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FLOW-R, A MODEL FOR DEBRIS FLOW SUSCEPTIBILITY MAPPING AT A REGIONAL SCALE – SOME CASE STUDIES

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ABSTRACT

Every year, debris flows cause huge damage in mountainous areas. Due to population pressure in hazardous zones, the socio-economic impact is much higher than in the past. Therefore, the development of indicative susceptibility hazard maps is of primary importance, particularly in developing countries. However, the complexity of the phenomenon and the variability of local controlling factors limit the use of processbased models for a first assessment. A debris flow model has been developed for regional susceptibility assessments using digital elevation model (DEM) with a GIS-based approach.. The automatic identification of source 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. One of the main advantages of this model is its workability. In fact, everything is open to the user, from the data choice to the selection of the algorithms and their parameters. The Flow-R model was tested in three different contexts: two in Switzerland and one in Pakistan, for indicative susceptibility hazard mapping. It was shown that the quality of the DEM is the most important parameter to obtain reliable results for propagation, but also to identify the potential debris flows sources.

Key words: *model, regional, debris flow, susceptibility mapping*

INTRODUCTION

Physical modelling of debris flows in the framework of regional mapping is difficult because of the complexity of the phenomenon and the variability of controlling factors. Flow-R (Flow path assessment of gravitational hazards at a Regional scale) aims at giving a quick assessment of debris flows susceptibility at a regional scale with minimum data requirement (Horton *et alii,* 2008). It identifies potential source areas and delimits the zones in the path ofthe propagation. The proposed method merges several existing GISbased approaches, which makes it an evolution of past ones (e.g. Huggel *et alii,* 2003).

The three case studies provide examples of debris flow susceptibility maps produced using the Flow-R model in different contexts and based on very different datasets. Susceptibility mapping aims to give an insight of existing or potential new susceptibility zones. This is equally important in mountainous areas of industrialized or developing countries

FLOW-R MODEL

Flow-R is a numerical model (compiled with Matlab) that was first developed for the Canton de Vaud case study. The characteristics of the software are (i) limited requirement of datasets and (ii) customization of the inputs, the algorithms and the parameters through a graphical user interface. The model, originally developed for debris flows, has proved to be as well applicable for other processes such as rockfall, floods and avalanches. The model and its various concepts have been and are tested in various countries and contexts by partners in France, Italy, Austria, Canada and Norway (Blahut *et alii,* 2010; Lari *et alii*, in review; Kappes *et alii*, in review; Lari *et alii*, this volume).

PRINCIPLES

The modelling comprises two distinct steps: 1) the identification of the potential source area and 2) the assessment of the spreading (Fig. 1). First, the sources are identified on the basis of the Digital Elevation Model (DEM) and user-defined datasets. From these sources mass points are propagated on the topography, using a probabilistic and energy approach, respectively (Horton *et alii* 2008). The mass of the sources is not taken into account because of the difficulties in assessing volume at a regional scale and because of significant mass changes occurring through deposition and erosion (Iverson & Denlinger, 2001) which are difficult to estimate.

IDENTIFICATION OF SOURCE AREA

The source areas are identified by means of a combination of criteria based on the morphology of the terrain and on user-defined datasets. Those layers are processed to classify every cell as potential source, or as an excluded or ignored area. The cell is considered as source if it was at least once considered as a potential source, but never excluded (Horton *et alii,* 2008). For example, a cell with considerable slope and large water inflow, makes a good candidate for debris flows, but having a bedrock that reduces the possibility of material availability, would be excluded.

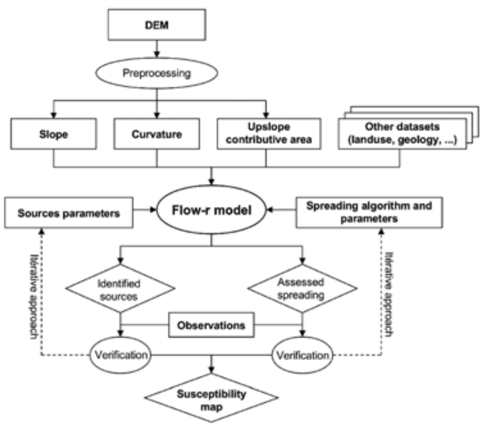

Fig.1 - Scheme of the method (Jaboyedoff et alii, in review)

The primary dataset is the DEM. On this basis, various morphological data can be derived. Three criteria are considered as critical by Rickenmann & Zimmermann (1993), Takahashi (1981) and Delmonaco *et alii* (2003): (1) sediment availability, (2) water input and (3) gradient. The two last are directly derived from the DEM, whereas (1) can be defined manually or using DEM information such as curvatures

GRADIENT

The gradient is a decisive criterion for debris flow susceptibility (Takahashi, 1981). Generally, debris flows occur when the gradient of the bed is above 15° (Rickenmann & Zimmermann, 1993; Takahashi, 1981). This is the default threshold in this model.

