A comparison of two runout programs for debris flow assessment at the Solalex-Anzeindaz region of Switzerland

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ABSTRACT
Debris flows are a major consideration in land-use planning and assessing the integrity of infrastructure in mountainous regions. In the present study, two computer programs, "Flow-R" and "DebrisFlow Predictor," are used to simulate debris flows in the Solalex-Anzeindaz region of the Swiss Alps, where many historic debris flow hazards are known. Both tools use the same Digital Elevation Model. Flow-R simulates the process based on spreading and runout distance algorithms. DebrisFlow Predictor uses a set of probabilistic rules for scour, deposition, path selection, and spreading. In the present simulations, both programs give comparable results in terms of spread. However, the additional information on the area, volume, and depth of debris along the landslide path provided by the DebrisFlow Predictor might make it a better hazard assessment tool.

RÉSUMÉ
Les coulées de débris sont à prendre en considération dans la planification de l'utilisation des terres et l'évaluation de l'intégrité des infrastructures dans les régions montagneuses. Dans la présente étude, deux programmes informatiques, « Flow-R » et « DebrisFlow Predictor », sont utilisés pour simuler des coulées de débris dans la région de Solalex-Anzeindaz dans les Alpes suisses, où de nombreux cas historiques de coulée de débris sont connus. Les deux outils utilisent le même modèle numérique d'élévation. Flow-R simule le processus en se basant sur des algorithmes de distance d'étalement et d'étalement. DebrisFlow Predictor utilise un ensemble de règles probabilistes pour l'érosion, la déposition, la sélection de chemin et le comportement des débris. Sur la base des résultats de simulation, les deux programmes donnent des résultats comparables en termes de propagation. Cependant, les informations supplémentaires sur l'aire, le volume et la profondeur des débris le long de la trajectoire du glissement de terrain fournies par le DebrisFlow Predictor pourraient en faire un meilleur outil d'évaluation des risques.

1 INTRODUCTION

Debris flow is a gravity-driven moving mass of soil, mud, rock, and water. It is an extremely rapid flow-type landslide, which tends to travel long distances from its source (Hungr et al. 2014). Debris flows pose considerable threats to communities, infrastructure, people, and resources.

Debris flow runout analysis can simulate the displacement of the failed materials originating from past landslides and can also predict the motion of debris in future landslides (McDougall 2017). This type of analysis should be a key component of hazard and risk assessment (Loew et al. 2016). Runout analysis can further help to estimate the runup height and impact loads on structures, a necessary step when assessing mitigation strategies (Kwan 2012). Estimating landslide extents, runout distances, and depths of debris is one of the most challenging tasks. Complete models of debris flow incorporating appropriate constitutive relationships of the flowing materials may not be practical because of significant uncertainties involved in material behavior and the computational cost of the simulation, especially when it occurs over a large area. McDougall (2017) classified the available runout analysis methods into two broad categories: (i) empirical–statistical methods and (ii) analytical methods. Analytical modeling can provide in-depth information; however, it is highly reliant on correct parameterization and may be difficult to implement at the regional scale. Iverson (1997) suggested using simplified spatially distributed models based on empirical or semi-empirical approaches for regional-scale modeling. These simplified approaches can incorporate the information derived from statistical analysis of data.

Flow-R is a computer program developed in Matlab by the researchers at the University of Lausanne, Switzerland, incorporating spatially distributed empirical models, which can be used to identify the debris flow initiation zones based on the combination of user-defined criteria. The program can also calculate the extent (inundation) and directions (path) of debris flows. This open-source software has been used for runout assessments of debris flows in different countries, including Switzerland (Horton et al. 2008; Horton et al. 2013), France (Kappes et al. 2011), Italy (Blahut et al. 2010), Norway (Fischer et al. 2012), and Argentina (Baumann et al. 2011).

DebrisFlow Predictor is a separate stand-alone computer program that was developed by Stantec (Guthrie and Befus 2021) based on the cellular automata methods (Wolfram 1984). It follows a set of simple rules for scour, deposition, path selection, and spread. The simulation of runout with this program provides, in addition to inundation and path selection, the area, volume, and depth of debris along the flow path. Guthrie and Befus (2021) used this program to estimate sediment input to a stream network in a mountainous area in Papua province in Indonesia and also assessed the risk of debris flow in a community in Vancouver, Canada.

