DEBRIS FLOW SUSCEPTIBILITY MAPPING AT A REGIONAL SCALE

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RÉSUMÉ
La cartographie des laves torrentielles à une échelle régionale a fait l'objet de divers travaux. La complexité du phénomène et la variabilité des paramètres de contrôle locaux rendent l'utilisation de modèles à base physiques difficile. Les approches d'identification automatique des zones sources et d'estimation de la propagation, fondées sur les outils SIG, offrent une base intéressante pour une première estimation de la susceptibilité à l'échelle d'une région. L'utilisation d'un modèle numérique de terrain d'une résolution de 10 m sur le Canton de Vaud (Suisse), d'une carte lithologique et d'une carte d'utilisation du sol a permis une identification automatique des sources potentielles de manière pertinente. L'estimation de la propagation est fondée sur des calculs probabilistes et énergétiques simples définissant les zones d'extension maximale qu'une lave torrentielle pourrait vraisemblablement atteindre.

ABSTRACT
Debris flow susceptibility mapping at a regional scale has been the subject of various studies. The complexity of the phenomenon and the variability of local controlling factors limit the use of process-based models for a first assessment. GIS-based approaches associating an automatic detection of the source areas and a simple assessment of the debris flow spreading may provide a substantial basis for a preliminary susceptibility assessment at the regional scale. The use of a digital elevation model, with a 10 m resolution, for the Canton de Vaud territory (Switzerland), a lithological map and a land use map, has allowed automatic identification of the potential source areas. The spreading estimates are based on basic probabilistic and energy calculations that allow to define the maximal runout distance of a debris flow .

1. INTRODUCTION

Debris flows occur mainly in mountainous regions and are a severe potential threat for inhabited regions (Rickenmann and Zimmermann 1993). The Alps contain numerous potential debris flows, so potential new threats exist and must be considered.

This paper presents the methodology used for a first assessment of debris flow hazards over the Canton de Vaud territory (figure 1), Switzerland, for creation of an indicative debris flow susceptibility map (Loat and Pertrascheck 1997). This one aims to give an insight of existing or potential new susceptibility zones, by locating dangerous processes, without any notion of intensity or occurrence probability.

The framework of this study implies working on a whole region with limited data, in a GIS environment. The results must allow a quick overview of areas potentially reached by the specific threat.

Process based modeling of debris flow is difficult because of the complexity of the phenomenon and the variability of controlling factors. The automatic identification of sources areas and the estimation of debris flow spreading, based on GIS tools, provide a substantial basis for a preliminary susceptibility assessment at a regional scale. The proposed method merges several existing GIS-based approaches, which makes the proposed method an evolution of past ones (Huggel *et al.* 2003)

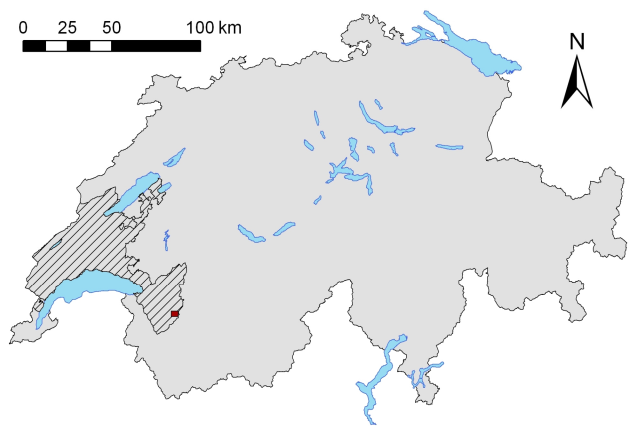

Figure 1. Location of the Canton de Vaud territory (dashed area) and the Solalex - Anzeindaz region (small red rectangle).

2. METHODOLOGY

2.1 General description

The methodology results in a 2 steps work. First, the debris flow sources were identified through different geological, morphological and hydrological criteria, and then, these sources were propagated and spreaded trough a probabilistic and energetic approach on the basis of a Digital Elevation Model (DEM) with 10 x 10 m grid.

