Factors Explaining the Spatial Distribution of Hillslope Debris Flows

Authors: Lorente, Adrián, García-Ruiz, José M., Beguería, Santiago, and Arnáez, José

Source: Mountain Research and Development, 22(1) : 32-39

Published By: International Mountain Society

URL: https://doi.org/10.1659/0276-4741(2002)022[0032:FETSDO]2.0.CO;2

Mountain Research and Development Vol 22 No 1 Feb 2002: 32–39

Adrián Lorente, José M. García-Ruiz, Santiago Beguería, and José Arnáez

Factors Explaining the Spatial Distribution of Hillslope Debris Flows

A Case Study in the Flysch Sector of the Central Spanish Pyrenees

The spatial distribution of 961 debris flows in the Upper Aragón and Gállego valleys (Central Spanish Pyrenees) was analyzed. Most were located in the Flysch Sector (with a colluvium mantle derived from strongly tectonically modified materials), between 1000 and 1400 m above sea level, on 25–35° gradients with sunny exposure. These gradients were either hillslopes covered by frequently burned scrubland, abandoned fields, or reforested land, confirming the influence of land use and disturbed landscapes on the occurrence of debris flows.

Keywords: *Debris flows; spatial distribution; Flysch Sector; topographic factors; land uses; Central Spanish Pyrenees.*

Peer reviewed: *August 2001.* ***Accepted:*** *December 2001.*

Introduction

Hillslope debris flows (Brunsden 1979) are one of the most common geomorphic phenomena in mountainous areas (Innes 1983; Johnson and Rodine 1984; Blijenberg 1998) (Figure 1). They have been described as the "rapid mass movement of blocky, mixed debris of rock and soil by flow of wet, lobate mass" (Rapp and Nyberg 1981), as "the downslope flow of debris mixed with a minor, yet significant, amount of water" (Innes 1983), and as "rapid mass movements similar to viscous fluids" (Varnes 1978). Brunsden (1979) pointed out that they typically occur on slopes with abundant nonconsolidated 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 develops with lateral levees ending in a frontal lobe with imbricated, nonsorted clasts (Varnes 1978; Rapp and Nyberg 1981; Johnson and Rodine 1984). They are usually linked to intense, relatively infrequent rainstorms (Kotarba 1989; Van Steijn 1996; Blikra and Nemec 1998).

Most hillslope debris flows are small (less than 10-m scar width and 50- to 100-m run-out) and, in general, disconnected from fluvial networks. They pose the most active geomorphic risk in mountainous areas, affecting infrastructure, human settlements, and tourist resorts (Takahashi et al 1981). This is partly why they have received attention worldwide (Innes 1983), especially in terms of spatial distribution and rainfall thresholds (Caine 1980). In some cases, debris flows have been predicted by multivariate statistical analysis and geographical information systems (GIS) (Carrara et al 1995; Guzzetti et al 1999).

Hillslope debris flows are the result of a complex interaction between environmental (lithology, gradient, shape of the hillslope, plant cover, microtopography) and human factors (land use) under certain pluviometric conditions (Blijenberg 1998; Blikra and Nemec 2000). The main purpose of the present article is to identify and define the importance of the factors that trigger debris flows and explain their spatial distribution in a highly variable mountain area with a long history of human disturbance. Most of the analysis concentrates on the Flysch Sector of the Central Spanish Pyrenees, where a high density of debris flows has been recorded and mapped.

Study area

The upper basins of the Aragón and Gállego rivers in the Central Spanish Pyrenees (Figure 2) occupy 1727 km^2. The highest altitudes exceed 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. The geological structure runs in parallel bands from west-northwest to east-southeast, whereas the main fluvial network runs from north to south. Four of these bands run through the study area (García-Ruiz et al 1990) (Figure 3):

- The axial or paleozoic area, with granitic massifs and massive, intensively folded slate and limestone outcrops, resulting in a very contrasted relief.
- The Inner Ranges, which correspond to an overthrusting anticline composed of Cretaceous and Paleocene limestone and sandstone. The relief is very rough, with vertical cliffs and karstified areas.
- The Eocene Flysch Sector (867 km^2), with thin beds of calcareous sandstone and marls. The gradients are smoother and homogeneous, in spite of intense tectonization, including complex faults and folds. The divides reach 2200 m. Contact with the marls of the Inner Depression is at about 800 m, by means of an overthrusting fault.
- The Inner Depression, composed of Eocene marls, forming a large valley from west to east. Most of the landscape is occupied by fluvial terraces and short pediments (glacis).