1.1 Study Area

The Solalex-Anzeindaz region in the Swiss Alps is considered herein to test the performance of both above-mentioned programs. Debris flows are very frequent on the south side of the Diablerets Range and regularly block the road that traverses the Solalex-Anzeindaz region (Horton et al. 2013). The accumulations of sediment on fans in the area of interest are ongoing and constructed of sediment from folded limestone and marl layers from the upslope Diablerets nappes (Badoux and Gabus 1990). We selected a subset of the region (~4 km^2) for computational efficiency.

The objective of the study was to compare the simulation results of debris flow runout in the Solalex-Anzeindaz region using Flow-R and DebrisFlow Predictor.

2 MODEL CONCEPTS

2.1 Flow-R

In Flow-R, the users primarily define two sets of parameters/criteria. First, in source areas, the debris flow initiation zones are identified. There are several options available within the program. For example, the initiation zone could be identified based on the combination of user-defined criteria for geological, morphological and hydrological conditions. The users can also select predefined sources (e.g., if the landslide initiation zones are known). Second, for propagation, debris flow criteria are defined.

2.1.1 Source Area Identification

Debris flow source areas can be identified by applying conditions to selected parameters, including slope gradient, aspect, curvature, flow accumulation, geology, land-use and lithology. According to Rickenmann and Zimmermann (1993), the combination of three criteria, namely sediment availability, water input, and slope gradient, primarily controls the initiation zone for the Swiss Alps. Sediment availability basically refers to the lithological unit. The majority of debris flows in the Swiss Alps originate from the terrain with slope gradients greater than 15° (Rickenmann and Zimmermann 1993). Water inputs can be represented by flow accumulations. Horton et al. (2013) determined that 0.01 km^2 was an appropriate threshold for the upslope contributing area for identifying the debris flow initiation zones in the Central Alps; however, these values can fluctuate depending upon the location. Analyzing the past events in Switzerland, a limit relationship was developed between slope gradient and upslope contributing area for the Central Alps. Every point above that limit should be considered critical (Rickenmann and Zimmermann 1993; Horton et al. 2013).

Curvature is another morphological characteristic considered for identifying debris flow initiation zones. It is the second derivative of the slope, and debris flows tend to be concentrated in slope concavities (i.e., gullies rather than ridges) (Delmonaco et al. 2003; Wieczorek et al. 1997). Plan curvature, which is perpendicular to the direction of the steepest slope, was considered to identify the gullies. By analyzing the orthophotographs, Horton et al. (2013) suggested the plan curvature value of 2/100 m^{-1} for a 10-m DEM of the Solalex-Anzeindaz region.

Fischer et al. (2012) applied Flow-R to develop a national debris flow susceptibility map for Norway. They chose five different sites (Troms county, Balsfjord, Junkerdal, Nesna, and alpine fjord landscape) of varying topography and geomorphology to test and calibrate the model. They determined different threshold values of the criteria for identifying the initiation zones, including plan curvature of -1.5/100 m-1 to -0.5/100 m-1, upslope contributing area of 0.3–1.0 ha, and slope thresholds 25°–45°.

Despite the ability to model debris flow sources found in Flow-R, susceptibility maps (for source zones) are common in literature and practice. This step has been excluded from the present study. Instead, the debris flow trajectories provided by SilvaProtect-CH were used, where the extent of debris flow (bounded by two solid black lines in Figure 1) was developed based on historical debris flow and simulations. We considered the starting point of the individual trajectory as the initiation point (red circles in Figure 1).

A total of 190 initiation points were considered in this study. A 0.5 m DEM was downloaded from the Federal Office of Topography database (swissALTI3D) and resampled into a 5 m DEM for simulation using Flow-R and DebrisFlow Predictor.