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2.2 Developed model

A new model has been developed for a regional debris flow susceptibility assessment. The objective of the model is to allow a transparent algorithm choice and an easy customization of the method. Thus, every decisive algorithm is an external function that can be easily selected among others in the main graphical user interface (figure 2). The Matlab environment was chosen for its optimized matrices data management and its large build-in libraries. It allows also a stand alone version.

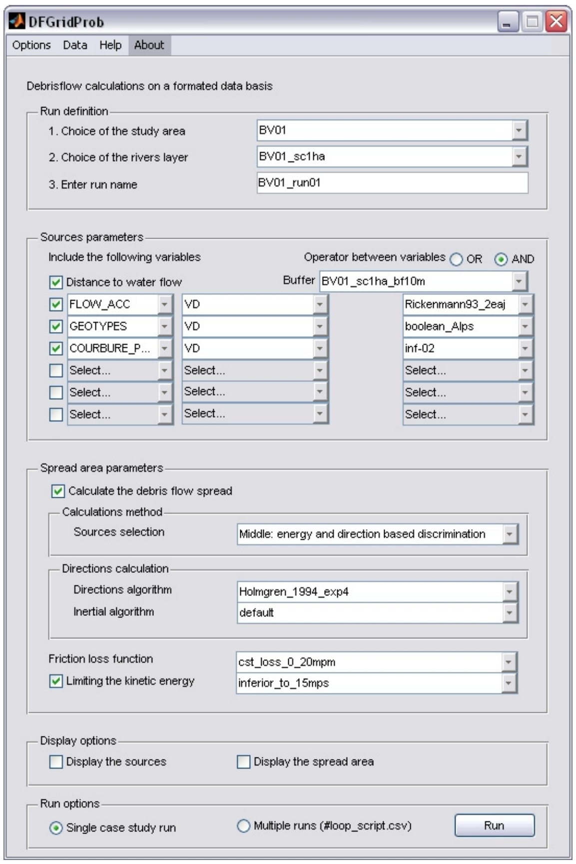

Figure 2. Graphical user interface of the model.

Both the sources identification and the spreading area assessment are based on a regular grid with a resolution of 10 meters, which is needed to capture the variability of the topographic form for hillslopes (Wilson 1996). Each algorithm is then constrained to work on a grid basis. This approach is quite common in models for spreading assessment, and become increasingly interesting as the DEMs resolution increase. Such data are a solid basis for estimating a flow development on slopes.

Input data (ASCII files) for sources identification can represent different types of spatial information, as the corresponding parameters are user-defined. Thus, some preliminary work can be undertaken in a GIS software.

The source volumes are not taken into account, due to impossible large scale rapid assessments, and due to the significant mass changes occurring through deposition and erosion (Iverson *et al.* 2001) which is excessively difficult to estimate.

3. SOURCE AREAS IDENTIFICATION

According to Rickenmann and Zimmermann (1993) and Takahashi (1981), three criteria in a critical combination are relevant for a debris flow initiation : sediment availability, water input and slope gradient.

The sediment availability is linked to the lithology, as some geological units produce more or less debris and fine paticles prone to be eroded, such as flysch and marls. The upslope contributing area was taken into account as a characteristic of water input. The slope angle is a major criterion, and finally the plan curvature and the land use map are added to increase the detection quality.

For each criterion, a grid is generated containing three possible values for each cell: possible source – excluded – ignored. The possible source option means that according to the selected criterion, the cell is a potential source area. The ignored option means that there is no evidence if the cell is a source or not, so no decision is fixed. The excluded option means that the cell cannot be a debris flow source area. In combining the grids established for the different criteria, a cell is selected as a source area if it was at least once identified as a possible source but never classified as excluded.

3.1 Slope

The slope angle is a determining factor in triggering of debris flows (Takahashi 1981). Most debris flows occur from terrain with a slope higher than 15° (Rickenmann and Zimmermann 1993; Takahashi 1981). Some initiation threshold of other factors can be expressed as a relation with the slope angle, as for the lithology and the contributive area.

3.2 Curvature

Another potential morphological characteristic is the curvature, as debris flows are found where curvature is concave (Delmonaco *et al.* 2003; Wieczorek *et al.* 1997). To allow an identification of gullies, the plan curvature, which is perpendicular to the steepest slope, was considered. Although this characteristic is often used to recognize the gullies, there is no admitted threshold. A limit had to be established on the basis of aerial photographs and the analysis of the 10 meters DEM. On our study area, a curvature of -2/100 m^{-1} was found as optimal on the basis of the analysis of orthophotographs.

