

# **DAMOCLES PROJECT WORK**

Instituto Pirenaico de Ecología, CSIC, Spain  
Section 3: Field and Laboratory activities during 2000

Report prepared by

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### SECTION 3

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In the Central Spanish Pyrenees, as in other Mediterranean mountains and in the Alps, debris flows represent the most active geomorphic hazard, affecting infrastructures, human settlements and touristic resorts. This is the reason why it is necessary to know the prevailing location of debris flows and to forecast their probability of occurrence. Furthermore, it is necessary to take into account the influence of both land use and plant cover changes affecting the mountain areas. Such changes cause a disturbance of hillslope hidrological flows and the strength of colluvium and bedrock.

#### **3.1. Objectives of the reporting period**

During the first year, the contribution of the IPE's group to the DAMOCLES Project has been related to

i) the assessment of the factors explaining the location and occurrence of debris flows in the Central Spanish Pyrenees.

ii) the realization of a first essay of debris flow susceptibility maps using geomorphological mapping and statistical analysis.

iii) the assessment of plant cover and land use changes on debris flows.

During 2000 the following steps have been done by the IPE's group:

- Compilation and organisation of basic information for studying and predicting the spatial distribution of debris flows (WP 1).

- Organisation of a data base and first statistical approach to the problem of spatial distribution of debris flows (WP 1).

- A first essay to forecast the spatial probability of debris flow occurrence (debris flow susceptibility map) (WP 2).

- Initiation of the field measurements of different morphometric parametres of debris flows (WP 3). Preparation of a data base for statistical analysis and modelling.

- Preparation of different papers and assistance to international and national meetings (WP 5).

This report informs on the work done in each one of the previous points.

### **3.2. The study area**

The study is carried out in the Upper Aragon and Gallego basins (1727 km<sup>2</sup>), in the Central Spanish Pyrenees (Fig. 1). Both rivers spring close to the French border and run from north to south, crossing the geological structure of the Pyrenees Range. They offer several important features for the purposes of the DAMOCLES Project:

- i) There are many cases of debris flows located in different environments.
- ii) Land uses and plant cover have changed very much in the past century, causing hydrological and geomorphological disturbances.
- iii) There is a large spatial variability (topography, lithology, plant cover, land uses and even climate).
- iv) Finally, there is quite information on many environmental and human aspects of both basins, including about 40 weather stations and 12 gauging stations. Information on plant cover and land uses is also available after correction from maps made at the Instituto Pirenaico de Ecología (IPE, CSIC).

The relief is the typical from mountain, alpine areas, prevailing the steep slopes and the altitudinal contrasts between divides and valley bottoms. The study area can be divided in five great unities from north to south (Fig. 2).

i) The northernmost part corresponds to large Paleozoic outcrops, with shales, schists, limestones and clays. The granitic massifs of Panticosa and Balaitus as well as their metamorphic aureoles reach the highest altitudes of the study area (Infierno Peak, 3077 m; Balaitus Peak, 3100 m).

ii) The Inner Sierras consist of Cretaceous and Eocene limestones and sandstones. The relief is very craggy, with big vertical cliffs.

iii) The flysch sector occupies a large area, with many folds and faults. Divides are smooth and the versants are almost straight.

iv) The Eocene marls form the so called Inner Depression, a large valley from west to east where smooth reliefs prevail.

v) The southernmost area is occupied by continental sandstones and clays, forming a structural relief with low altitudes.

The contribution of the IPE's group is mainly engaged on the three first unities described above, due to the actual distribution of debris flows. Nevertheless, the Inner Depression has been also included in the statistical analysis and mapping..

Precipitations and temperatures show a clear decreasing gradient toward the south and the east. It is important to take into account that the Upper Aragon and

Gallego River Basins occupy a transition area between the Atlantic influences (from north and west) and the Mediterranean influences (from south and east). The consequence is that the highest precipitations are recorded in the northernmost part of the Aragon Basin (more than 1500 mm). Southwards, precipitation quickly decreases toward 820 mm at Jaca and 720 mm at Artieda, both in the Inner Depression. The wet season enlarges from November to May, with a remarkable decrease in January and February. The most intense rainstorms tend to occur in autumn. No clear patterns on the spatial distribution of the intense rainstorms has been found.

The areas the most intensively used by human population are in the middle south part of the study area. The flysch sector has supported the most important changes, with the almost complete abandonment of the farmed area, shrub recovering and artificial reforestation. Until 50 years ago most of the sunny hillslopes were cultivated, even in very difficult topographic conditions, and with poor systems of soil and water conservation. Farmland abandonment has resulted in a progressive process of plant recolonisation. In the Inner Depression the cultivated area is still very large, though cereals have lost their original importance. Natural forests are mainly located in the flysch sector (northern exposures) while the subalpine grassland areas are located in the highest and northernmost areas.

### **3.3. Methods**

i) First of all the maps necessary for studying and predicting the spatial organisation of debris flows have been made. This includes:

- The lithological map of the Upper Aragon and Gallego River Basins at a 1:50,000 scale (Fig. 3). It has been made using the geological maps of the IGME and field work.

- The vegetation map at a 1:50,000 scale, distinguishing the most important forest covers and the distribution of the scrubs (Fig. 4). It has been obtained from a re-elaboration of the vegetation maps made by the Department of Biogeography of the Instituto Pirenaico de Ecología.

- The land use map, especially the distribution of the historical and actual distribution of agricultural fields (Fig. 5). It has been made from the land use maps made by the Department of Soil Erosion and Land Use Changes of the Instituto Pirenaico de Ecología.

- A map on the probability of occurrence of extreme rainfalls in the Upper Aragon and Gallego River Basins (Fig. 6).

- The Terrain Digital Model (Fig. 7) has allowed to obtain maps of altitude, gradient (Fig. 8), aspect, shape of the hillslope (concave, convex, straight), distance between the divide and the starting point of each debris flow, the area drained by each

debris flow scar (FL), and the ratio between the area drained by each debris flow scar and its gradient (topographic index, IT).

- A map with the location of the debris flow scars in the study area has been made (Fig. 9). In total, 968 debris flow scars have been mapped using aerial photographs and field work.

All this information has been digitised and implemented in a GIS (ARC/INFO, v.7). All the maps have been stored as a table by dividing the study area into 50 x 50 m pixels. The resulting matrix includes data from the pixels affected and non affected by debris flows, and accounts with almost 600,000 rows and twelve columns (each column corresponding to the factors cited above).