2.1.2 Assessment of Propagation

From initiation points, the program calculates the debris flow over the DEM according to the following: (i) a spreading algorithm and (ii) a runout distance algorithm.
The spreading algorithms provide the direction of flow, which are defined by two sub-algorithms, namely flow direction algorithm and inertial algorithm (also known as persistence function). Several direction algorithms were implemented in Flow-R, and the user can choose one of them for an analysis. In the present study, the algorithm proposed by Holmgren (1994) was selected (Eq. 1).

$$p_i^{fd} = \frac{(tan\beta_i)^x}{\sum_{j=1}^{8}(tan\beta_j)^x} \forall \begin{cases} tan\beta > 0 \\ x\varepsilon[1; +\infty] \end{cases} \quad [1]$$

where i, j are flow directions; p_i^{fd} is the susceptibility proportion in direction i; $\tan\boldsymbol{\beta}_i$ is the slope gradient between the central cell and the cell in direction i, and x is an exponent. In this study, x = 4 is considered based on the work of Claessens et al. (2005).

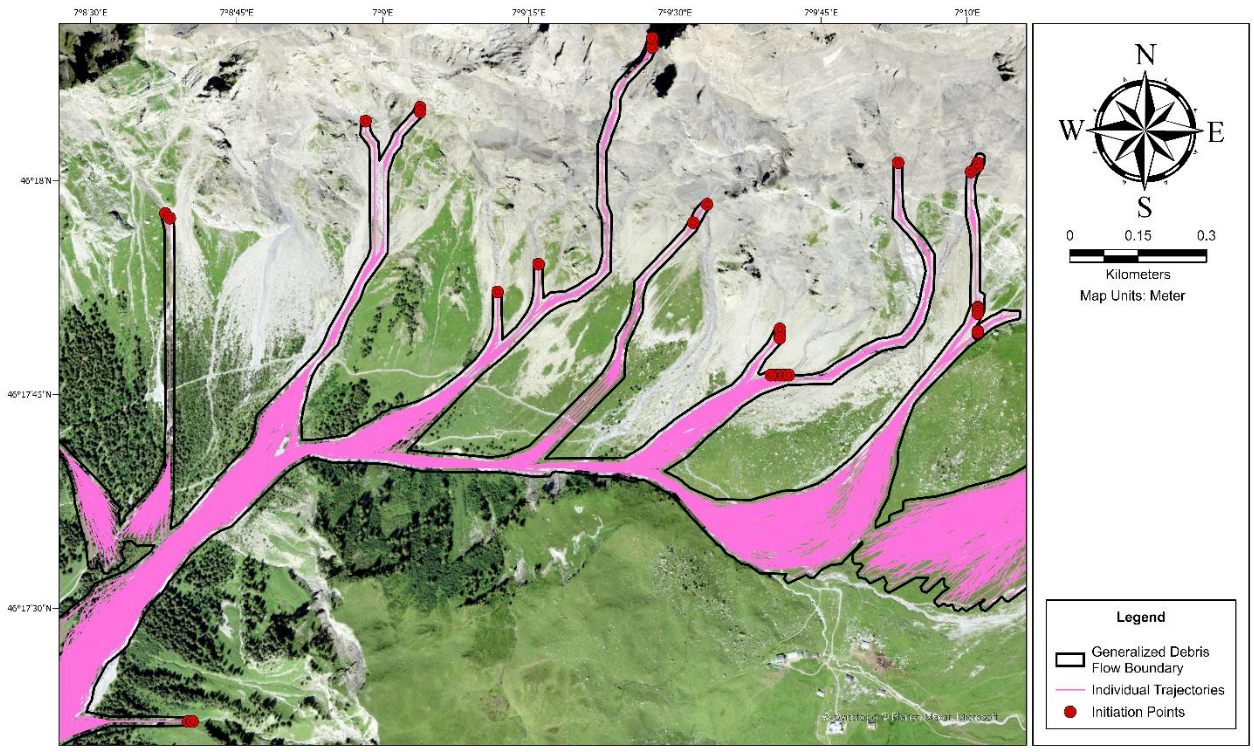

Figure 1: Debris flow trajectories developed by SilvaProtect-CH for Solalex-Anzeindaz region, Source: SilvaProtect-CH © BAFU

Two options are available for the inertial algorithm (weight and direction memory). In this study, the weight option is selected, which calculates the flow with a change in direction relative to the prior direction as

$$p_i^p = w_{\alpha_i} \quad [2]$$

where p_i^p is the flow proportion in direction i, and α_i is the angle between the previous direction and the direction from the central cell to cell i. The weight (w_{α_i}) was selected based on the work of Gamma (2000). Further details on inertial algorithms are available in Horton et al. (2013).