3.3 Hydrology

Debris flows are found along waterways, where the morphology is concave and where water converges

(Delmonaco *et al.* 2003). The upslope contributing area, as a characteristic of water input, is used widely in distributed hydrological models (Erskine *et al.* 2006). On the basis of the calculated flow accumulation, by use of the D∞ algorithm (Tarboton 1997), the cells with a contributing area inferior to 1 ha were not considered as potential sources. A detection of the sources on the remaining cells was done through a relationship with the slope.

A first limit relationship was defined by Heinimann (1998) for the Swiss Federal Office for the Environment (FOEN) (eq. 1). This relationship, built on observations, is the lower limit for a debris flow source identification. Every point above that limit is considered as critical.

$$\tan \beta_{lim} = 0.32 \cdot S_{UA}^{-0.2} \qquad [1]$$

where $\tan \beta_{lim}$ = slope gradient, S_{UA} = surface of the upslope area.

Rickenmann and Zimmermann (1993) established a similar relationship with the 1987 observations of debris flows. An important difference was found with the previous limit on small catchments between 1 and 10 ha. Indeed, most of the 1987 observed debris flows with a small contributive area are located below that limit. Those with a catchment close to 1-2 ha are even integrally beneath the limit. Thus, considering the standard limit would lead to an omission of many potential sources with slopes below the threshold, but important enough for a triggering.

The 1987 event in Switzerland could be considered as extraordinary, so it may be advisable to differentiate the obtained limits as an approximation for different probabilities of occurence. Thus, we established two new limiting curves: the first one for rare events, based on the Heinimann (1998) limit, and the second one for extreme events, based on Rickenmann and Zimmermann (1993) observations (figure 3). Both curves are bounded by the theoretical 15° limit slope.

The known threshold for rare events is bounded by (eq. 2).

$$\begin{cases} \tan \beta_{lim} = 0.32 \cdot S_{UA}^{-0.2} & \text{if } S_{UA} < 2.5\text{km}^2 \\ \tan \beta_{lim} = 0.26 & \text{if } S_{UA} \geq 2.5\text{km}^2 \end{cases} \qquad [2]$$

where $\tan \beta_{lim}$ = slope gradient, S_{UA} = surface of the upslope contributing area.

The new limit for extreme events is the following (eq. 3).

$$\begin{cases} \tan \beta_{lim} = 0.31 \cdot S_{UA}^{-0.15} & \text{if } S_{UA} < 2.5\text{km}^2 \\ \tan \beta_{lim} = 0.26 & \text{if } S_{UA} \geq 2.5\text{km}^2 \end{cases} \qquad [3]$$

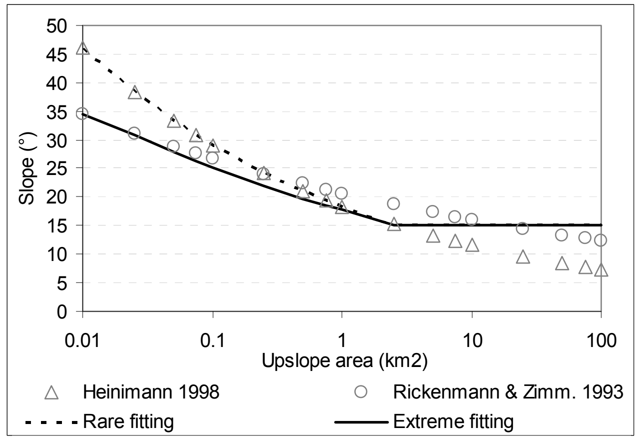

Figure 3. Built slope thresholds with regard to the upslope area for rare and extreme events. After Heinimann (1998) and Rickenmann and Zimmermann (1993).

