DOI: 10.4408/IJEGE.2011-03.B-022

SIMPLE GEOMORPHOLOGIC APPROACH TO ESTIMATE DEBRIS-FLOW ENTRAINMENT. APPLICATIONS TO THE PYRENEES AND THE ALPS

Claudia ABANCÓ (*) & Marcel HÜRLIMANN (*)

(*) Dept. of Geotechnical Engineering and Geosciences, Technical University of Catalonia, Spain

ABSTRACT

The basal incorporation of material, also called entrainment, is a common characteristic of debris flow dynamics. The volume of a debris flow can considerably increase when compared to the initial volume, due to the erosion of material produced along the travel path. This study is a preliminary attempt to establish a simple geomorphologic approach for the calculation of volume to be entrained in a torrent, if a granular debrisflow event would occur. The methodology presented has been developed using data obtained by comprehensive field surveys, carried out in six torrents affected by granular debris-flow events. The torrents, divided into 43 reaches, are located in the Pyrenees and the Alps. The application of the methodology requires data to be measured along the flow path (geologic and geomorphologic factors). As a result, a predicted erosion rate for determined reaches can be estimated in function of these factors, properly weighted. Although the results indicate a high scatter, the total predicted erosion volume calculated for each test site using the proposed approach coincides rather well with the volumes observed in the field.

Key words: *entrainment, granular debris flow, erosion rate, Pyrenees, Alps*

INTRODUCTION

The entrainment is a common characteristic of debris flows and can be described as the incorporation of material along the travel path. The entrainment has a great influence on both the final volume of the event and the flow behaviour, since it causes variations in the bulk density.

A basic step towards debris flow hazard assessment is the prediction of the magnitude (volume). In order to predict the volume of a possible event, the entrainment has to be considered, however there are very few quantitative approaches proposed (e.g., Hungr *et alii,* 1984; Spreafico *et alii*, 1999)

On the other side, some authors have suggested that entrainment varies the mobility of the debris flows; therefore it is also relevant to delineate the possible runout lengths (Hungr *et alii*, 2005; Crosta *et alii,* 2008).

The "channel yield rate" or "erosion rate" is a parameter used to describe the amount of material entrained along a travel path. It is described as the volume of debris entrained along the travel path, proportioned to the length of the path (Hungr *et alii*, 1984).

Several authors have shown that the amount of material involved in a debris-flow event can considerably increase compared to the volume of the initial landslide (in landslide triggered debris flows), due to the erosion of material produced along the travel path (e.g., Hungr *et alii*, 2005; Guthrie *et alii*, 2009) The Glyssibach case study, located in Switzerland, is a perfect example of the significance of the entrainment. The total volume of the event obtained by LIDAR data was of about 80000 m^3, while approximately 50000 m3 correspond to entrainment occurred along the debris-flow path (Scheidl *et alii*, 2008).

Some attempts to quantify the entrainment produced by debris flows are found in the literature. Hungr *et alii* (1984) established a classification of stream channels in British Columbia, based on geologic and geomorphologic parameters, which is linked to a channel debris yield rate. Meanwhile, others have looked for correlations between geomorphologic factors and entrainment produced in specific events (Breien *et alii,* 2008). However, no clear empirical relationships have been established because in many cases there is a wide scatter in the available data sets (Chen *et alii*, 2005; Hungr *et alii*, 2005). Thus, only general rules have been derived up to now.

The main purpose of the present study is to propose a general and simple methodology to estimate the entrainment that can occur in a torrent.

DESCRIPTION OF EVENTS OCCURRED IN THE TEST SITES

The data used in this study was gathered in 6 torrents subdivided in 43 reaches, located in two different mountainous regions: the Pyrenees and the Alps. In all these torrents a granular debris flow occurred and field surveys were carried out after the events, in order to collect data about erosion patterns (Table 1).

The events of the Pyrenees (Figure 1) can be divided in: landslide triggered debris flows (Sant Nicolau), and in-channel debris flows (Ensija, Riu Runer and Port Ainé). The in-channel events are generally characterized by large catchment areas above the initiation point and lower bed slopes in the initiation reach, while the landslide triggered one presents a smaller catchment area and higher bed slope at the initiation zone (Portilla *et alii*, 2010).