A significance test of the differences between pixels affected and non-affected by debris flows has been made.

In order to classify the debris flows into different groups, a conglomerate analysis has been used, as well as a discriminant analysis to define the main factors that contribute to the triggering of debris flows.

A first essay to forecast the spatial probability of debris flow occurrence (debris flow susceptibility map) has been made, according to the following steps:

- A logistic regression model has been used. The main product of this model are the logistic coefficients, allowing us to know the influence of each independent variable on the probability of occurrence of the dependent variable (debris flows).

- With the logistic coefficients a predictive model has been built, assigning a probability of occurrence to each pixel.

- The final result is a continuous variable map (debris flow susceptibility map), to which the map of the observed debris flows can be superposed in order to assess the predictive efficiency of the model.

Finally, in the field several parameters of debris flows are being measured in order to prepare a matrix to be used for modelling purposes. This matrix includes information on the altitude of the scar, the altitude of the tongue front, the total length, the gradient of scar, channel and front, the length of the tongue and the width of scar, channel and front.

### **3.4. Results (scientific achievements)**

#### *3.4.1. Workpackage 1: Development of functional relationships for debris flow behaviour*

968 debris flows have been identified in the study area, representing a mean density of 0.56 cases per square kilometre. Nevertheless, their spatial distribution is very irregular. In Fig. 9 each point represents the location of a debris flow scar. The map shows that debris flows can trigger in almost any place of the study area.

However, there is a clear preference for the southern sector (coinciding with the flysch), where they reach a large density, especially in the contact with the marly Inner Depression and in the Ijuez and Acumuer valleys.

Fig. 10 shows the contrasts between the characteristics of the study area and the frequencies observed in the debris flows. Thus, debris flows occur most frequently in gradients between 20 and 30° (with a mean gradient of 26.4°). Below 15° their frequency quickly diminishes, and also over 40°, where the instability hinders the presence of loose material susceptible to mobilize.

The altitudinal distribution of the study area shows very similar proportions between 500 and 2000 m. Debris flows also appear at any altitude, although there is a greater concentration between 1000 and 1400 m, and especially between 1100 and 1200 m, where their density arrives to 1.48 cases/km<sup>2</sup>.

In the study area the southern aspects slightly prevail. This is also the most frequent location of debris flows. Southwestern and southern aspects concentrate 45 per cent of the cases, followed by western (17 per cent) and southeastern (14 per cent) aspects. In the northern aspects the occurrence of debris flows is very low.

The lithology shows a great variety in the study area, though the flysch is much more represented than the other classes (42 per cent of the total), followed by limestones and quaternary deposits. The rest of the classes represent proportions lower than 10 per cent. If the debris flow distribution is studied, then a remarkable concentration in the flysch sector is observed, with 785 cases (82 per cent of the total) and a mean density of 1.09 cases/km<sup>2</sup>.

As for plant cover and land uses, 26 per cent of the study area is cultivated (mainly in the Inner Depression) followed by shrubs (17 per cent), oak forests and evergreen oak forests (17 per cent), subalpine grasslands (15 per cent), pine woods (12 per cent), beech trees (11 per cent) and reforested pines (2 per cent). The distribution of debris flows is scarcely related to the previous proportions, showing a clear preference by reforestation (275 cases, 29 per cent of the total, 7.5 cases/km<sup>2</sup>), followed by the shrub cover (24 per cent of the cases) and natural pine woods (19 per cent of the cases). The occurrence is very low in beech trees (6 per cent of the cases) and in the cultivated area (3 per cent of the cases).

Finally, within the historically cultivated area, debris flows tend to occur in the old sloping fields (273 cases, 1.6 cases/km<sup>2</sup>) and in the shifting agricultural fields (145 cases, 1.2 cases/km<sup>2</sup>).

Thus, figure 10 suggests that in the study area, debris flows tend to trigger in sunny hillslopes, between 1000 and 1400 m a.s.l., in slopes between 25 and 30°, in the flysch sector and in areas affected by human activities (old sloping fields, shrub-covered hillslopes and reforested areas).

The application of a cluster to the matrix of data allows us to distinguish three groups of debris flows:

i) The first group includes 70 per cent of the cases. Debris flows are located at a mean altitude of 1161 m, in southwestern exposures, in gradients around 26° and at a mean distance from the divides of 194 m. They develop preferably in the flysch sector and in hillslopes covered by scrubs or reforestations.

ii) The second group includes 6.6 per cent of the cases. Their mean altitude is 1262 m, with a mean gradient of 25°, in southern aspects and at a distance of 685 m from the divides. They also prevail in the flysch sector, and are very frequent in sloping fields and shifting agriculture fields, as well as in scrubs.

iii) The third group includes 22.6 per cent of the cases. These debris flows show a mean altitude of 1752 m. and a mean gradient of 27.5° in southern exposures and at a distance of 237 m from the divide. This is a group of debris flows preferably located over slates and quartzites, in subalpine and alpine environments.

The two first groups are clearly separated from the third one by altitude and vegetation. Those of the third group are triggered at higher altitudes and probably are linked to semiactive and active scree deposits, whereas the first and the second groups are located in the most human disturbed area., where they are differentiated by the land use and the distance from the divide.

This information is completed with the logistic coefficients obtained from the logistic regression (Fig. 11). Eight factors (independent variables) appear to be the most favourable for debris flow triggering:

- The flysch sector
- Quaternary deposits (scree and lateral moraines)
- Sloping fields
- Reforested areas
- Shifting agriculture fields

On the opposite, the following factors act as negative ones:

- Granites
- Sandstones
- Flat fields
- Present farmed area
- Northern aspects
- Beech and fir woods

The debris flow susceptibility map (Brabb, 1984; Carrara et al., 1991 and 1995; Guzzetti et al., 1999) resulting from the model of logistic regression shows the

irregular spatial distribution of debris flows in the study area (Fig. 12). The greatest probabilities of occurrence appear in southern aspects, in the flysch sector, especially in the contact with the marly Inner Depression. This contact occurs by means of an overthrusting fault and a number of fractures contributing to inestabilising this area, especially between the Aragon and Gallego rivers. Within the flysch sector, other smaller valleys are also subject to a high probability of occurrence of debris flows, as is the case of the Ijuez, Lubierre and Acumuer valleys, coinciding with the sector the most intensively affected by historical human disturbances. The Aragon Subordan Valley also shows many favourable hillslopes, due to farming activities in steep slopes. In the Gallego valley the highest probabilities occur in slopes near the main valley, maybe due to the U-shape inherited from the Pleistocene glacial activity. In any cases, both in the field and in aerial photographs the relationships between the occurrence of debris flows and the presence of old scars of big slumps has been assessed, thus suggesting that the slump scars tend to inestabilize the slope and to encourage the triggering of debris flows.