3.4 Lithology

The lithology was taken into account by means of a “geotypes” map (Perret 2007), which contains uniform and complete information about outcropping formations for the whole study area. This map was established by the Swiss Institute of Technology (EPFL) based on the Swiss Atlas of Geological 1:25’000 maps (www.swisstopo.ch). However, the geotypes map does not consider the tectonic origin of the different rock types. This simplification does not allow to differentiate the disparity in fracturation and the weathering degree within the same rock type. For this reason, it was necessary to distinguish between the Alpine part of the Canton and the other areas of the Canton for some geological units, because some areas are for instance intensely folded.

No evident relationship was found between lithological types and slope values. Therefore, the considered threshold slope for the selected lithology types is the theoretical limit of 15°.

The selected lithologies are debris flow prone rocks (marl, slate, siltstone) and slope deposits.

3.5 Land use

Land use helps to identify certain inaccurate sources, that are located in built-up areas or that are man-made infrastructures. Outcropping or suboutcropping rocks were also excluded from potential sources, but forested areas were selected, as some debris flows can be observed in forests, and as the protective effect of trees can be removed by a fire or a cut down.

3.6 Criteria compilation

The sources are determined by compiling the various results from each dataset listed hereinbefore. Figure 4 depicts source areas identified for the Anzeindaz – Solalex (figure 1) region.

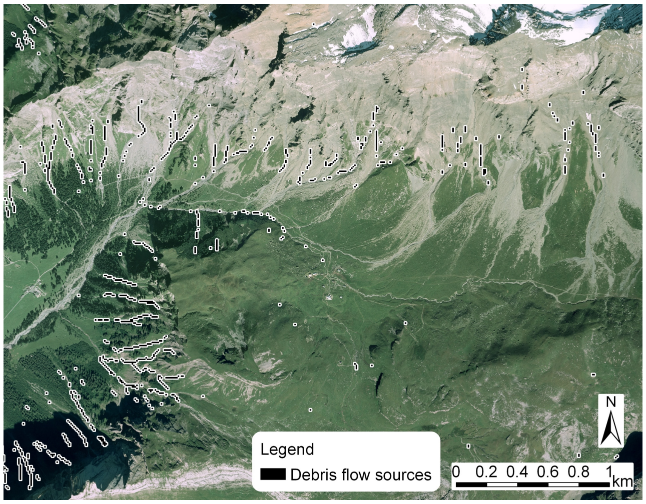

Figure 4. Identified potential debris flow sources for the Anzeindaz – Solalex (Switzerland) region. (Orthophotograph by Swisstopo)

4. SPREADING AREA ASSESSMENT

The debris flow spreading can be mathematically estimated by two types of algorithms: the first ones are called flow direction algorithms and rule the path that the debris flow will follow; the second ones determine the runout distance.

The spreading area assessment selects each source area, and spreads it on the DEM which is the only data needed.

4.1 Flow direction algorithms

Flow direction algorithms apportion the flow from one cell to its eight neighbors. Some conditions are defined so that there is always at least one cell in which the flow can run, so that runout distance algorithms only determine if it flows further or if it stops. Thus, pits and other DEM-linked problems are easily handled.

The final probabilities (eq. 7) are function of the slope and the persistence, which is a weighting of the directions according to the previous direction, allowing an integration of the notion of inertia. Debris flows behavior on fan-like terrain, with low slope gradients, is best represented by a probability function. It is, however, not a mathematical probability in a strict sense, but it has to be to be interpreted in a qualitative way (Huggel *et al.* 2003).

4.1.1 Slope-related algorithms

The slope has a leading effect on the debris flow path. Various flow direction algorithms have been integrated and evaluated. The model contains all these algorithms and the choice is entirely open to the user. A short overview of some conclusions is given hereafter.

The D8 algorithm, which assigns the flow to only one adjacent cell, is limited to directions of 45° and is very sensitive to small errors, which makes a good fit with the terrain impossible (Desmet and Govers 1996; Tarboton 1997). The flow paths are indeed unrealistically straights and parallels (Erskine *et al.* 2006). Moreover, in moderate slopes, observed debris flows tend to deflect from the steepest slope and so a spreading is observed (Huggel *et al.* 2003). The D8 algorithm would produce many errors of omission (Endreny and Wood 2003).

The D∞ algorithm, which assigns the flow to one or two adjacent cells, increases the D8 performance (Tarboton 1997). However, this condition is still too limiting for debris flow spreading calculations, that present a strong divergence on the fan.