WATER INPUT (FLOW ACCUMULATION)

The upslope contributing area, processed by means of flow direction algorithms (see Section "Flow Direction Algorithms"), can represent the amount of water flowing through the cell. The flow directions and flow accumulation is processed for the whole DEM to produce a map of the values of flow accumulation at every cell. It is used widely in distributed hydrological models (Tarboton, 1997; Erskine *et alii*, 2006). A threshold that is related to the slope angle is commonly used in Switzerland (Heinimann, 1998). Based on this threshold and the observation of an extreme event (Rickenmann & Zimmermann, 1993), two thresholds were considered for rare and extreme events in Switzerland (Fig. 2). Both threshold curves are limited by the 15° slope angle

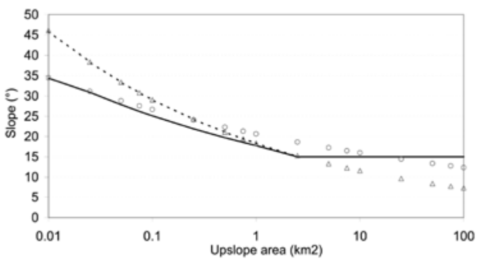

Fig 2 - River bed gradient in relation to upslope area: threshold values for rare and extreme events. After HORTON et al. (2008), based on data by HEINIMANN (1998) and RICKENMANN & ZIMMERMANN (1993) given by TAKAHASHI (1981)

The rare event threshold is given in Eq. 1:

$$\begin{cases} \tan\beta_{lim} = 0.32 \cdot S_{UA}^{-0.2} & \text{if } S_{UA} < 2.5\text{km}^2 \\ \tan\beta_{lim} = 0.26 & \text{if } S_{UA} \geq 2.5\text{km}^2 \end{cases} \quad (1)$$

where tan β_{lim} = slope gradient, SUA = surface of the upslope contributing area.

The extreme event threshold is given in Eq. 2:

$$\begin{cases} \tan\beta_{lim} = 0.31 \cdot S_{UA}^{-0.15} & \text{if } S_{UA} < 2.5\text{km}^2 \\ \tan\beta_{lim} = 0.26 & \text{if } S_{UA} \geq 2.5\text{km}^2 \end{cases} \quad (2)$$

SEDIMENT AVAILABILITY (CURVATURE)

Debris flows sources are found where curvature is concave (DELMONACO *et alii,* 2003; WIECZOREK *et alii,* 1997). The plan curvature, perpendicular to the steepest slope derived from the DEM, provides identification of gullies that are considered as potential sources.

OTHER DATASETS

Any other user-defined input can be taken into account, should it be numerical or classified data. In the first case, the selection is based on ranges, and in the second, on values. This allows, for example, to asses sediment availability using geological or lithological information or land use data.

SPREADING ASSESSMENT

The assessment of the spreading area is based on the one hand on a probabilistic spreading by means of flow direction algorithms, and on the other hand on a basic energy balance, which defines the maximal runout distance. Both are customizable and can be combined according to the user choice.

FLOW DIRECTION ALGORITHMS

The flow direction algorithms allow distributing the probabilities to the neighbouring cells, according to a relationship using gradient. In contrast to its use for water contribution in the source detection, the direction of the debris flow is here processed step by step for every cell. Various algorithms are implemented, like the D8, D(x) (TARBOTON, 1997), *p*8 (FAIRFIELD & LEYMARIE, 1991) and different multiple flow direction methods (QUINN *et alii*, 1991, FREEMAN, 1991, HOLMGREN, 1994). Holmgren's algorithm (Eq. 3) is frequently chosen in our case studies as it allows controlling the spreading by means of an exponent, and thus enables replacement of most of the other algorithms. And the Holmgren algorithm fits the real cases better. The higher the exponent, the more convergent the flow becomes. When x = 1, it turns into the basic multiple flow direction, and when x → ∞, it becomes a single flow direction.

$$f_{si} = \frac{(\tan\beta_i)^x}{\sum_{j=1}^{8}(\tan\beta_j)^x} \quad \text{for all} \quad \tan\beta > 0 \quad (3)$$

where i, j = flow directions (1..8) with angular intervals of 45 degrees, f_{si} = flow proportion (0..1) in direction i, tan(β_i) slope gradient between the central cell and cell in direction i and x the variable exponent.