The probabilities of occurrence of debris flows very much decrease in the north of the study area, in spite of the existence of steeper slopes. In the southernmost part the probabilities are null due to the smooth gradients, a very limitant factor.

By analysing the results of the debris flow susceptibility map, several areas can be distinguished:

i) Areas where debris flows are observed and predicted (75.1 per cent of the observed cases).

ii) Areas where debris flows are not observed but predicted. They represent 34.7 per cent of the study area and can be considered as areas where it is very probable the future occurrence of debris flows.

iii) Areas where debris flows are observed but not predicted. They represent 24.9 per cent of the observed cases and clearly they can be considered as failures of the method. Up to now there is no information about the reason of these failures.

iv) Areas where debris flows are neither observed nor predicted. They represent 65.3 per cent of the territory and are not subject to debris flow hazards, at least with the actual climatic, land use and plant cover conditions. Changes in any of these parameters would represent changes in the spatial distribution of debris flow susceptibility.

#### *3.4.2. Development of a small basin debris flow impact model*

Information on detailed features of debris flows have been taken directly from the field. The objective is to prepare a data base for statistical analysis and modelling.



This work is in an initial stage but it will be finished at the beginning of summer 2001. The work consisted on taking the following information in each debris flow:

- Altitude of the scar
- Altitude reached by the frontal lobe
- Total length
- Gradient of the scar, channel and frontal lobe
- Length of the tongue
- Width of the scar, channel and frontal lobe

By the moment, 25 per cent of the total information has been taken.

### **3.5. Socio-economic relevance and policy implication**

The work done is only a part of the deliverables foreseen within DAMOCLES Project. The statistical analysis and, especially, the debris flow susceptibility map need important improvement and to complete the basic information from the westernmost part of the study area, a work that is nowadays being done. Nevertheless, the results obtained represent an important step to understand the distribution and triggering factors of debris flows in the Central Spanish Pyrenees. It is important to take into account that detailed information of geomorphic hazards is scarce or rare in the Central Pyrenees, where the Public Administration has been especially engaged in the study of snow avalanches and floods as the most visible and seemingly destructive geomorphic hazards.

The work done is in the way of the socio-economic goals outlined in the original project proposal. During the meetings with people responsible of natural hazards (regional government) they have expressed their interest in the results and have informed about their necessities. The most important problem is that they would like i) immediate results (not to expect 2 years more) and ii) the probability of spatial occurrence of debris flows according to a 500 year return period of the precipitation, which is considered in Spain as the threshold for an unforeseeable or unexpected event.

### **3.6. Discussion and conclusion**

It is well known that debris flows occur during rainfalls of high intensity and volume (Caine, 1980; Van Steijn, 1996), but their spatial distribution is not random. The distribution of debris flows in the Central Spanish Pyrenees confirms the very important role played by the lithology, altitude, aspect and plant cover/land uses. Thus, the flysch sector concentrates the main number of cases identified (82 per cent of the total) due to

i) The presence of alternating layers of sandstones and marls, yielding abundant, loose colluvions;

ii) some areas of the flysch sector appear to be intensively faulted and folded, increasing the instability of poorly sorted material. A special linkage between the scars of big slumps and the occurrence of debris flows has been detected in the field.

The rest of the factors are closely related to the strong disturbances caused by human activities in the hillslopes. This is the case for

i) The southern aspects, which are the most favourable for farming activities in the Central Spanish pyrenees;

ii) Altitudes between 1000 and 1300 m a.s.l., coinciding with the hillslopes most used for sloping fields and shifting agriculture;

iii) The areas covered by scrubs and reforested pines, coinciding with eroded areas after centuries of man-induced fires and overgrazing; in fact, reforestations have been introduced, in general, there where the landscape was affected by intense soil erosion and with evidence of severe degradation (high soil stoniness, open shrub cover...);

iv) the hillslopes covered by sloping fields or subject in the past to shifting agriculture, with scarce structures established for soil conservation.

Previous studies in the Central Spanish Pyrenees (Garcia-Ruiz & Puigdefabregas, 1982; Gonzalez et al., 1995) suggested that debris flows locate in the most disturbed areas (due to farming, fires and grazing). Other authors consider that debris flows are not exclusively but especially linked to the periglacial environment (Zimmermann, 1990; Van Steijn et al., 1995). The results obtained by the IPE's group in the Central Spanish Pyrenees do not show a close relationships between debris flows and the periglacial belt; nevertheless, it is important to take into account that many debris flows triggered in active, high altitude screes disappear few years later, owing to the great geomorphic activity of the periglacial deposits.

The gradient is, of course, other important factor. The obtained results show that debris flows do not occur where the gradient is gentle or where is excessively strong. Other papers also confirm the relevant role of the gradient (Takahashi et al., 1981; Innes, 1983).

The method used to elaborate a debris flow susceptibility map (Fig. 12) seems to be relatively adequate. The map shows the areas where the debris flow occurrence hazard is greater, and the areas where, according to the available information, the hazard is very low or even inexistent. In fact, a good agreement exists between the actual map of debris flow distribution and that predicted by the logistic regression. Nevertheless, a relatively high number of actual debris flows (24.9 per cent) are not predicted and can be considered as failures of the model. This means that some

improvements must be introduced (both in the field work and in the statistical procedure) in order to reduce the percentage of failures.

