The **DAMOCLES** European Project

**Debris fall assessment in mountain catchments for local end-users**

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# DEBRIS FLOW RELATIONSHIPS IN THE CENTRAL SPANISH PYRENEES

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## 1. Introduction

It is commonly accepted that, in terms of volume moved in a short space of time, debris flows are one of the most powerful mechanisms for transporting material downslope (Johnson & Rodine, 1984; Takahashi, 1991; Bathurst et al., 1997). They occur if i) sediment availability, ii) water input, and iii) slope gradient are present in a critical combination (Takahashi, 1981; Rickenmann & Zimmermann, 1993).

A simple classification distinguishes between confined and unconfined debris flows, depending on the characteristics of the channel and sedimentation area. Confined debris flows develop within incised channels that occasionally can wotk as torrents or avalanche channels. Unconfined debris flows occur in a previously non incised hillslope. Brunsden (1979) points out that they typically are triggered on slopes with abundant non-consolidated sediments, steep gradients, scarce plant cover and no previous rills or incised channels. Scars develop at the rupture area ("a shallow landslide that evolves into a debris flow": Bathurst et al., 1997), and a tongue with lateral levees ending in a frontal lobe with imbricated, non-sorted clasts (Varnes, 1978; Rapp & Nyberg, 1981; Johnson & Rodine, 1984). They are usually linked to intense, relatively infrequent rainstorms (Kotarba, 1989; Van Steijn, 1996; Caine, 1980).

Debris flows represent the most active geomorphic risk in mountainous areas, affecting infrastructures, human settlements and touristic resorts (Takahashi et al., 1981). For this reason, much effort has been put in assessing where debris flows occur and ranking the factors that trigger them, but also in defining two essential parameters in establishing debris flow hazards: what is the distance travelled by debris flows (especially the runout distance), and what is the volume of material carried out by debris flows, as well as the relationships between different debris flow parameters. This information is a very relevant input for debris flow modelling and to predict the areas most probably affected by future debris flows.

In this report the characteristics of debris flow parameters are studied, in order to establish formulas allowing the calculation of debris flow transport distance and sediment volume delivered to the streams. Parallel effort has been put to predict the occurrence of debris flows in the hillslopes. The results from this report are the base to assess the debris flow hazard for infrastructures and settlements, as well as for arriving to the fluvial network and deliver large volumes of sediment.

In previous progress reports we informed that a statistical analysis was made with the information obtained from the location of almost 1,000 debris flows distributed by the whole study are. With this information we were able to explain the distribution of debris flows according to the lithology, gradient, aspect, altitude, distance to the divide, plant cover, evolution of the land use and other environmental factors. Furthermore, using complex statistical procedures we obtained a debris flow susceptibility map, which needs to be improved by adding information on the spatial distribution of extreme rainfall events. Now we have made an intensive field work in order to obtain detailed information on different debris flow parameters which has allowed us to establish statistical relationships between such parameters (see Bathurst et al., 1997).

## 2. The study area

The study area for the DAMOCLES Project occupies the upper basins of the Aragon and Gallego rivers, in the Central Spanish Pyrenees, with a total area of 1727 $km^2$. The highest altitudes surpass 3000 m (Infierno Peak, 3090 m; Balaitús, 3151 m), and much of the area is above 2000 m, with strong altitudinal contrasts between divides and valley bottoms. Landforms differ in lithological strength, geological structure and inherited morphology from the last Pleistocene glaciation.

For this report, the Flysch Sector (867 $km^2$) has been selected, since most of debris flows of the study area are located in this lithology. It is important to take into account that the Flysch Sector is a geomorphologically active area, with relatively steep gradients and the alternance of thin sandstone and marl beds, encouraging the triggering of shallow (as well as deep) landslides. The gradients are smoother and more homogeneous than in the rest of the Central Pyrenees, in spite of intense tectonization, including complex faults and folds. The divides reach 2200 m a.s.l. Southward, the contact with the marls of the Inner Depression is at about 800 m, by means of an overthrusting fault.

