and can depend on several interacting static and dynamic parameters. Estimating the runout and extent of debris flows is, therefore, a challenging task.

Despite the challenge, the need to credibly estimate runout remains. Empirical, analytical, and numerical methods have been developed to assess debris flow impacts. By simulating the runout extent, volume, and velocity of debris, the impact loads and the effects of runup height on the infrastructure can be estimated (Kwan 2012). Properly simulated debris flow results could be used to identify the hazard and risk zones of a specific area, which can help engineers make decisions and develop mitigation strategies.

Landslides runout analysis includes the simulation of past landslides and prediction of future potential events. Debris flow runout analysis can be performed numerically by using three-dimension models such as smoothed particle hydrodynamics (SPH) (McDougall and Hungr 2004) and two-dimension models (i.e., shallow water equations) (Hungr et al. 2005). Over the last two decades, more than 20 different numerical tools have been developed based on the hydrodynamic modelling approaches (e.g., DAN3D, Flow-2D, RAMMS). An overview of these models can be found in McDougall (2017). One of the major challenges of this type of modeling technique is the selection of model parameters. Han et al. (2017) summarized the challenges in estimating model parameters for numerical simulations. For example, while SPH is based on advanced theories and can handle complex geometries, it requires estimates of yield strength and dynamic viscosity, which may themselves be unknown or difficult to obtain. In addition, the simulations tend to be computationally very expensive, especially for large areas and smaller mesh sizes. Therefore, comprehensive numerical simulations to identify the effects of key parameters are difficult.

To overcome some of the limitations of existing numerical modeling, a different methodology using cellular automata (CA) has been deployed in several studies to model complex natural phenomena, including debris flows (Iovine 2003; Guthrie et al., 2008), snow avalanches (Barpi et al. 2007), and lava flows (Spataro et al. 2004). Cellular automata evolves in a discrete space-time context. It involves a collection of cells arranged in a grid shape, where the state of each cell depends on a function of time according to a defined set of rules driven by the states of neighbouring cells. The main advantages of cellular automata models are that they require fewer model parameters and less computational time than those of numerical simulation (e.g. SPH) yet provide satisfactory results. Several studies showed successful applications of the cellular automata model for debris flow runout simulations (Han et al. 2021; Guthrie and Befus 2021; Guthrie et al., 2008; D'Ambrosio et al. 2003(a); D'Ambrosio et al. 2003(b)). Further details on CA and its application in debris flow modelling are available in previous studies (Han et al. 2017).

Between 1880 and 2019, 123 landslides caused fatalities in British Columbia (BC), and among all landslides from 1950 to 2019 in BC, 53% were debris flows (Strouth and McDougall 2021). The frequency of debris flows is higher on the windward side of mountains exposed to higher rainfall. For example, the west coast of Vancouver Island has approximately three times as many debris flows as the eastern zone over similar time periods (Guthrie 2009).

Forestry, the primary resource-based industry over the last century in BC, has directly and indirectly increased the rate of landslides. Guthrie and Brown (2008), for example, reported that human activities that induced landslides (e.g. forest harvesting) had doubled the landscape erosion compared to the next highest millennia over the Holocene. Consequently, understanding potential debris flow impacts also represents an important management objective for the forest industry.

The objective of the present study was to simulate debris flows in a selected area of the Klanawa watershed on the west coast of Vancouver Island, BC, using the computer program DebrisFlow Predictor and then compare the results with available historical debris flows. We intend to provide a calibrated model that could be used as a predictive tool for subsequent hazard assessment in this area.

1.1 Study Area

The Klanawa watershed on Vancouver Island, British Columbia, is approximately 240 km^2 in size and located on the southwest coast side of the island. The floodplain is made up of glaciofluvial and alluvial sediments. Mid and upper slopes consist of glacially over-steepened morainal till or gravelly colluvium veneers (Morgan 2001) that frequently show signs of instability in the form of open slope and channelized debris flows. The watershed is also critical for the aquatic habitats, which are sensitive to peak flow disturbances and are affected by erosion and bedload sediment.

Guthrie et al. (2008) reported 331 debris flows over 500 m^2 in the Klanawa watershed from the available 1994–2001 air photograph record. Guthrie et al. (2010) examined the role of slope angle on erosion, deposition of debris, and the effects of topographic settings (i.e., presence of forest and roads) on spreading (e.g. width of the flow).

