DAMOCLES PROJECT

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Final Report

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SECTION 6: DETAILED REPORT, RELATED TO OVERALL PROJECT DURATION

Section 6.1. Background

The Central Spanish Pyrenees have been intensively studied by the Department of Soil Erosion and Land Use Changes of the Pyrenean Institute of Ecology. One of the main topics studied were the spatial distribution of geomorphic processes and the assessment of sediment delivery areas. A regional study in 1982 underlained the great importance of debris flows in the entire upper Aragón and Gállego valleys, especially within the Flysch Sector. These debris flows affected many hillslopes and were the responsible for the development of most of alluvial fans. From time to time, during infrequent rainstorms, they affected roads and other infrastructures and were considered as one of the main processes supplying coarse debris to the fluvial network, partly defined as torrential, with very instable braided channels. Posterior studies confirmed the importance of debris flows for landscape and fluvial evolution and that debris flows are a relatively common geomorphic phenomenon in the Central Pyrenees, occurring even with rainstorms corresponding to low return periods.

Surprisingly, few attempts have been made in the Pyrenees and, in general, in Spain, to assess the debris flow hazard and to relate debris flows to channel morphology and sediment transport. In addition, little information exists about debris flow periodicity and the relationships between different intensities of precipitation and debris flow occurrence. The participation of the Department of Soil Erosion and Land

Use Changes of the Pyrenean Institute of Ecology within the DAMOCLES Project has been focused on these topics, trying ultimately of performing a debris flow susceptibility map and the corresponding hazard map.

This study is focused on unconfined debris flows, that differ greatly of confined debris flows 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 and scarce plant cover (Brunsden, 1979). 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).

Section 6.2. Scientific/tecnological and socio-economic objectives

These have been the most relevant scientific and socio-economic objectives of the IPE's group, included in workpackages 1, 4 and 5, for the entire study period (2000-2003):

(i) To assess the spatial distribution of debris flows in the Central Spanish Pyrenees.

(ii) To identify and rank the environmental and man-induced factors that explain the spatial distribution of debris flows.

(iii) To analyse the information on different debris flow parameters in order to establish statistical relationships between them. This information is especially relevant for modelling the debris flow hazard.

(iv) To get information on the periodicity of debris flows in the study area in relation to the occurrence and spatial distribution of rainstorms corresponding to different return periods. In addition, the occurrence of debris flows within the context of most common equations calculated to relate debris flow triggering and the rainfall intensity-duration has been analysed.

(v) To develop a logistic model to accurately forecast not only the areas where debris flow scars will occur, but especially the areas affected by debris flow tongues and runouts.

(vi) To compare both the methods used by the Italian and Spanish groups and the debris flow characteristics in the Pyrenees and in the Alps.

(vii) To disseminate the results obtained among the end-users and by means of publications and participation in conferences and meetings.

To summarize, the objectives of the IPE's participation have been closely related to the spatial distribution of debris flows, their periodicity, theis relationships with intense precipitations and their modelling using past evidences of debris flows, GIS procedures and field work.

Section 6.3. Applied methodology, scientific achievements and main deliverables

6.3.1. Main characteristics of the study area

The upper basins of the Aragón and Gállego rivers in the Central Spanish Pyrenees occupy 1,727 km^2. The highest altitudes surpass 3000 m and much of the area is above 2000 m, with strong altitudinal contrasts between divides and valley bottoms.

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):

i) The axial or paleozoic area with granitic massifs and massive, intensively folded slate and limestone outcrops, resulting in a very contrasted relief.

ii) The Inner Ranges correspond to an overthrusting anticline composed of Cretaceous and Paleocene limestone and sandstone. The relief is very rough, with vertical cliffs and karstified areas.

iii) The Eocene Flysch Sector (867 km^2) has 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 a.s.l.

iv) The Inner Depression is 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 due to the Atlantic influence. A Mediterranean climate prevails toward the south and 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 ranges 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).