The mean annual precipitation in the study area exceeds 800 mm, increasing to 2000 mm above 2000 m (Garcia-Ruiz *et al.*, 1985). The wet season ranges from October to May, with very little rain in January and February. The whole area is occasionally subject to very intense rainstorms (Garcia-Ruiz *et al.*, 2000), which can cause serious damage by flash floods (White *et al.*, 1997) and mass movements .

Human disturbance is intense below 1600 m. In the Flysch Sector most sunny hillslopes have been cultivated (even steep sections) using shifting agriculture systems (Lasanta, 1989). Old fields outside the Inner Depression are often abandoned and substituted by dense shrubland (Molinillo *et al.*, 1997) and reforested pines. Crops (meadows) only persist in the valley bottoms. Above 1600 m, the landscape is dominated by dense forests and subalpine and alpine grasslands, occasionally affected by intense erosion (Garcia-Ruiz *et al.*, 1990).

The occurrence of debris flows is especially dense in the areas intensively managed for centuries, mainly in the most tectonized areas and where very old slumps have been identified.

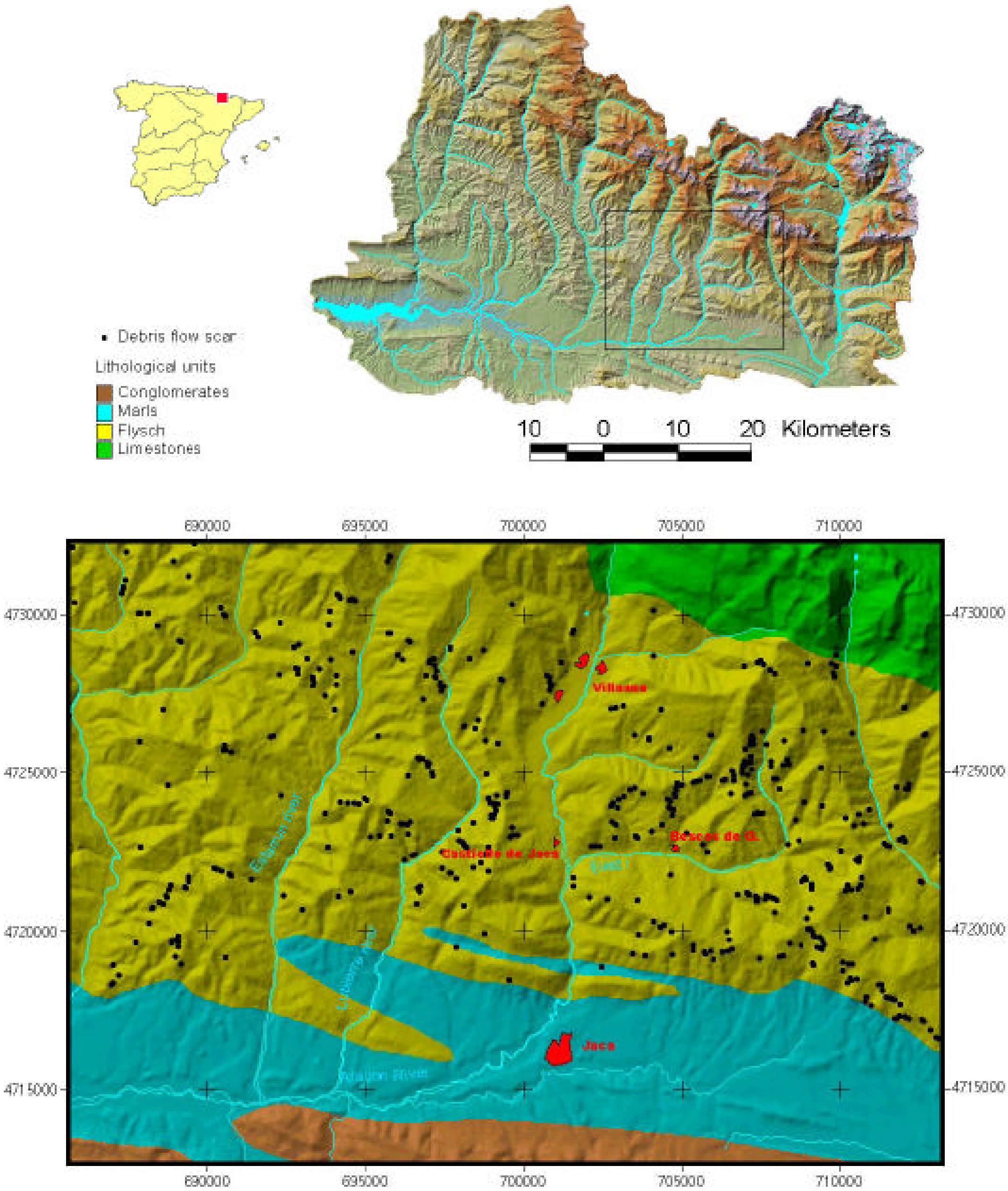



Fig. 1. Location of Focus Area

**3. Methods**

In total, 961 debris flows were identified in the upper Aragon and Gallego basins. From them, 98 debris flows have been selected in the most geomorphologically active areas of the Flysch Sector, that is, close to the contact between the Flysch Sector and the marls of the Inner Depression, especially in the Ijuez and Acumuer valleys and in the southern aspects of the Flysch Sector between Jaca and Sabinanigo (Fig.1).