Based on GAMMA (2000), inertia was implemented under the form of persistence (Eq. 4), which is a weighting function of the change in direction.

$$\begin{cases} f_{pi} = w_0 & \text{if } \alpha_i = 0° \\ f_{pi} = w_{45} & \text{if } \alpha_i = 45° \\ f_{pi} = w_{90} & \text{if } \alpha_i = 90° \\ f_{pi} = w_{135} & \text{if } \alpha_i = 135° \\ f_{pi} = 0 & \text{if } \alpha_i = 180° \end{cases} \quad (4)$$

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.

The final probabilities (Eq. 5) are function of the flow direction algorithm and the persistence (HORTON *et alii*, 2008):

$$f_i = \frac{f_{si} \cdot f_{pi}}{\sum_{j=1}^{8} f_{sj} \cdot f_{pj}} \cdot f_0 \quad (5)$$

where i, j = flow directions (1..8), fi = total flow proportion (0..1) in direction i, f_{si} = flow proportion from the slope-related algorithm, f_{pi} = flow proportion from the persistence, f0 = previously determined flow proportion of the central cell.

From a given source, the spreading is processed once, integrating every possible path and attributing probabilities to every cell. The spreading areas of all sources are combined by keeping the maximum probability values. 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 alii,* 2003).

RUNOUT DISTANCE ASSESSMENT

Energy based algorithms are used to assess the runout distance. This constraint defines if a cell can be reached by the debris flow, or if the actual energy of the flow portion is not high enough. Thus,they control the distance reached by the debris flow and in addition may reduce lateral spreading.

As the source mass is unknown, the energy balance is processed on a unit mass (Eq. 6), which is clearly simplistic compared to the complex real physical processes.

$$E^{i}_{kin} = E^{i-1}_{kin} + \Delta E^{i}_{pot} - E^{i}_{loss} \qquad (6)$$

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

Two main algorithms are available for energy balance assessment: a slope angle concept or single parameter friction model, and a two parameters friction model.

The single parameter friction model assumes an incrementaz energy loss by a friction coefficient using

$$\Delta E_{loss} = g\ \Delta x\ \mu = g\ \Delta x \tan \phi_b \qquad (7)$$

where Δx is the increment of horizontal displacement, Φ_b is the basal angle of friction linked to the friction coefficient μ and g the acceleration due to gravity. This algorithm is available in the model along with a kinetic energy limit that aims at keeping a realistic velocity of the propagation. This permits the use of very simple arguments to run the model using the observed mean slope angle of the path for which the debris flow stops as the lower limit for Φ_b, and the maximum expected velocity of the debris flow.

The two parameter friction model is described in PERLA (1980). It was then established for avalanches, but can be used for other hazards with the corresponding parameters. In that case, the equation governing the velocity is given by PERLA (Eq. 8) (1980)

$$V_i^B = \left[\alpha_i \left(\frac{M}{D} \right) (1 - \exp(\beta_i)) + (V_i^A)^2 \exp(\beta_i) \right]^{\frac{1}{2}} \qquad (8)$$

Where V_i^B is the velocity at the end of the ith segment, V_i^A is the velocity at the beginning of the ith segment $\alpha_i = g\,(\sin \theta_i - \mu_i \cos \theta i)$, $\beta i = -2L_i/(M / D)$ i with θ the slope angle of the segment, μ the coefficient of friction, M/D the mass-to-drag ratio (m) and L the horizontal distance of the segment.:

SIGNIFICANCE OF THE SIMPLE ENERGY LOSS MODEL

The velocity limit, adapted from PERLA (1980), for an infinite slope with a constant slope angle (θ) and a friction coefficient μ = tan Φ, can be seen in equation 9:

$$V_\infty = \left[\frac{Mg}{D} \left(\sin\theta - \tan\phi \cos\theta \right) \right]^{\frac{1}{2}} \qquad (9)$$

Fixing the mass to drag ratio, the velocity limit is depending on the slope angle and the friction coefficient that can also be expressed by means of an angle (Fig. 3). The Perla model and the constant friction mod-

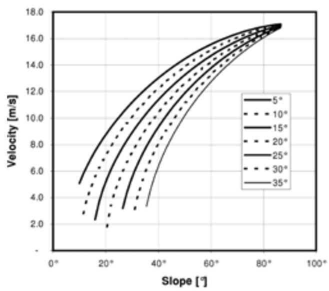

Fig. 3 - Relationship between the slope angle and the maximum velocity for different friction angles and a mass to drag ratio of 30

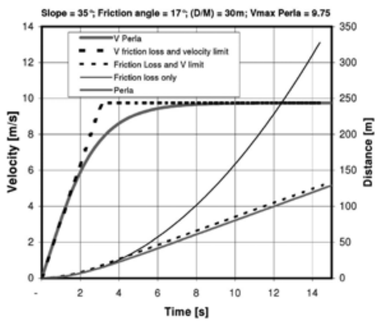

Fig. 4 - Comparison of the two models of the velocity and distance reached over time

el with limiting velocity were compared for an infinite slope (Fig. 4). It can be shown that the behaviour of both models provide very similar results for the same μ, when the velocity limit for the second model is set to V∞, making the velocity limit quite efficient.

