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# DEBRIS FLOW CHARACTERISTICS AND RELATIONSHIPS IN THE CENTRAL SPANISH PYRENEES

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**Abstract:** Unconfined debris flows (i.e., not in incised channels) are one of the most active geomorphic processes in mountainous areas. Since they can threaten settlements and infrastructure, statistical and physically based procedures have been developed to assess the potential for landslide erosion. In this study, information on debris flow characteristics was obtained in the field to define the debris flow runout distance and to establish relationships between debris flow parameters. Such relationships are needed for building models which allow us to improve the spatial prediction of debris flow hazards. In general, unconfined debris flows triggered in the Flysch Sector of the Central Spanish Pyrenees are of the same order of magnitude as others reported in the literature. The deposition of sediment started at 17.8º, and the runout distance represented 60% of the difference in height between the head of the landslide and the point at which deposition started. The runout distance was relatively well correlated with the volume of sediment.

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## 1. Introduction

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 under a critical combination of sediment availability, water input, and slope gradient (Takahashi, 1981; Rickenmann & Zimmermann, 1993). This is especially true in the Pyrenees, as in other alpine areas, due above all to the steep slopes, the high availability of debris in both channels and hillslopes, the presence of metamorphic and flysch rock outcrops and the relatively frequent occurrence of high intensity rainstorms.

Confined and unconfined debris flows can be distinguished by the characteristics of the channel and sedimentation area. Confined debris flows develop within incised channels that can occasionally become torrents or avalanche channels. Unconfined debris flows occur in previously non incised hillslopes, typically triggered on slopes with abundant non-consolidated sediments, steep gradients, scarce plant cover and no previous rills or incised channels (Brunsden, 1979). Scars develop at the rupture area of a shallow landslide that evolves into a debris flow (Bathurst *et al.*, 1997), and terminates in a tongue with lateral levees ending in a frontal lobe with imbricated, non-sorted clasts. A flow track or channel develops between the source of the shallow landslide and the lobe (Varnes, 1978; Rapp & Nyberg, 1981; Johnson & Rodine, 1984; Clark, 1987). They are usually linked with intense, relatively infrequent rainstorms (Caine, 1980; Kotarba, 1989; Van Steijn, 1996; Blijenberg, 1998).

Debris flows are the most active geomorphic hazards in mountainous areas, affecting infrastructures, human settlements and tourist resorts (Takahashi et al., 1981). They can also play a very important role in determining basin sediment yield (Bathurst *et al.*, 1997), sometimes contributing to channel aggradation (Martínez-Castroviejo & García-Ruiz, 1990), flooding and reservoir siltation (Burton *et al.*, 1998). For this reason, many studies have tried to assess where debris flows occur and rank the factors that trigger them, as well as to improve management strategies that minimise the potential for landslide erosion and related off-site impacts (Wieczorek, 1987; Burton *et al.,* 1998; Morgan *et al.,* 1999).

In this paper the characteristics of debris flow parameters are studied to establish statistical relationships between them. Special emphasis has been put on the distance travelled by debris flows (especially the runout distance) as influenced by the volume of material carried by debris flows. This information is very relevant for debris flow modelling and to predict areas subject to debris flow hazards. Thus, the findings lay the groundwork for assessing the debris flow hazard for infrastructure and settlements, as well as for the fluvial network where debris flows can deliver large volumes of sediment (Martínez-Castroviejo & García-Ruiz, 1990).

A previous paper (Lorente *et al.,* 2002) considered the location of almost 1,000 debris flows distributed in the Upper Aragón and Gállego basins, Central Spanish Pyrenees. With this information the distribution of debris flows was correlated with the lithology, gradient, aspect, altitude, distance to the divide, plant cover, evolution of land use and other environmental, microtopographical factors. Most debris flows in the Spanish Pyrenees are found in disturbed areas, on steep slopes cultivated some decades ago and affected by overgrazing and recurrent wildfires (González *et al.,* 1995). The highest density of debris flows occurs on the Flysch Sector, especially in those areas affected by intense tectonic activity, as has been reported in other mountain regions (i.e., Tishchenko, 2000; Corominas, 1996).

## 2. The study area

The study area includes the upper basins of the Aragón and Gállego rivers, in the Central Spanish Pyrenees. The Flysch Sector (867 $km^2$) was selected for this study since it contains most of the debris flows in the study area (Fig. 1). It is geomorphologically active with relatively steep gradients and alternating thin sandstone and marl beds which promote 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 and complex faults and folds. The divides reach 2200 m, decreasing southward. Contact with the marls of the Inner Depression is at about 800 m by means of an overthrusting fault (Puigdefábregas *et al*., 1992).

The mean annual precipitation in the study area exceeds 800 mm, increasing to 2000 mm above 2000 m (García-Ruiz *et al.,* 1985). The wet season lasts from October to May, with very little rain in January and February. The whole area is occasionally subject to very intense rainstorms (García-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. Most sunny hillslopes in the Flysch Sector have been cultivated (even steep sections) using shifting agriculture systems (Lasanta, 1989). Old fields outside the Inner Depression are often abandoned and revegetated by dense shrubs (Molinillo *et al.*, 1997) and reforested pines. Crops (meadows) only persist at the valley bottoms. Above 1600 m, the landscape is dominated by dense forests and subalpine and alpine grasslands, occasionally affected by intense erosion (García-Ruiz *et al.*, 1990).