Precipitation increases toward the north along the altitudinal gradient, and to the west because of the

FIGURE 1 Scar of a shallow landslide that evolves into a debris flow. (Photo by José M. García-Ruiz)

Atlantic influence. A Mediterranean climate prevails toward the south and the east. 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 extends 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. In the Flysch Sector most of the 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 and meadows persist only on the valley floors.

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). Periglacial activity above 2400 m explains the scarcity of plant cover and geomorphic processes linked to frost–thaw processes.

FIGURE 2 The study area in the Spanish Pyrenees. (Map by authors)

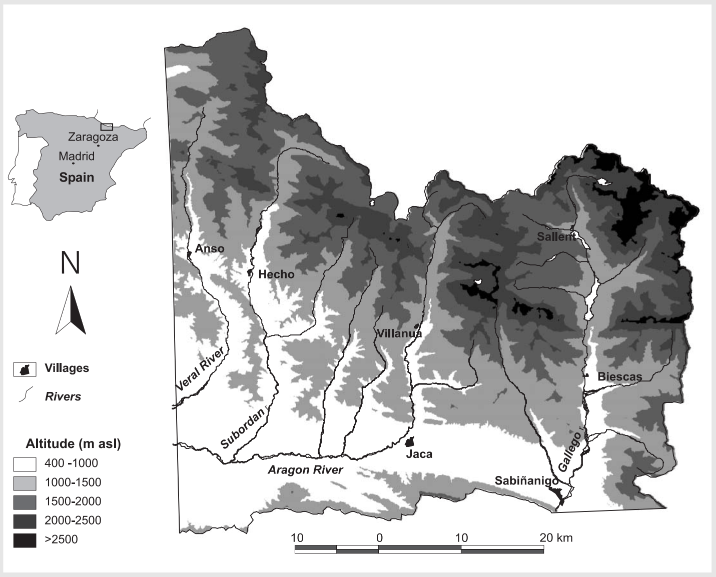
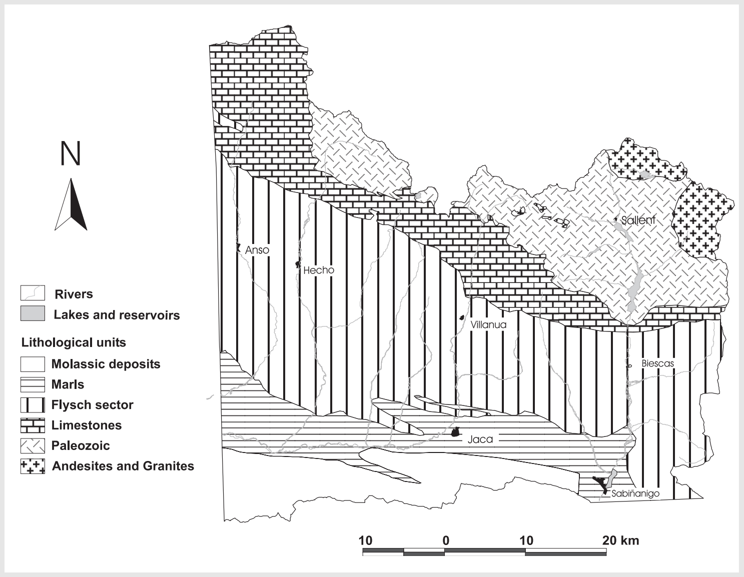


FIGURE 3 Morphostructural units of the study area. (Source: IGME and own data)



Methods

Debris flows in the upper Aragón and Gállego basins were mapped by aerial photographs and during fieldwork. They were defined by the presence of a small scar at the starting point and a lobate tongue with marginal levees (Johnson and Rodine 1984; Costa 1988; Zimmermann 1990). We identified 961 debris flows that were also digitized into a GIS (ARC/INFO, v. 7).

A Digital Elevation Model was also developed with a 50 × 50-m pixel resolution. The following continuous variables were derived:

- Altitude (m).
- Gradient: maximum rate of change in elevation in each cell and in 8 neighboring cells (deg).
- Aspect: compass direction of the maximum slope (deg), reclassified in 8 classes.
- Profile curvature: surface curvature in the direction of slope, resulting in acceleration or deceleration of flow.
- Planform curvature: surface curvature perpendicular to the direction of slope, resulting in convergence or divergence of flow.
- Contributing area: area drained by each cell (m^2).
- Distance to divide: distance between the cell and the divide following the flow path (m).
- Topographic index: TOPMODEL topographic index (Beven and Kirkby 1979) $k = \ln(a/\tan \beta)$, where a is the upslope contributing area of each cell and β the local slope angle.

