AN INTEGRATED METHOD FOR DEBRIS FLOW HAZARD MAPPING USING 2D RUNOUT MODELS

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ABSTRACT

Hazard mapping of rapid mass movements in Alpine regions, especially debris flows, remains a challenging task in land-use management. Physically-based 2D runout models are capable of predicting debris-flow intensities over natural topography for use in the generation of detailed hazard maps. However constitutive hypothesis underlying the models are rarely fully tested and it is difficult to consider all natural variables. Differences in simulation results among different models are not negligible, causing uncertainty in application methodology to hazard mapping and increasing the risk if the model results are not generalized appropriately in hazard map drawing. In two cases in the Swiss Alps, a pragmatic method is proposed which accounts differences in model results, herein shown using two 2D models (FLO-2D and RAMMS) and empirical equations. This approach represents an alternative or complementary way to assess the degree of uncertainty in hazard maps.

Keywords: debris flows, hazard maps, 2D models, empirical relations, methodology

INTRODUCTION

Debris flows are one of the main causes of natural disasters in Alpine Regions (Brundl et al., 2009; Barbolini et al., 2008) and the problem is augmented by population growth and the increasing exposure of infrastructure and human activity (Hurlimann et al., 2006; Greminger, 2003). Brundl et al. (2009) have identified risk as the exposure of people and infrastructure to a hazard, and the event magnitude related to an expected return period is the starting point to calculate the risk (Raetzo et al., 2002). The use of GIS and increasing computational efficiency allow the use of physically-based computational models to estimate debris-flow hazards (Barbolini et al., 2008). Spatial prediction of debris-flow intensity can result in deceptively precise predictions of debris-flow intensity for use in hazard maps, while hazard maps should be made by following objective guidelines which may include simulation model results but also should include analyses of previous events, other supporting calculations, and expert judgement from experienced practitioners (Barbolini et al., 2008; Hurlimann et al., 2008; Rickenmann, 2005; BUWAL, 1997).

When a hazard map is produced using a computer model, the four following assumptions are generally explicitly taken:

a) The magnitude of the simulated event is related to return period of the triggering rainfall event considering the hydrology of the basin;
b) The physical characteristics of the flow are properly represented in the scenario which is being modeled;
c) The Digital Terrain Model (DTM) accurately contains all relevant topography details;
d) The numerical model correctly simulates debris flow dynamics in all critical situations.

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The first assumption is not always met because a accurate historical data are commonly lacking in Alpine regions (Rickenmann et al., 2006) and rainfall-based return periods are a crude approximation. The physical characteristics of debris flows are variable in space and time and field data are rarely available to validate the second assumption. The influence of DTM resolution on simulation results is a well known and common problem (Stolz and Huggel, 2008), and many commercial routing models are not capable of providing simulation results at appropriately fine grid resolutions even if such high-resolution data are available, thus making it difficult to support the second assumption. Finally, models are constructed using many additional numerical/physical assumptions which make full validation an impossible task (Hurlimann et al. 2008). Many authors (e.g. Cesca and D'Agostino, 2006; Stolz and Huggel, 2008; Rickenmann et al., 2006) have highlighted the uncertainties in debris-flow simulations, finding important sources of biases that may be disregarded in hazard mapping.

Consequently, users of hazard maps, such as local authorities and municipalities, may not be fully aware of the potential inaccuracies and the sharp boundaries typically shown on such maps may lead to a false sense of accuracy.

Using two specific case studies, this contribution develops a procedure for computer-assisted hazard mapping which aims to merge spatial runout modeling results and frequently used empirical event-based relationships.

STUDY AREA

The study area is in the village of Zinal, situated at an altitude of approximately 1800 m a.s.l, in Canton VS, Switzerland. Zinal is endangered by debris flows and snow avalanches. Mitigation measures have been constructed in five catchments descending from the Les Diablons mountain chain (~3500 m a.s.l.) and were intended to protect farm buildings at the time when the village was inhabited only during the grazing season. In 1960 a ski resort was built and tourism and related activity resulted in the development of the village, with all-year inhabitation. Historical records are incomplete, and generally only catastrophic events are remembered by elderly residents and in local records (Zinal defi a la Montagne, Vianin and Crettaz, 1988).