The following variables have been measured in each one of the 98 selected debris flows:

- ALTSCAR: The altitude of the debris flow scar in metres above the sea level.
- ALTBASE: The altitude where the runout deposit begins (in m).
- $\Delta$h: Difference in height (m) between ALTSCAR and ALTBASE.
- LENGTH: Total length of the debris flow between the upper part of the scar and the beginning of the deposit.
- SCARº: Gradient of the debris flow scar.
- CANALº: Gradient of the debris flow canal.
- BASEº: Gradient of the debris flow deposit.
- RUNOUT: Length (in m) of the debris flow deposit.
- SCAR2: Width (in m) of the debris flow scar.
- CANAL2: Width (in m) of the debris flow canal.
- BASE2: Width (in m) of the debris flow deposit.
- VOLUME: Estimated volume ($m^3$) of the material mobilized by the debris flow.
- SOILM: Average soil depth (m).

In the office, the relationship between DEPOSIT and $\Delta$h has been obtained, that is, the relationship between the length of the debris flow deposit and the difference in height. This parameter has been called $\alpha$.

In total, 13 variables have been measured in the field. Fig. 2 shows a longitudinal profile of a typical debris flow, with some of the measured variables. Furthermore, in the most recent debris flows soil samples were taken in order to obtain their grain size distribution. The results from soil analysis are not included in this report.