### **3.7. Plan and objectives for the next period**

During the year 2001 the work plan of the IPE's group is the following:

1. To complete the spatial information of different environmental parameters of the study area. At present, information on most of the territory is available except for a small area in the westernmost sector of the Upper Aragon River Basin. Once completed, a new statistical and definitive analysis to study the relationships between debris flow location and environmental factors will be made. New information on debris flow occurrence in the periglacial belt will be introduced. **(End of May, 2001).**

2. To improve the debris flow susceptibility map, reducing the percentage of failures, by correcting those debris flows not predicted by the model. **(End of June, 2001).**

3. To complete the data base on detailed morphometric parameters of debris flows. **(End of July, 2001).**

4. To apply a complex statistical analysis to the previous data base. **(End of October, 2001).**

5. To obtain detailed information from a small catchment selected to apply the SHETRAN model. The catchment has been already selected (the Ijuez catchment, in the Upper Aragon River Basin), and soil samples and analysis will be made at short term, as well as the compilation of climatic and plant cover information. **(No date; tentatively in May, 2001).**

6. Preparation of papers to be (tentatively) published in international journals (Mountain Research and Development, Natural Hazards & Earth Science Systems, Geomorphology...). The first papers deals on the factors explaining the spatial distribution of debris flows, and the second one on the development of a debris flow susceptibility map. **(No date; along the year 2001).**

### **3.8. References**

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#### PUBLICATIONS SUPPORTED BY THE PROJECT

##### Peer reviewed articles

- Arnaez, J., Marti-Bono, C., Begueria, S., Lorente, A., Errea, M.P. & Garcia-Ruiz, J.M. (1999): Factores en la generacion de crecidas en una cuenca de campos abandonados, Pirineo Central. *Cuadernos de Investigación Geográfica*, 24: 7-24
- Begueria, S. & Lorente, A. (1999): Distribucion espacial del riesgo de precipitaciones extremas en el Pirineo aragones occidental. *Geographicalia*, 37: 17-36.
- Garcia-Ruiz, J.M., Valero-Garces, V., Gonzalez-Samperiz, P., Lorente, A., Marti-Bono, C., Begueria, S. & Edwards, L. (in press): Stratified scree deposits in the Central Spanish Pyrenees: Paleoenvironmental implications. *Permafrost and Periglacial Processes*.

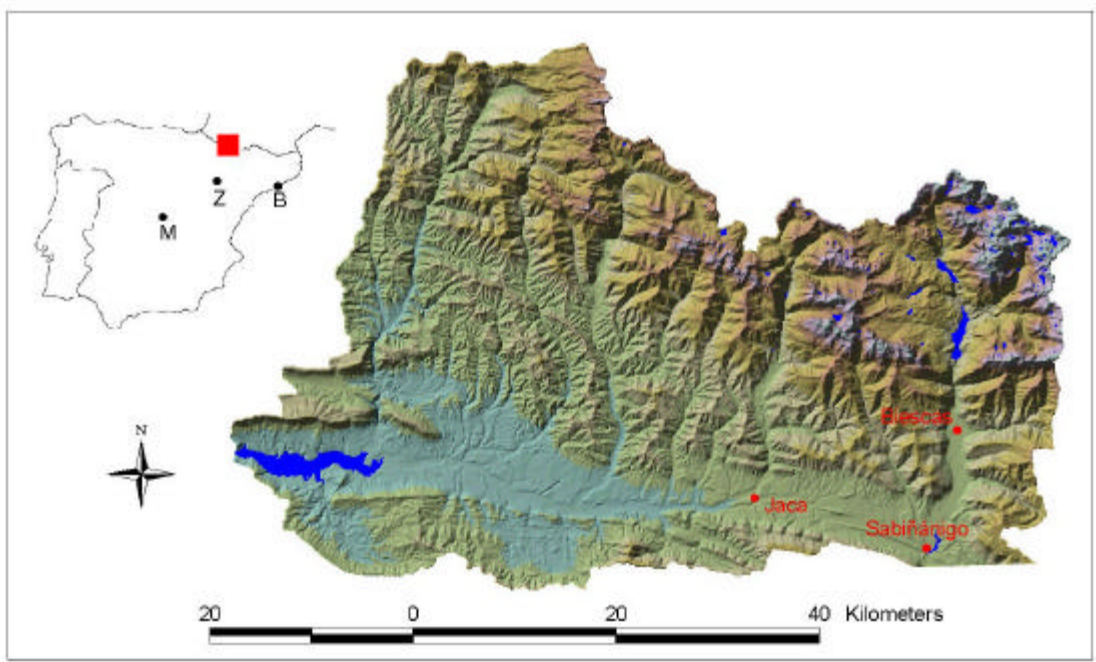


Fig. 1. The study area.

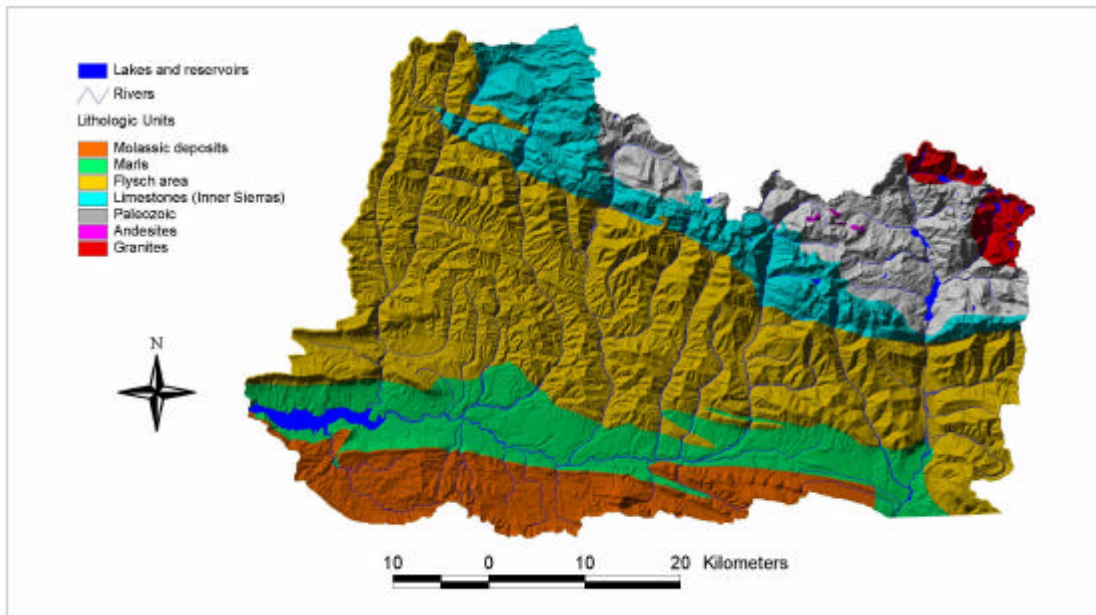


Fig. 2. Geological unities of the study area.