The difficulty is to choose the velocity limit, because the slope angle changes along the flow path. But from Fig. 4, it can be seen that the order of magnitude can be compared for both models. It is clear that the relationship between both models can be tuned by changing both μ and the max velocity value according to the topographic profile.

MODEL OUTPUTS

The outputs of the model are the source areas, the propagation kinetic energy and its probability, as illustrated on Fig. 5.

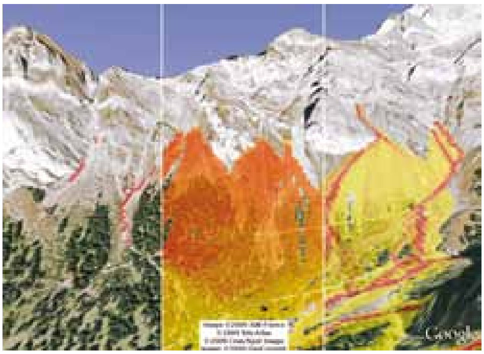

*Fig. 5 - Illustration of the model outputs: possible sources, kinetic energy and spreading probability (*Jaboyedoff *et alii, in review)*

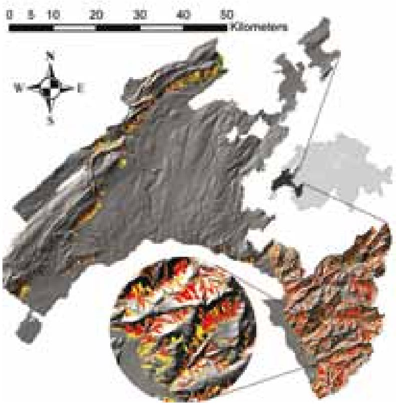

Fig. 6 - Resulting susceptibility map for the Canton de Vaud. Red identifies debris flows and yellow, hyperconcentrated flows and mud flows

CASE STUDY OF THE CANTON DE VAUD, SWITZERLAND

The Canton de Vaud (western Switzerland) (Fig. 6) susceptibility mapping was established at a scale of 1:25000 on the entire territory. Amongst other hazards, debris flows were studied along with mud flows and hyperconcentrated flows (Jaboyedoff *et alii*, 2008). Only debris flows are presented hereafter.

The state has an area of 2'822 km². The elevation ranges approx. from 400 m to more than 3000 m a.s.l.

USED DATASETS

A 1 m resolution digital elevation model (DEM) was available, derived from aerial laser scanning, with an accuracy of 30 cm and a standard deviation of 5 cm (MNT-MO Swisstopo factsheet, 2005). Because of the time required for processing, the high resolution DEM was scaled down to 10 m.

A "geotypes" map (Turberg *et alii*, 2008), which contains uniform and complete information about outcropping geological formations, was available for the whole region. This map is based on the Swiss Atlas of Geological maps 1:25'000 (swisstopo.ch). However, it has some limitations for debris flow susceptibility assessment, as it does not consider the tectonic origin of the different rock types. This simplification does not allow differentiating the disparity in fracture and the weathering degree within the same rock type.

A land use map based on the product Vector 25 from SwissTopo (www.swisstopo.ch) was available and has been considered to identify certain inaccurate sources, that are located in built-up areas or that are man-made infrastructures

SOURCES CRITERIA

The standard morphological data (slope, flow accumulation and curvature) were integrated with the following parameters:

Slope threshold: 15°

Flow accumulation threshold: 1 ha

Flow accumulation – slope relationship: extreme threshold

Curvature: -2/100 m-1

The lithology was considered by means of the geotypes map. The selected lithologies are debris flow prone rocks (marl, slate, siltstone) and slope deposits.

The land use was integrated to remove zones located in built-up areas or that are man-made infrastructures. Outcropping or suboutcropping rocks were also excluded.