Other relevant categorical variables were added to the GIS, following the same 50 × 50-m grid structure:

- Lithology (6 classes).
- Plant cover (7 classes).
- Land use (4 classes).

Approximately 88% (851 cases) of the debris flows were in the Flysch Sector, although flysch only represents 42% of the study area. Other lithologies (58%) accounted for 11.5% of the flows. Thus, most of the statistical analysis was focused on the Flysch Sector.

The database was divided into cells with or without debris flows in order to evaluate significant differences. For nominal variables we performed a test of the difference between proportions, based on the c2 distribution for a 2 by 2 table. A Mann–Whitney *U*-test was used to analyze continuous variables.

Debris flows (from both the whole study area and the Flysch Sector) were classified into groups by a conglomerate analysis (cluster, k-means) and a discriminant analysis to define the main triggering factors.

Results

The study area contained an average of 0.56 debris flows per square kilometer, with an irregular spatial distribution (Figure 4). Debris flows could be triggered almost anywhere, but densities increased in the Flysch Sector (1 case/km^2), especially near the Inner Depression. There, the flysch is affected by many faults and folds, especially a long overthrusting fault that encouraged the triggering of old slumps, in whose scars many debris flows are located.

Debris flows are rare in other lithologies, except for some Quaternary deposits (talus screes). A primary cluster analysis of the whole study area established 3 groups of debris flows: the first at 1150 m, the second at 1250 m, both in the Flysch Sector, and the third at 1750 m in different lithologies, clearly demonstrating the differences between the middle and the high mountain debris flows. As a result of this classification and the high number of debris flows in the Flysch Sector, we concentrated on this restricted area in order to identify the most important triggering factors, regardless of lithology.

Figures 5 and 6 illustrate the contrasts between the Flysch Sector and the frequency distribution of debris flows, according to both categorical and continuous variables (only significant factors were included). Tables 1 and 2 summarize the significant differences between the distributions of both categorical and continuous variables in cells with or without debris flows. These differences help to illustrate where debris flows are generally found.

The Flysch Sector has slightly more southern exposures. This trend is clearly more pronounced in the case of debris flows (Figure 5). The southwestern and southern aspects make up 44% of the cases (>1.2 cases/km^2), followed by the western (16%) and southeastern exposures (16%). The occurrence of debris flows is very low (6%) in the north and northeast exposures.

With respect to plant cover, 9% of the Flysch Sector is farmland, especially on the valley floor on fluvial terraces and alluvial fans. Natural pine forests make up 25% of the study area, followed by shrubs (19%), reforested pine (17%), oak and evergreen oak woods (12%), subalpine grasslands (10%), and beech and fir woods (9%). The distribution of debris flows shows a higher concentration in reforested areas (31% or 1.7 cases/km^2), followed by shrubs (24%) and natural pine woods (20%), as compared with beech and fir woods (6%) and farmland (0%).

Approximately 74% of the study area has never been farmed. Cultivated sections include sloping fields (17%) followed by flat fields (5%) and bench terraced fields (2%). The noncultivated area contains 68% of all

FIGURE 4 Location of hillslope debris flows in the Upper Aragón and Gállego valleys, with special reference to the Flysch Sector. Each dot represents the location of a debris flow scar. (Map by authors)

the debris flows, and sloping fields contain 30% (256 cases or 1.7 cases/km^2, Figure 5).

As for continuous variables, the altitudinal distribution of the study area is very homogeneous from 500 to 2000 m and above. Debris flows appear at any altitude but are more common between 1000 and 1400 m, especially from 1100 to 1200 m (1.5 cases/km^2, Figure 6). This belt is the most affected by deforestation and intense farming on the southern aspects, with sloping fields and shifting agriculture.

Most debris flows (82%) are on 20–35° gradients, especially between 25 and 30° (1.8 cases/km^2, Figure 6). Few are found under 15°. The role of gradients over 35° has not been assessed because of the lack of steep slopes in the Flysch Sector.