Debris flows are especially dense in areas that have been intensively utilized agriculturally for centuries, mainly in the most tectonized parts and where very old slumps have been identified. They affect to a colluvium covered by poorly developed, shallow carbonate-rich regosols in the south facing slopes and Kastanozems in the north facing slopes. The colluvium is a matrix-supported deposit with sandstone gravels and blocks. The matrix (around 70% of the mkixture) is composed, in average, of 50% of Sand, 30% of silt and 30% of clay.

Debris flows occur with a relatively high frequency in the study area García-Ruiz et al., 2003). The mean rate of occurrence is 0.06 debris flows $km^{-2}$ $yr^{-1}$. The triggering of shallow landslides is related to reletively frequent intense rainstorms, having a recurrence of no more than 2 to 5 years. The mapped and measured debris flows have been triggered in the last 30 years.

## 3. Methods

A total of 961 unconfined debris flows were identified in the Upper Aragón and Gállego basins (Lorente *et al.*, 2002). Ninety-eight were selected in the most geomorphologically active areas of the Flysch Sector, close to the contact with the marls of the Inner Depression (Ijuez and Aurín valleys and southern aspects between Jaca and Sabiñánigo; Fig.1).

The following variables were defined and measured in the field (numbers are referred to in Fig. 2):

1. ALTSCAR: The altitude of the top of the debris flow scar above sea level (m).
2. ALTBASE: The altitude where debris flow deposition begins (m).
3. ALTDEP: The altitude where the runout deposit ends (m)
4. $\Delta$h: Difference in height (m) between ALTSCAR and ALTBASE.
5. $\Delta$hTOT: Difference in height (m) between ALTSCAR and ALTDEP.
6. LENGTH: Total length (m) of the debris flow between the upper part of the scar and the beginning of the deposit.
7. RUNOUT: Length (m) of the debris flow deposit from end of channel to toe or front of debris. Also defined as the distance travelled downslope from the onset of large scale deposition (Fannin & Wise, 2001).
8. TOTLENGTH: The total length of the landform, from the upper part of the scar to the end of the deposit (m).
9. SCARº: Average gradient (degrees) at the debris flow scar, by measuring the natural unfailed slope along the sides of the landslide scar.
10. CANALº: Average gradient (degrees) of the debris flow channel.
11. BASEº: Average gradient (degrees) of the debris flow deposit.
12. SCAR2: Average width of the debris flow scar (m).
13. CANAL2: Average width of the debris flow channel (m).
14. BASE2: Average width of the debris flow deposit (m).

15. VOLUME: Estimated volume of the material mobilized by the debris flow ($m^3$). It has been obtained from the debris flow scar.

16. SOILM: Average depth (m) of the failure surface in the shallow landslide.

According to the histograms, the variables were distributed normally with some outliers. The latter were eliminated, leaving a total 85 cases. Finally, a new selection was made to avoid cases that were doubtful or unsatisfactory (i.e., uncertain runout distances), leaving 64 cases.

Descriptive statistics (average, median, standard deviation, maximum and minimum values, etc.) and Pearson correlation coefficients were calculated for the variables measured. Linear and power regressions were performed to predict ther variables RUNOUT and TOTLENGTH, to compare with the empirical relations proposed by several authors (Vandre, 1985; Rickenmann,1999). A multiple linear regression was also carried out upon the variable RUNOUT. A stepwise procedure was used to identify the most relevant variables for its prediction.

## 4. Results

Table 1 shows the main features of the debris flows measured in the field, and Table 2 the correlation matrix between the different debris flow parameters. Only the most relevant characteristics of the debris flows (i.e., size parameters, volume, gradient) are described, as well as the most important relationships between parameters. Some irrelevant, though statistically significant correlations are not considered in the presentation of the results. All the parameters try to inform on the basic characteristics of debris flows (in the scar, channel and deposition area), which can be compared to those triggered in other areas of the world. Different relationships can be used to predict the length of the debris flow and its runout distance, once a shallow landslide susceptibility map is obtained by means of different field and statistical procedures (i.e., Guzzetti *et al.*, 1999).

1. The characteristic landslide scar widths (SCAR2) averaged 15.4 m (standard deviation: 5.3 m) and the median was 14.5 m. The largest scar was 30 m wide and the minimum was 7.4 m.

2. The mean altitude (ALTSCAR) at which the landslides were triggered was 1157.4 m, coinciding very well with the results obtained from the general distribution of debris flows in the Flysch Sector (Lorente *et al.*, 2002), where debris flows are especially frequent between 950 and 1200 m. This altitude is very well related to the area affected most intensively by cultivation of steep slopes, and confirms the influence of past land uses on the triggering of debris flows (Lorente *et al.*, 2002).