For the present study, approximately an 8 km^2 area was selected where debris flow footprint information was publicly available (Fig. 1). Ten debris flows within the study area were reported by Guthrie et al. (2008) (blue coloured landslides in Fig. 1). Of those, seven debris flows are simulated in this study and named P1–P7 (Fig. 1). Six more recent debris flows were identified using Google Earth Pro for the period of 2015–2021 (C1–C6 on Fig. 1). C1 occurred sometime between July 2019 and April 2021, while C2–C6 occurred between April 2021 and October 2021. We note that debris flow might have occurred during other periods (e.g., 2008–2015); however, because of vegetation and the unavailability of time series maps in Google Earth Pro, those debris flows were not recorded here.

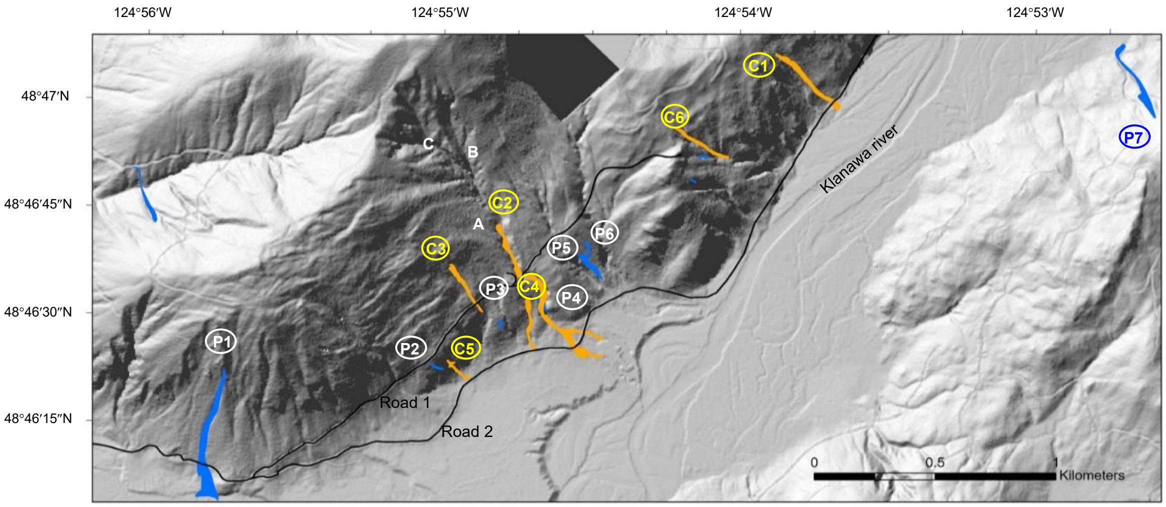

Figure 1. Debris flow footprints in the study area.

The above-mentioned debris flows (P1–P7 & C1–C6) occurred in varying settings (e.g., topography) and the spatial extent varied widely between them. The present study attempts to simulate these debris flows to show the performance of the program and to identify the influence of some input parameters which could be site-specific.

2 MODELLING CONCEPTS

DebrisFlow Predictor is a computer program developed by Guthrie and Befus (2021) and based on a cellular automata model. The simulation of runout with this program provides landslide pathways and sediment volume (scour and deposition) along the flow path. One of several advantages of the program is that these simulation results can be imported into any GIS software to compare with the mapped (actual) landslides and land use managers with subsequent decisions.

DebrisFlow Predictor follows a set of simple rules for scour, deposition, path selection, and spread. These rules were developed empirically based on the observations of debris flows in coastal areas of BC. These rules follow probability distributions for 12 slope classes (See Table.1 Guthrie and Befus 2021). These probabilities are based on the fieldwork conducted by Wise (1997), Guthrie et al. (2008) and on work by Guthrie and Befus (2021).

The program requires limited input parameters for runout assessment. Firstly, it requires the digital elevation model (DEM) of the area with a resolution of 5 m × 5 m. Secondly, the user has to identify the initiation zones of the debris, which can be done in multiple ways. Users can select a single cell (5 m × 5 m), a small group of cells (15 m × 15 m), or multiple cells (a larger source zone) simply by painting over a larger area. The user could also import the initiation zones as a shapefile in the program, which can automatically be turned into 15 m × 15 m initiation zones. In the present study, debris flow initiation points were imported (identified from google earth images) as a shapefile within the program.