Debris flow runout can be determined by combining the flow direction algorithm and the persistence function (Eq. 3).

$$p_i = \frac{p_i^{fd} p_i^p}{\sum_{j=1}^{8} p_j^{fd} p_j^p} p_0 \quad [3]$$

where p_i is the susceptibility value in direction i, p_0 is previously determined flow proportion of the central cell.

The runout distance algorithms were developed based on energy balance, which can be written as

$$E_k^i = E_k^0 + \Delta E_p^i - E_f^i \quad [4]$$

where E_k^i is the kinetic energy of the cell in the direction i; E_k^0 is the kinetic energy of the central cell; ΔE_p^i is the change in potential energy, and E_f^i is the energy loss due to friction for the flow in direction i. The friction loss was calculated in this study by using a simplified-friction limited model (Corominas 1996), as discussed below. Note, however, that the user can also choose the two-parameter friction model proposed by Perla et al. (1980).

Corominas (1996) proposed a simplified approach to calculate the energy loss due to friction as:

$$E_f^i = g\, \Delta x \tan\varphi \quad [5]$$

where Δx is the increment of horizontal displacement in direction i; $\tan\varphi$ is the gradient of energy line in the direction i; φ is the travel angle, and g is the gravitational acceleration. An average slope angle (that connects the starting and ending points of the debris flow track) of roughly 11° characterizes the most probable maximum runout in the Central Alps (Rickenmann and Zimmermann1993; Huggel et al. 2002; Horton et al. 2013). Therefore, φ = 11° is considered in this study.

Finally, simulation results might be misleading if the slope is very steep. To control that, Flow-R incorporated a limiting velocity (V_{max}), as suggested by Horton et al. (2013). That is,

$$V_i = \min\left\{\sqrt{(V_0^2 + 2g\Delta h - 2gx\Delta x \tan\varphi)}\,, V_{max}\right\} \quad [6]$$

where Δh is the difference between the elevation of the central cell and the cell in the direction *i*. The maximum velocity measured in debris flow incidents in Switzerland was 13 to 14 m/s (Rickenmann and Zimmermann 1993). Therefore, V_{max} = 15 m/s is used in the present study.

2.2 DebrisFlow Predictor

The DebrisFlow Predictor is also a landslide runout simulation tool, which is similar to Flow-R, as both are empirically based. However, the underlying mechanics differ somewhat; DebrisFlow Predictor is an agent-based program where the landslide is represented by agents that occupy cells on a raster grid at a specific time step on which a set of rules could be applied. Also, the identification of source areas and debris flow propagation criteria are different from those used in Flow-R (Sections 2.1.1 & 2.1.2).

For source areas, using the tools in the program itself, users of DebrisFlow Predictor can manually select a single cell (5 m x 5 m), a small group of a 15 m × 15 m slide initiation zone, or multiple cells (a larger source zone) simply by painting over a larger area. Manual selection is done directly on the DEM in the program itself. Landslide initiation areas can also be imported from a point shapefile (.shp) and automatically populated with 15 m x 15 m landslide initiation zones.

In the simulations using DebrisFlow Predictor, the same initiation points used in the Flow-R simulation were used.

In DebrisFlow Predictor, the direction of movement is identified by a Moore Neighborhood algorithm, where the elevations of the surrounding eight cells around the central cell are obtained. In each time step, the agent faces and will flow toward the lowest unoccupied cells. In the case where cells are not unoccupied or where three cells have the same elevation, the direction is a combination of random chance and the preservation of momentum. A detailed description of this approach is available in Guthrie et al. (2008)

Also different in DebrisFlow Predictor is that agents scour and deposit in each timestep and account for their mass. Occasionally mass is shed to new cells on the matrix (DEM), spawning additional agents. The redistribution of mass is described by a probability density function defining the standard deviation (σ) as

$$\sigma = \left(\frac{m_{max} - m}{m_{max}}\right)^n (\sigma_L - \sigma_s) + \sigma_s \qquad [7]$$

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. Further details of these parameters could be found in Guthrie and Befus (2021).