3. Most landslide scars developed around 30º (mean 33.9º; median: 33º; standard deviation: 5.0º; maximum value: 45º; minimum value: 18.5º). This is consistent with other studies where most debris flows occur between 25 and 38º (Takahashi *et al.,* 1981), between 18 and 50º (Corominas, 1996), between 32 and 42º (Innes, 1983), around 38º , with 33º as minimum value (Blijenberg, 1998), or between 27º for poorly drained soils and 40º for rapidly drained soils (Fannin & Rollerson, 1993). A good example of debris flow event was studied by Wieczorek *et al*. (1997) during the June 27, 1995 storm in the Blue Ridge mountains of Central Virginia, which triggered about 1000 debris flows ranging in the source area between 17 and 41º, with both a mean and median value of 30º. More generally, the gradient of the initiation point is established between 15 and 60º (Moser & Hohensinn, 1983; Sidle *et al.*, 1985; Reneau & Dietrich, 1987; Rickenmann & Zimmermann, 1993; Bathurst *et al.,* 1997).

4. The difference in height between the upper part of the scar and the beginning of deposition ($\Delta$h) was 36.6 m (standard deviation: 17.9 m) and the median was 35 m. The maximum difference was 85 m and the minimum was 7 m. This reveals that in the study area few of the debris flows that occur in the upper and middle part of the slopes are able to reach the fluvial channels.

5. The mean length of the deposit (RUNOUT) was 22.1 m (standard deviation: 11.1) and the median was 20 m. The maximum length was 55.6 m, and the minimum was 5.8 m. Relatively large differences in the length of the deposit are expected due to the influence of local topography. Thus, for example, those debris flows triggered in the upper part of a hillslope can develop a longer runout distance, whilst those triggeres in the lower part stop when they arrive to the toe of the versant.

6. The value of the gradient where deposition started (BASEº) was 17.8º, with a large range from 8 to 27º. This variance can be explained by the conditions under which debris flows occur in the Flysch Sector. The angle of deposition can be strongly influenced by the presence of bench terraced fields or forest patches and by variations in water content. The value obtained is appropriate for unconfined debris flows, that is, shallow landslides that evolve into debris flows.

7. One of the most interesting problems when determining debris flow hazard is to devise a simple formula for runout distance using other parameters. One of these formulas, considering the best compromise between simplicity and reliability, is from Vandre (1985), who found that runout 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 derived from his data (Bathurst *et al.,* 1997) is:

$$\text{RUNOUT} = \alpha\Delta h \qquad (1)$$

where $\alpha$ is an an empirically derived fraction parameter expressing the ratio of RUNOUT to $\Delta$h

According to Vandre's (1985) data, the $\alpha$ value is 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 $\alpha$ value is 0.605.

8. The volume of material mobilized by the landslides (VOLUME) averaged 179.9 $m^3$ (standard deviation: 131.9). The median was 135.7 $m^3$ and the maximum value was 562 $m^3$. Thus, the studied debris flows can be included among those defined as “small scale debris flows” as defined by Innes (1983). These values are of the same order of magnitude as most debris flows cited in the literature (Blijenberg, 1998). Nevertheless, a large variability of volumes can be expected even in the same area (see, for example, the study of Rickenmann & Zimmermann, 1993, on debris flows in the Swiss Alps).

9. The depth of the failure surface (SOILM) occurred at 0.6 m (standard deviation, 0.12, median, 0.6, and extreme values 1.1 and 0.45 m), confirming that debris flow scars affect only the soil and superficial colluvium. No debris flows affecting the unweathered flysch substratum have been found.

10. $\Delta$h was very well correlated with LENGTH (r = 0.80) and with the distance travelled by the deposit (RUNOUT) (r = 0.80). Good relations were also obtained with the width of the scar (SCAR2) (r = 0.46) and the VOLUME (r = 0.46). These results confirm that a larger difference in height can explain the runout distance, due to the potential energy of the landslide. The volume of the deposit was also larger as $\Delta$h increased, probably due to erosion along the channel. In fact, Wieczorek *et al.* (1997) underline that erosion along the channel is a very important process to explain the final volume of the debris flow deposit, and that the erosive volume from channels is often many times greater than from source landslide areas. Nevertheless, channel erosion do not seem to be very relevant in the study are and is, at least in part, compensated by the development of lateral levees. Similar relationships were obtained for the variable LENGTH.

Fig. 3 plots the total length of debris flows *(L)* (that is, TOTLENGTH) vs. potential energy, represented by the *M H* factor, obtained by the multiplication of the derbis flow volume (VOLUME) and the difference in height between the highest point of the debris flow scar and the lowest end of the debris flow lobe ($\Delta$hTOT). Fig. 3 also includes Rickenmann’s (1999) relationship, obtained from valley-confined debris flows in the Alps.