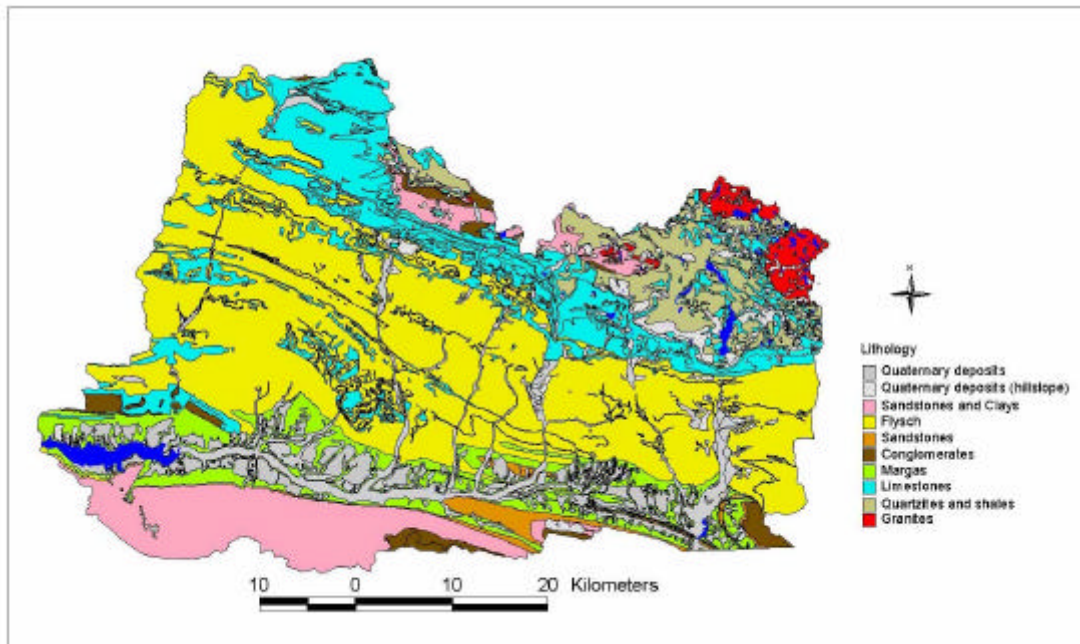


Fig. 3. Lithological map of the study area.

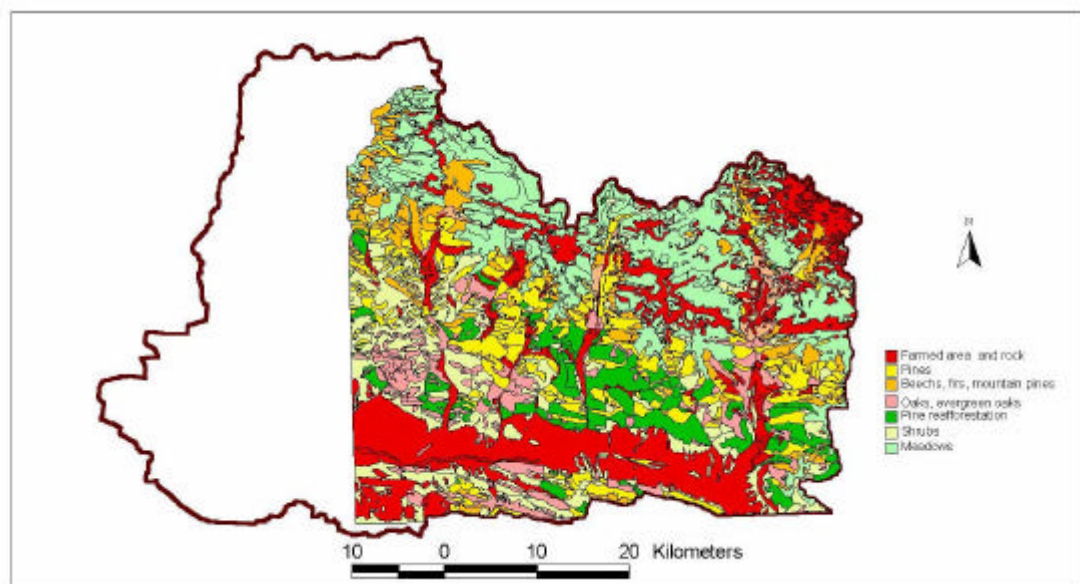


Fig. 4. Vegetation map of the study area.

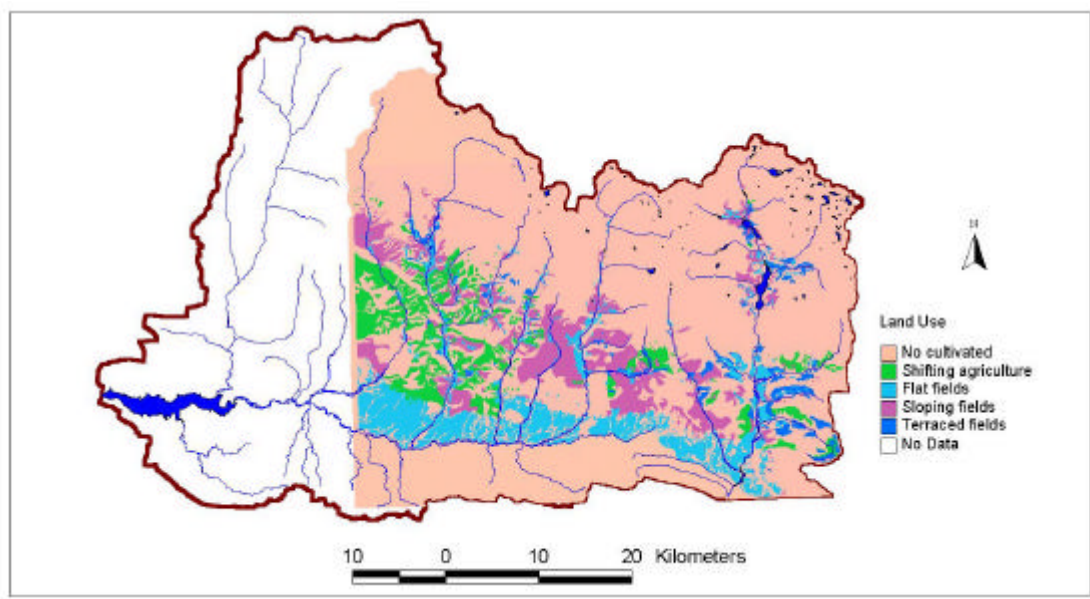


Fig. 5. Land use map of the study area.