The events of the Alps are in-channel triggered debris flows. However, they show higher bed slopes in the initiation reach than the landslide triggered debris flows in the Pyrenees. Detailed information on the Schipfenbach event can be found in Hürlimann *et alii* (2003), while only unpublished reports are available on the Gesäuse event.

The events of the Alps are in-channel triggered debris flows. However, they show higher bed slopes in the initiation reach than the landslide triggered debris flows in the Pyrenees. Detailed information on the Schipfenbach event can be found in Hürlimann *et alii* (2003), while only unpublished reports are available on the Gesäuse event.

Event	Region	Volume (m^3)	Runout (m)	Mean slope (°)	Elevation (m) Max	Elevation (m) Min	Catchment area (km^2)
Ensija	P	1500	1080	19	2140	1669	0.75
Sant Nicolau	P	1800	960	19	1965	1473	0.7
Riu Runer	P	14000	5175	13	1403	849	8.2
Port Ainé	P	26000	4830	15	2175	957	5.75
Schipfenbach	A	5000	2100	29	1754	498	1.37
Gesäuse	A	1300	365	32	768	679	0.01

Tab 1 - Description of the events occurred in the surveyed torrents

There are two approaches to describe the mechanism of the entrainment:

1) The "sliding mechanism" approach based on Mohr- Coulomb failure criterion.

2) The hydrodynamic approach based on bedload transport formulas of fluvial hydraulics.

The first one, the "sliding mechanism", is a static approach supported by some authors (e.g.Takahashi 1978; Takahashi 1991; Hungr *et alii*, 2005) where the entrainment can be easily explained by the infinite stability slope theory (Fig. 2). Based on this model, the erosion depth

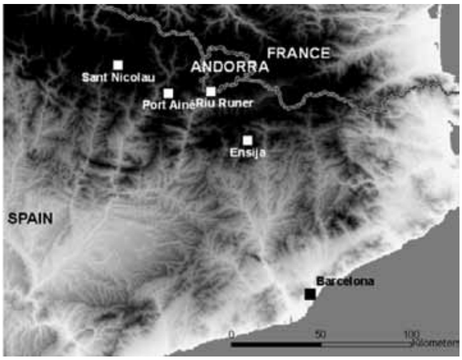


Fig 1 - Location of the surveyed torrents in the Pyrenees

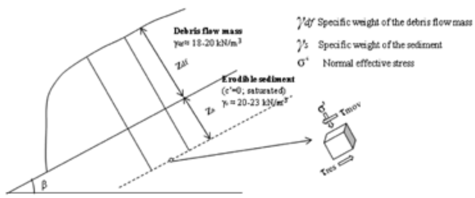


Fig 2 - Scheme of a channel bed with a layer of loose deposits that is being overflowed by a debris- flow mass. This approach supports that the entrainment occurs when the shear motion stress (τmov) overcomes the resistant one (τres) (maximum depth of material entrained) can be estimated.

Other authors assume that, as in bedload transport formulas of fluvial hydraulics, the flow can entrain material until the equilibrium condition is reached (Rickenmann *et alii*, 2003, Fraccarolo & Capart, 2002). This approach is dynamic, since it depends on the velocity and other parameters associated to the movement.

Another aspect that must be taken into account for estimating total debris-flow volume is the effect of secondary failures. The mechanism of this sediment supply is not related to a sliding mechanism caused by the passage of the flux over the erodible sediment, but rather to the erosion at the foot of the slope (Hungr *et alii*, 2005). In our approach this type of sediment incorporation has only been considered when estimating the total event volume in the field, but has not been taken into account for the erosion rate.

Factor	Class	Rating
Sediment availability	Bedrock	0
	High limitation	0.25
	Medium limitation	0.5
	Low limitation	0.75
	No limitation	1
Slope	<10º	0
	10º-20º	0.25
	20º-30º	0.5
	30º-40º	0.75
	>40º	1
Shape	Wide	0
	Medium	0.5
	Incised	1
NUCA	<0.2	0
	0.2-0.4	0.25
	0.4-0.6	0.5
	0.6-0.8	0.75
	0.8-1	1
Catchment Area	<0.1 km^2	0
	0.1-1 km^2	0.5
	>1 km^2	1

Tab 2 - Five governing factors selected for the calculation of the entrainment (NUCA: normalised upstream contributing area)

DEFINITION OF GOVERNING FACTORS

The entrainment estimation in the present work is based on geologic and geomorphologic features that can be reported in the field and by GIS analysis, while hydrometeorological conditions in the catchments have not been considered. The main goal is to obtain a volume estimation of material that can be entrained, from observations of static features of the torrent.