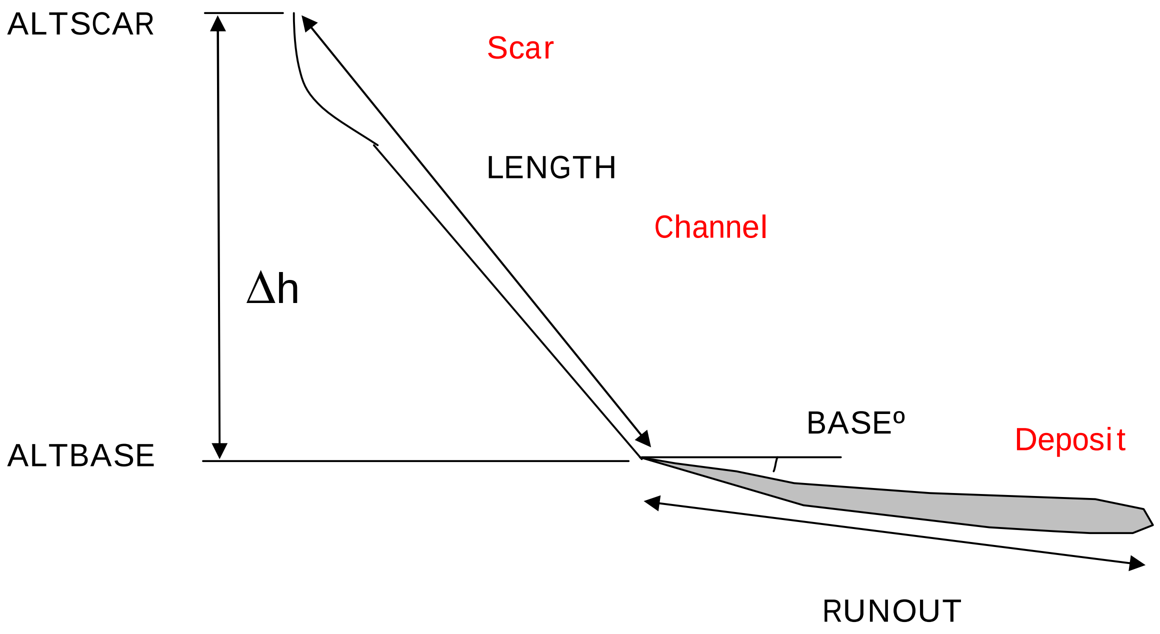



Fig.2. Some of the parameters measured in the debris flows.

A general table was obtained, to which descriptive statistical procedures were applied. First of all, the statistical analysis was carried out with all the measured debris flows (98 in total), thus obtaining the Mean, Median, Standard deviation, Variance, Rank, Maximum and Minimum value, as well as the percentiles. Posteriorly the Pearson correlation coefficients between the different variables were obtained.

Nevertheless, the construction of histograms of the variables allowed us to observe the normality of the variables and the presence of the so-called outlayers. These anomalous data have been eliminated, in such a manner that a new statistical approach has been made with 85 cases. It is interesting to note that, after this selection, the correlation coefficients have been considerably improved.

Finally, taking into account our experience in measuring the debris flows in the field, a new selection was made, avoiding those cases that were doubtful or unsatisfactory (i.e., existence of uncertainties in the determination of the runout distance). This new statistical analysis considered 64 cases. The results obtained do not represent almost any variation comparing the average values with the previous analysis. However, this reduced Table leads to better correlation coefficients between the parameters, and to lower figures of standard deviation and variance, and this is the reason why the 64 cases analysis has been used in this report.

## 4. Results

These are the main features of debris flows as measured in the field:

1. The characteristic landslide scar dimension is in average 15.4 m width, (standard deviation: 5.3). The median is 14.5 m. The larger scar measured is 30 m width, and the minimum, 7.4 m.

2. The mean altitude at which the landslides are triggered is 1157 m, coinciding very well with the results obtained from the general distribution of debris flows in the Flysch Sector. The difference in height between the upper part of the scar and the beginning of deposition ($\Delta$h) is 36.6 m (standard deviation: 17.9), and the median is 35 m. The maximum difference is 85 m, and the minimum 7 m.

3. Most of landslide scars develop around 30º. Mean: 33.9º; Median: 33º; standard deviation: 5.0º; Maximum value: 45º; Minimum value: 18.5º. This is consistent with the results supplied by other authors, who find most debris flows occurring between 25 and 38º (Takahashi et al., 1981) or between 32 and 42º (Innes, 1983). In a more general sense, the gradient of the initiation point is establishes between 15 and 60º (Bathurst et al., 1997; Reneau & Dietrich, 1987; Moser & Hohensinn, 1983).

4. The mean length of the deposit (runout distance) is 22.1 m (standard deviation: 11.1), and the median is 20 m. The maximum length is 55.6 m, and the minimum 5.8 m.