PROPAGATION PARAMETERS

Propagation parameters were taken from literature or calibrated on the basis of traces of old debris flows visible on orthophotographs:

1 Holmgren's exponent was set to 4, as established in Claessens *et alii* (2005).
2 The energy loss function is the slope angle algorithm (Eq. 7) with a value of 11° according to Huggel *et alii* (2002) for the probable maximum runout.
3 The velocity threshold, considered along with the slope angle

algorithm, is 15 m/s. It is based on the observed maximum velocity of 13 to 14 m/s among various debris flow events in Switzerland (Rickenmann & Zimmermann, 1993).

CASE STUDY OF THE BAGNES VALLEY, SWITZERLAND

A susceptibility map was established with a 1:25000 scale for the Bagnes valley (Fig. 7). The method is similar to the case study of the Canton de Vaud, with improvements by means of field work to check the accuracy of the sources. Four test sites in the valley were chosen to calibrate the model parameters for the source areas detection and the propagation. This was made possible due to the small size of the catchment. Then, source areas were divided into two classes: proven and potential, resulting in two propagation area types

Fig. 7 - Resulting susceptibility map for the Bagnes valley. Red identifies proven, orange probable and yellow potential debris flows

The valley has an area of 282 km². The elevation ranges from 600 m to 4200 m a.s.l.. The geology is characterized by three main paleogeographical domains of the Alps: Helvetic, Penninic and Austro-Alpine (Trümpy, 1980). The rocks are then diverse, from some Cambrian polycyclic basements to Mesozoic-Cenozoic sedimentary covers (Sartori *et alii*, 2006). Various schists can be found in some areas, as on the Merdenson catchment, where fine mobilizable material is present in important quantities.

USED DATASETS

A 2 m resolution digital elevation model (DEM) was available, derived both from aerial laser scanning for altitudes below 2000 m and from a 25 m DEM (MNT25, swisstopo) built from the national maps at 1:25000 (CN25, swisstopo) for altitudes above 2000 m. The resolution for modelling was also 10 m.

Geological and tectonic vector maps at 1:500000 were available to assess the sediment availability, which is an important criterion for the debris flow initiation (Rickenmann & Zimmermann, 1993; Takahashi, 1981). For this study, only 11 different lithologies were taken into account based on those maps

As for the Canton de Vaud, a land use map based on the product Vecteur25 (Swisstopo) was available and improved the determination of the source areas.

SOURCES CRITERIA

As for the case of the Canton de Vaud, the morphological data were integrated with the following parameters:

1 Slope threshold: 15 - 40°. The upper threshold was found useful to remove cliffs where debris flow cannot occur.
2 Flow accumulation threshold: 1 ha
3 Flow accumulation – slope relationship: extreme threshold
4 Curvature: -2/100 m^{-1}

The selected lithologies from the structural map are debris flow prone rocks (limestone, conglomerate, flysch, meta-felsic, marble,quartzite, schist) and slope deposits.

The land use and the geological information were integrated in order to suppress source areas detected on man-made structures. Bedrock was consid-

Category	Past event	Phenomena evidences & debris
Proved	Recorded	Recent evidence of debris flow activities. Debris stock sufficient for debris flow triggering
Potential	No record	Evidence of past debris flow activities or suspected activities. Debris stock sufficient for debris flow triggering
Incorrect	No record	No activity evidences. Not enough debris stock for debris flow triggering

Tab. 1 - Classification of the debris flow source areas for the Bagnes valley (after Jaboyedoff *et alii, 2010)*

ered as potentially susceptible.

After field work and aerial photos analyses, the sources were classified into 3 classes (Tab. 1).

PROPAGATION PARAMETERS

Propagation parameters were calibrated on the basis of field observations and numerical data analysis (orthophotos, DEM, topographic maps). After testing, the 2-parameters friction model (Eq. 8) was chosen for its good reproduction of past events.

1 Holmgren's exponent was set to 6.

2 The parameters of the Perla friction model were optimal at $\mu = 0.09$ and M/D = 30.

The classification made on the sources was also applied to the propagation areas. Moreover, a distinction was made between the probabilities that are below 2% (probable danger) and above 2% (strong probable danger).

CASE STUDY IN PAKISTAN

The susceptibility map for Pakistan was established on two pilot districts: Muzaffarabad and Manshera (Fig. 8). Two main hazards were mapped: on the one hand common debris flows, and on the other hand major hyperconcentrated flows or major debris flows (called major debris flows hereafter) that take place in large rivers with an important upslope area. The areas of the two districts are respectively 2496 km² for Muzaffarabad and 4579 km² for Manshera. The altitude goes up to 4500 m a.s.l..

USED DATASETS

The available Digital Elevation Model is the SPOT DEM that has been furnished with a resolution of 20 m.