Geologically, the study area is comprised of Cretaceous-Jurassic weathered schists of the Tsate Nappe at high elevations, Cretaceous marble of the Frilihorn Nappe at middle elevations and Quaternary sediments at the lower elevations, below approximately 2200 m a.s.l. (Stampfly, 2001). Large areas of the upper zone are covered by moraines. The valley is north-south oriented, with a continental climate and 700 mm precipitation per year. Debris flow activity is typically caused by rainstorms (e.g. 1 July 2008), but also by intense snow and glacier melting (June 1965), with a number of significant events recorded (1929, 1936, 1950, 1956, 1970, 1987, 2008), and the melting of the Bonnard rock glacier occasionally causes debris flows associated with warm periods without rainfall. The present study procedure was implemented in two catchments, Bondes and Tracuit which were chosen because they are typical hazard management examples and because the mitigation measures are similar in typology but different in size by one order of magnitude (Fig. 1).

The Bondes catchment (Fig. 1) occupies an area of 0.94 km^2, with a mean channel average slope of 0.40 m/m and a mean fan slope of 0.17 m/m. Debris flows were observed in 1929, 1956 and 2008. Mitigation measures and subsequent modifications were built by cantonal authorities, culminating in a major project in 2008 which increased the height and length of the walls. Presently, a complex system of walls, and deflectors comprises a network of three retention basins. The upper basin has an internal height of 21 meters, 12 meters tall dams and a design capacity of 140,000 m^3. The second and third basin are smaller, and are intended to manage residual debris flow surges, with a total design capacity of 200,000 - 210,000 m^3.

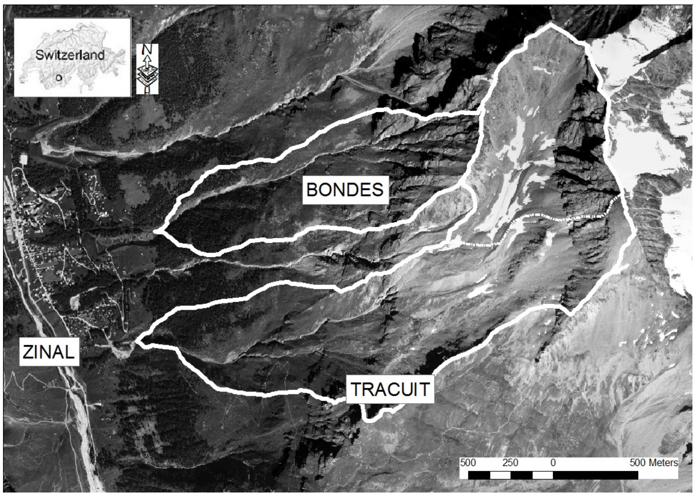

Fig.1 The study at the village of Zinal south-western Switzerland (VS). Bondes and Tracuit watersheds are outlined in white. The Bondes mitigation measure is clearly visible in the aerial photo, however the Tracuit measures, at the outlet of the basin, are not visible at this scale because part of the sidewalls was built to exploit natural topography.

The Tracuit catchment includes the entire Bonnard glacier (2.50 km^2), resulting in a poorly defined watershed area in the upper part of the basin (Fig. 1). IDEALP (2009) reports that the active basin of Tracuit occupies only 1.9 km^2 of the total DEM-derived area (Fig. 1). The main sediment contributions is from the main northern channel at the Bonnard frontal moraine. The channel in the lower gorge has a relatively low gradient (s-shape in planform) reach where small debris flows are observed to stop relatively frequently, causing an accumulation of large amounts of sediment. In 1987 a debris flow with a volume of less than 20,000 m^3 destroyed barns and damaged a hotel. A retention basin with a capacity of 16,000 m^3 was built in 1998-2000, and a project of enlargement and reshaping was completed in 2009 by IDEALP.