For the Pyrenean debris flows the relationship is expressed by

$$L = 7.13\,(M\,H)^{0.271} \qquad (2)$$

For the Alpine debris flows (Rickenmann, 1999) the relationship is

$$L = 30\,(M\,H)^{0.25} \qquad (3)$$

The differences are obvious since the adjusted power function for the Pyrenean debris flows is clearly lower than for the Alpine ones. That is, with the same volume of debris, the valley-confined debris flows develop a larger displacement than unconfined, Pyrenean debris flows. This is probably a logical or expectable result, as the displacement of a debris flow (and its runout) is highly sensible to the water content (Chau *et al.,* 2000), and it is obvious that, in general, the valley-confined debris flows are likely to have higher water discharges than the hillslope debris flows.

11. The gradient of the debris flow scar (SCARº) was well related with the gradient of the channel (CANALº) (r = 0.57) and the width of the channel (CANAL2) (r = 0.41).

12. The runout distance (RUNOUT) mainly depended on the difference in height ($\Delta$h) (r = 0.80), the LENGTH (r = 0.67), the gradient at which deposition started (BASEº) (r = 0.39), the width of the scar (SCAR2) (r = 0.48), and the volume of the deposit (VOLUME) (r = 0.48).

13. Finally, the volume of the deposit was correlated with the difference in height ($\Delta$h) (r = 0.46), the length of the debris flow (LENGTH) (r = 0.55), runout distance (r = 0.48), soil depth (r = 0.40) and the width of the debris flow scar (SCAR2) (r = 0.94), that is, most of the factors that characterize the size of the debris flow. It is important to note that many of the correlations are only significant at the 0.01 level (Table 2).

A stepwise multiple linear regression was performed to predict the length of the runout distance (RUNOUT) using the variables that presented the highest correlation and a physical meaning: $\Delta$h, LENGTH, SCARº AND BASEº, SCAR2 and VOLUME. The variables selected by the model were $\Delta$h and SCARº, with $r^2 = 0.696$. The equation relating the runout distance to these two variables is:

$$\text{RUNOUT} = -12.609 + 0.568\,\Delta h + 0.412\,\text{SCAR}^{o} \qquad (4)$$

Due to the negative intercept, this equation is valid only in the case that

SCARº >30.6, or

$\Delta h > (12.609 - 0.412\,\text{SCAR}^{o}) / 0.568$

Fig. 4 depicts the observed and the predicted values of the runout distance. Predicted values were obtained from the multiple linear regression with two variables. In general, observed and predicted values were scattered about a straight line, confirming that the runout distance can be predicted quite well using equation (4), but the model slightly underestimates the largest values and overestimates the lowest values. This is confirmed in Fig. 5, which relates the observed values of the runout distance and the residuals (predicted minus observed values) from the regression in Fig. 4. Fig. 5 illustrates the distribution of the residuals in relation to the observed runout distance, showing that the highest values of runout distance correspond to positive residuals, whilst the lowest values correspond to negative residuals.

## 5. Discussion and conclusions

Two basic problems when studying landslide hazards are predicting whether the landslide material arrives directly to fluvial channels (and in what percentage it is delivered) and whether it affects infrastructures or human settlements. Thus, two lines of work are necessary to solve both questions: i) a debris flow susceptibility map including the areas with the highest probability of debris flow occurrence (Guzzetti *et al.*, 1999), and ii) the assessment of relationships between different debris flow parameters to predict the distance travelled by the deposit according to the gradient along the hillslope and the volume of sediment (Scheidegger, 1973; Burton *et al.*, 1998). This paper provides information on these relationships.

In general, the width and depth values for debris flow scar and sediment volume were of the same order of magnitude as in other studies, such as in 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 were slightly different:

- The deposition of the sediment carried by the debris flows started at 17.8º, much higher than other reports. Bathurst *et al.* (1997) found that deposition begins once the slope falls below 6-10º, Ikeya (1981) suggested that deposition should begin at 10º, and Fannin & Rollerson (1993) conclude that the mean slope angle of the depositional area is 5-13º for debris flows deposited on fans of the Queen Charlotte Islands, British Columbia. A range of 10-12º is reported by Hungr *et al.* (1984) for debris flow sedimentation in the south coastal region of British Columbia. It is unclear why sedimentation begins at steeper slopes in the Flysch Sector. Further analysis is needed to assess the role of the volume of sediment involved as well as microtopography and vegetation. In any case, one reason for such difference could be that this paper deals only with unconfined debris flows.

- The $\alpha$ value calculated using Vandre's formula (1985) for the study area was 0.6. Thus, the runout distance represents 60% of the difference in height between the debris flow scar and the point at which sedimentation starts which is longer than the 0.4 in Vandre (1985). The difference can be due to two factors:

i) The material involved in the landslide, a matrix-supported colluvium, containing less stones than in other studies on debris flows. Most probably the mixture of stones, water and fine material is fluid enough to promote a longer debris flow runout.

ii) The gradient at which deposition started (17.8º) was higher than other areas which probably helps to maintain high energy levels.

Equation (4) can be used to predict the runout distance according to two factors, that is, the difference in height between the head of the landslide and the point at which deposition starts (Δh), and the gradient of the debris flow scar (SCARº).