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 and meadows only persist in the valley bottoms. Above 1600 m, the landscape is dominated by dense forests and subalpine and alpine grasslands. Periglacial activity above 2400 m explains the scarcity of plant cover.

6.3.2. The spatial distribution of debris flows

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, that contains an average of 1 case/km^2, especially near the Inner Depression. There, the flysch is affected by many faults and folds, and especially a long overthrusting fault that encouraged the triggering of old slumps, in whose scars many debris flows are located.

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 two by two table. A Mann-Whitney test was used to analyse 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.

Debris flows are often triggered in a colluvium mantle derived from strongly tectonically modified materials (i.e., 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).

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

i) southern aspects, which are the most favourable for farming in the Central Spanish Pyrenees in order to counteract the short growing season (Lasanta, 1989).

ii) altitudes between 1000 and 1400 m a.s.l., with sloping fields and where shifting agriculture was most intensively practised (Lasanta, 1989);

iii) scrubland and reforested pines, coinciding with eroded areas after centuries of human-induced fires and overgrazing. Most 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 to deforested areas.

iv) 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.

6.3.3. Debris flows frequency

The Ijuez catchment (54.6 km^2) has been selected for a detailed assessment of the recurrence of debris flows. A sequential cartography of debris flows has been made, using the aerial photographs of 1956, 1977 and 1990. The map of debris flows has been completed in 2001 by a field recognition of debris flows.

Fig. 1 shows (black dots) the cumulative number of debris flows observed in different moments. A linear disposition of the dots can be clearly seen, and demonstrated by the high coefficient of determination of the adjusted line (r^2 = 0.997). The high linear trend on the occurrence of debris flows demonstrates that, far from being a rare phenomena, the triggering of shallow landslides in the area is a relatively common and constant process in the Ijuez catchment (and, most probably, in the Flysch Sector of the Spanish Pyrenees). The slightly lower than expected number of debris flows mapped in 2001 can be attributed to the change in the methodology, as field recognition mapping is less exhaustive than aerial photo analysis. The mean rate of occurrence is 3.4 debris flows per year, what makes a relative value of 0.06 debris flows km^{-2} yr^{-1}.

No information exists in the area about the exact timing of the different debris flows, so to relate them to specific events is a hard and very uncertain task. Fig. 4 also presents information on the series of annual maximum precipitation recorded in the Ijuez catchment ('Bescós de la Garcipollera' weather station). Snowmelt is a very marginal runoff producer process in the area, so rainfall is likely to be the main cause for shallow landsliding. The series of extreme events does not show any trend in the period 1955-1999. Rainfalls exceeding 45-50 mm in one day are relatively frequent, the absolute maximum recorded being 82.5 mm. Considering the high regularity in the occurrence of debris flows, even during the last and shortest sampling period (1990-2001), it can be concluded that the triggering of shallow landslides in the Ijuez Valley is related to relatively frequent intense precipitations, having a recurrence of no more than 2 to 5 years. The corresponding quantiles, calculated using the Generalized Pareto distribution and probability weighted moments for parameter estimation, are 36.8 and 46.6 mm, respectively.