The parameters used in this application of DebrisFlow Predictor are listed in Table 1. Parameters can be calibrated in an iterative fashion within the model by adjusting the sliders and comparing results to known events or landforms. The parameter m_{max} limits spreading to slopes flatter than 27º, as recommended by Guthrie and Befus (2021), where additional information is not available. The parameters n, σ_L, and σ_S control the amount of mass (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.

In DebrisFlow Predictor, the spread is controlled by the redistribution of mass (Eq. 7), spawning new agents, which, themselves, are subject to the same rules as existing agents. These parameters are adjusted efficiently by moving sliders within the program. The reader can compare this to the spreading algorithm in Flow-R (Eqs. 1–3).

Agent mass is a critical part of DebrisFlow Predictor, and each agent continues to move downslope so long as it's mass > 0. Mass follows probabilistic rules for scour and deposition based on the underlying slope. The probability curves come from approximately 1700 field observations (Wise 1997; Guthrie et al. 2008, 2010). Nonetheless, variations in local geomorphology may necessitate adjustments to scour or deposition depth. These are achieved using the deposition and erosion multipliers (Table 1) that are independently applied to the agent mass after calculation in each timestep. DebrisFlow Predictor also considers mass loss during the turn. As the neighbouring cells are at 45° angle with respect to the central cell, the mass loss parameter is defined per 45° turn. Once again, each of these parameters is efficiently adjusted using sliders in the program itself. Overall, the role of these parameters could be compared to the runout distance algorithms in Flow-R (Eqs. 4–6).

DebrisFlow Predictor has the ability to set a minimum scour depth in the initiation zone to account for the observed experience of (for example) a half-meter headscarp. The minimum scour depth is subtracted to the calculated depth for that slope.

Because the results are probabilistic, no two runs are identical; therefore, multiple runs are recommended to determine the potential cumulative footprint of a debris flow path and to calculate the probability that any location within the cumulative footprint will be occupied by an event. Five hundred landslide runs were modeled from each landslide initiation zone in this simulation.

Table 1. Parameters used DebrisFlow Predictor

Fan maximum slope (m_{max})	27°
Low slope coefficient (σ_L)	0.36
Steep slope coefficient (σ_S)	1.36
Skew coefficient (n)	1.1
Maximum spawns allowed	100
Deposition multiplier	0.5x
Erosion multiplier	1x
Mass loss per 45° turn	20%
Minimum initiation depth	0
Number of model runs	500

3 RESULTS

Figure 2 represents the spreading of debris flow hazard potential for the Solalex-Anzeindaz region modeled in Flow-R. The darker color shows higher susceptibility, while the lighter color represents comparatively lower susceptibility. By using Flow-R, the user can determine runout distance and generally estimate the probability of occupying a place in the landscape. However, at least in this simulation, the susceptibility appears to be either high (dark lines) or low (lighter background), with limited intermediate values between the two.

DebrisFlow Predictor is functionally limited to a 5 m DEM (the same DEM was used in both models) but produces considerable additional information at that scale. It predicts the area, volume, and depth along the landslide path, as well as the probability of inundation over multiple runs. Figure 3 (DebrisFlow Predictor) is similar to Figure 2 (Flow-R), with a perhaps better discretization of intermediate probabilities. The darker areas represent higher inundation probabilities, and lighter areas represent lower inundation probabilities. If the reader considers only the high probability paths from both models, DebrisFlow Predictor, as modeled in this case, appears to produce more realistic fanning and path behavior.

In our test, results of the DebrisFlow Predictor model runs were improved from those using Flow-R; for example, in Figures 2 and 3. Figure 4(a) shows an enlarged view of the landslide footprint where the debris comes from the upslope areas along the path PQ and then diverges into two flow paths (QRT and QST), converging later at point T. The Flow-R simulations in Figure 4(b) show only one flow path QST. While we acknowledge that this could be a parameterization problem, we note that the simulations conducted for SilvaProtect-CH found a similar path (see Figure 1). On the other hand, DebrisFlow Predictor simulates some flow of debris along QRT, as shown in Figure 4(c), which is consistent with the observed landslide footprint (Figure 4(a)).