Figure 6 also includes information on the frequency of 2 microtopographic variables: the Topographic Index and the Profile Curvature. The remaining continuous variables are not statistically significant. The Topographic Index confirms that debris flows tend to occur on steep gradients draining relatively few cells and disappear on gentle gradients draining large surfaces.

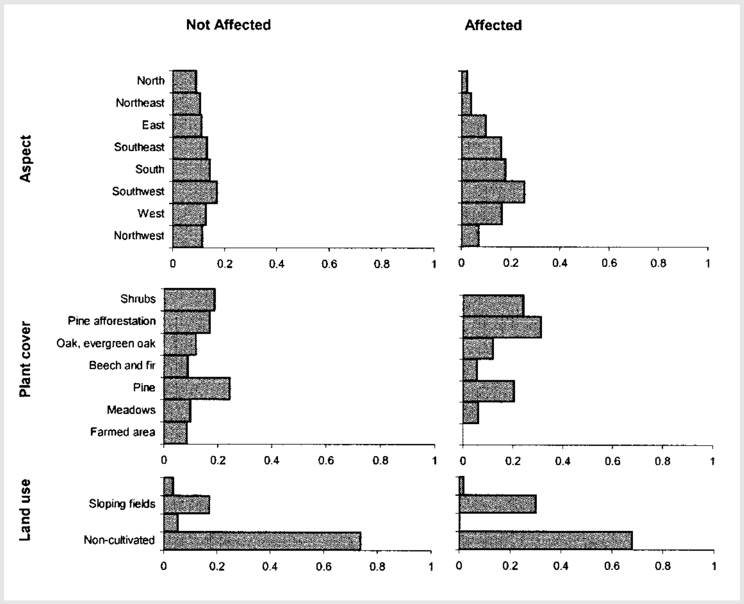
Profile Curvature shows little difference between the study area and the location of the observed debris flows. Both are very frequent around zero (a straight versant), but debris flows tend slightly more toward concave hillslopes.

Tables 1 and 2 and Figures 5 and 6 suggest that, within the Flysch Sector, debris flows are triggered on sunny, slightly concave hillslopes between 1000 and

1400 m on 20–35° gradients and in areas with human disturbance (especially old sloping fields, scrub areas, and reforested areas).

The cluster analysis (k-means) helped to distinguish 3 groups of debris flows in the Flysch Sector. A discriminant analysis has defined the most important variables in the differentiation of the 3 groups. This method points out 2 functions that explain 100% of the variance. The first absorbs 87.7% of the variance and separates Group 1 from the other 2 groups. The second absorbs 12.3% of the variance and separates Groups 2 and 3. The factors most related to Function 1 are the Topographic Index, the area draining toward each debris flow scar, and the distance between the divide and the debris flow scar. The most important factors in Function 1 are related to land use.

FIGURE 5 Proportional distribution of cells affected and not affected by debris flows according to continuous and categorical variables.



Debris flows in Group 1 (323 cases) are 200–400 m from the divide, whereas Groups 2 (290 cases) and 3 (348 cases) are less than 200 m away. The same trend is apparent using the Topographic Index and the area draining toward each scar.

Groups 2 and 3 differ because of the prevalence of old, abandoned sloping fields and reforested areas in Group 3. Group 2 is located in areas that have never been cultivated.

Table 3 demonstrates the similarity between the classification of the defined groups and those predicted by the discriminant analysis (95.9% of the cases have been correctly classified).

Discussion and conclusions

We attempted to identify the most important factors that trigger hillslope debris flows and classify them