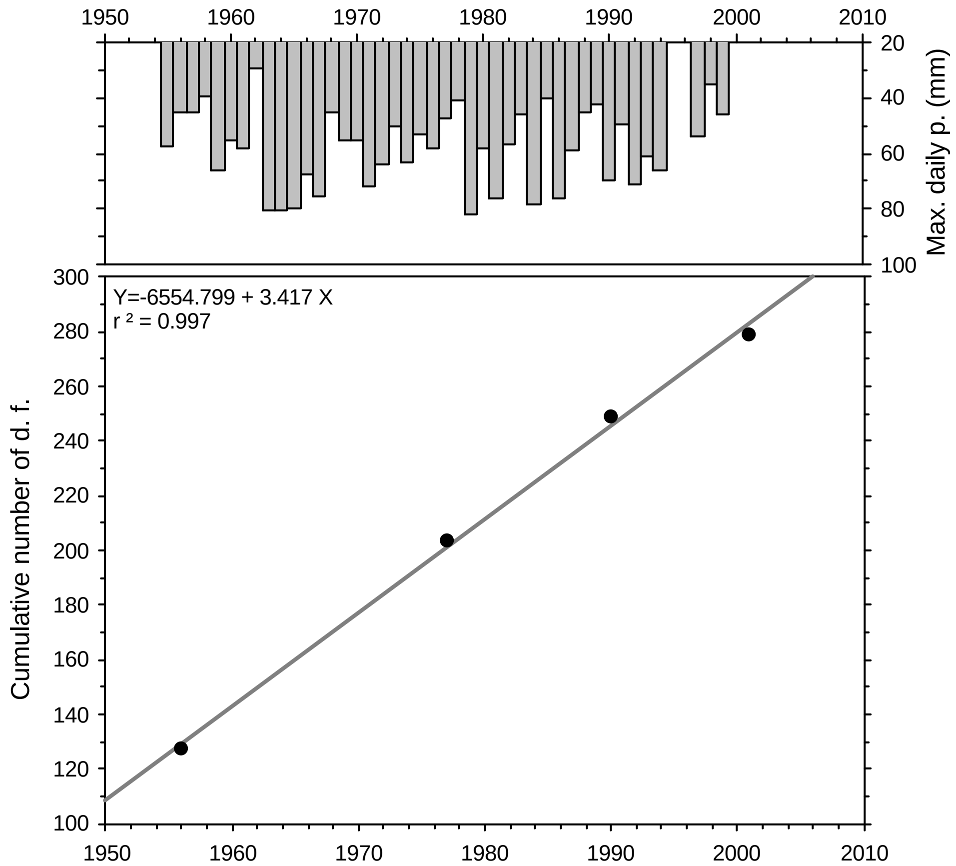

Figure 1. Cumulative number of debris flows in the Garcipollera valley, and annual maximum precipitation series at Bescós station

This leads naturally to the question of the existence of rainfall thresholds for the triggering of debris flows. The hypothesis of the existence of a critical depth / duration has been investigated by many authors, and several empirical thresholds have been proposed. Fig. 2 shows the threshold curves proposed by Caine (1980) and Innes (1983), along with empirical data from the Ijuez Valley. These empirical data are shown both as the observed annual maximums (black dots) and the adjusted depth / duration / recurrence curves (black lines). The observed extreme rainfalls are located significantly below the Caine limiting curve. that corresponds to precipitations of 200 to 500 years recurrence in the area. The curve from Innes is much more reliable. The estimated return period for rainfall events triggering landslides in the Ijuez Valley (2-5 years) is not very far from the Innes threshold curve. This situates the Ijuez Valley among the most susceptible areas for debris flows reported in the literature.