A land cover was extracted from a Landsat image. Six classes were defined: Forest, Water body, Snow and Ice, Vegetation, Urban barren and Unclassified.

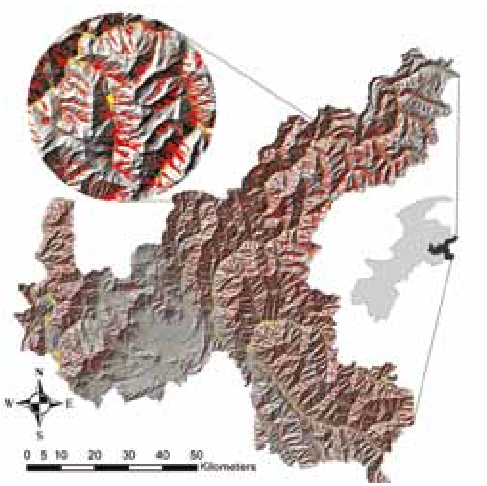

Fig. 8 - Resulting susceptibility map for the two pilot districts in Pakistan. Red identifies debris flows and yellow, hyperconcentrated flows

A geological map existed at scales of 1:50'000 or 1:1'000'000 according to the region.

SOURCES CRITERIA

The land cover and the geology layers were not considered. Land cover information derived from the Landsat image has too low resolution and many inconsistencies. Geological data are not taken into account due to the fact that no mapped geology type can be excluded as debris flow source areas. Indeed, there is no main geology type in the studied area that is not susceptible to debris flows. This has been confirmed by field observations.

Thus, only the DEM and its derivatives remain. Based on observation debris flows were divided in two classes (1) common and (2) major. The first phenomenon is found in torrents with a limited flow accumulation and an important slope. The second is found in riverbeds that are much gentler, but that have a larger water input leading to debris flows being less viscous. Those were considered with the following parameters:

COMMON DEBRIS FLOWS

- Slope threshold: 15°
- Flow accumulation threshold: 2 ha. New sources found below that limit are not relevant, and introduce new channels where no accurate debris flow was found. Above that limit, some noticeable source areas are missing.

- Flow accumulation – slope relationship: extreme threshold. According to the high rainfall intensity during monsoon in Pakistan, this threshold for extreme events is accurate.
- Curvature: -1/100 m-1. It succeeded in identifying the gullies prone to debris flows.

MAJOR DEBRIS FLOWS

- Slope threshold: 5-10°. Those events occur in riverbeds that are relatively flat, as the water input is higher than for common debris flows.
- Flow accumulation range: 500 ha to 5000 ha.
- Curvature: it was not taken into account for the major debris flow source areas. Those happen in relatively large riverbeds that are best identified by the contributing area (flow accumulation).

PROPAGATION PARAMETERS

Propagation parameters were calibrated on the basis of orthophotographs and field trips. For common debris flows, the runout distance was found best represented by means of the 2 parameters friction model (Eq. 8). Parameters were found optimal as following:

- Holmgren's exponent was set to 6.
- The parameters of the Perla friction model were optimal at $\mu = 0.09$ and M/D = 30.
- No velocity limitation was considered.

PARAMETERS FOR MAJOR DEBRIS FLOWS ARE DIFFERENT:

- Holmgren's exponent was set to 1, meaning it corresponds to the multiple flow direction model. The dispersion can be important for major debris flows.
- The runout distance was found best represented by means of the energy line method with a 5° slope.
- No velocity limitation was considered

RESULTS

All three case studies resulted in susceptibility maps, fully usable for a first assessment. However, it remains to do field validation and detailed mapping. The results should not be considered for local hazard mapping without fieldwork. The results must be analysed at 1:25,000 scale. All interpretation of the model at a finer scale makes little sense, particularly for the source area assessment.

Results of the Canton de Vaud showed good agreement with past debris flow features found through aerial photograph interpretation. No obvious active torrent was missing. However, the lithological map was not sufficient to exclude some unrealistic source areas in regions where geology is the factor discrediting the possibility of a debris flow.

The Val de Bagnes case study was interesting, as fieldwork was possible due to the size of the valley. Some occurred events were documented as they affected roads (as the one depicted in Fig. 9). Those could be compared to the model output detail. The possibility to classify every source area as proven, potential or incorrect, adds value to the indicative mapping process. The statistics on this classification (Tab. 2) shows that 86% of the identified source areas were found to be pertinent. Most of the 14% remaining is found in the bedrock class of the land use classification. The identification of the source areas was comprehensive, as no actual debris flow source was found outside of this susceptibility map.