Fairfield and Leymarie (1991) introduced a stochastic method called ρ8, which gives a probability to every cell having an altitude inferior to the central cell. The path is randomly determined afterwards, producing a single flow direction. One difficulty is that the random nature of the algorithm induces a lack of deterministic results (Erskine *et al.* 2006).

The basic multiple flow direction method (Quinn *et al.* 1991) is based on the previous method and considers the spreading over every non-zero cell in a continuous, and not random, way (eq. 4).

$$f_{si} = \frac{\tan\beta_i}{\sum_{j=1}^{8}\tan\beta_j} \quad \text{for all} \quad \tan\beta > 0 \qquad [4]$$

where i, j = flow directions (1..8), f_{si} = flow proportion (0..1) in direction i, tan β_i = slope gradient between the central cell and cell in direction i.

If the multiple flow direction algorithm generates a more detailed spreading that is closer to reality, its divergence is much too high (Huggel *et al.* 2003).

Freeman (1991) developed some variants of the basic multiple flow direction algorithm, but without introducing noticeable changes.

Holmgren (1994) introduced an exponent in the algorithm, with an optimal value between 4 and 6 (eq. 5). The higher is the exponent, the more convergent the flow becomes. When x = 1, it turns into the basic multiple flow direction, and when $x \to \infty$, it becomes a single flow direction.

$$f_{si} = \frac{\left(\tan\beta_i\right)^x}{\sum_{j=1}^{8}\left(\tan\beta_i\right)^x} \quad \text{for all} \quad \tan\beta > 0 \qquad [5]$$

where i, j = flow directions (1..8), f_{si} = flow proportion (0..1) in direction i, tan β_i as defined above and x = variable exponent.

We have chosen Holmgren's algorithm, for its best fitting with occurred debris flows observed on orthophotographs. The exponent was set to 4, as established in Claessens *et al.* (2005) on the basis of field and laboratory measurements.

4.1.2 Persistence

A weighting of the directions is included to take into account the persistence of the debris flow, representing its inertia. Based on Gamma (2000), the weight is a function of the change in angle from the last flow direction (eq. 6).

$$\begin{cases} f_{pi} = w_0 & \text{if} \quad \alpha_i = 0° \\ f_{pi} = w_{45} & \text{if} \quad \alpha_i = 45° \\ f_{pi} = w_{90} & \text{if} \quad \alpha_i = 90° \\ f_{pi} = w_{135} & \text{if} \quad \alpha_i = 135° \\ f_{pi} = 0 & \text{if} \quad \alpha_i = 180° \end{cases} \qquad [6]$$

where i = flow directions (1..8), f_{pi} = flow proportion (0..1) in direction i, α_i = angle between the previous direction and the direction from the central cell to cell i, $w_{0,45,90,135}$ = weights for the corresponding change in direction.

4.1.3 Resulting probabilities

Resulting probabilities are the combination of the slope-related algorithm and the persistence (eq. 7, figure 5).

$$f_i = \frac{f_{si} \cdot f_{pi}}{\sum_{j=1}^{8} f_{sj} \cdot f_{pj}} \cdot f_0 \qquad [7]$$

where i, j = flow directions (1..8), f_i = total flow proportion (0..1) in direction i, f_{si} = flow proportion from the slope-related algorithm, f_{pi} = flow proportion from the persistence, f_0 = previously determined flow proportion of the central cell.

Each cell having a minimal probability is then included in the debris flow path. For the spreading assessment of a source cell, the calculation thus integrate different paths or divergences in one run. There is no need of random multiple runs as the field of all probabilities is covered.