Finally, good correlations were obtained between different parameters. Special attention must be paid to the relation between sediment volume and runout distance, as in other experimental or simulated studies (Scheidegger, 1973; Benda & Cundy, 1990; Okura *et al.*, 2000). Kilburn & Sorensen (1998) note that, in sturtzstroms, the distance of runout lengths are proportional to the square root of their volume. This is mainly due to the fact that there is a negative correlation between the friction coefficient of the mass movement and its volume (Straub, 1997). Hsü (1975) concludes that there is a minimum volume of 50,000 $m^3$ for long runout distances, what explains the short distances travelled by debris flows in the Flysch Sector where they do not exceed 500 $m^3$.

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Table 2. Correlation matrix between the diferrent debris flow parameters

Pearson Coefficient

| | ALTSCAR | ALTBASE | Δh | LENGTH | SCARº | CANALº | BASEº | RUNOUT | SCAR2 | CANAL2 | BASE2 | VOLUME | SOILM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ALTSCAR** | 1 | | | | | | | | | | | | |
| **ALTBASE** | .99(**) | 1 | | | | | | | | | | | |
| **Δh** | 0.06 | -0.11 | 1 | | | | | | | | | | |
| **LENGTH** | 0.03 | -0.10 | .80(**) | 1 | | | | | | | | | |
| **SCARº** | 0.22 | 0.22 | 0.00 | -0.04 | 1 | | | | | | | | |
| **CANALº** | 0.13 | 0.14 | -0.10 | -.33(*) | .57(**) | 1 | | | | | | | |
| **BASEº** | -0.03 | -0.07 | 0.27 | 0.09 | 0.23 | -0.19 | 1 | | | | | | |
| **RUNOUT** | 0.02 | -0.10 | .80(**) | .67(**) | 0.23 | -0.17 | .29(*) | 1 | | | | | |
| **SCAR** | 0.03 | -0.04 | .46(**) | .57(**) | 0.02 | -.31(*) | .32(*) | .48(**) | 1 | | | | |
| **CANAL2** | -0.09 | -0.05 | -0.29 | -0.31 | .41(*) | 0.02 | 0.30 | -0.08 | -0.05 | 1 | | | |
| **BASE2** | -0.43 | -0.39 | -0.18 | -0.34 | -0.13 | -0.32 | 0.05 | 0.39 | -0.07 | 0.53 | 1 | | |
| **VOLUME** | 0.07 | -0.01 | .46(**) | .55(**) | 0.05 | -0.23 | 0.26 | .48(**) | .94(**) | -0.07 | -0.12 | 1 | |
| **SOILM** | 0.12 | 0.09 | 0.20 | 0.04 | 0.03 | -0.22 | .316(*) | 0.11 | 0.24 | -0.06 | -0.35 | .40(**) | 1 |