Five main factors were selected according to their relevance in the process, but also to the simplicity to obtain all of them directly from field surveys or GIS analysis: the available sediment, the bed slope of the analysed reach, the shape of the torrent in this particular reach, the normalised upstream contributing area of the reach and the catchment area of the torrent.

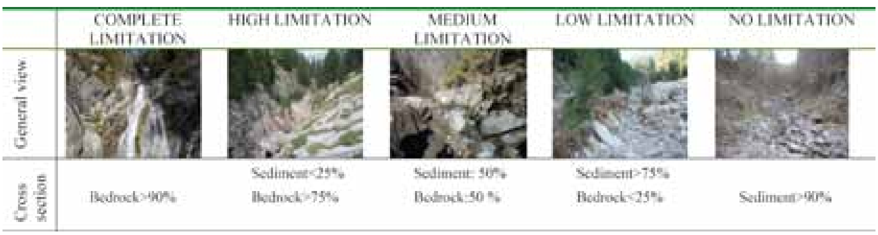
The five governing factors are divided into different classes (Tab. 2), which will be described in the following. The ratings of the classes vary from 0 to 1 depending on their relevance in entrainment process.

SEDIMENT AVAILABILITY

One of the factors most influencing the entrainment during a debris-flow event is the sediment availability. In one torrent, some reaches may have unlimited sediment (here called "not limited" reaches). Then, the erosion produced is totally conditioned by other factors. But, in some other reaches, the lack of sediment limits the entrainment (here, classified in different classes, depending on the level of limitation)

The purpose of this work has been to classify the reaches regarding the sediment availability. Five main classes have been described depending on how much material is available to be entrained. Some authors have done similar work in other regions, like in British Columbia (Hungr *et alii*, 1984), or the Swiss Alps (Spreafico *et alii,* 1999), but the description of the classes depends on the characteristics of each study area.

The definition and description of the five classes



Tab 3 / Sediment availability classes defined for granular debris flow. The limits have been described according to the characteristics of the surveyed areas, specially the Eastern Pyrenees, but it should be adapted to the regional features is based on the amount or percentage of the cross section that is covered by sediment (Table 3). In addition the reach is considered as a unique global part, without considering local exceptions.

The class "no limitation of sediment" means that the bedrock is almost not visible in the cross sections along the reach analysed. The class "low limitation of sediment" is related to reaches, when sediment is covering more than 75%of the cross section but the bedrock is still visible. "Medium limitation of sediment" means that bedrock and sediment appear in the cross section at equal proportion, while "high limitation of available sediment" indicates reaches where bedrock appears at both sides of the channel, but some sediment is covering the channel bed. Finally, the class "complete limitation of sediment" means that bedrock is visible at both sides of the channel. Even though, little sediment can be available in the channel bed.

SLOPE

Some authors studied the relation between the erosion rate and the slope of the reach or the local cross section. In some cases the relation clearly shows that as the slope increases, the entrainment rate also gets higher (Rickenmann & Zimmermann 1993; Guthrie et al. 2009). In other circumstances it can be seen that there is a feedback effect, which means that the entrainment is higher at low slopes. It can be justified with the increasing flow concentration or peak discharge as the travelled distance increases (and the slope decreases, normally) (Breien *et alii*, 2008). Other studies contradict these two situations indicating that, there is not a clear tendency, as it is completely related to the availability of sediment in the reach (Hungr *et alii*, 1984; Marchi *et alii,* 2009).