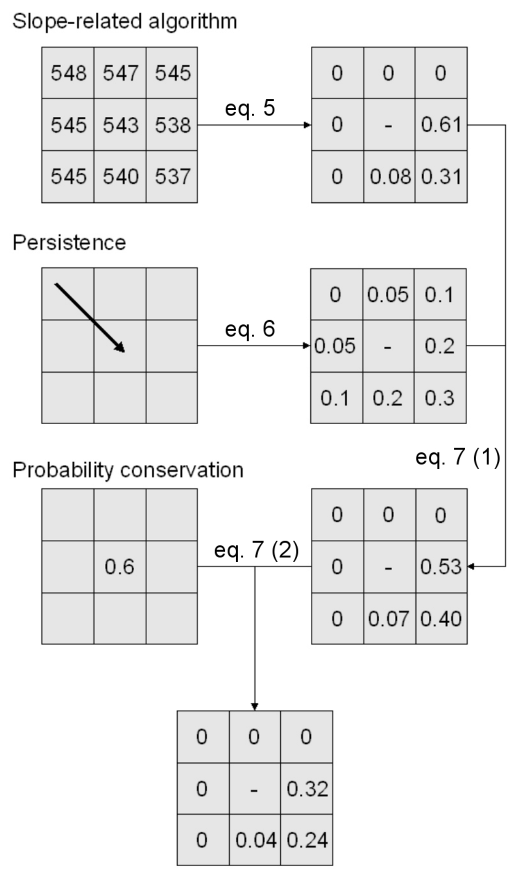

Figure 5. Example of probability computation.

4.2 Runout distance calculation

Runout distance algorithms are basic energy-based calculations that define if a part of the debris flow can potentially reach another cell. Thus, they control the distance reached by the debris flow and in addition reduce the divergence. In that way, the energy-based algorithms also influence the flow direction, as each cell that cannot be reached has a probability set to zero.

In a first regional assessment, the source mass is unknown. Thus, runout distance calculation is based on a unit energy balance (eq. 8), a constant loss function and a maximum threshold. This approach does not aim to represent exact physical processes, but to remain realistic.

$$E_{kin}^{i} = E_{kin}^{i-1} + \Delta E_{pot}^{i} - E_{loss}^{i} \qquad [8]$$

where i = time step, E_{kin} = kinetic energy, ΔE_{pot} = change in potential energy and E_{loss} = constant loss.

The probable maximum runout is characterized by an average slope angle of 11° (Huggel *et al.* 2002). The average slope is the slope between the starting and end point following the debris flow path. So we considered a constant friction loss corresponding to that angle, what would result in a runout distance equal to the probable maximum runout.

The maximum threshold aims to limit the debris flow energy to reasonable values. The chosen threshold is a maximum velocity of 15 $m \cdot s^{-1}$. The observed maximum velocity among various debris flows events in Switzerland is 13 to 14 $m \cdot s^{-1}$ (Rickenmann and Zimmermann 1993).

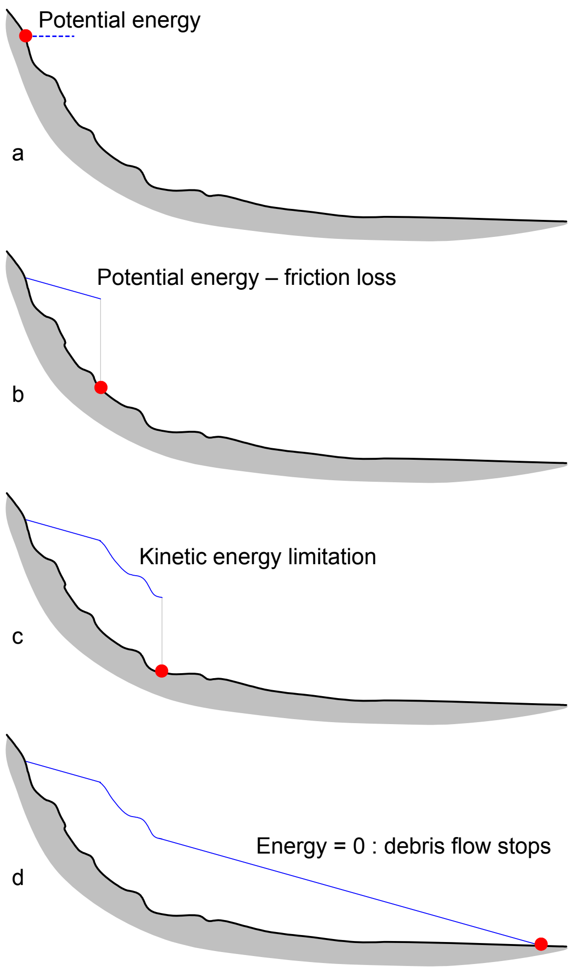

Figure 6. Illustration of the runout distance calculation principles.