During establishment of the susceptibility map for Pakistan, field work was conducted at two different regions to check the model outputs. No actual source area in torrents seemed to miss on the map, and by far the largest part of the modelled sources and spreading could be confirmed. However, these field investigations revealed the necessity to add the category of the major

Category	Proven	Potential	Incorrect
Percentage	51%	35%	14%

Tab. 2 - Statistics of the source areas classification for the Bagnes valley. (after Jaboyedoff *et alii, 2010)*

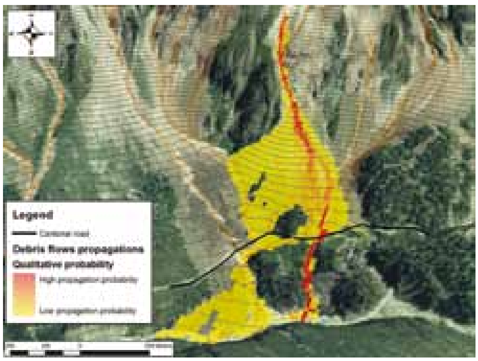

Fig. 9 - Example of spreading assessment in the Mauvoisin region. A documented spreading zone is highlighted, but the model identified a source area and their respective propagation for every torrent (modified after Jaboyedoff *et alii, in review)*

hyperconcentrated flows and major debris flows that occur in large riverbeds with a gentle slope.

DISCUSSION AND CONCLUDING REMARKS

Results of the various case studies confirm the significance of the model outputs although the model has some limitations and cannot account for certain local controlling factors. Observations of past events in the field were satisfyingly reproduced during the calibration and validation procedures. Thus, for the purpose of susceptibility mapping, the outputs can be considered as accurate. In the framework of susceptibility mapping, the identified areas are often larger than the observed events on the field. This is on purpose, as the map should be representative of the worst cases, soalways rather conservative (Jaboyedoff *et alii*, in review).Susceptibility hazard maps provide an excellent overview to indicate where detailed field investigation should be conducted to develop a hazard map

The DEM and its derivative are the most valuable data for the method. Morphological criteria were found to be very pertinent for debris flow sources identification, whereas other inputs just helped removing inaccurate source areas. However, those still improve the mapping pertinence. This means that the results are conditioned by the DEM quality both in terms of resolution and accuracy. Indeed, artefacts can be misleading for both sources identification and propagation assessment. This was observed in every case study. In Pakistan, where the DEM quality was lowest of all case studies, some spreading were blocked by non-existing dams present in the DEM (Fig. 10).

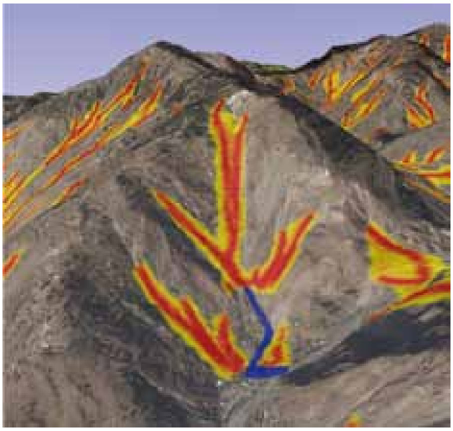

Fig. 10 - Effect of a DEM error above Nardajian (Muzaffarabad). The model stops due to an anomaly in the DEM. Thus, the model misses a past event (depicted in blue)

The DEM resolution and accuracy is a key element which will condition the quality of outputs. It has been observed in the Val de Bagnes, that for mountain slopes above 2000 m, where the DEM is coarser, the source areas identification is not as accurate as at lower elevations. This is due to the fact that on the 1:25000 map data, gullies and small trenches are not represented, where they can be identified by aerial laser scanning. This has been observed for Pakistan as well. However, Pakistan is more concerned by large debris flow hazards, starting from wider source areas that are present in the low resolution DEM data.

Flow-R has been applied with success also in Italy and France (Blahut *et alii*, 2010; Lari *et alii*, in review; Kappes *et alii*, in review; Lari *et alii*, this volume). It permitted also to create a regional risk analysis in Valentine area, showing the efficiency of the model at a regional scale (Lari *et alii,* this volume). Its strengths are low requirements of data and a full control for the user, namely it can provide meaningful results with a DEM only and its derivatives, and all data inputs, algorithms and parameters are open to the user and can be changed.

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REFERENCES

Blahut J., Van Westen C.J & Sterlacchini S. (2010) - *Analysis of landslide inventories for accurate prediction of debris-flow source areas.* Geomorphology, **119** (1-2)**:** 36-51.

Claessens L. (2005) - *DEM resolution effects on shallow landslide hazard and soil redistrib.* modelling. Earth Surf. Proc. Land., **30:** 461-477.