APPLICATION OF HAZARD MAPPING METHODS

An extensive procedure for hazard management was proposed by Hurlimann et al. (2006), identifying four stages of hazard management: A) geomorphologic and geologic analysis, B) runout analysis, C) hazard zonation, D) hazard mitigation. The general structure of this procedure is apparent in general practice, but practical application is difficult, especially due to a lack of data, and is therefore may be in some cases largely based on runout model results. For this kind of procedure, the pragmatic approach by Brundl et al. (2009) can be used to supply lack of data (stage a) and novel approaches to runout analysis and hazard zonation (stages b and c) are proposed with a modified version of the Hurliman et al. (2006) procedure.

A) Geomorphologic and geologic analysis

Swiss guidelines (BUWAL, BRP & BWW, 1997) describe a hazard intensity rating system that is a function of the debris flow depth and or velocity, and the probability o inundation (return periods 30, 100 and 300 years, in Switzerland). But a lack of historical data and strong anthropomorphic modification of the fans make it quite difficult to unambiguously reconstruct the occurrence of debris flows and avalanches over the last few centuries, which would be necessary to establish the historical magnitude-frequency relations for the basins.

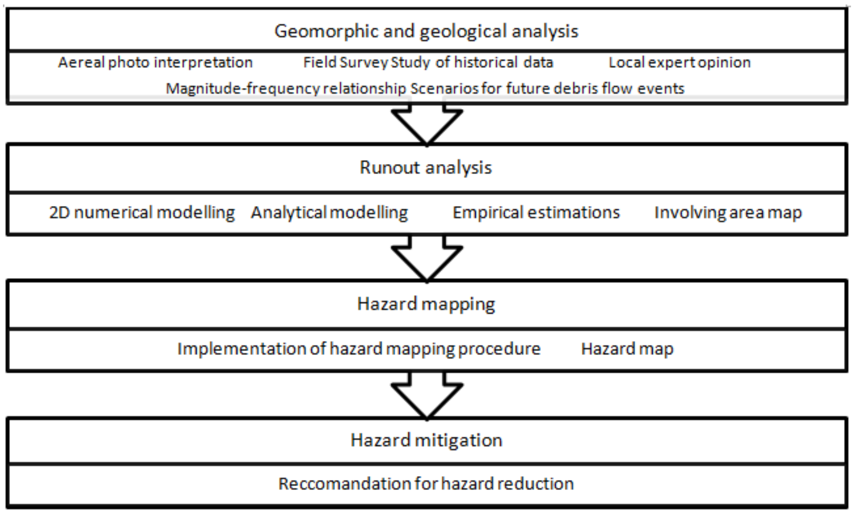

Fig. 2 Hurlimann et al. (2006) procedure, modified and adopted herein for debris flow hazard assessment.

Extensive field surveys were carried out to generate debris flow volume scenarios. Aerial photo interpretation guided the geomorphic estimation of debris availability in channels and source areas. The estimates were carried out following the Spreafico et al. (1999) procedure as modified by D'Agostino and Marchi (2003). Practically, the channel was inspected in the field where possible, and estimates were made for sediment availability in the banks and channel bed. Sediment source areas were mapped and the sediment supply was estimated separately. Volumetric estimates following the D'Agostino and Marchi (2003) method were performed using the seven nearest MeteoSwiss weather station datasets interpolated with a spline procedure. Comparison between field, volumetric and empirical estimation was conducted, also considering the opinions of local experts.

B) Runout analysis

Runout analysis methods are often classified into statistical-empirical equations and physically-based models (Barbolini et al. 2008, Rickenmann, 2005). This study considers both types in a mixed hazard mapping procedure, which addresses the uncertainty in the physical model predictions.

Empirical equations

Empirical equations (Table 1) are widely used for estimating hazard mapping parameters (Rickenmann, 1999), and classification schemes are available to estimate the required parameters (D'Agostino et al., 2010).

Tab. 1 Empirical relations used in the paper, sorted by the resulting variable; R = runout, V = volume, θ_u = source area slope, L = travel distance, H_e = elevation difference between the starting point and the lowest point of deposition of the mass movement, B = lateral spread, B_c = width of channel at the outlet.