Methods to estimate damage from debris flows include analytical (Corominas et al. 2014), empirical (Jakob et al. 2012), and engineering judgment approaches (Winter et al. 2014). Perhaps the simplest approach is to consider only landslide depth (Ciurean et al. 2017). In this case, the landslide depth is provided as an output from DebrisFlow Predictor (Figure 5). However, with those depths and assumptions about the velocity (estimated at 15 m/s over this site), detailed calculations could be performed, such as design parameters for mitigation structures. Similarly, with respect to mitigation, individual scenario runs from DebrisFlow Predictor will produce volumes. In other words, the operator can get a range of expected volumes as well as the expected depths. Representativeness of volumes will depend on input parameters and the calibration stage, however, the calibration is efficient for a user with experience in debris flows, and was shown to match real world examples in several cases (Wasklewicz et al. 2022; Guthrie et al. 2022).

Both programs are highly dependent on DEM quality and resolution, with DebrisFlow Predictor being limited to a 5-m pixel size. Changing the ground surface from that surface represented in the DEM might result in some errors in the runout model.

Horton et al. (2013) showed that outcomes could vary substantially according to different resolutions of DEM. He proposed that a 10 m pixel resolution is appropriate for regional debris flow susceptible mapping. In recent years, the computational power has been increased rapidly; therefore, simulations could be performed even for smaller pixels. Guthrie and Befus (2021) suggested that a 5 m DEM strikes a balance of processing power and provides reasonable results

4 CONCLUSIONS

Flow-R and Debrisflow Predictor were deployed at the Solalex-Anzeindaz region to simulate debris flow runouts. Both programs were developed based on empirical approaches, and neither of the models emphasizes local triggering factors or underlying conditions to determine the path. They rely instead on the overall behavior of debris flows derived from empirical studies. A number of successful case studies demonstrated the suitability and applicability of Flow-R for debris-flow susceptibility mapping, while DebrisFlow Predictor is, in comparison, relatively new.

For DebrisFlow Predictor, the source area is identified manually or computationally outside the program and imported. Flow-R, on the other hand, comes with a landslide susceptibility module (for landslide initiation). While landslide initiation zones are readily determined through a variety of methods, if the user wishes to automate this process in a single program, Flow-R is perhaps a better choice (though expert judgement is still required to parameterize the program correctly).

Once source zones are identified, DebrisFlow Predictor appears to provide more information and better path results (individual runs or high probability inundation zones from multiple runs to show morphological features that one would expect to see in a real debris flow) and additional depth information obtained along the runout path. That depth data (scour and deposition) can help engineers prepare mitigation strategies and design parameters. Calibration occurs within the program using a relatively intuitive GUI, and the model accounts, therefore, for second-order differences in local conditions (e.g. geology, viscosity, surficial geology) experimentally.

DebrisFlow Predictor, at this time of writing, is free for non-commercial use, while Flow-R is open-source software.

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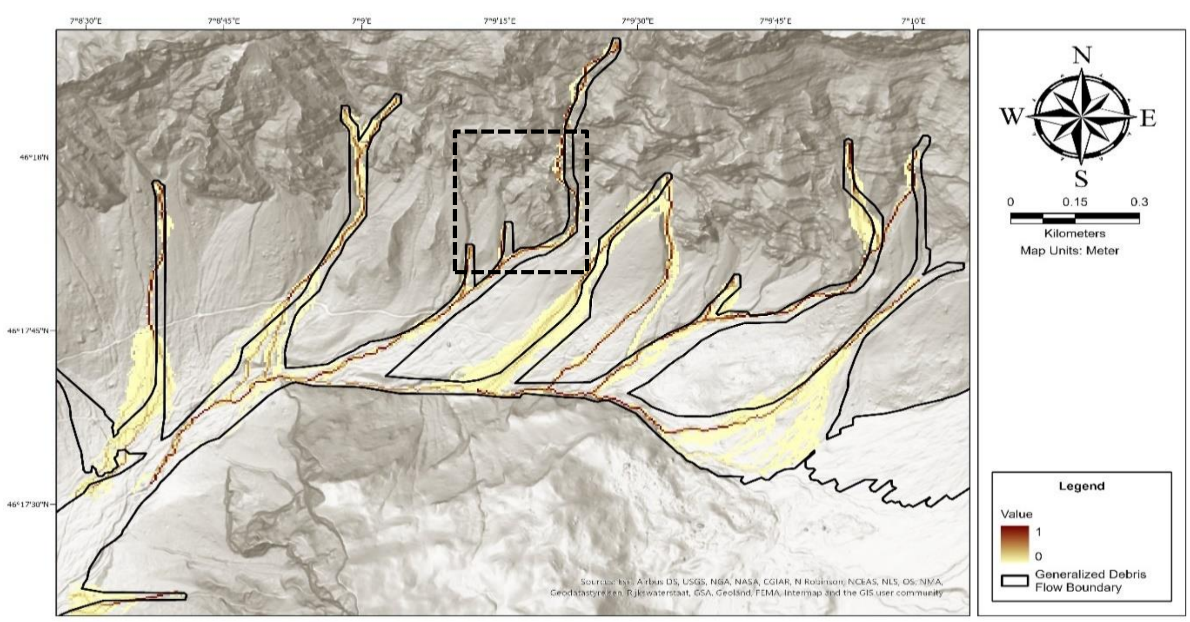