When the DEM is imported into the program, each cell in the working grid collects the basic information from the DEM, including elevation, position, slope, and aspect. Each activated cell (i.e. each cell selected manually or by the computer model to generate an agent) contains an agent—an autonomous subroutine that interacts with the surface model and other agents. At a given time step, erosion and deposition are calculated, and the difference between these two gives the net mass. The mass is shed to the new cells by spawning additional agents. Each agent continues to move downslope until its mass balance is zero.

The direction of debris flow is determined by a Moore Neighborhood algorithm. The Moore Neighborhood method determines the direction of debris flow by obtaining the elevations of the eight cells surrounding the core cell. In each time step, the debris from the core cell flows toward the surrounding lowest vacant cells. When there are no vacant cells, or three cells have the same elevation, the flow direction is determined by a combination of random chance and momentum preservation.

The redistribution of mass or spreading behaviour is described by a probability density function defining the standard deviation (σ) as

$$\sigma = \left(\frac{m_{max} - m}{m_{max}}\right)^n (\sigma_L - \sigma_s) + \sigma_s \qquad [1]$$

where m_{max} is the fan maximum slope to limit spreading above the selected slope value, m represents DEM slope, n is a skew coefficient, σ_L is low slope coefficient, and σ_S is steep slope coefficient.

These parameters can be calibrated iteratively within the model, and the results compared to known (observable) events or landforms. The parameter $m_{\max}$ limits spreading to slopes flatter than the selected value. Guthrie and Befus (2021) recommended using 27° where additional information is not available. The parameters n, σ_L, and σ_S control the amount of spread and, therefore, the creation of new agents redistributed to surrounding cells. With an increase in the value of σ_L and σ_S the spreading increases in the low and steep slope areas, respectively. The parameters used in this application of DebrisFlow Predictor are listed in Table 1. Further details of these parameters could be found in Guthrie and Befus (2021).

The user can make modifications to account for variations in local geomorphology (e.g. surficial material depth) by changing the program's deposition and erosion multiplier sliders button. The program also considers mass loss in turns, if crudely, specified every 45° of departure from a straight line. Finally, it has the ability to set a minimum scour depth in the initiation zone to account for the observed experience.

Table 1. Parameters used DebrisFlow Predictor

Fan maximum slope ($m_{\max}$)	34°
Low slope coefficient (σ_L)	0.35
Steep slope coefficient (σ_S)	1.35
Skew coefficient (n)	1.1
Maximum spawns allowed	4
Deposition multiplier	1x
Erosion multiplier	0.7x
Mass loss per 45° turn	20%
Minimum initiation depth	0
Number of model runs	50

3 RESULTS AND DISCUSSION

Figures 2(a) and 2(b) show the debris flow over an area of a relatively steep slope (C1). The simulated debris flow trajectory shown in Fig. 2(b) is very similar to the mapped debris flow shown in Fig. 2(a). In the simulation, yellow and red colours represent scour, while green and blue represent the areas of deposition. Deeper deposition (blue) is found near the toe of the debris flow.

A close examination of the LiDAR slope profile shows that the slope angle along the path of this debris flow varies primarily between 40° and 50° with some local flatter

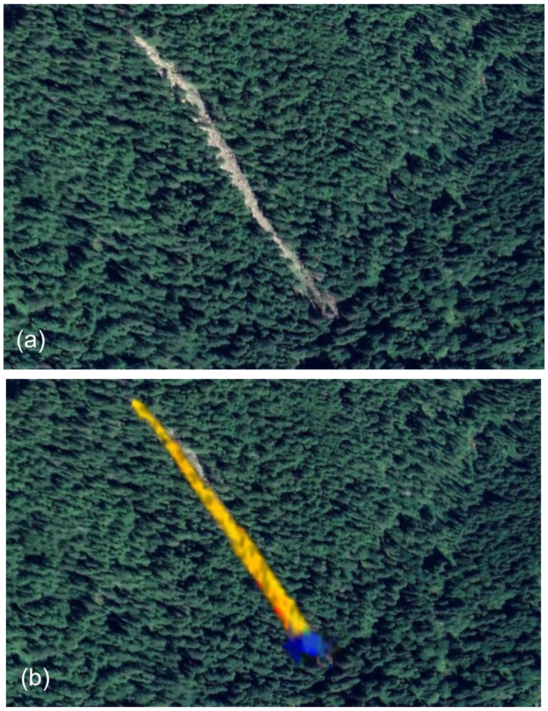

Figure 2: Debris flow in a steep area: (a) mapped footprint (background image from google earth); (b) DebrisFlow Predictor simulation.

slopes near the toe and steeper slopes near the initiation zone and at the middle of the travel path. In this case, flow occurred almost along a line without significant lateral spreading or formation of multiple paths or diversion because the slope is relatively steep and uniform.