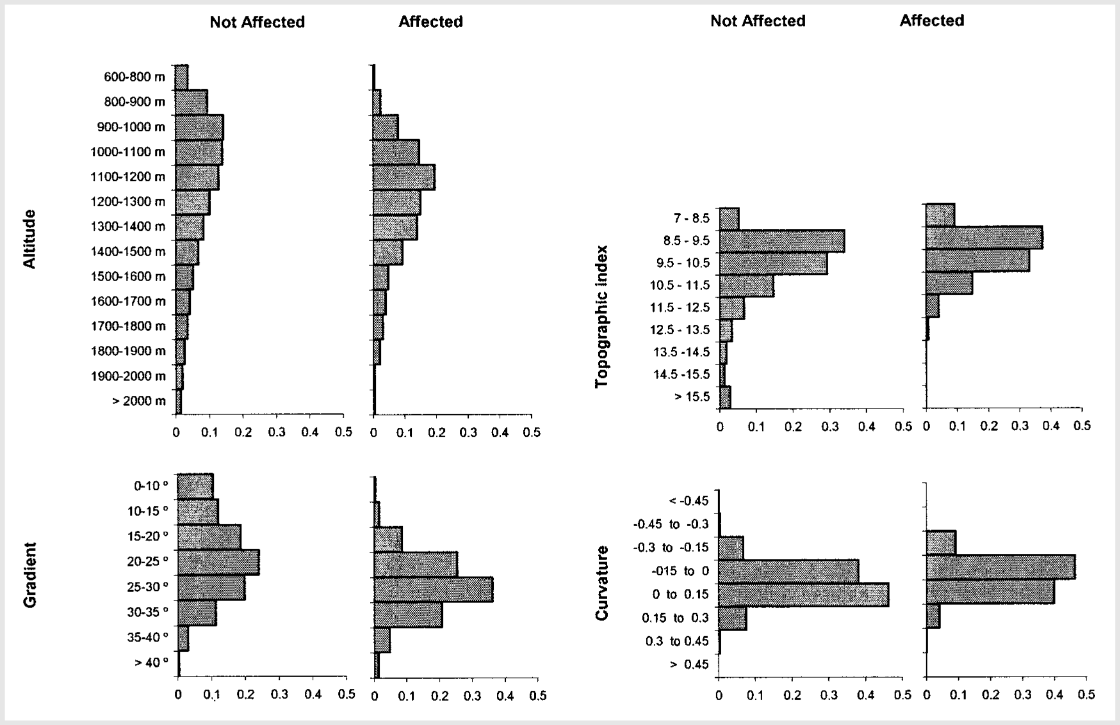


FIGURE 6 Frequency distribution of cells affected and not affected by debris flows according to significant continuous variables.

TABLE 1 Significance test between proportions of cells affected and not affected by debris flows (DF). Z, normalized difference between proportions.

		Not affected	Affected		Significance test	
		(%)	(%)	(DF/km^2)	Z value	a
Land use	Non-cultivated	73.8	67.9	0.90	4848.30	<0.001*
	Flat fields	5.3	0.2	0.04	691.68	<0.001*
	Sloping fields	17.2	30.1	1.71	1304.52	<0.001*
	Terraced fields	3.6	1.8	0.48	562.51	0.004*
	Total	100.0	100.0	0.98		
Plant cover	Farmed area	8.7	0.0	0.00	901.53	<0.001*
	Meadows	9.9	6.2	0.62	960.27	<0.001*
	Pine	24.6	20.6	0.82	1648.66	0.007*
	Beech and fir	9.0	5.8	0.63	911.92	<0.001*
	Oak, evergreen oak	11.9	12.0	0.99	1061.03	0.952
	Pine reforestation	17.1	31.3	1.80	1295.76	<0.001*
	Shrubs	18.8	24.2	1.26	1384.83	<0.001*
	Total	100.0	100.0	0.98		
Aspect	North	9.0	2.5	0.27	917.10	<0.001*
	Northeast	10.6	4.1	0.38	998.70	<0.001*
	East	11.2	10.0	0.88	1023.64	0.277
	Southeast	13.3	16.2	1.20	1127.17	0.012*
	South	14.4	18.0	1.23	1177.99	0.003*
	Southwest	17.2	25.7	1.47	1305.57	<0.001*
	West	12.9	16.5	1.25	1105.25	0.002*
	Northwest	11.5	7.1	0.60	1045.26	<0.001*
	Total	100.0	100.0	0.98		

*: Significant at a = 0.01.

according to several variables. It is well known that debris flows are triggered by high-intensity rainstorms (Caine 1980; Kotarba 1989; Van Steijn 1996; Blijenberg 1998; Deganutti et al 2000), but their spatial distribution is not random. Lithology, altitude, aspect, plant cover, and land use play important roles.

The Flysch Sector contains most of the debris flows identified in the Upper Aragón and Gállego valleys (88%), as also reported in other countries (Tischenko 2000). In the Alps, Blijenberg (1998) found that, "regions with a high debris flow frequency are mostly situated in flysch deposits … or rapidly alternating rocks with dense faulting" (p 178). The reasons for this are:

1. The presence of alternating beds of sandstones and marls, yielding a deep and loose colluvium.
2. Intensively faulted and folded areas of the Flysch Sector that increase the instability of poorly sorted material, especially in old slump scars.