Figure 2: Debris flow runout modeled in Flow-R. The cumulative footprints and probability of occupying a cell are provided; however, the probability distribution appears to be bimodal, with only high and low probabilities well represented.

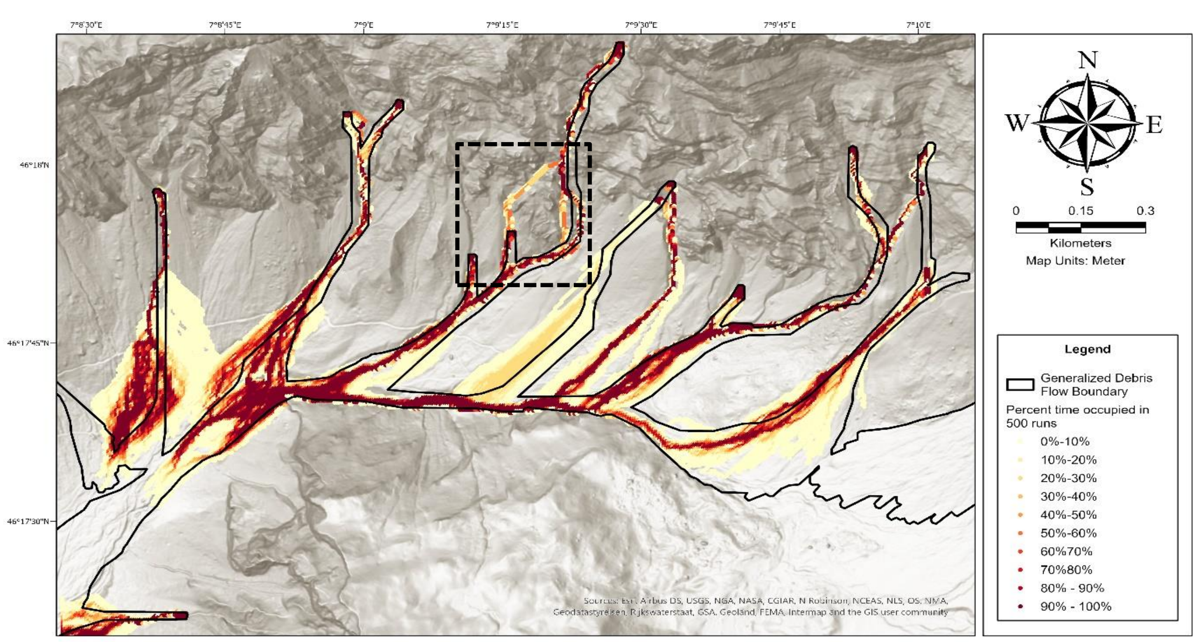

Figure 3: Debris flow runout from DebrisFlow Predictor. The result shows both the cumulative footprint of multiple runs and the likelihood that any location on the map would be occupied in a single run.