The debris flow C2 was a channelized debris flow that occurred in a pre-existing gully (Fig. 3(a), 2019 map). Figure 3(b) shows the trace of a long debris flow(s) along this gully which occurred in 2021. Vegetation covered the upper part of the gully (above point A in Fig. 1) and the location and size of the debris flow initiation zone were difficult to find. Several attempts were made to simulate the observed debris flow footprint by varying the location (points A–C in Fig.1) and the size of the initiation zones. The following were the key observations: (a) for a smaller initiation zone (15 m x 15 m) at point A, the debris flow stopped after travelling a small distance (~ 90 m); (b) when the size of the initiation zone was enlarged (e.g., ~ 50 m x ~ 50 m), the debris travel distance increased but still less than the observed extent; (c) when the location of the initiation zone was moved to a higher elevation (e.g., B or C), travel distance increased, presumably because of increased higher kinetic energy that facilitated the flow over gentler slopes (even opposite near the road) downstream; and (d) an increase in the size of the initiation zone for locations B and C increased the extent of debris flow. Better simulation results could be obtained by adjusting the parameters in Table 1. However, none of the simulations of case C2 for the above-mentioned conditions closely matched the observed debris flow pattern. Though this may be an error of parameterization, it may also represent a complication modeling regional debris flows, particularly if parameters are different within a single area. Despite the ease of the use, the program does seem to require expert judgement to calibrate and provide representative scenarios.

Figure 4 highlights another program feature, the ability to determine the probability of inundation based on multiple runs (assuming calibration has been successful). In this case, the darker areas represent higher inundation probabilities. As the program results are probabilistic, any two runs are not identical, and multiple runs are recommended to reach a conclusion on the likely path of debris flow. In this study, the simulation was run for 50 times.

Figure 3: Satellite image along the flow path of C2: (a) image in 2019; (b) image in 2021.

The simulated debris flow paths for most cases are similar to the footprint observed in the field (compare Figs. 1 & 4). However, there are some differences. For example, three potential flow paths were identified in the simulation of P1, while there was only one path observed by Guthrie et al. (2008). This may simply be the stochastic distribution of individual runs in a similar landscape, but it could also be an effect of the DEM resolution or the actual 2019 topography that was altered by the earlier (mapped) landslide. Again, expert judgement as to the applicability of the results is recommended.

Debris travelled only a limited distance in C2 simulation and considerably less than the channelized flow observed in the field. Potential reasons for this have been described above. The simulated travel distance for case C6 was larger than that observed in the field. Again, this may be the result of local effects, parameterization, or simply the stochastic nature of a single event versus multiple modeled events. Despite the foregoing, DebrisFlow Predictor gives, by and large, comparable flow paths to those observed in the field.

Several studies reported the role of roads and logging on the mobility of debris. For example, Guthrie (2009) reported that while road building and logging could increase the occurrence of landslides, the existence of roads could also reduce debris flow volumes by creating a topographic resting place for sediment. For several cases (e.g., P1, C1 & C3), debris flows were reduced or were stopped by the two existing roads in this area.