Debris flows are often triggered in a colluvium mantle derived from strongly tectonically modified materials (Lin et al 2000). This is why debris flow scars are abundant in the southern part of the Flysch Sector, where marls of the Inner Depression make contact via a long overthrusting fault, fractures, and related slumps (Martí-Bono et al 1997).

TABLE 2 Significance test between distributions of continuous variables in cells affected and not affected by debris flows.

Continuous variable	Z value	a
Altitude	–5.34	<0.001*
Gradient	–20.36	<0.001*
Profile curvature	–6.79	<0.001*
Planar curvature	–0.57	0.566
Topographic index	–8.00	<0.001*
Ln (contributing area)	–0.29	0.769
Ln (distance to divide)	–0.08	0.936

*: Significant at a = 0.01.

The remaining factors were closely related to important human disturbance on the hillslopes, especially in:

FIGURE 7 Hillslope debris flows in a reforested area of the Central Spanish Pyrenees, showing scars, channels, and the run-out distance. (Photo by José M. García-Ruiz)

1. Southern aspects, which are the most favorable for farming in the Central Spanish Pyrenees in order to counteract the short growing season (Lasanta 1989).
2. Altitudes between 1000 and 1400 m, with sloping fields and where shifting agriculture was most intensively practiced (Lasanta 1989).
3. Scrubland and reforested pines, coinciding with eroded areas after centuries of human-induced fires and overgrazing (Figure 7). Most of the reforested areas were previously affected by intense soil erosion and severe degradation (high soil stoniness, open shrub cover) (Ortigosa et al 1990). Some debris flows are also triggered on hillslopes covered by natural forests (especially pine, as was pointed out by Caine and Swanson [1989]), but these are rare in the Spanish Pyrenees compared with the deforested areas.
4. Hillslopes covered by sloping fields or previously subject to shifting agriculture with few man-made structures for soil conservation. Sloping fields were once the response to a higher population density, giving rise to increased deforestation and farming of sunny hillslopes.

Debris flows are most frequent in the Flysch Sector, especially where human disturbance is high. 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 (García-Ruiz and Puigdefábregas 1982; González et al 1995). García-Ruiz et al (1988) demonstrated a close relationship between wildfires and debris flows in a similar mountain environment (see also Cannon 2000). Similarly, Wu and Swanston (1980) and Squier and Harvey (2000) related them to forest logging, because of changes in the subsurface conditions, but this is not always the case. In the Alps, Zimmermann (1990) reported a high proportion of debris flow scars in the periglacial belt. Van Steijn et al (1995) arrived at a similar conclusion. Although periglacial conditions are not necessary, certain features of the periglacial environment encourage the development of debris flows. We cannot confirm this because our study concentrated on the Flysch Sector, below 2200 m with few limestone cliffs, but some debris flows were found in the alpine and subalpine belts when the whole Upper Aragón and Gállego valleys were considered.

Gradient is another limiting factor because no debris flow scars occurred on hillslopes with gentle gradients. Takahashi et al (1981) also found that most of the debris was between 25 and 38°, whereas Innes (1983) found that it was between 32 and 42°.

The 3 groups of debris flows from the cluster and discriminant analyses were distinguished by land use, plant cover, and microtopographic factors. The first group showed a large distance between debris flow scars and divides, as well as a relatively large area drained by each debris flow scar. The other 2 groups, with a shorter distance from the scar to the divide, were separated by the characteristics of plant cover and traditional land use. This confirms that human disturbance introduces changes in shear strength and flow distribution responsible for triggering shallow landslides, as is the case with debris flows. These results can help to identify high-risk areas in mountain environments in order to reduce the impact of debris flows on infrastructure, tourism, and human settlements.

TABLE 3 Results of the discriminant analysis: classification of cases; percent of cases correctly classified = 95.88%.

Actual group	No. of cases	Predicted group membership		
		1	2	3
Group 1	323	322 (99.7%)	1 (0.3%)	0. (0.0%)
Group 2	290	4 (1.0%)	274 (94.4%)	13 (4.6%)
Group 3	348	21 (5.9%)	1 (0.3%)	326 (93.8%)

AUTHORS

Adrián Lorente, José M. García-Ruiz, and Santiago Beguería
Instituto Pirenaico de Ecología, CSIC, Campus de Aula Dei, Apartado 202,
50080 Zaragoza, Spain.
adlor@ipe.csic.es; humberto@ipe.csic.es

José Arnáez
Department of Geography, University of La Rioja, 26004 Logroño, Spain
jose.arnaez@dchs.unirioja.es

ACKNOWLEDGMENTS

This article was prepared with the support of the following research projects: "Debris fall assessment in mountain catchments for local end-users—DAMOCLES" (EVG1-1999-00027P), financed by the European Commission, and "Assessment of sediment sources and runoff generation areas in relation to land-use changes—HIDROESCALA" (REN2000-1709-C04-01/GLO), financed by CICYT.