Delmonaco G., Leoni G., Margottini C., Puglisi C. & Spizzichino D. (2003) - *Large scale debris-flow hazard assessment: a geotechnical approach and GIS modelling.* Nat. Hazard Earth Sys., **3:** 443-455.

Erskine R.H., Green T., Ramirez J. & MacDonald L. (2006) - *Comparison of grid-based algorithms for computing upslope contributing area*. Water Resour. Res., **42** (9).

Fairfield J. & Laymarie P. (1991) - *Drainage Networks From Grid Digital Elevation Models.* Water Resour. Res., **30** (6)**:** 1681-1692.

Freeman T.G. (1991) - *Calculating catchment area with divergent flow based on a regular grid. Computers & Geosciences,* **17** (3)**:** 413-422.

Gamma P. (2000) - *dfwalk - Ein Murgang- Simulationsprogramm zur Gefahrenzonierung. Bern, Switzerland.*

Heinimann H.R. (1998) - *Methoden zur Analyse und Bewertung von Naturgefahren.* Bundesamt für Umwelt, Wald und Landschaft (BUWAL).

Holmgren P. (1994) - *Multiple flow direction algorithms for runoff modelling in grid based elevation model.* Hydrol. Process., **8**(4)**:** 327-334.

Horton P., Jaboyedoff M. & Bardou E. (2008) - *Debris flow susceptibility mapping at a regional scale. 4th Canadian Conference on Geohazards*: From Causes to Management, Université Laval, Québec, Qc, Canada, Presse de l'Université Laval.

Huggel C., Kääb A., Haeberli W. & Krummenacher B. (2003) - *Regional-scale GIS-models for assessment of hazards from glacier lake outbursts: evaluation and application in the Swiss Alps*. Nat. Hazard Earth Sys., **3:** 647-662.

Iverson R.M. & Denlinger R.P. (2001) - *Mechanics of debris flows and debris-laden flash floods*. Seventh Federal Interagency Sedimentation Conference, Reno, Nevada, USA.

Jaboyedoff M., Pedrazzini A., Loye A., Horton P. & Surace I. (2008) - *Cartes Indicatives de Danger des Mouvements de Versants du Canton de Vaud.* Technical report, University of Lausanne, Switzerland.

Jaboyedoff M., Michoud C., Mazotti B., Choffet M., Dubois J., Breguet A., Metraux V., Derron M.H., Horton P., Loye A. & Pedrazzini A. (2010) - *Cartes Indicatives de Dangers pour le Val de Bagnes et de Vollèges.* Carnet méthodologique, 89 pp.

Lari S., Crosta G.B., Frattini P., Horton P. & Jaboyedoff M. (this volume) - *Regional-scale debris-flow risk assessment for an alpine valley*.

Perla R. (1980) - *A two-parameter model of snow-avalanche motion.* J. Glaciol., **26** (94)**:** 197-207.

Quinn P., Beven K., Chevalier P. & Planchon O. (1991) - *The Prediction Of Hillslope Flow Paths For Distributed Hydrological Modelling Using Digital Terrain Models.* Hydrol. Process., **5** (1)**:** 59-79.

Rickenmann D. & Zimmermann M. (1993) - *The 1987 debris flows in Switzerland: docum. and analysis.* Geomorphology, **8** (2-3): 175-189.

Sartori M., Gouffon Y. & Marthaler M. (2006) - *Harmonisation et définition des unités lithostratigraphiques briançonnaises dans les nappes penniques du Valais.* Eclogae Geologicae Helvetiae, **99:** 363-407

Takahashi T. (1981) - *Estimation of potential debris flows and their hazardous zones : soft countermeasures for a disaster.* Natural disaster science, **3** (1)**:** 57-89.

Tarboton D.G. (1997) - *A new method for the determination of flow directions and upslope areas in grid digital elevation models.* Water Resour. Res., **33** (2)**:** 309-319.

Tarboton D.G., Bras R.L. & Rodriguez-Iturbe I. (1991) - *On the extraction of channel networks from digital elevation data.* Hydrol. Process., **5** (1): 81-100.

Turberg P., Parriaux A., Kalbermatten M., Golay F. & Lance J.M. (2008) - *The geotype concept to develop GIS oriented analysis in engineering geology application.* Swiss Geoscience Meeting conference, Lugano, Switzerland.

Wieczorek G.F., Mandrone G. & Decola L. (1997) - *The Influence of Hillslope Shape on Debris-Flow* Initiation. In: ASCE (Editor), First International Conference Water Resources Engineering Division, San Francisco, CA: 21-31.