Variable	Empirical relation	Author	Eq. number
Runout (R)	$R = 8{,}6 \cdot (V \tan \theta_u)^{0{,}42}$	Ikeya (1989)	(1)
	$R = 25 V^{\frac{1}{3}}$	Rickenmann, 1994, in D'Agostino et al. (2010)	(2)
Travel distance (L)	$L = 1{,}9 V^{0{,}16} H_e^{0{,}83}$	Rickenmann (1999)	(3)
Lateral spread (B)	$B\max = R$ (granular) $B\max = 0{,}55R$ (low cohesion)	Cesca (2008)	(4a) (4b)
	$\frac{B}{B_c} = k_1 + k_2 \left(\frac{R}{B_c} \right)$, k_1=1,788 e k_2=0,185	D'Agostino e Cesca (2009)	(5)

Physically-based models

Physically-based runout models are available, with 2D models often used for debris flow mapping, including the commercial mudflow routing model (FLO-2D) and a new Swiss debris flow and avalanche hazard mapping model, which, at the time of this writing, is also commercially available for debris flow routing (RAMMS). Both models describe debris flows as non-Newtonian fluids moving on a digital terrain model (DTM). The main advantages of 2D models are the simplified description of the flow properties (e.g. the friction relations used as an approximation of the flow "rheology"), and the ability to describe the flow routing in case of irregular ground topography. Frequently the models assume a fixed set of friction coefficients for an event which are difficult to accurately calibrate (Stolz and Huggel, 2008; Hurlimann et al., 2008; Hungr and McDougall, 2009). For this study RAMMS and FLO-2D have been used on a 2x2 m DTM (Swisstopo 2005), modified to include mitigation measures built in 2009 in the Bondes basin.

RAMMS is based on a finite-volume solution to the equations of motion for granular flows over general three-dimensional topography (Gruber and Bartelt, 2007; Christen et al., 2008). The model uses the Voellmy friction relation to describe the flowing friction which easy to calibrate for practical problems because the Coulomb-friction term (the first term on the right hand side of Equation 6) dominates the total friction when the flow is relatively slow (e.g. stopping behavior) and the turbulent friction parameter tends to dominate the total friction when the flow is rapid:

$$S_f = \mu \cos\theta + \frac{U^2}{\xi h} \tag{6}$$

where S_f is the friction slope, θ is a friction angle, U the depth-averaged flow velocity and h is the flow depth normal to the bed. Following Cesca and D'Agostino (2006) and Scheuner (2007), the mass density was fixed to 2000 kg/m^3, and the earth-pressure coefficient (λ) to 2.5, ξ to 200 m/s^2 and μ was selected to be similar to the tangent of the slope of the fan where deposition takes place. Although newer versions of the model allow for an input hydrograph, the version used herein uses the block-release of a volume of material from a source area in or near the channel.

FLO-2D is widely used in hazard assessment for floods and mud flows. The model is based on the continuity and on the momentum conservation equations, solved with a finite difference solution method on square grid. The FLO-2D quadratic friction ("rheological") model assumes the following depth-integrated friction slope:

$$S_f = \frac{\tau_c}{\gamma_m h} + \frac{K\mu_N}{8\gamma_m}\frac{U}{h^2} + \frac{n_{nd}^2 U^2}{h^{4/3}} \tag{7}$$

where the friction slope is composed by four sources of flow resistance. The first term is a yield stress where τ_c is a cohesive and Mohr Coulomb yield stress and γ_m is the specific weight of debris flow. The second term describes a viscous stress where K is a resistance parameter growing with roughness and μ_N is the Bingham dynamic viscosity. The third and fourth terms are turbulent and dispersive stress, respectively, merged into one variable n_{nd} that is described as a turbulent dispersive roughness connected with fluid concentration and Manning's n.

FLO-2D uses an estimation of yield stress τ_c, and viscosity $\mu_{N,}$ calculated as function of fluid concentration as:

$$\mu_N = \alpha_1 \cdot e^{\beta_1 C_v} \qquad \tau_n = \alpha_2 \cdot e^{\beta_2 C_v} \tag{8}$$

Where C_v is the sediment concentration and coefficients α and β are back calculated. FLO-2D simulations were run on a 3m grid due to software and hardware limits.