REFERENCES

Bathurst JC, Burton A, Ward TJ. 1997. Debris flow run-out and landslide sediment delivery tests. *Journal of Hydraulic Engineering* 123(5):410–419.
Beven KJ, Kirkby MJ. 1979. A physically-based variable contributing area model of basin hydrology. *Hydrological Sciences Bulletin* 24:43–69.
Blijenberg H. 1998. *Rolling Stones? Triggering and Frequency of Hillslope Debris Flows in the Bachelard Valley, Southern French Alps.* Utrecht, The Netherlands: Utrecht University.
Blikra LH, Nemec W. 1998. Postglacial colluvium in western Norway: depositional processes, facies and paleoclimatic record. *Sedimentology* 45:909–959.
Blikra LH, Nemec W. 2000. Reply. *Sedimentology* 47(5):1058–1068.
Brunsden D. 1979. Mass movements. *In:* Embleton C, Thornes J, editors. *Process in Geomorphology*. London: Edward Arnold, pp 131–186.
Caine N. 1980. The rainfall intensity–duration control of shallow landslides and debris flows. *Geografiska Annaler* 62A:23–27.
Caine N, Swanson NJ. 1989. Geomorphic coupling of hillslope and channel systems in two small mountain basins. *Zeitschrift für Geomorphologie* 33(2):189–203.
Cannon SH. 2000. Debris flow response of southern California watersheds burned by wildfire. *In:* Wieczorek GF, Naeser ND, editors. *Debris Flow Hazards Mitigation: Mechanics, Prediction and Assessment.* Rotterdam, The Netherlands: Balkema, pp 45–52.
Carrara A, Cardinali M, Guzzetti F, Reichenbach P. 1995. GIS technology in mapping landslide hazard. *In:* Carrara A, Guzzetti F, editors. *Geographical Information Systems in Assessing Natural Hazards*. Dordrecht, The Netherlands: Kluwer, pp 135–175.
Costa JE. 1988. Rheologic, geomorphic and sedimentologic differentiation of water floods, hyperconcentrated floods and debris flows. *In:* Baker VR, Kochel RC, Patton PC, editors. *Flood Geomorphology*. Chichester, UK: Wiley, pp 387–393.
Deganutti AM, Marchi AM, Arattano M. 2000. Rainfall and debris flow occurrence in the Moscardo basin (Italian Alps). *In:* Wieczorek GF, Naeser ND, editors. *Debris Flow Hazards Mitigation: Mechanics, Prediction and Assessment.* Rotterdam, The Netherlands: Balkema, pp 67–72.
García-Ruiz JM, Alvera B, Del Barrio G, Puigdefábregas J. 1990. Geomorphic processes above timberline in the Spanish Pyrenees. *Mountain Research and Development* 10(3):201–214.
García-Ruiz JM, Arnáez J, Ortigosa L, Gómez-Villar A. 1988. Debris flows subsequent to a forest fire in the Najerilla river valley (Iberian System, Spain). *Pirineos* 131:3–24.
García-Ruiz JM, Arnáez J, White S, Lorente A, Beguería S. 2000. Uncertainty assessment in the prediction of extreme rainfall events: an example from the Central Spanish Pyrenees. *Hydrological Processes* 14(5):887–898.
García-Ruiz JM, Puigdefábregas J. 1982. Formas de erosión en el flysch eoceno surpirenaico (Erosion forms in the south-Pyrenean Eocene flysch). *Cuadernos de Investigación Geográfica* 8:85–128.
García-Ruiz JM, Puigdefábregas J, Creus J. 1985. *Los recursos hídricos superficiales del Alto Aragón (Surface water resources in the Upper Aragón).* Huesca, Spain: Instituto de Estudios Altoaragoneses.
González C, Ortigosa L, Martí C, García-Ruiz JM. 1995. The study of the spatial organization of geomorphic processes in mountain areas using GIS. *Mountain Research and Development* 15(3):241–249.
Guzzetti F, Carrara A, Cardinali M, Reichenbach P. 1999. Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, central Italy. *Geomorphology* 31(1–4):181–216.