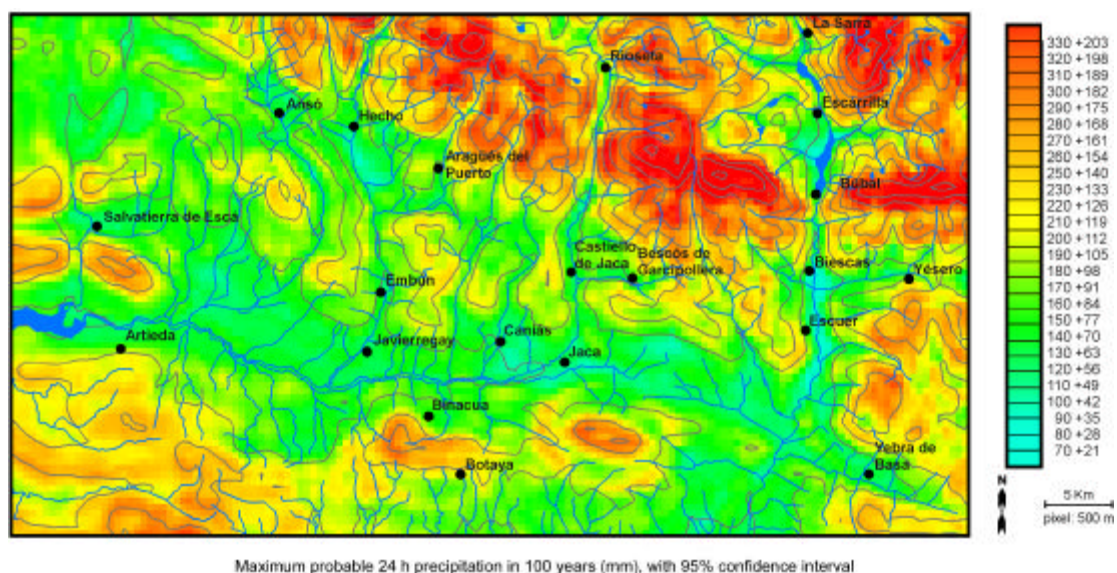


Fig. 6. Probability occurrence of extreme rainfalls in the study area.

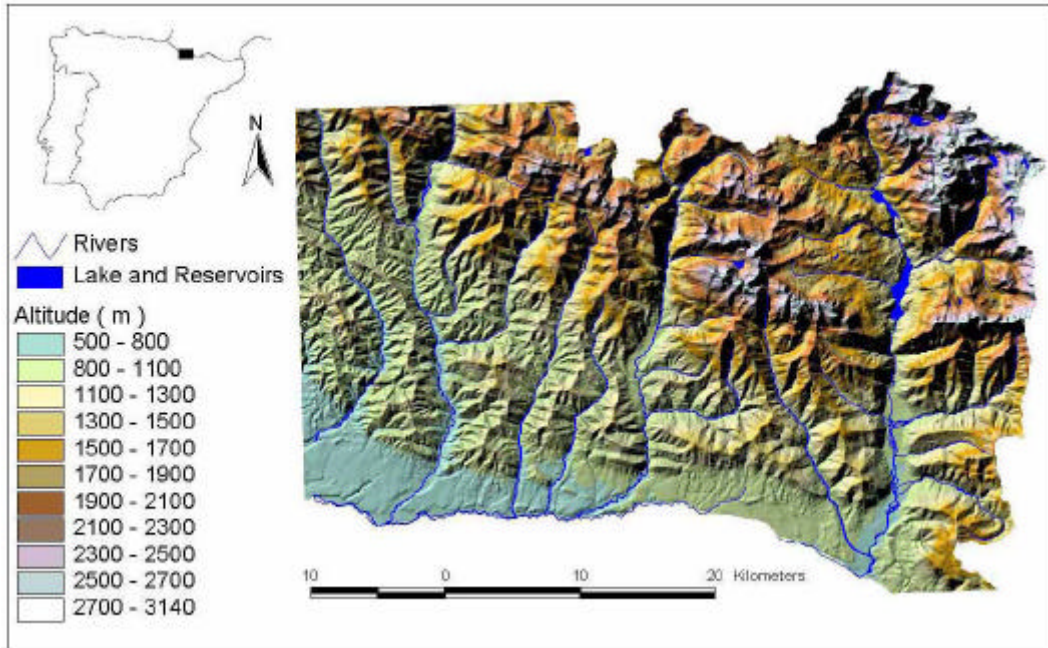


Fig. 7. Terrain Digital Model of the study area.

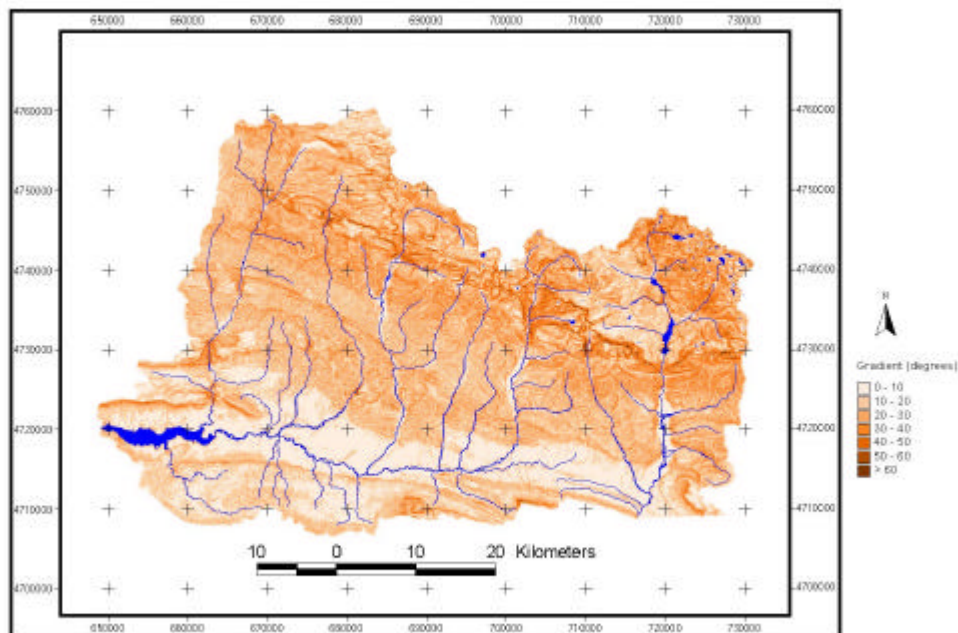


Fig. 8. Gradient distribution of the study area.