In our work the average slope of the reaches has

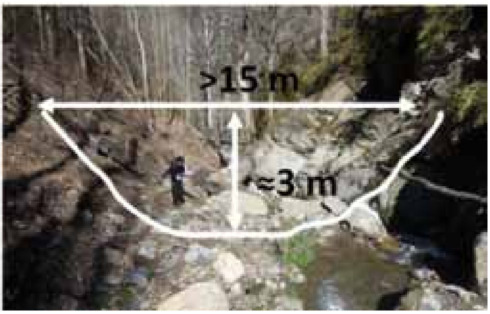


Fig. 3 - Wide reach in a debris flow torrent (Pyrenees)

been divided into classes of intervals of 10º, considering the upper limit of 40º, according to the characteristics of the Pyrenean events (Portilla *et alii*, 2010). In the present study, the mean slope was calculated from a Digital Elevation Model (DEM) with 5 m resolution. Alternatively, the mean slope can also be obtained from a topographic map or from measurements in the field.

SHAPE

The shape of the reach is a factor that has been considered in order to explain how the incision of the reach can be important in the entrainment process of the debris flow. Although no relationships between the shape of the torrent and the erosion rate were established in previous works, our field observations were an evidence of this fact. Gabet & Bookter (2008) described the shape of the studied gullies in southwest Montana (USA) using the "mean width to depth ratio", and the relation between the width at different heights from the bed. A similar concept is proposed in our work.

Here we suggest the width at 3 m height as the relevant dimension to describe the reach incision. According to the morphologic properties of the torrents in the Pyrenees, if the width (at 3 m height) is over 15 m, the reach can be considered wide (Fig. 3). If it is between 15 and 5 m, we called it medium, and if it is less than 5 m it can be considered as incised reach. These are limits absolutely depending on the characteristics of the torrents in the area, and should be verified for other areas.

NORMALISED UPSTREAM CONTRIBUTING AREA

The upstream contributing area, UCA, of a reach represents the drainage basin at the lowest point of the reach. The UCA-value of each reach i, UCA_i, can be normalized by the total catchment area CA:

$$NUCA = \frac{UCA_i}{CA_i} \quad (1)$$

where NUCAi is the normalised upstream contributing area of reach i (Fig. 4). This factor ranges from 0 to 1 and it has been divided into 5 classes according to Table 2.

The normalisation of UCA should be a way to identify the hydraulic load of the reach, that is clearly influencing the mean erosion (Rickenmann *et alii,* 2003). A better way would be to calculate the concentration of the flow, however this information needs detailed calculations, and therefore it's not adequate for a simple approach. Hence we propose to use the normalised upstream contributing area to give semi-quantitative information on thehydraulic load of the flow.

CATCHMENT AREA

The relationship between debris-flow volume and catchment area is characterised by a large scatter, but there is a general positive trend (Rickenmann & Zimmermann 1993; D'Agostino & Marchi 2001).

At the same time, a larger volume produces a higher peak discharge (Hungr *et alii,* 1984; Rickenmann 1999). Finally, we assume that as the peak discharge increases, the capability of the flow to entrain material grows. Therefore, in conclusion, the capacity to entrain volume is higher for larger catchment areas

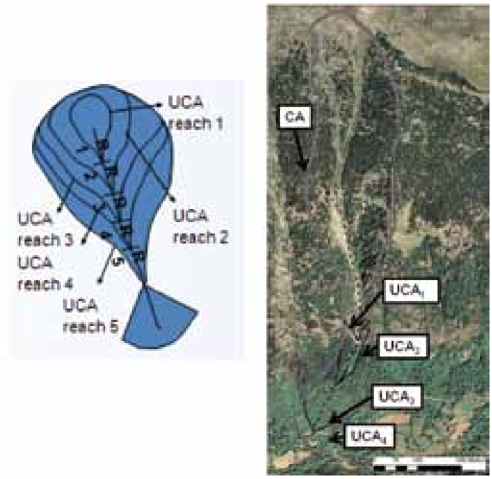


Fig 4 / Left:Scheme of the upstream contributing area of various reaches in a catchment. Right:Example in Sant Nicolau torrent (Pyrenees)