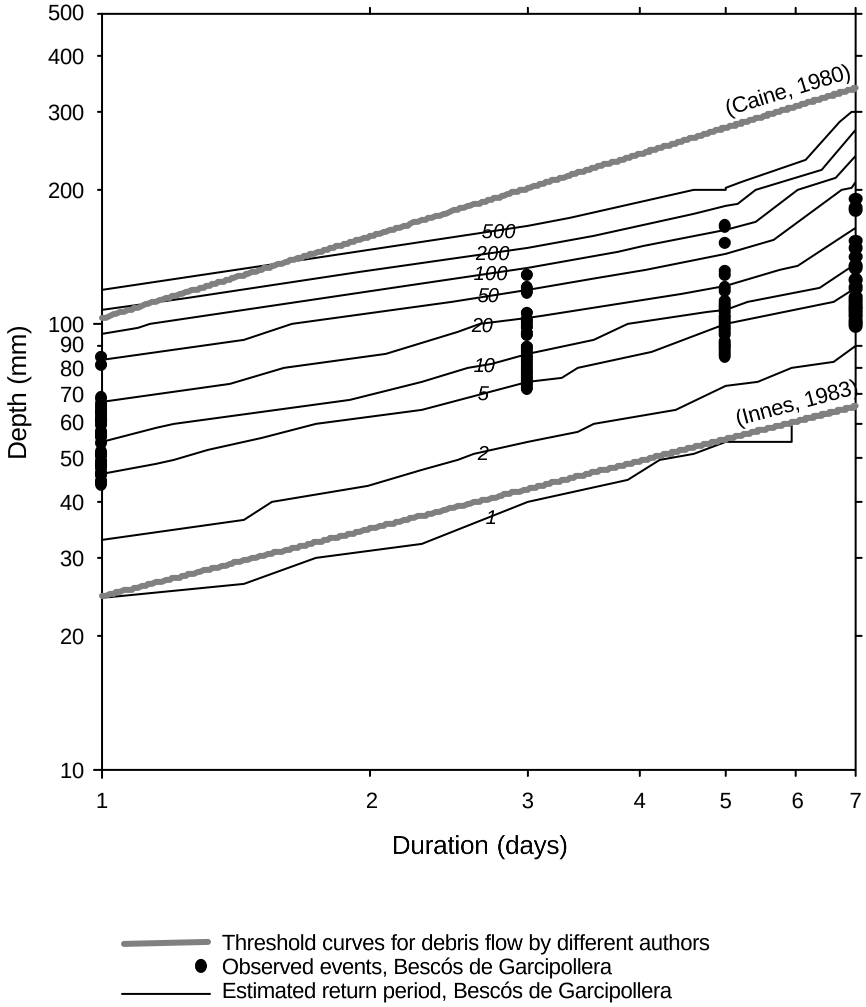

Figure 2. Precipitation depth / duration / recurrence curves and observed extreme events at Bescós station, 1955-1999, and theoretical debris flow triggering threshold curves by different authors

6.3.4. Regional modelling of extreme rainfalls

The methodology of the index flood method (Dalrymple, 1960) has been used to obtain a cartography of the probability of extreme rainfall events in the study area. The index flood method is a regional derivation of local frequency analysis of extreme events. The regional approach is based on the assumption of the similarity of the extreme distribution's shape parameter between climatic stations belonging to a given hydro-climatic region. Data coming from the different stations can then be used conjointly to estimate the shape parameter, reducing the great uncertainty involved in its estimation (Cunnane, 1988; GREHYS, 1996).

The partial duration series (PDS, also known as peaks over threshold) procedure has been used for extracting the extreme events series from the 37 original daily precipitation series. PDS series are constructed including all the records exceeding a given threshold level x_0, independently of their time of occurrence. Thus, the length of the series is variable, depending on this value.

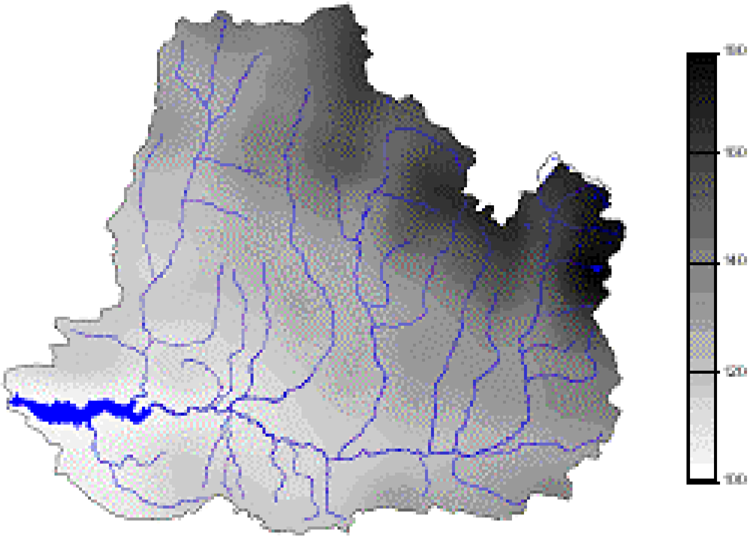

Fig. 3. Distribution of the 24-hour maximum precipitation corresponding to a return period of 100 years (mm).