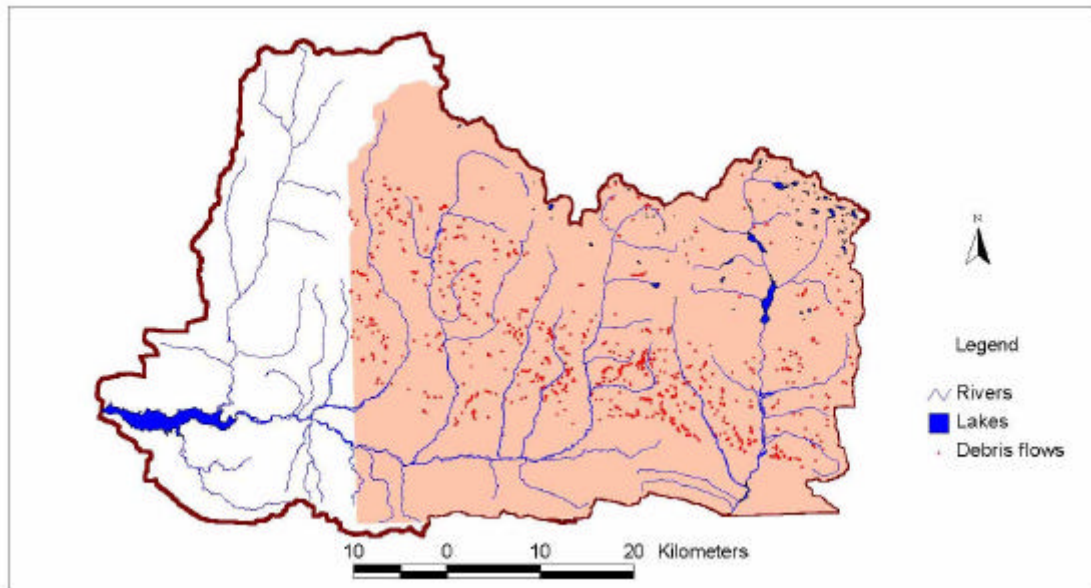


Fig. 9. Location of the debris flows identified in the study area. Each point represent the scar of a debris flow.

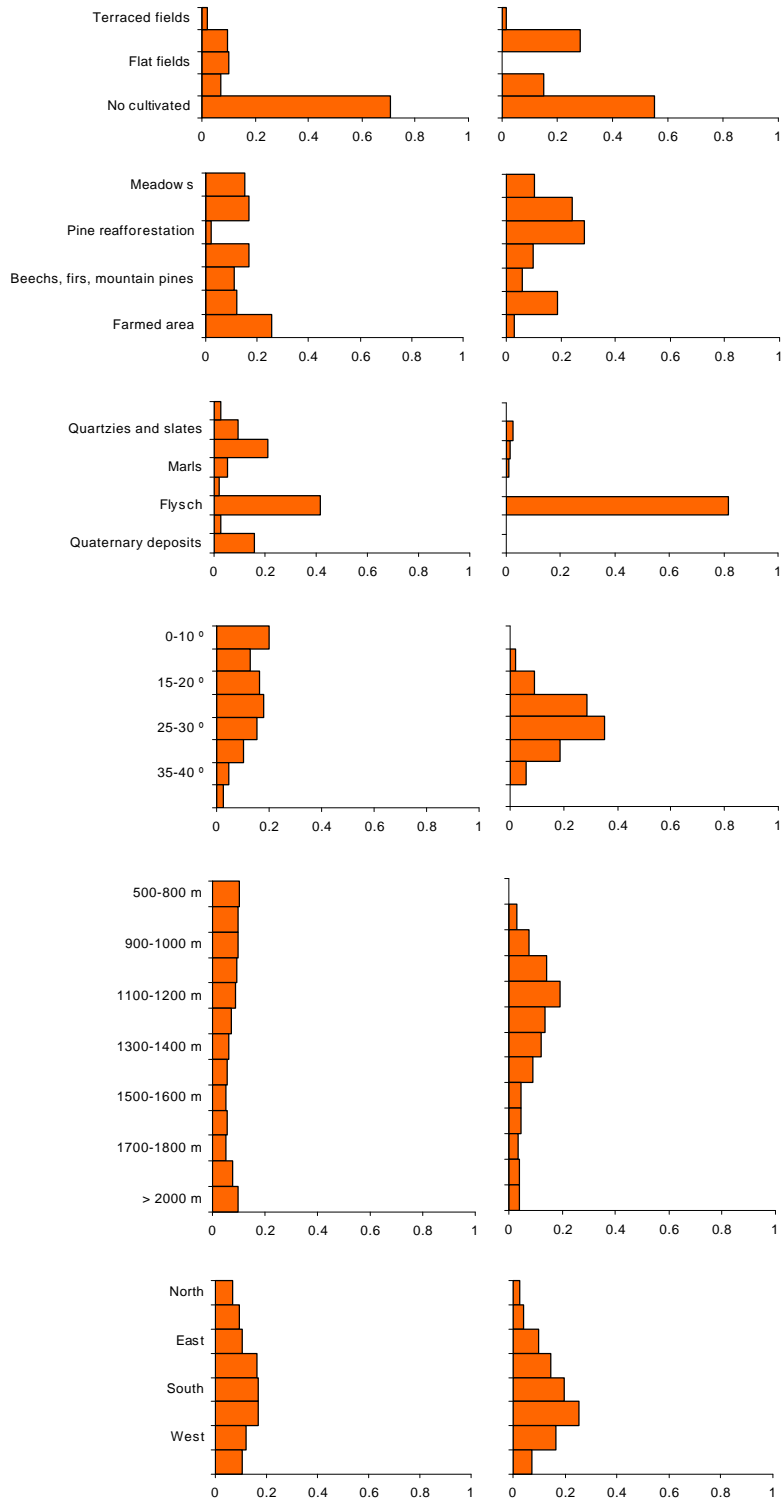


Fig. 10. Frequency distribution observed in the study area and in debris flows.