FLO-2D was calibrated performing small scale experiments (tilting plane rheometer) and looking for correspondence between measured and computed travel distance mobility ratio (D'Agostino and Cesca, 2009). The closest fit to the coefficients for Zinal material was Aspen Natural Soil, with yield stress coefficient $\alpha_2 = 0.152$, $\beta_2 = 18.7$ and viscosity coefficient $\alpha_1 = 0.00137$, $\beta_1 = 28.4$. Debris flow volume is input as a triangular liquid hydrograph constructed following the D'Agostino and Marchi (2003) methodology, calculated on the estimated magnitude for an extreme event.

B) Hazard zonation

As described above, traditional historically-based hazard zonation methods are difficult to apply in this case. Our procedure implements a new mapping methodology that considers the advantages of run out model simulations combined with empirical and analytical methods. The new procedure is based on following assumptions:

a) 2D physically-based models adequately describe the influence of the real topography, and are a reliable tool for forecasting inundated areas and depositional patterns of debris flows;
b) 2D model simulations result in detailed results that may be locally too intense for the velocity and depth based hazard delimitations imposed by traditional hazard mapping criteria (e.g. there may be a local bias);
c) empirical relations are useful for general hazard zone delineation but are not capable of resolving local details.

Our hazard mapping is based on the typical three intensity/color scales to delineate the expected intensity, but is added an optional fourth level intensity hazard (red and black pattern) to illustrate similarity in the predictions from the use of two numerical models (Table 2, Fig. 3). Following these three criteria we constructed the four hazard levels in a GIS environment. Following assumption a), the physically-based model results are used to delineate the highest levels of hazard, however using assumption b) the delineation of precise lines corresponding to flow intensity zones is adjusted. In particular:

- considering that the overlap of predicted intensity of two models may reflect an increased certainty in the model results, we identify it as a very likely high hazard intensity, with a red and black striped pattern (black and white in figures).
- the total area predicted by both (sum-overlap) models, merging the results, is considered as an area with a large expected probability of being inundated during a debris flow event, and this is considered as a high-intensity zone and assigned the red color (black in figures).
- Following assumptions b) and c), empirical relations are used to generate buffer zones to consider the uncertainty in run out model prediction:
- blue zone (medium hazard intensity, dark grey in figure) is mapped as a runout distance with a constant width built as a buffer along the main channel, or flow main direction. Runout distance is calculated with an empirical equation adapted to the region and the morphology of the catchment, width (B) is calculated using equation (5).
- yellow zone (low intensity, light grey in Fig. 3) is an external, cautionary buffer to account for uncertainty in the predictions. It is mapped using the same R in the same way as blue zone. The width on a fan is constructed considering the maximum width $B_{max}=R$ (worst case), apply at the end of runout perpendicular to the fan axis.

For both yellow and blue zones the runout is considered to start at the morphological apex of the fan, in the middle of the channel.

While this color scheme may not specifically consider the hazard intensity at any given location, e.g. for the production of hazard maps in Switzerland, it provides a direct indication of the degree of coincidence of model predictions, and therefore it may be useful when rapid zonation is desired.

Tab. 2 Criteria for debris flow and hazard mapping.

Type of data	Debris flow		Hazard intensity
2D physical models	Overlap flooded area		**Very high**
2D physical models	Not overlap flooded area		**High**
Emphirical or analytical method	Buffer along main channel in depositional zone with R=empirical runout and constant B (eq. 5)		**Medium**
Emphirical or analytical method	Empirical fan with R=empirical runout and B max=R (eq. 4a).		**Low**