Innes JL. 1983. Debris flows. *Progress in Physical Geography* 7(4):469–501.
Johnson AM, Rodine JR. 1984. Debris flow. *In:* Brunsden D, Prior DB, editors. *Slope Instability*. Chichester, UK: Wiley, pp 257–361.
Kotarba A. 1989. On the age of debris flows in the Tatra Mountains. *Studia Geomorphologica Carpatho-Balcanica* 23:139–152.
Lasanta T. 1989. *Evolución reciente de la agricultura de montaña: El Pirineo aragonés (Recent Evolution of Mountain Agriculture: The Central Pyrenees).* Logroño, Spain: Geoforma Ediciones.
Lin CW, Wu MC, Shieh CL, Shieh YC. 2000. Influence of geology on debris flows: examples from Hsin-Yi, Nantou County, Taiwan. *In:* Wieczorek GF, Naeser ND, editors. *Debris Flow Hazards Mitigation: Mechanics, Prediction and Assessment.* Rotterdam, The Netherlands: Balkema, pp 169–176.
Martí-Bono C, Valero B, García-Ruiz JM. 1997. Large, historical debris flows in the Central Spanish Pyrenees. *Physics and Chemistry of the Earth* 22(3–4):381–385.
Molinillo M, Lasanta T, García-Ruiz JM. 1997. Managing mountainous degraded landscapes after farmland abandonment in the Central Spanish Pyrenees. *Environmental Management* 21(4):587–598.
Ortigosa L, García-Ruiz JM, Gil E. 1990. Land reclamation by reforestation in the Central Spanish Pyrenees. *Mountain Research and Development* 10(3):281–288.
Rapp A, Nyberg R. 1981. Alpine debris flows in northern Scandinavia. *Geografiska Annaler* 63A:183–196.
Squier LR, Harvey AF. 2000. Two debris flows in Coast Range, Oregon, USA: logging and public policy impacts. *In:* Wieczorek GF, Naeser ND, editors. *Debris Flow Hazards Mitigation: Mechanics, Prediction and Assessment.* Rotterdam, The Netherlands: Balkema, pp 127–138.
Takahashi T, Ashida K, Sawai K. 1981. Delineation of debris flow hazard areas. *In: Erosion and Sediment Transport in Pacific Rim Steeplands.* International Association of Hydrological Sciences (IAHS) Publication 132. Wallingford, UK: IAHS Press, pp 589–603.
Tischenko AS. 2000. Debris flow activity in Transcarpathia due to heavy rains in autumn 1998. *In:* Wieczorek GF, Naeser ND, editors. *Debris Flow Hazards Mitigation: Mechanics, Prediction and Assessment.* Rotterdam, The Netherlands: Balkema, pp 161–168.
Van Steijn H. 1996. Debris flow magnitude–frequency relationships for mountainous regions of Central and Northwest Europe. *Geomorphology* 15(3–4):259–273.
Van Steijn H, Bertran P, Francou B, Hétu B, Texier JP. 1995. Models for the genetic and environmental interpretation of stratified slope deposits: review. *Permafrost and Periglacial Processes* 6:125–146.
Varnes DJ. 1978. Slope movements, type and processes. *In:* Schuster RL, Krizek RJ, editors. *Landslide Analysis and Control.* Transportation Research Board, Special Report 176. Washington, DC: National Research Council, National Academy of Science, pp 11–33.
White S, García-Ruiz JM, Martí-Bono C, Valero B, Errea MP, Gómez-Villar A. 1997. The 1996 Biescas campsite disaster in the Central Spanish Pyrenees and its spatial and temporal context. *Hydrological Processes* 11:1797–1812.
Wu TH, Swanston DN. 1980. Risk of landslides in shallow soils and its relation to clearcutting in southeastern Alaska. *Forest Science* 26(3):495–510.
Zimmermann M. 1990. Debris flows 1987 in Switzerland: geomorphological and meteorological aspects. *In:* Sinniger O, Monbaron M, editors. *Hydrology in Mountainous Regions. II—Artificial Reservoirs: Water and Slopes.* International Association of Hydrological Sciences (IAHS) Publication 194. Wallingford, UK: IAHS Press, pp 387–393.