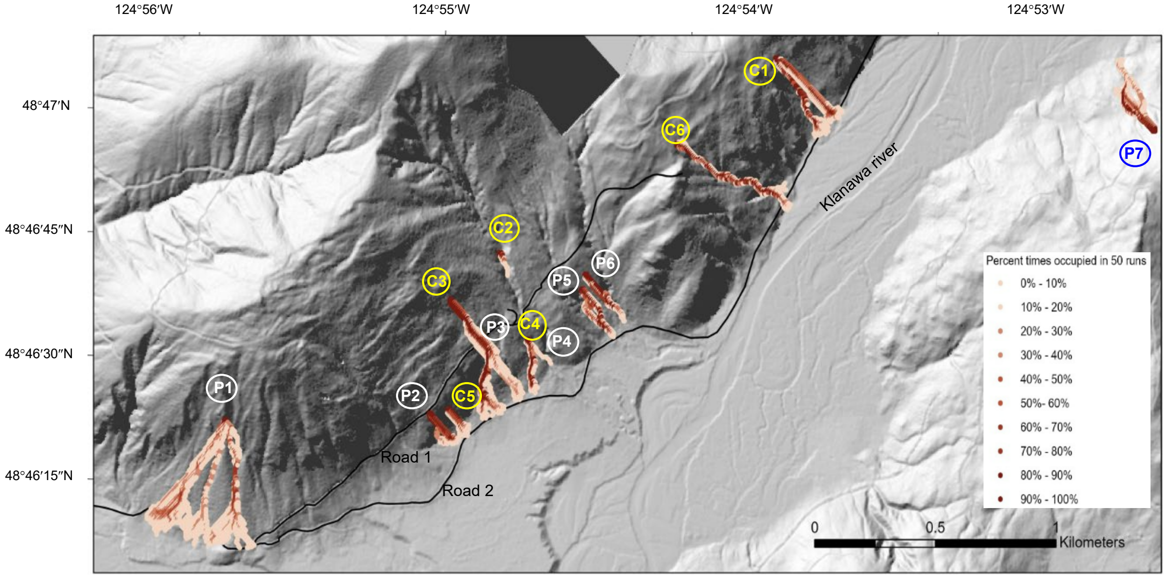

Figure 4: Debris flow simulation results. The results show both the cumulative footprint of multiple runs and the likelihood that any location on the map would be occupied in a single run.

The depth of the debris could be calculated using the simulated results. The depth information can be used to facilitate vulnerability calculations and ultimately develop mitigation strategies for the impact of debris flow. For example, Ciurean et al. (2017) used the depth of debris to define damage class. As shown in Figure 5, a higher accumulation of debris occurred near the toe, and the maximum depth is 3.85 meters, which occurred in case C3.

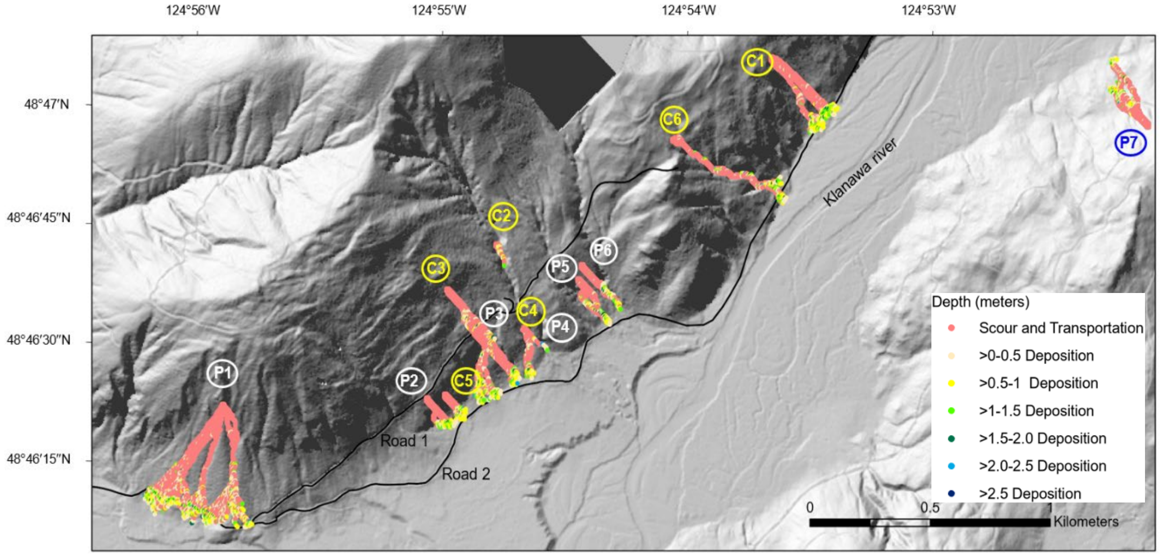

Figure 5: Depth of debris obtained from DebrisFlow Predictor.

4 CONCLUSIONS

DebrisFlow Predictor was used to simulate debris flow in a selected area of the Klanawa watershed, Vancouver Island. Simulations were performed for a total of 13 cases using the 2019 DEM. Most of the simulations showed debris flow patterns similar to the footprints observed in the field. For some, DebrisFlow Predictor provided multiple potential flow paths, of which the observed landslide used just one. Finally, with the parameters selected herein, the model underestimated the flow through a pre-existing channel.

Further studies are recommended to model channelized debris flows and provide a better estimation of model parameters.

5 ACKNOWLEDGEMENTS

The works presented in this paper were supported by the Natural Sciences and Engineering Research Council (NSERC) and Equinor Research Chair grants.

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