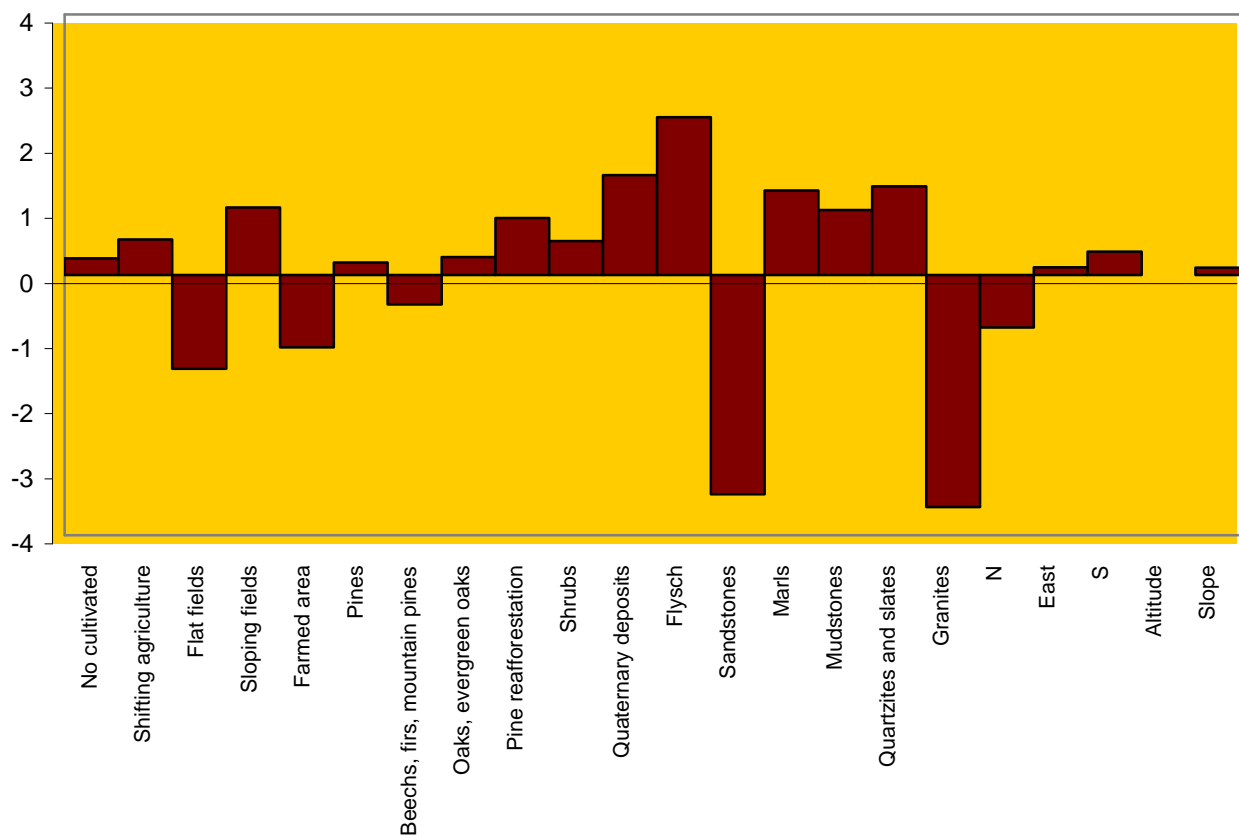


Fig. 11. Logistic coefficients obtained from the logistic regression.

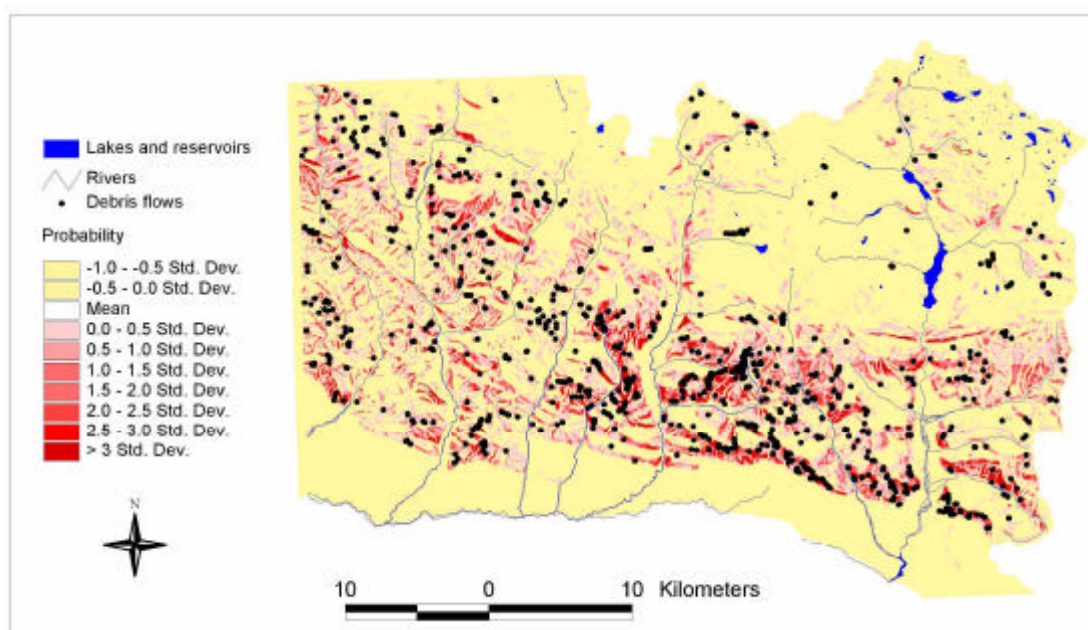


Fig. 12. Debris flow susceptibility map in the Upper Aragon and Gallego basins.