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

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

Table 1. Descriptive statistics for different debris flow parameters

| | | ALTSCAR | ALTBASE | Δh | LENGTH | SCARº | CANALº | BASEº | RUNOUT | SCAR2 | CANAL2 | BASE2 | VOLUME | SOILM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **N** | **Valid** | 64 | 64 | 64 | 61 | 64 | 47 | 51 | 53 | 61 | 28 | 8 | 63 | 63 |
| | **Missing** | 0 | 0 | 0 | 3 | 0 | 17 | 13 | 11 | 3 | 36 | 56 | 0 | 1 |
| **Mean** | | 1157.4 | 1120.8 | 36.6 | 51.4 | 33.9 | 33.7 | 17.8 | 22.1 | 15.4 | 5.2 | 9.3 | 179.9 | 0.7 |
| **Median** | | 1175.0 | 1140.0 | 35.0 | 49.5 | 33.0 | 33.0 | 18.0 | 20.0 | 14.5 | 4.8 | 8.8 | 135.7 | 0.6 |
| **Mode** | | 1245.0 | 1095.0 | 35.0 | 55.0 | 31.0 | 32.0 | 15.0 | 20.0 | 13.4 | 4.5 | 8.0 | 103.0 | 0.6 |
| **Std. Deviation** | | 108.8 | 109.3 | 17.9 | 21.0 | 5.0 | 4.2 | 4.9 | 11.1 | 5.3 | 1.7 | 4.5 | 131.9 | 0.1 |
| **Variance** | | 11843.8 | 11944.2 | 318.7 | 441.6 | 25.2 | 17.5 | 23.6 | 123.5 | 27.9 | 3.0 | 20.2 | 17391.7 | 0.0 |
| **Skewness** | | -0.351 | -0.372 | 0.906 | 0.415 | 0.050 | 0.552 | -0.138 | 1.048 | 0.628 | 1.057 | -0.010 | 1.166 | 1.021 |
| **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 | 0.302 |
| **Kurtosis** | | -0.800 | -0.786 | 0.472 | -0.371 | 0.639 | 0.207 | -0.298 | 0.938 | -0.139 | 1.227 | -1.116 | 0.804 | 1.184 |
| **Std. Error of Kurtosis** | | 0.590 | 0.590 | 0.590 | 0.604 | 0.590 | 0.681 | 0.656 | 0.644 | 0.604 | 0.858 | 1.481 | 0.590 | 0.595 |
| **Range** | | 425.0 | 445.0 | 78.0 | 94.8 | 26.5 | 19.0 | 19.0 | 49.8 | 22.6 | 7.5 | 12.0 | 562.5 | 0.7 |
| **Minimum** | | 930.0 | 890.0 | 7.0 | 10.2 | 18.5 | 25.0 | 8.0 | 5.8 | 7.4 | 2.5 | 3.0 | 32.9 | 0.5 |
| **Maximum** | | 1355.0 | 1335.0 | 85.0 | 105.0 | 45.0 | 44.0 | 27.0 | 55.6 | 30.0 | 10.0 | 15.0 | 562.5 | 1.1 |
| **Percentiles** | **10** | 989.5 | 955.0 | 18.5 | 25.3 | 29.0 | 29.0 | 10.0 | 10.1 | 8.6 | 3.0 | 3.0 | 41.9 | 0.6 |
| | **20** | 1030.0 | 990.0 | 20.0 | 33.2 | 30.0 | 30.0 | 15.0 | 12.5 | 11.1 | 3.9 | 3.8 | 70.0 | 0.6 |
| | **25** | 1071.3 | 1038.8 | 22.8 | 35.9 | 31.0 | 32.0 | 15.0 | 14.0 | 12.1 | 4.1 | 5.0 | 88.6 | 0.6 |
| | **30** | 1117.0 | 1067.5 | 25.0 | 37.2 | 31.0 | 32.0 | 15.0 | 15.4 | 12.6 | 4.4 | 6.8 | 103.0 | 0.6 |
| | **40** | 1145.0 | 1105.0 | 30.0 | 44.5 | 32.0 | 32.0 | 16.0 | 16.2 | 13.4 | 4.5 | 8.0 | 115.2 | 0.6 |
| | **50** | 1175.0 | 1140.0 | 35.0 | 49.5 | 33.0 | 33.0 | 18.0 | 20.0 | 14.5 | 4.8 | 8.8 | 135.7 | 0.6 |
| | **60** | 1205.0 | 1170.0 | 35.0 | 55.1 | 35.0 | 33.8 | 18.5 | 23.4 | 15.6 | 5.2 | 10.3 | 179.1 | 0.7 |
| | **70** | 1237.5 | 1192.5 | 42.5 | 60.5 | 35.0 | 35.0 | 21.0 | 26.2 | 17.4 | 5.6 | 12.6 | 215.5 | 0.7 |
| | **75** | 1245.0 | 1203.8 | 45.0 | 67.0 | 36.0 | 36.0 | 21.0 | 28.0 | 18.7 | 5.6 | 14.2 | 241.7 | 0.8 |
| | **80** | 1250.0 | 1210.0 | 50.0 | 70.2 | 38.0 | 37.4 | 22.0 | 29.8 | 21.2 | 6.0 | 15.0 | 270.8 | 0.8 |
| | **90** | 1287.5 | 1262.5 | 65.0 | 83.6 | 42.0 | 41.0 | 25.0 | 38.7 | 23.1 | 8.0 | 15.0 | 407.0 | 0.8 |