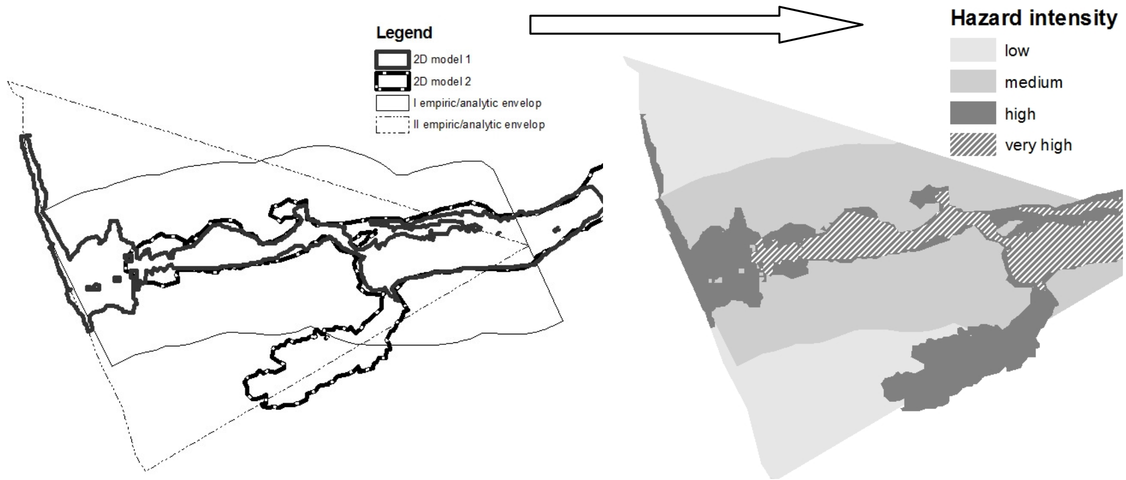

Fig.3 Example of hazard zonation following the proposed procedure.

C) Hazard mitigation

An analysis of the hazard map is required at the end of the process to identify critical areas and propose mitigation measures to reduce the hazard and or risk (Kunz and Hurni, 2009). 2D models allow the prediction of local flow intensities, also considering the presence of proposed mitigation measures (if they can be incorporated into the topographic model or otherwise incorporated into the model), and should be a useful tool for mitigation measure design. A critical revision of a hazard map should involve both 2D model results and comparison with empirical results as part of a discussion, in the most objective way possible.

PROCEDURE IMPLEMENTATION ON STUDY CASE

A) Geomorphologic and geologic analysis results

Geomorphic estimation indicates large debris availability in both catchments described above, both in the source areas as well as the main channels. An order of magnitude separates the empirical and geomorphic volume estimates (Table 3). Taking a pragmatic approach, the results and the values estimated by local experts, a volume of 6/7 of the Spreafico et al. (1999) geomorphic estimation was choose as this study debris flow extreme scenario (* in Table 3).

Tab. 3 Overview of estimated volumes (m^3) for extreme debris flows. The last column shows the values used in this study. The volumetric method underestimation of the extreme scenario is probably caused by the influence of snow and ice melting, which are not considered in that method.

	Geomorphic estimation methods	Volumetric method	Empirical estimation		Local extreme expected value (IDEALP)	Extreme scenario debris volume (*)
	Spreafico et al. (1999)	T_r 300 years	Takey (1984)	D'Agostino et al. (1996)		
Bondes	141 700	12 500	13 100	3 700	> 80 000	120 000
Tracuit	131 200	35 300	18 300	10 500	60-95 000	110 000

B) Runout and model results analysis

Comparison of debris flow runout and depositional patterns shows an important difference between the two numerical models. RAMMS runout is 35% less than FLO-2D in Bondes basin and 45% less in Tracuit Basin, while maximum spread and area are larger in RAMMS than FLO-2D simulation in both basins. Empirical equations show runout similar to models on Bondes basin, and larger for Tracuit. The Rickenmann (1994) equation appears to describe the maximum envelope of empirical equations, and therefore may be considered as a cautious estimate for hazard mapping in this case. Lateral maximum spreading is overestimated using equation (4a), especially in Bondes, where equation (5) better reproduces the models results. In the Tracuit basin, models results are similar between the predictions from equations (4a, 4b) and (5) (Table 4).

Tab. 4 Runout and depositional debris flow results obtained with different equations and methods.