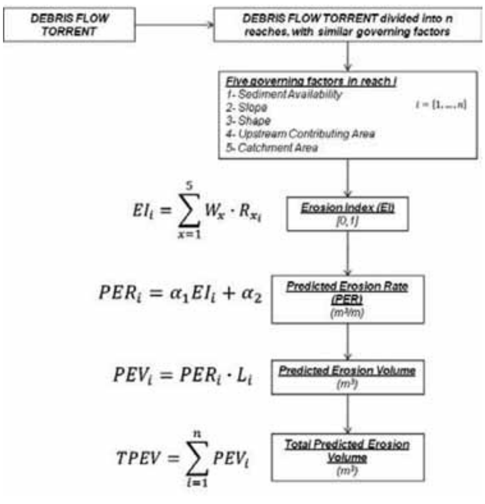


Fig. 5 - Flow-chart of approach

In our approach, the catchment area is a global factor and thus equal for all the reaches. The factor was divided into three classes: <0.1 km^2, 0.1 - 1 km^2, and >1km^2 (Table 2). The catchment area as the afore mentioned UCA$_i$ can be obtained directly by hydrological GIS tools and a DEM, or manually from topographic maps..

SIMPLE APPROACH TO ESTIMATE THE EROSION RATE

The purpose of this methodology is to estimate the volume of material that we can expect to be eroded in a certain torrent due to a debris-flow event

An overview of the different phases related to the approach is shown in Figure 5. The first phase consists in the division of the debris-flow torrent into reaches, with similar characteristics regarding the governing factors. Using the values of classes in Table 2, the Erosion Index, EI, can be calculated. This value is used to obtain the Predicted Erosion Rate, PER, that expresses the volume of material that might be eroded in a reach (cubic meter per running meter). The total volume to be eroded in the torrent can be obtained easily from the Predicted Erosion Rate and the length of each reach, L_i..

Pyrenees and the Alps that we collected in the field surveys. Nevertheless, this approach may also be applied in an adapted form to other mountainous areas, where granular debris flows occur. In the following, the two most important steps of the approach, the calculation of EI and PER, are explained in detail

EROSION INDEX

The erosion index is a dimensionless parameter and is calculated for every reach using the selected class rating of each governing factor (Table 2). In addition, the weight of each governing factor is introduced, which leads to the final expression:.

$$EI_i = \sum_{x=1}^{5} W_x \cdot R_{x_i} \qquad (2)$$

where W_X is the weight of governing factor X and R_{Xi} is the value of the governing factor in reach i. The index X stands for SA: sediment availability; S: bed slope; SH: cross section shape; NUCA: Normalised Upstream Contributing Area and CA: Catchment Area

While the class rating can be determined using field observations and Table 2, the weights of each governing factor are determined in a second phase applying statistical analysis. This statistical analysis calibrates the weights by the comparison of the erosion rates observed in the field with the EI calculated.

The EI-values range from 0 to 1, as the terms of the summation are normalized. High values of Erosion Index indicate more erosion than values close to 0.

.

PREDICTED EROSION RATE

In order to quantify the entrainment, the dimensionless erosion index is transformed into the Predicted Erosion Rate, PER. PER expresses the amount of material per running meter that may be entrained by a debris-flow event along a defined reach. Thus, the Predicted Erosion Rate, in contrast to the Erosion Index, has a physical meaning, and is expressed in m^3/m.

The transformation of EI into PER can be done using the best-fit function obtained during the statistical analysis. This function can be expressed in a simple form by

$$PER = f(EI, \alpha) \tag{3}$$

where α represents the pair of parameters (α1 and α2) that define the linear regression (see below for detailed explanation).

RESULTS

FIELD DATA ON GOVERNING FACTORS

The field data collected in the Pyrenees and the Alps has been plotted in order to study the relation between the five governing factors and the erosion rate observed in the reaches. Additionally, the class ranges of values of the governing factors established in Table 1 have been checked.

As observed in other studies (Chen *et alii*, 2005; Hungr *et alii*, 2005), the data show a large scatter. Nevertheless, some genera patterns of particular interest can be detected. On one hand, it can be seen that there is an increase of scouring in the steepest reaches (Fig. 6), as was also revealed by Guthrie *et alii* (2009). The importance of the sediment availability for the entrainment process is also relevant.