5. As for the gradient from which deposition starts, the value is 17.8º, showing a large rank from 8 to 27º. This variance can be explained due to the conditions in which the debris flows occur in the Flysch Sector, since the angle of deposition can be very much influenced by the presence of bench terraced fields or forest patches. The value obtained is appropriate for unconfined debris flows, that is, shallow landslides that evolve into debris flows.

6. One of the most interesting problems in determining debris flow hazard is to devise a simple formula for run-out distance starting from other parameters. One of these formulas is that from Vandre (1985), who found that run-out distance is about 35-45% of the difference in height between the head of the landslide and the point at which deposition starts. The formula devised is:

$$L = a\Delta h$$

where L = runout distance from the point at which deposition starts,

$\Delta$h = elevation difference between the head of the landslide and the point at which sedimentation starts,

$\alpha$ = an empirically derived fraction.

According to Vandre's (1985) calculations, a value is set at 0.4, that is, runout distance is 40% of the parameter $\Delta$h.

In the case of debris flows measured in the Flysch Sector of the Spanish Pyrenees, the mean value is 0.605.

7. The volume of material mobilized by the landslides is, in average, 179.9 $m^3$ (standard deviation: 131.9). The median is 135.7 $m^3$.

8. The depth at which the plane of the landslide occurs is 0.67 m (standard deviation, 0.12, median, 0.6, extreme values, 1.1 and 0.45), confirming that they affect the soil and superficial colluvium.

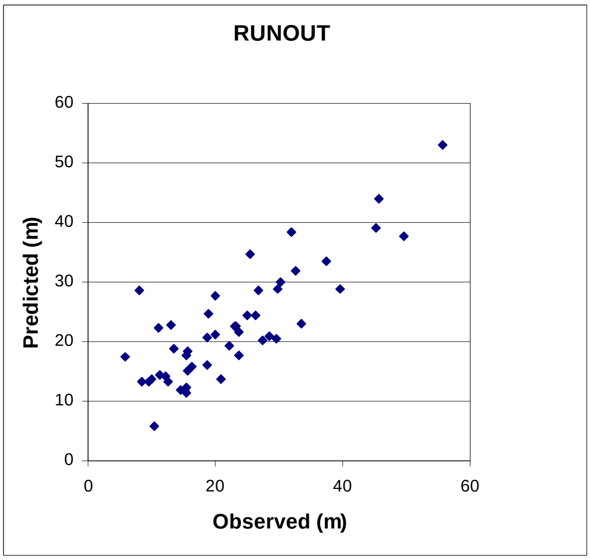
Pearson correlations show good relationships between some of the parameters. Thus:

- $\Delta$h is very well correlated with LENGTH (r = 0.80) and with the distance travelled by the deposit (runout distance) (r = 0.80). Good relations are also obtained with the width of the scar (r = 0.46) and the volume (r = 0.46). These results confirm that a larger difference in height can explain very well the runout distance, due to the energy of the landslide. Besides, the volume of the deposit is also larger due probably to the erosion along the channel. Similar relationships are obtained for the LENGTH.
- The gradient of the debris flow scar (SCARº) is well related with the gradient of the channel (r = 0.57) and the width of the channel (r = 0.41).
- The runout distance mainly depends on the difference in height ($\Delta$h) (r = 0.80), the LENGTH (r = 0.67), the gradient at which deposition starts (r = 0.29), the width of the scar (r = 0.48), and the volume of the deposit (r = 0.48).
- The width of the debris flow scar is well related with the gradient in the channel and deposit, and the difference in height ($\Delta$h) and very well related with the volume of the deposit (r = 0.94).
- Finally, the volume of the deposit is correlated with the difference in height (r = 0.45), the length of the debris flow (r = 0.55), run-out distance (r = 0.48), the soil depth (r = 0.40) and the width of the debris flow scar (r = 0.94), that is, most of the factors that characterise the size of the debris flow.