	Bondes					Tracuit				
Authors	R (m)	(4) B = R (m)	(4) B=0,5 5R (m)	(5) B (m)	A (km^2)	R (m)	(4) B = R (m)	(4) B=0,55R (m)	(5) B (m)	A (km^2)
Ikeya (1989) (1)	949	949	522	277		882	882	485	249	
Rickenmann, 1994, in D'Agostino et al. (2010) (2)	1242	1242	683	239		1199	1199	659	328	
Rikenmann (1999) (3)	1101	1101	606	321		728	728	400	211	
RAMMS	825	188			0.74	392	517			0.91
FLO-2D	1252	172			0.57	704	357			0.64

C) Hazard Zonation

Following our procedure, demonstration hazard maps were prepared, with substantial differences with those prepared using traditional methods. Hazard zones are more homogeneous, more cautious, less influenced by mitigation measures and therefore include a crude estimate of the uncertainty of model results (Fig. 3). Note, however, that the frequency of inundation for a given exceedance of intensity, as required for constructing hazard maps in Switzerland, has not been incorporated into this procedure. With additional verification, it might be possible to use this method to objectively define areas of residual risk, e.g. areas which are threatened by debris flows but for which the expected return period is smaller than 300 years or where too little information is available to more accurately estimate the return period or magnitudes, but are judged by experts to be quite small.

D) Hazard mitigation

Debris flows in the Bondes catchment are usually predicted to be contained within the large mitigation measure system on the fan, and the small channel downstream of the last basin seems be sufficient to contain the residual discharge. The upper basin capacity is evidently close to the volume estimate for the extreme event. A hazard map could also be constructed to consider the case of insufficient time between events for emptying the basins. This is also true for all three basins forming this mitigation measures. With this perspective, a cautionary hazard zone around mitigation measures system, as a consequence of our procedure, should effectively cause an increase on safety and encourage rapid maintenance of mitigation measures. The Tracuit basin is apparently too small to contain the extreme debris flow scenario volume, a prediction also described in a technical report by the Canton of Valais. As suggest by Cantonal authorities, an enlargement of Tracuit basin and the relocation of the dam in southern part are priorities. In the hazard maps the houses of the southern part of Zinal (involved in the 1963 debris flow) belong to the blue zone, and the two main roads (inundated during the 1963 event) are in the yellow zone due to torrential flooding (not debris flow, in the case of the yellow zone) (Fig. 3). In our procedure these elements were assigned to the red zone.

Fig. 3 Comparison between traditional (left) and this study (right) debris flow hazard maps.

DISCUSSION

Geomorphologic and geologic analysis results

The lack of historical data is a common problem in Alpine valleys, but also where data are available detailed study on the catchment geomorphology is necessary for a reliable hazard mitigation strategy (Corominas and Moya, 2008). Considering that one of the most critical variables in debris hazard management is the magnitude of the scenario, particular attention and effort have to be focused on magnitude estimation. Runout model predictions are quite sensitive to volume: it may not be realistic to produce precise model results when only crude volume estimates are available. Emphirical realtions are usually a conservative prediction to establish the proper order of magnitude (Rickenmann, 1999; D'Agostino et al., 2010), but in this case the particular condition of Zinal basin caused an underestimation of runout. In particular the weathering of the rocks, the high degree of channelization, the slope of the main channel and the additional source of water due to glacial melting result in an underestimation, which is difficult to compare with the real situation due to a lack of accurate historical records. In this case more weight is assigned to geomorphic estimates. The combination of the three analyses described above suggest that the largest hazard arises during a high temperature period combined with intense rainfall in the late spring or early summer, when abundant snow is present in higher part of the basins (Bertoldi, 2010).

A) ***Runout analysis***

Stolz and Huggel (2008), Armento et al. (2007), Rickenmann et al. (2006), Cesca and D'Agostino (2006), Raetzo et al. (2002), investigated the uncertainty in debris flows run out simulation results, finding important source of bias between different models and between model results and events. In particular, physically-based model investigations are typically limited by a lack sufficient background data such as historical records of event magnitude, digital terrain model resolution, and it is typically impossible to unambiguously calibrate the friction parameters (Stolz and Huggel, 2008; Cesca and D'Agostino, 2006; Rickenmann et al. 2006) to permit perfect model calibration for a given historical event. The problem is compounded because it is reasonable to expect variation in the flow properties of debris flows due to the sensitivity of their frictional behavior to the properties of the debris, water content, and so on.