Four different maps have been produced, showing the distribution of the maximum expected daily precipitation in the study area for a return period of 1, 5, 25 and 100 years (Fig. 3). The results obtained show a relatively close relationship between the distribution of extreme precipitacions and the characteristics of the relief. Thus, the lowest values are recorded close to the Yesa Reservoir and in the Inner Depression. The maximum values grow slowly throughout the Flysch Sector, following a SW-NE gradient, due, on the one hand, to the effect of the relief, and on the other hand to the effect of a decreasing oceanic influence.

The values of estimated extreme reainfalls for a 100 years return period can be considered as moderate if compared with the values published by other authors for the Spanish Mediterranean coast. Thus, in the Central Pyrenees, 180 mm have been calculated at more than 2500 m a.s.l., whereas in the Valencian coast more than 400 mm have been estimated. In fact, a value of 180 mm corresponds to a period lower than 5 years in most of the Mediterranean coast.

6.3.5. Debris flow relationships

Two basic problems when studying landslide hazards are predicting whether the landslide material arrives directly to the fluvial system (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).

Ninety-eight debris flows 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 Acumuer valleys and southern aspects between Jaca and Sabiñánigo). The variables measured have been included in Fig 3.

The deposition of the sediment carried by the debris flows started at 17.8º, much higher than other reports. Bathurst *et al.* (1997) find that deposition begins once the slope falls below 6-10º, Ikeya (1981) suggests 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 study deals only with unconfined debris flows.

The α value in Vandre's formula (1985) 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).

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).

6.3.6. Landslide hazard mapping by multivariate statistics

The variables entered in the model come from very different sources. A detailed digital elevation model (DEM) was constructed at a resolution of 10 m, from topographic maps at 1:10 000 scale. Several morphological variables were derived from the DEM: slope, aspect, planform and profile curvature, upstream slope length, contributing area and the topographic index. Several variables were log or power transformed to better adjust to a normal distribution. Other variables, referring mainly to the vegetation cover, were obtained from a Landsat TM summer image: the normalized difference vegetation index (NDVI), and the three first components of the tasselled cap transformation (namely brightness, greenness and soil humidity). Several thematic variables, like plant cover or the past land use, where obtained from thematic digital maps. Finally, the distance to a rotational landslide scar was calculated within the GIS. A 10 m grid format was selected for the model. This resolution allowed to fully exploit the detailed morphological information, as topographic variables like slope are known to play a very important role in debris flow triggering. The rest of the variables were adapted to that resolution. The grid format was considered optimum for this kind of process, as the size of the debris flows were similar to the grid cells. For that reason, each debris flow scar was recorded as a single pixel.

Due to the binary character of the response and some predictor variables, and the dubious normality of some of the variables, a logistic regression procedure was selected. Logistic regression states that the natural logarithm of odds (logit) is linearly related to the independent variables:

$$\ln\left(\frac{p_1}{1-p_1}\right) = b_0 + b_1 \cdot X_1 + \ldots + b_n \cdot X_n$$

where p_1 is the probability of occurrence of a debris flow, X_n is a set of n independent variables, and b_n is a set of n+1 parameters. Developing expression 1:

$$p_1 = \frac{\exp\left(b_0 + b_1 \cdot X_1 + \ldots + b_n \cdot X_n\right)}{1 + \exp\left(b_0 + b_1 \cdot X_1 + \ldots + b_n \cdot X_n\right)}$$

As landsliding is normally a rare event, the population can have hundreds or even thousands of times fewer events (ones) than non-events (zeros). This is specially true in grid or raster based models, but is also frequent in spatially lumped ones. It is well known that common statistical multivariate procedures, such as discriminant analysis and logistic regression, are designed to work with groups that are more or less equal in size. When dealing with rare events, like landslides, the groups tend to be very unequal, and the models tend to sharply underpredict the probability of rare events. This was the case for the Garcipollera valley model, where the pixels with debris flow were around 2.5 in 10 000 cases.