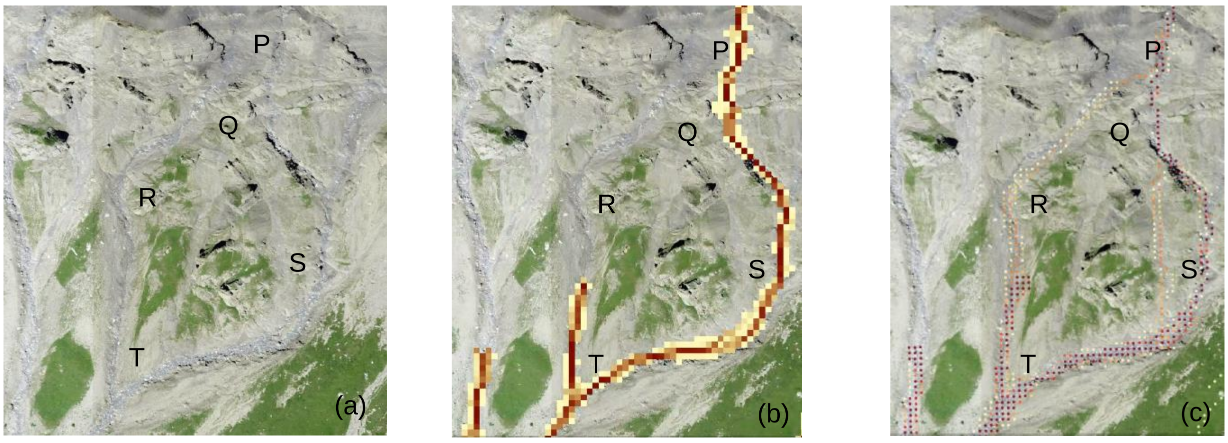

Figure 4: Comparison of simulation results with landslides footprints for a selected location: (a) landslide footprint; (b) Flow-R simulation; (c) DebrisFlow Predictor simulation (Background image source: www.swisstopo.admin.ch/en/geodata/images .html)

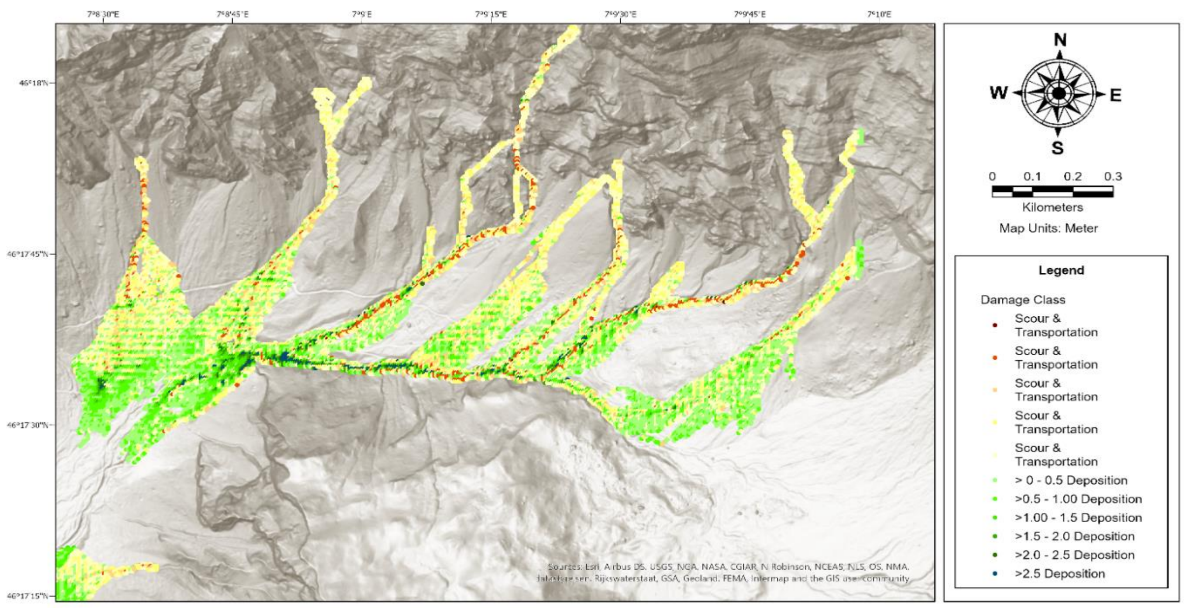

Figure 5: Debris flow runout showing depths (scour from red to yellow, deposition from green to dark green) along the path. Volume is retained for each individual landslide in the program and can be exported to Excel spreadsheets for scenario analysis.

5 ACKNOWLEDGEMENTS

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