Figure 6 illustrates the runout distance calculation principles. At start, a debris flow source has a certain unit potential energy (whithout considering the volume) regarding its adjacent cells downhill (a). During propagation, part of this energy is lost in friction (b). The kinetic energy is increasing and may reach the maximum threshold, leading to an energy line having the same shape as the terrain (c). The debris flow stops when the energy becomes null (d).

5. RESULTS

The results are based on the extreme events threshold for source areas identification (eq. 3).

The spreading areas of all sources are combined by keeping the maximum probability values (figures 6 and 7).

The result is the total area exposed to debris flow spreading, with an associated qualitative probability qualifying the susceptibility potential, as shown in figure 7. A surface with a red color has a higher probability to be reached by a debris flow than a yellow one.

The kinetic energy is a subresult of the computations, as shown in figure 9, where a red color represents a high kinetic energy, and a yellow color is a low kinetic energy.

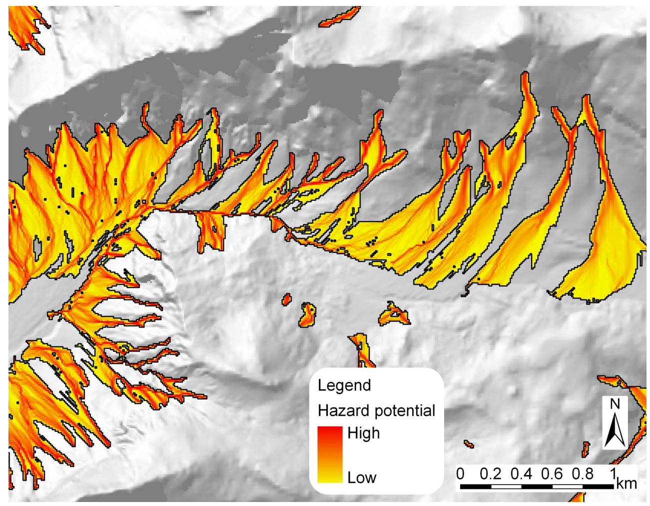

Figure 7. Spreading results for extreme events for the Anzeindaz – Solalex (Switzerland) region, with representation of the probability values. (DEM by SITVD)

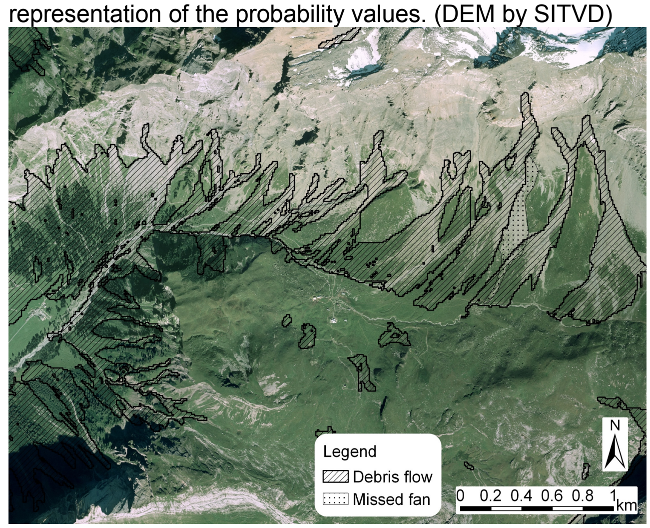

Figure 8. Spreading results for extreme events for the Anzeindaz – Solalex (Switzerland) region, as a mask of the maximum extent on an aerial photograph of the area. The stippled area is a missed fan due to a lower DEM resolution in that area (25 m). (Orthophotograph by Swisstopo)

6. DISCUSSION

Although the approach presented has its limits and cannot reflect local controlling factors and specific conditions, a good coherence between the simulation results and field observations was observed on specific catchments where major debris flow events occurred (figure 9). As the purpose is a region scale assessment, the required data were to be rather standard and distributed over the entire study area. On that basis, it is impossible to take into account the volume, material and differences in physical behavior of the various debris sources.