On the other hand, it can be noted that there is a

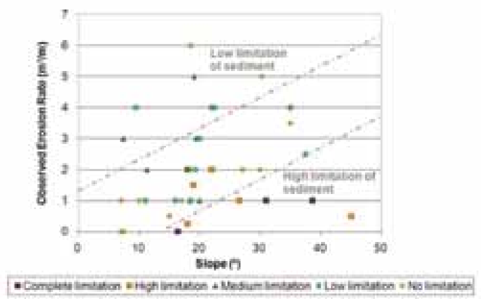


Fig 6: Slope vs. Erosion rate of the reaches in the surveyed catchments, depending on the sediment availability class. Each point corresponds to a reach

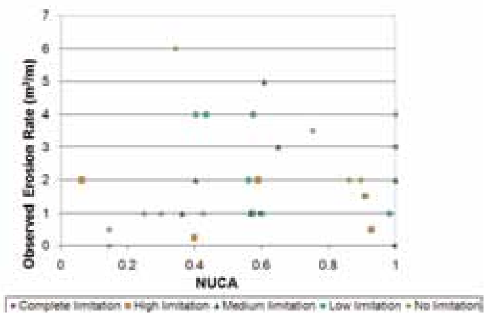


Fig 7: Normalised upstream contributing area vs. Erosion rate of the reaches in the surveyed torrents, depending on the sediment availability class. Each point corresponds to a reach

rough trend between the upstream contributing area and the erosion produced in the reaches (Fig. 7). It can be related to the amount of water-solid volume entering to the reach (Hungr *et alii,* 2005).

EROSION INDEX

As described previously, the weights of the different governing factors must be defined by a statistical analysis comparing the estimated EI-value with the observed erosion rate (OER). The OER is the channel yield rate estimated after occurring an event, along a certain reach (Hungr *et alii,* 1984).

In a first attempt (Tab. 4), we assumed the same weights for each governing factors, which means Wx–values of 0.2 in (2). The results of the calculated EI-values are compared with the erosion rates observed in the field, OER. A qualitative analysis of this plot shows an overestimation of the EI-values, since all EI-values are higher than 0.4, even for very low or no OER. The quantitative check of the results was performed by a statistical analysis and the coefficient of determination, R^2. In our case we applied a very simple linear regression given by:

$$ER_i = \alpha_1 EI_i + \alpha_2 \quad (4)$$

where ER_i is the erosion rate we want to approximate to the one observed in a torrent reach i, and α1 and α_2 are two coefficients. The low R2-value of 0.045 is not surprising due to the high scatter of the data. Other statistical regressions may provide a better fit, but only a slight improvement could be observed in our field data applying polynomial or other functions

In the next attempts, the weights of the governing factors were adjusted. The results were checked again by linear regression and the coefficient of determination R2 was compared. Finally, the bestfit weights were obtained in attempt 4, when the weights of the sediment availability and slope were increased and the other onesreduced. The results of this best-fit attempt are shown in Figure 9..

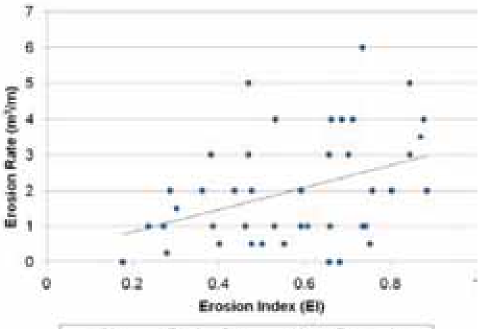


Fig. 9 EIi vs OERi, fourth attempt (Table 4): Regression line is calculated with best-fit weights for the governing factors

Attempt	Weights of governing factors					R^2
	SA	S	SH	NUCA	CA	
1	0.2	0.2	0.2	0.2	0.2	0.045
2	0.7	0.1	0.05	0.05	0.1	0.132
3	0.6	0.1	0.1	0.1	0.1	0.146
4	0.6	0.3	0.02	0.03	0.05	0.152

Tab. 4 - Results of the linear regression analysis applied to calibrate the weights of the governing factors in order to calculate EI

PREDICTED EROSION RATE

The transformation from the dimensionless EI into the quantitative PER was performed by using the best-fit linear function obtained in the previous section. Then, the ER_i is called PER_i, and the final equation can be given by:

$$PER_i = 3.117 EI_i + 0.215 \quad (5)$$

This expression was applied to all reaches and the results were compared with the OER_i (Figure 10). The plot shows that the PERvalues are generally overestimated when low erosion rates were observed in the field and underestimated when high erosion rates were detected. This means that extreme values may not be represented correctly by our approach, since most of the PER-values are in the range from 1 to 3 m^3/m. This fact should be taken into account in the application of the approach and may be corrected incorporating additional field data.