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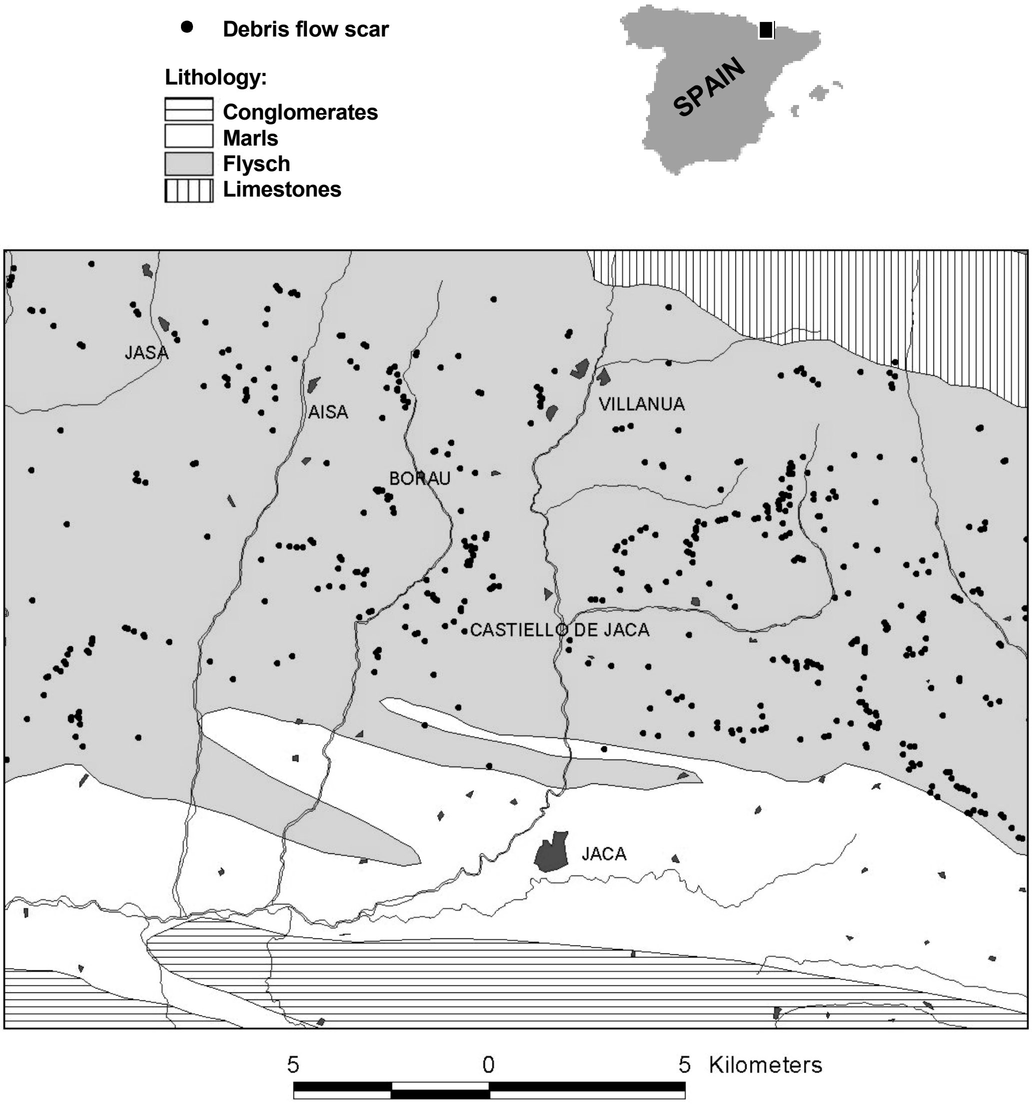

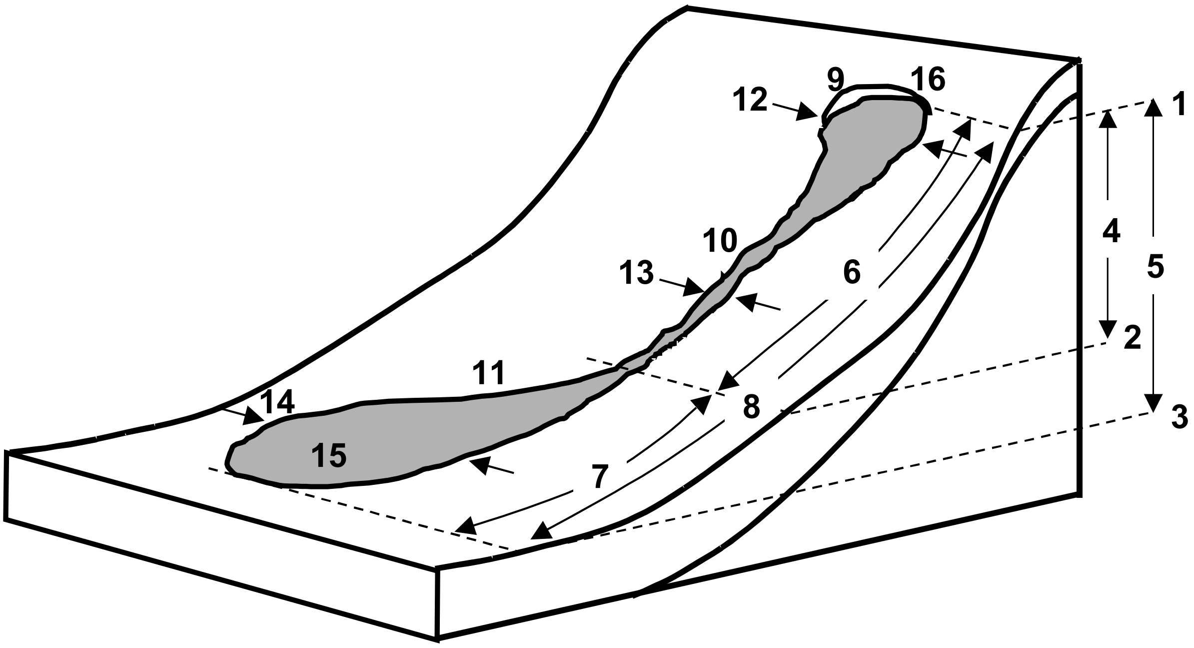
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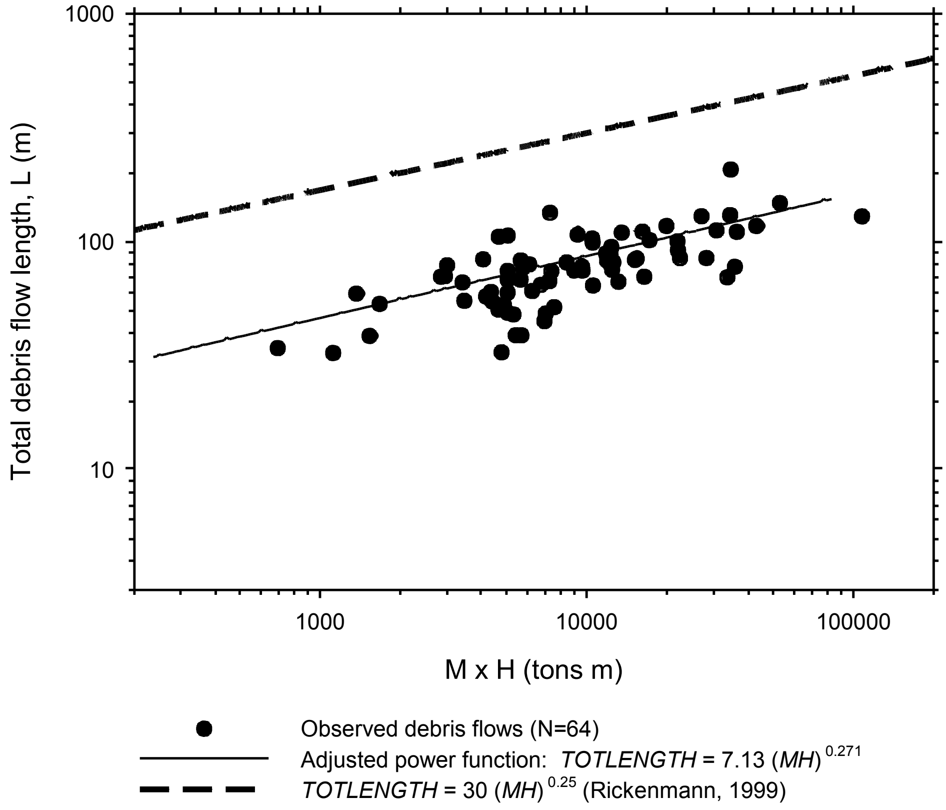