Debris-flow run out models typically produce sharp boundaries for flow intensity that may lead to a false sense of accuracy. It is often useful to evaluate the sensitivity of model predictions to random or systematic changes in channel-bed topography, as might be expected given typical torrent bed changes through time, or due to debris flow deposits remaining from earlier events. Similarly, for a given case, the user should investigate the sensitivity of the results to model parameters, especially the friction coefficients and the the event volume for a given return period. However, given the difficulty in anticipating every reasonable change in channel topography, and event volume, and trying to estimate the variability of friction coefficients based on limited historical data, the procedure as suggested herein may provide useful, if somewhat cautionary hazard maps.

Conversely, Berti and Simoni (2007) and Rickenmann (1999 and 2005), stressed the value and accuracy of empirical relations for debris flows runout and spreading. Drawbacks of empirical relations are principally the regional validity of the dataset used and the fact that the topography on any given fan may vary strongly from case to case (Rickenmann, 2005; Hurlimann et al. 2008). Additionally, the influence of mitigation measures is typically not accounted for. Lateral spreading is difficult to accurately predict, and appropriate caution should be used when making predictions.

B) ***Hazard Zonation***

The hazard zones predicted with the proposed method typically exceed those predicted using traditional methods. In many steep fan environments, such as Zinal, traditional hazard maps are often dominated by the high-hazard red zone, and the surrounding blue zone is often small in comparison. With our method, the red zone delineates the entire area predicted to be inundated with two models and it typically produces an area similar to a red zone predicted using traditional methods. The "very high" (red-black) hazard level is somewhat smaller than a traditional "red" hazard zone, and it delineates areas predicted to have frequent very high intensity flows. The "dramatic" enlargement of the blue produces a conservative buffer zone. The yellow zone (in the Swiss system this represents other torrential hazards because it is not defined for debris flows) provides some indication of areas which may be inundated in rare, extreme events. In practice, hazard maps are produced using engineering judgment, empirical relations, historical information, and possibly simulation model results. The synthesis which is required to make a general hazard map is rarely described and to the best of our knowledge, no objective procedures are publically available. The procedure described herein is a first step towards an objective procedure.

C) ***Hazard mitigation***

2D model simulations are useful to identify critical points for the design of mitigation measures. However effort should be taken to improve the model behavior in presence of structural mitigation measures (Johanneson et al., 2009; Barbolini et al., 2005). The definition of a probable debris flow inundation zones, with the zones based on 2D model results, will become a central point in hazard mapping as more physically realistic debris flow models become available. The construction of buffer zones based on other methods provides a realistic (and at the same time objective) way to consider unanticipated effects and also the imprecision of the models. In particular, topographic changes in torrent channels are expected due to e.g. changes in sediment loading from upstream or bedrock incision, changes in topography due to other processes such as deposition of rockfall debris or the creation of dams of woody debris. It is difficult to forecast all plausible and realistic changes in torrent channels, so a conservative procedure as has been shown, has the potential to increase the degree of public safety.

CONCLUSION

Our procedure, illustrated with case studies from Zinal, is a pragmatic and objective method to rapidly generate a kind of hazard map. In summary:

- Regarding event magnitude, we propose an integrated approach using geomorphic field surveys, and historical data, but also considering the opinion of local experts. Our results for Bondes and Tracuit extreme events are consistent with official estimates.
- Runout scenarios are evaluated both with empirical relations and 2D physically-based based model results. In Zinal, this allows us to consider fine changes in topography (mitigation measures), but also possible changes in the event of mitigation structures failure or other unforeseen changes in land use and structures.
- The combination of several model results into one procedure may reduce the uncertainty in hazard mapping and reduce the subjectivity in hazard analysis. In Bondes our procedure would lead to a more cautionary development of infrastructure near the mitigation structures, and in Tracuit it supports the decision of local authorities to enlarge mitigation measures and relocate the southern check dam.
- We proposed an objective alternative or preliminary approach to support the rapid generation of hazard maps in developing countries and when either local experts or existing hazard maps are unavailable.

Future developments to harmonize the procedure with the Swiss guidelines could include the automatic extraction of maximum intensity data (for a given series of model runs designed to simulate the variability of the processes, as described above).

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