A multiple lineal regression have been done in order to predict the length of the runout distance using 4 variables: $\Delta$h, LENGTH, SCARº AND BASEº. The adjusted $r^2$ is 0.664 and the most significant variables are $\Delta$h and SCARº. The equation that relates the runout distance to the 4 variables is as following:

$$RUNOUT = -14.447 + 0.477\Delta h + 0.709 LENGTH + 0.365 SCAR^{o} + 0.18 BASE^{o}$$

Fig. 3 faces the observed and the predicted values of the runout distance. Predicted values have been obtained from the multiple linear regression with 4 variables. In general, observed and predicted values are scattered around a straight line, but the model subestimates the largest values and overestimates the lowest values. This is confirmed in Fig. 4, which relates the observed values of the runout distance and the residuals from the previous regression.



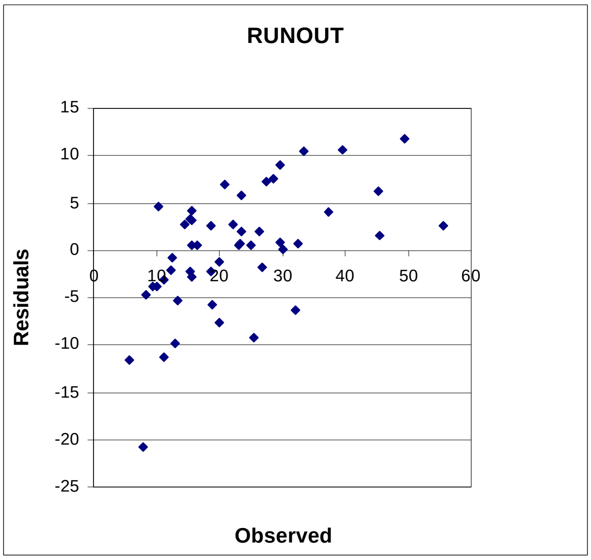




Fig. 3. Relationships between the observed and predicted values of the runout deposit, according to the regression model with 4 variables.

Fig. 4. Relationship between the observed values of the runout deposit and the residuals from the regression of the Fig. 3.