1000
100
10
Total debris flow length, L (m)
1000
10000
100000
M x H (tons m)
Observed debris flows (N=64)
Adjusted power function: *TOTLENGTH* = 7.13 (*MH*) 0.271
*TOTLENGTH* = 30 (*MH*) 0.25 (Rickenmann, 1999)

FIGURE CAPTIONS

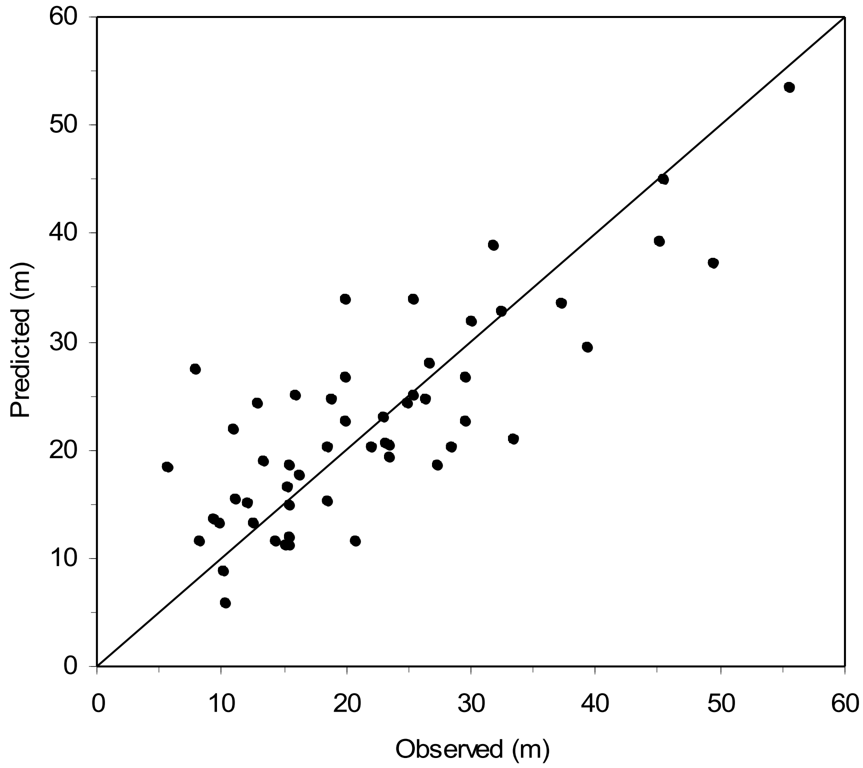
Fig. 1. Location of the study area and distribution of debris flows in the Flysch Sector.

Fig.2. Parameters measured in the debris flows.

Fig. 3. Total length of debris flows vs. the available potential energy, represented by the *M H* factor. The adjusted power function is also represented, along with the Rickenmann (1999) relationships (bold dashed line).

Fig. 4. Relationships between observed and predicted values of the runout area, according to the regression model with four variables (equation 4).

Fig. 5. Relationships between the observed values of the runout deposit and the residuals from the regression in Fig. 4.


Predicted (m)
Observed (m)
0
10
20
30
40
50
60

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