The spreading area is deeply linked to the DEM. Thus, in case of misrepresentation of the reality, the spreading area will contain nonsense results. A typical example is a stream flowing under a high bridge. This last one will act first as a dam (in case of a non-filled DEM), then as a channel. If this can be not so far from reality for low bridges, it is improbable in case of a large capacity under the bridge. Moreover, a debris flow can deeply erode the riverbed, leading to a different affected area. That effect is not simulated by our model.

The lithology map is homogeneous over the whole Canton de Vaud, which is a condition for use, but has shown clear limitations, as it does not include any weathering information. Therefore, some identified sources are inconsistent.

Forested surfaces from the land use map were not removed from the potential sources, denying the protective effect of vegetation. This condition increases considerably the number of probable location of debris flows, but we must remember the underlying dangers of some tree cuts.

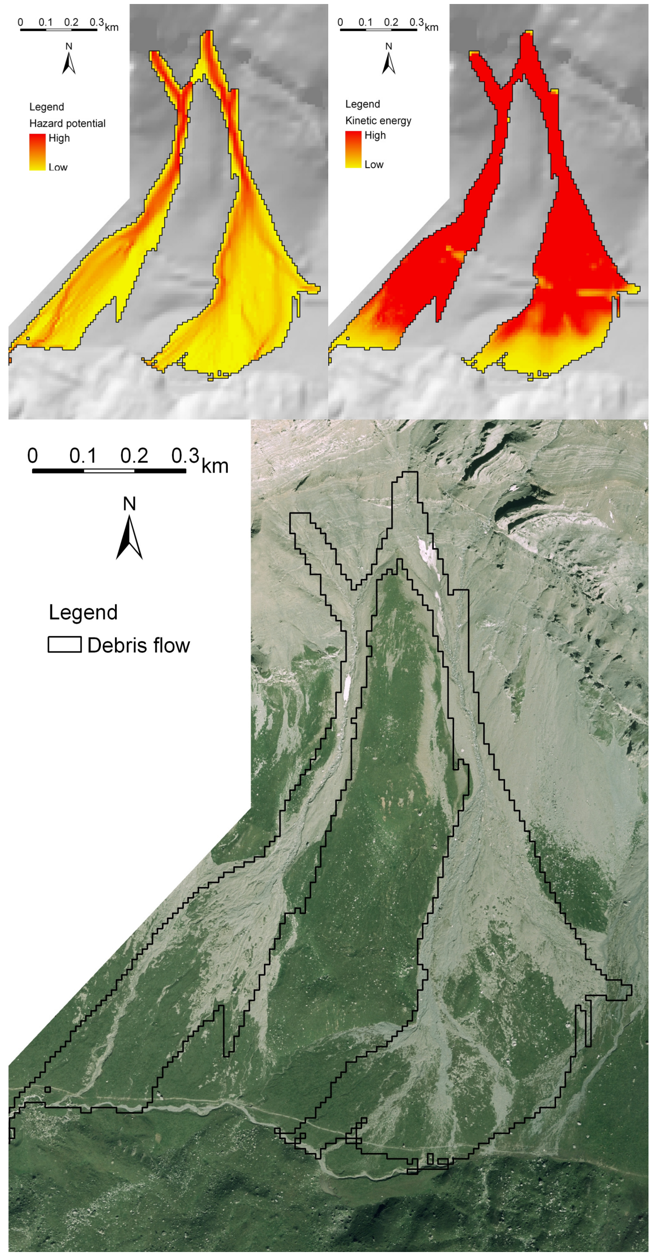

Figure 9. Closeup on the spreading results for the Anzeindaz – Solalex (Switzerland) region. Up left: susceptibility potential. Up right: kinetic energy. Bottom: orthophotograph of the existing debris flow fans. (DEM by SITVD , Orthophotograph by Swisstopo)

7. CONCLUSION

The chosen methods show realistic results and allow a first assessment of debris flow susceptibilty over a whole territory, despite a limited knowledge of the local controlling factors. Although we consider various datasets, the DEM is the most important one, and a reasonably good assessment can be undertaken with this unique source of in formation. The spreading assessment based on probabilistic and basic energy calculations, resulted in debris flow zonations close to observed events.

ACKNOWLEDGEMENTS

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