Finally, the total predicted erosion volume, PEV, for a torrent could be calculated by:

$$PEV_i = PER_i \cdot L_i \quad (6)$$

where L_i is the topographic length of the torrent reach i. This task was carried out and two examples will be presented in the following section.

EXAMPLES OF TOTAL EROSION VOLUME PREDICTED

Regarding debris-flow hazard assessment, the most interesting information is generally the total

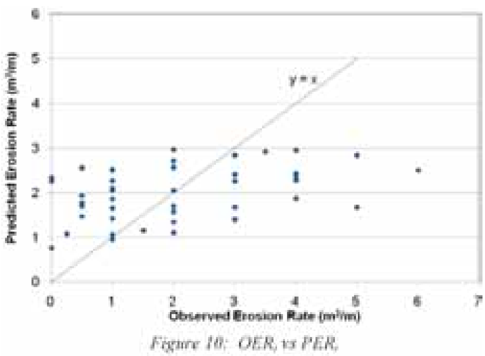


Fig 10 - OERi vs PERi

volume mobilized by a future event. With the purpose of making a first test of the approach proposed, the evolution of the volume along the flow path has been calculated for the five debris-flow events in the test sites. The cumulative eroded volume has been compared to the predicted one.

Figure 11 shows the two examples of Sant Nicolau (landslide triggered, with an initial volume of 800 m3) and Schipfenbach (inchannel debris flow).

From the comparison of the total predicted eroded volume and the total observed volume of the events, it can be seen that the methodology proposed shows rather coherent results

Although local differences in some reaches can be detected, the final volume is comparable between observations and calculations

CONCLUDING REMARKS

A simple methodology to approximate the entrainment that can occur in a torrent has been presented. The methodology estimates an erosion rate in a selected channel reach based on five governing factors. The factors have been weighted according to their relevance in the entrainment process. Each factor has been divided in several classes, with ratings from 0 (less prone to entrainment) to 1 (more prone to entrainment).

The ratings of the factor classes have been defined using the observations obtained from six debris flows within our test areas. The weights of the governing factors have been adjusted according to a linear regression. In future works, when more data is going to be available, this simple regression may be replaced with another statistical function

The results of the field observations showed that the relations between observed erosion rate and the governing factors indicate high scatter, even though some general trends can be observed. In spite of the uncertainties related to this simple approach, realistic total volumes could be estimated for the six debris flows in the test sites, and show that this methodology could be very helpful in hazard assessments.

The application of the presented methodology to other areas should include a verification of the class limits and weights of the five governing factors. Finally, similar approaches may be incorporated into numerical models in order to improve the entrainment processes in granular debris flow.

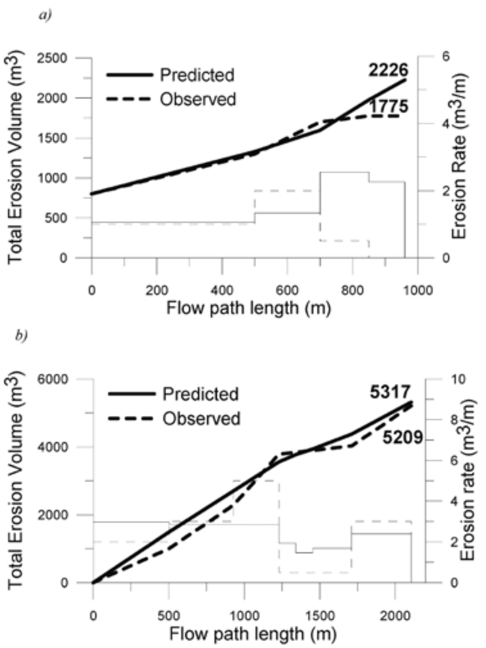


Fig 11. - PERi calculated in every reach and comparison between evolution of predicted and observed volume along the flow path. a) Sant Nicolau torrent (Pyrenees), b) Schipfenbach torrent (Alps)

ACKNOWLEDGEMENTS

The authors wish to thank the Institute of Natural Hazards in Universität für Bodenkultur Wien (BOKU), in particular to Christian Scheidl, for discussions and the field trip to Gesäuse. Special thanks to the administration of the Gesäuse National Park for the cartographical data and the DEM. The authors are also grateful to Christoph Graf, Swiss Federal Research Institute (WSL), for his collaboration in the Schipfenbach event.