The same problem has been analysed by King and Zeng (2001). They propose a design based in endogenous stratified sampling, or sampling within categories of the dependent variable. The strategy is to select all the cases for which (Y=1) and a random selection of cases for which (Y=0). This sampling procedure is specially useful when, as is the case of landslide inventory, the researcher knows the exact proportion of ones in the population (prior knowledge). The number of zeros to collect is a decision of the researcher. A number of zeros ten times higher than ones has been used for the Garcipollera valley model.

A stepwise procedure has been used to introduce the variables, with a probability to enter of 0.05. This procedure selects only the variables that significantly contribute to improve the model.

Four variables where selected by the stepwise procedure: slope (with a 5x5 filter), alpine pastures, south exposition and north exposition. Only the slope is a continuous variable, the rest being categorical. Slope and south exposition have a positive effect in the triggering of debris flows, whereas alpine pastures and north exposition have a negative effect. Slope is the most important variable in the model, as slopes in the Garcipollera valley range typically from 0 to 45 degrees. This means that $\boldsymbol{b}_1 X_1$ can yield values in the range (0-6.39). The other variables, due to their binary character, can only yield the values of their $\boldsymbol{b}$ parameters.

The temporal framework of the model equals that of the original sample, that is 33 years (1955-1990). So, the estimated probabilities are referred to this time period. It is easy to calculate a probability for a different time period of T years by multiplying the value yielded by the model by the correction factor T / 33.

Thanks to the implementation of the model in a GIS environment, a hazard map can be displayed (Fig. 4). In this map, the probability of debris flow triggering is shown by a colour ramp, and the exact probability of experiencing a debris flow at an exact point can be known.

In Fig. 4 a distinction is made between stable (in blue) and unstable (values of brown) locations. This distinction has been done for visualization purposes, and does not imply a discrete zonation of the study area in safe and unsafe places. In fact, completely safe places do not exist, and every cell has a certain probability of experiencing landsliding (even though this probability can be very low). A confusion arises at this point, as logistic models are frequently used in a classification approach. This implies selecting a given value of the response variable (the probability of debris flows, in our case) and classifying all the cells in one of two groups according to it. The threshold value is normally the 0.5 probability, as usually the two sample groups are similar in size. Sometimes a third group, 'unclassified', is added, for the values around the threshold probability. For the case where the two groups are very dissimilar, the proportion of ones in the sample ($\bar{y}$) should be used instead of the 0.5 value.

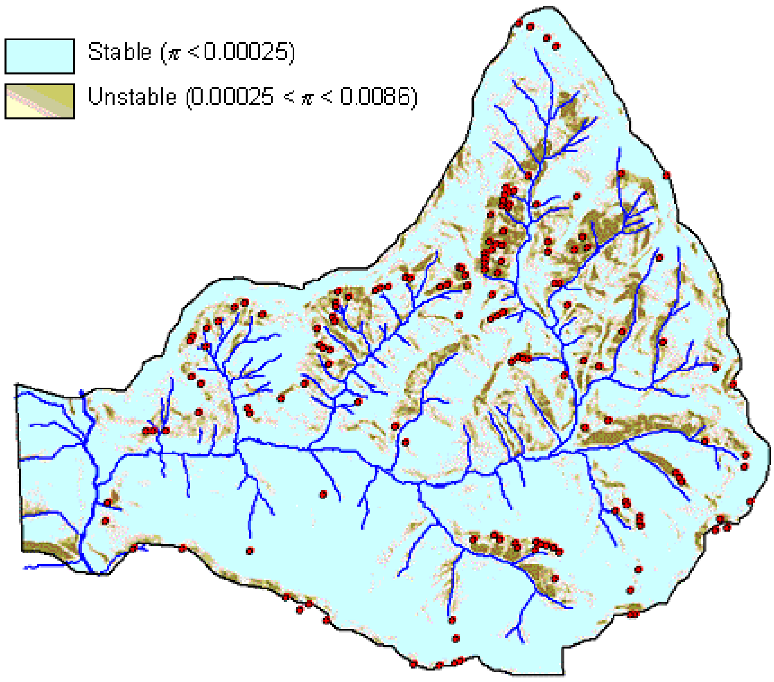

Figure 4. Debris flow hazard map of the Garcipollera valley. The red dots show the places where debris flows have been observed.