Tabla 1. Average values for different debris flow parameters

**Statistics**

| | | ALTSCAR | ALTBASE | Dh | LENGTH | SCARº | CANALº | BASEº | RUNOUT | SCAR | CANAL2 | BASE2 | VOLUME |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| N | Valid | 64 | 64 | 64 | 61 | 64 | 47 | 51 | 53 | 61 | 28 | 8 | 64 |
| | Missing | 0 | 0 | 0 | 3 | 0 | 17 | 13 | 11 | 3 | 36 | 56 | 0 |
| Mean | | 1157.4219 | 1120.8125 | 36.6094 | 51.4295 | 33.9141 | 33.6596 | 17.7647 | 22.1491 | 15.4131 | 5.1536 | 9.2625 | 179.947 |
| Median | | 1175 | 1140 | 35 | 49.5 | 33 | 33 | 18 | 20 | 14.5 | 4.75 | 8.75 | 135.666 |
| Mode | | 1245 | 1095.00(a) | 35 | 55 | 31.00(a) | 32 | 15 | 20 | 13.40(a) | 4.5 | 8.00(a) | 103.0(a) |
| Std. Deviation | | 108.82909 | 109.28932 | 17.85268 | 21.01352 | 5.02103 | 4.18214 | 4.85526 | 11.11121 | 5.28275 | 1.72035 | 4.49537 | 131.8775 |
| Variance | | 11843.77158 | 11944.15476 | 318.71801 | 441.56811 | 25.21075 | 17.49029 | 23.57353 | 123.45909 | 27.90749 | 2.95962 | 20.20839 | 17391.6741 |
| Skewness | | -0.351 | -0.372 | 0.906 | 0.415 | 0.05 | 0.552 | -0.138 | 1.048 | 0.628 | 1.057 | -0.01 | 1.166 |
| Std. Error of Skewness | | 0.299 | 0.299 | 0.299 | 0.306 | 0.299 | 0.347 | 0.333 | 0.327 | 0.306 | 0.441 | 0.752 | 0.299 |
| Kurtosis | | -0.8 | -0.786 | 0.472 | -0.371 | 0.639 | 0.207 | -0.298 | 0.938 | -0.139 | 1.227 | -1.116 | 0.804 |
| Std. Error of Kurtosis | | 0.59 | 0.59 | 0.59 | 0.604 | 0.59 | 0.681 | 0.656 | 0.644 | 0.604 | 0.858 | 1.481 | 0.59 |
| Range | | 425 | 445 | 78 | 94.8 | 26.5 | 19 | 19 | 49.8 | 22.6 | 7.5 | 12 | 562.5 |
| Minimum | | 930 | 890 | 7 | 10.2 | 18.5 | 25 | 8 | 5.8 | 7.4 | 2.5 | 3 | 0 |
| Maximum | | 1355 | 1335 | 85 | 105 | 45 | 44 | 27 | 55.6 | 30 | 10 | 15 | 562.5 |
| Sum | | 74075 | 71732 | 2343 | 3137.2 | 2170.5 | 1582 | 906 | 1173.9 | 940.2 | 144.3 | 74.1 | 11516.6 |
| Percentiles | 10 | 989.5 | 955 | 18.5 | 25.3 | 29 | 29 | 10 | 10.12 | 8.64 | 3 | 3 | 41.871 |
| | 20 | 1030 | 990 | 20 | 33.18 | 30 | 30 | 15 | 12.52 | 11.1 | 3.9 | 3.8 | 70 |
| | 25 | 1071.25 | 1038.75 | 22.75 | 35.9 | 31 | 32 | 15 | 14 | 12.05 | 4.05 | 5 | 88.643 |
| | 30 | 1117 | 1067.5 | 25 | 37.24 | 31 | 32 | 15 | 15.42 | 12.6 | 4.41 | 6.8 | 102.966 |
| | 40 | 1145 | 1105 | 30 | 44.5 | 32 | 32 | 16 | 16.24 | 13.36 | 4.5 | 8 | 115.2 |
| | 50 | 1175 | 1140 | 35 | 49.5 | 33 | 33 | 18 | 20 | 14.5 | 4.75 | 8.75 | 135.666 |
| | 60 | 1205 | 1170 | 35 | 55.1 | 35 | 33.8 | 18.5 | 23.36 | 15.6 | 5.24 | 10.34 | 179.114 |
| | 70 | 1237.5 | 1192.5 | 42.5 | 60.46 | 35 | 35 | 21 | 26.22 | 17.38 | 5.6 | 12.62 | 215.544 |
| | 75 | 1245 | 1203.75 | 45 | 67 | 36 | 36 | 21 | 27.95 | 18.65 | 5.6 | 14.15 | 241.698 |
| | 80 | 1250 | 1210 | 50 | 70.16 | 38 | 37.4 | 22 | 29.8 | 21.16 | 6 | 15 | 270.848 |
| | 90 | 1287.5 | 1262.5 | 65 | 83.58 | 42 | 41 | 25 | 38.66 | 23.08 | 8 | 15 | 406.961 |