This research was supported by the Spanish Ministry of Science and Innovation, contract CGL2008-00299/BTE.

REFERENCES

Breien H., De Blasio F.V., Elverhoi A. & Hoeg K. (2008) - *Erosion and morphology of a debris flow caused by a glacial lake outburst flood, Western Norway.* Landslides. **5**: 271-280.

Crosta G.B., Imposimato S. & Roddeman D. (2008) - *Numerical modelling of entrainment/deposition in rock and debris-avalanches.* Engineering Geology, **109**: 135-145.

Chen J., He Y.P. & Wei F.Q. (2005) - *Debris flow erosion and deposition in Jiangjia Gully, Yunnan, China.* Environ Geol, **48**: 771–777.

D'Agostino V. & Marchi L. (2001) - *Debris flow magnitude in the Eastern Italian Alps: data collection and analysis.* Physics and Chemistry of the Earth, Part C: Solar, Terrestrial & Planetary Science, **26**: 657-663.

Fraccarolo L, Capart H. (2002) - *Riemann wave description of erosional dam-break flows.* J. Fluid Mechanics, **461**: 183–228.

Gabet E.J. & Bookter A. (2008) - *A morphometric analysis of gullies scoured by post-fire progressively bulked debris flows in southwest Montana, USA.* Geomorphology, **96**: 298-309.

Guthrie R.H., Hockin A., Colquhoun L., Nagy T., Evans S.G. & Ayles C. (2009) - *An examination of controls on debris flow mobility: Evidence from coastal British Columbia.* Geomorphology, **114**: 601-613.

Hungr O., McDougall S. & Bovis M. (2005) - *Entrainment of material by debris flow.* In Debris-flow Hazards and Related Phenomena. Eds. Jakob M. & Hungr O.: 135-158. Springer, Berlin.

Hungr O., Morgan G.C. & Kellerhals R. (1984) - *Quantitative analysis of debris torrent hazards for design of remedial measures.* Canadian Geotechnical Journal, **21**: 663-677.

Hürlimann M., Rickenmann D. & Graf C. (2003) - *Field and monitoring data of debris-flow events in the Swiss Alps*. Can. Geot. J., **40**: 161-175.

Marchi L., Cavalli M., Sangati M. & Borga M. (2009) - *Hydrometeorological controls and erosive response of an extreme alpine debris flow.* Hydrological Processes, **23**: 2714-2727.

Portilla M., Chevalier G. & Hürlimann M. (2010) - *Description and analysis of major mass movements occurred during 2008 in the Eastern Pyrenees.* Nat. Hazards Earth Syst. Sci., **10**: 1635-1645.

Rickenmann D. (1999) - *Empirical relationships for debris flows.* Natural hazards, **19**: 47-77.

Rickenmann D., Weber D. & Stepanov B. (2003) - *Erosion by flow in field and laboratory experiments.* 3rd International Conference on Debris Flow Hazards Mitigation: Mechanics, Prediction and Assessment, Davos, Millpress.

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

Scheidl C., Rickenmann D. & Chiari M. (2008) - *The use of airbone LIDAR data for the analysis of debris flow events in Switzerland.* Nat. Hazards Earth Syst. Sci. **8**: *1113-1127.*

Spreafico M., Lehmann C. & Naef O. (1999) - *Recommandations concernant l'estimation de la charge sédimentaire dans les torrents.* Communication No. 4, Groupe de travail pour l'hydrologie opérationnelle (GHO) Berne.

Takahashi T. (1978) - *Mechanical characteristics of debris flow.* Journal of Hydraulic Division ASCE, **104**: 1153-1169.

Takahashi T. (1991) - *Debris Flow.* Balkema, Rotterdam. 165 pp.