An integration (addition) of the probabilities of debris flows triggering in the whole catchment can easily be made in a GIS. This value equals the expected number of debris flows in the study area during a period of time equivalent to the sample period. The integration of the probabilities of debris flow in all the Garcipollera valley yields an expected number of 150 debris flows, a value that is very close to the observed number, that is 136.

6.3.7. Main deliverables

The following deliverables have been sent to the Project Coordinator:

- A map with the spatial distribution of debris flows in the Central Spanish Pyrenees.
- A debris flow susceptibility map in the Flysch Sector of the Central Spanish Pyrenees.
- A report on the factors explaining the spatial distribution of debris flows.

- A report on the comparison of statistical methods used by the Italian and Spanish groups to model the debris flow hazard.

- A report on debris flow relationships.

- A report on the different debris flow behaviour and relationships in both the Alps and the Pyrenees.

- Maps on the distribution of 24-hour precipitation for different return periods.

Section 6.4. Conclusions, including socio-economic relevance, strategic aspects and policy implications

Hillslope debris flows are a very common geomorphic phenomenon in the Central Spanish Pyrenees, especially within the Flysch Sector. They occur everywhere although there are some triggering factors, i.e., the strong gradients (around 20-35º), the southern exposure, the shape of the hillslope and the past human activities. Deforested, frequently burnt areas, as well as shrub areas and old cultivated fields are especially affected by debris flows. The scars of old slumps in tectonized (presence of faults) areas also develop a number of debris flows.

This study has established good correlations between different debris flow parameters and has allowed to obtain a new equation for debris flow runout length according to the difference in height between the scar and the beginning of the deposition area. Other relationships have been obtained, underlining the important role played by debris flow volume.

The analysis of series of aerial photographs since 1956 has allowed us to analyse the frequency of occurrence of debris flows and their relation to different rainfall intensities. A relatively high density of debris flows has been obtained and no changes in their frequency have been detected throughout the study period. Rainfalls between 36 to 46 mm in 24 hours seem to be enough to trigger debris flows. These figures are closer to the Innes (1983) results than to those from Caine (1980). New maps of intense rainstorms corresponding to different return periods have been obtained, thus enabling a more detailed approach to study debris flow hazard both in space and time.

A logistic model has been constructed using information from this project, as well as data from a Digital Terrain Model implemented into a GIS. The model informs about the probability of occurrence of debris flows in any place of the Flysch Sector, including information not only about the scar location, but also about the length and deposition area of the debris flow. The procedure used seems to be the best for small shallow landslides and to identify the hazards for, i.e., roads, forest tracks and other infrastructures and settlements.

The results obtained show a high socioeconomic relevance, since they can contribute to improve the procedures for hazard mapping and even for forecasting extreme events for different return periods. The inclusion of debris flow length and runout in the logistic model gives much more detailed information about the areas directly affected by hillslope debris flows and about the probability of a debris flow to reach the fluvial channel. The results obtained and the methods used have been provided to the end-users, that can incorporate them to their natural hazard identification policy.

Section 6.5. Dissemination and exploitation of the results

The deliveries arisen from the project have been sent to Peruggia, in order to be included in the DAMOCLES Web Page. The main results will also be included in the Web Page of the Department of Soil Erosion and Land Use Changes of the Pyrenean Institute of Ecology.

Sevceral publications have been realized within the Project, including two to Mountain Research and Development and Natural Hazards and Earth System Sciences. The IPE's group has participated in many international and national meetings with oral presentations and poster related to the DAMOCLES Project results. Finally, a Workshop on "Methods on the prediction of landslide hazardin mountain areas" was organised in May, 2001 to transfer methods and results to the end-users and other interested professionals from private and public institutions. Other private meeting with the end-users have served to improve their knowledge about the methods we use to natural hazards forecasting.

Section 6.6. Main literature produced

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