a Multiple modes exist. The smallest value is shown

Tabla 2. Correlation matrix between the diferrent debris flow parameters

**Correlations**

Pearson Correlation

| | ALTSCAR | ALTBASE | Dh | LENGTH | SCARº | CANALº | BASEº | RUNOUT | SCAR | CANAL2 | BASE2 | VOLUME | SOILM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ALTSCAR | 1 | | | | | | | | | | | | |
| ALTBASE | .987(**) | 1 | | | | | | | | | | | |
| Dh | 0.056 | -0.107 | 1 | | | | | | | | | | |
| LENGTH | 0.027 | -0.099 | .802(**) | 1 | | | | | | | | | |
| SCARº | 0.221 | 0.22 | -0.004 | -0.039 | 1 | | | | | | | | |
| CANALº | 0.134 | 0.142 | -0.096 | -.334(*) | .572(**) | 1 | | | | | | | |
| BASEº | -0.031 | -0.071 | 0.265 | 0.09 | 0.232 | -0.186 | 1 | | | | | | |
| RUNOUT | 0.022 | -0.096 | .797(**) | .665(**) | 0.234 | -0.168 | .290(*) | 1 | | | | | |
| SCAR | 0.031 | -0.041 | .455(**) | .569(**) | 0.022 | -.305(*) | .320(*) | .476(**) | 1 | | | | |
| CANAL2 | -0.094 | -0.045 | -0.289 | -0.313 | .411(*) | 0.021 | 0.298 | -0.077 | -0.049 | 1 | | | |
| BASE2 | -0.434 | -0.385 | -0.182 | -0.338 | -0.13 | -0.315 | 0.053 | 0.391 | -0.066 | 0.527 | 1 | | |
| VOLUME | 0.069 | -0.005 | .455(**) | .547(**) | 0.047 | -0.232 | 0.26 | .479(**) | .937(**) | -0.065 | -0.115 | 1 | |
| SOILM | 0.122 | 0.088 | 0.204 | 0.035 | 0.029 | -0.222 | .316(*) | 0.105 | 0.242 | -0.057 | -0.348 | .403(**) | 1 |
| a | 0.23 | 0.25 | -0.176 | -0.042 | 0.217 | -0.142 | 0.172 | .423(**) | 0.078 | -0.042 | 0.432 | -0.023 | 0.043 |

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

## 5. Discussion and conclusions

When landslide hazards are studied in a given area, a basic problem is to predict weather or not landslide material i) arrives directly to the fluvial system, and what percentage it is delivered, and ii) affects infrastructures or human settlements. Thus, two work lines are necessary to solve both questions: i) a debris flow susceptibility map, in which the areas with the highest probability of debris flow occurrence are located, and ii) an achievement of relationships between different debris flow parameters in order to predict the distance travelled by the deposit, according to the gradient along the hillslope and the volume of sediment. In this report information on these relationships has been given.

In general, the width and depth values for debris flow scar, as well as the sediment volumes reported in this paper are of the same order of magnitude than those reported by other authors. This is the case for debris flows in the Central California (Reneau & Dietrich, 1987), Central Nepal (Caine & Mool, 1982; Ramsey, 1987) or Central Austria (Moser & Hohensinn, 1983). However, the relationships between some major parameters are somewhat different:

- Deposition of the sediment carried out by the debris flows starts at 17.8º, a value much higher than those reported by other authors. Thus, Bathurst et al. (1997) point out that deposition begins once the slope falls below 6-10º, and Ikeya (1981) suggests that deposition should begin at the 10º slope. The reason for the beginning of sedimentation at steeper slopes in the Flysch Sector of the Central Pyrenees remains unclear. Further analysis is needed in order to assess the role of the volume of sediment involved, as well as microtopography and vegetation.

- The $\alpha$ value in the Vandre's (1985) formula is 0.6 in de case of debris flows in the Flysch Sector of the Spanish Pyrenees, that is, the runout distance represents 60% of the difference in height between the debris flow scar and the point at which sedimentation stars. This value represents a longer distance than that derived from the Vandre's (1985) study, in which a is 0.4. The difference can be explained by two reasons:

i) The material involved in the landslide contains a high proportion of clay and sand (around 70%) and less stones than in other studies on debris flows. Most probably, the mixture of stones, water and fine material is fluid enough to encourage a longer debris flow runout.

ii) The gradient at which sedimentation starts (17.8º) is higher than in other areas, and this probably enables the maintenance of high energy levels.

Finally, it is interesting to note that good correlations have been obtained between different parameters. Special attention must be paid by the relations between the volume of sediment and the runout distance.

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