# IGME DAMOCLES FINAL REPORT (1/3/01 to 28/2/03)

**SECTION 6 :**

### Section 6.1 Background (description of the problems to be solved)

Our participation in the Damocles project has been as Assistant Contractor and possible End-User of the models that the Project have developed to know the hazard linked to some rapid slope movements in mountain areas.

Our field studies have been based in a geomorphologic cartography at 1/25.000 scale of a Palaeozoic valley in the Central Spanish Pyrenees of 300 $km^2$ of extension. We have paid special attention to knowing the characteristics of some rapid slope movements such as debris flows and rock-falls that have occurred in the study area in order to apply some of the models that the Project has developed to know natural hazard at regional or local scale, linked to this movements.

### Section 6.2 Scientific/technological and socio-economic objectives

A first step in our participation in the Damocles Project is to know natural hazard in relationship with debris flows and rock-falls into the study area and doing so, contribute to mitigate their effects. The application in our area of the models that the Damocles teams have developed, has given us experience and will enable us to investigate other mountain areas trying to define the impact of these natural hazards.

### Section 6.3 Applied methodology, scientific achievements and main deliverables

#### 6.3.1 WP1 Development of functional relationships for debris flow behaviour derived from field data end existing databases

We have based our study of the characteristics of some rapid slope movements in mountain areas, namely debris flows and rock falls, on field observations of modern geologic processes and recent sediment deposits developed on a Palaeozoic area of the Central Spanish Pyrenees of about 300 $km^2$ around the Benasque village.

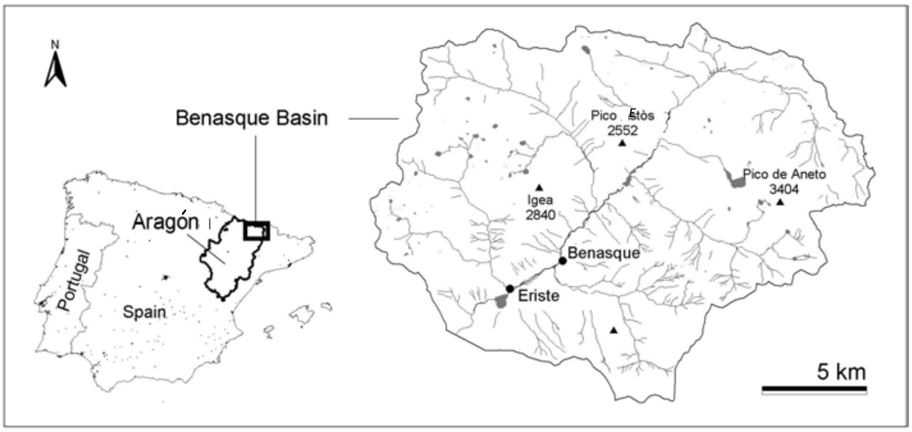


*Figure 1.- Location map of the Benasque study area.*

This information was represented in a geomorphologic cartography at 1/25.000 scale, which was implemented in a Geographical Information System. Some previous steps were necessary:

- Compilation of historical and technical information. Study of geologic and geomorphologic works done on the Central Pyrenees.
- Detail examination and comparison between aerial photographs at 1/30.000 (1981) and 1/20.000 (1997) and aerial ortho-images (after 1997).
- Recognition in the field of the most important slope instability phenomena (debris-flows, landslides and rockfall) as well as the different glacial deposits and morphologies.

Figure 2 gives an idea of  the geology of the region. The Palaeozoic materials were strongly folded, faulted and metamorphosed during the Hercynian orogeny and subsequently, tectonically piled up southwards through Alpine age thrusts.

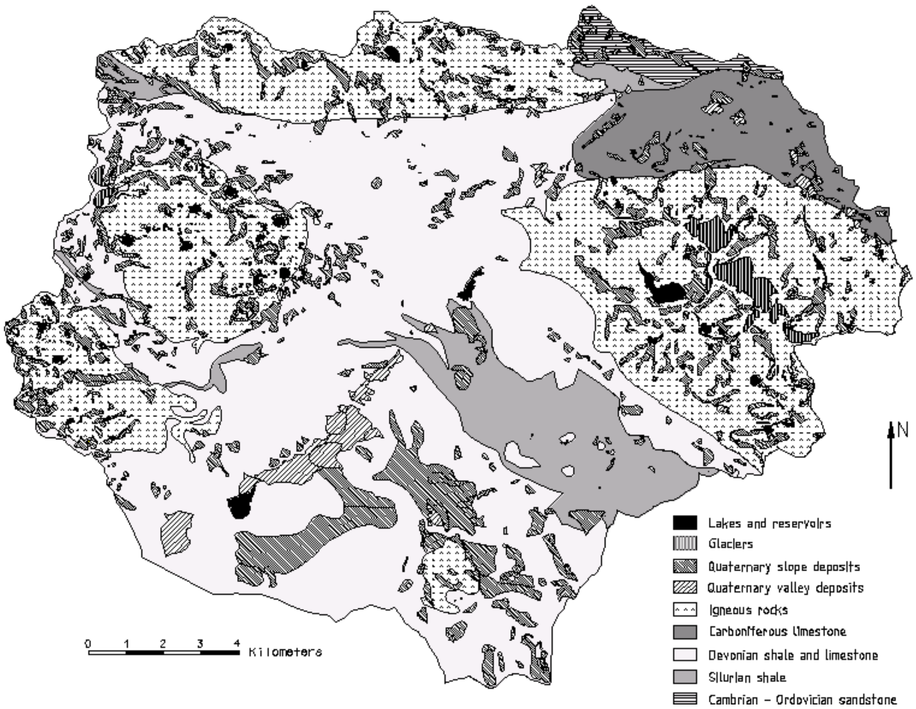


*Figure 2.- Benasque valley lithological map*

The relief is controlled mainly by the glaciarism and recent perigalcial processes and also by the lithology and structure of the materials. Figure 3 summarizes the geomorphology of the area studied.

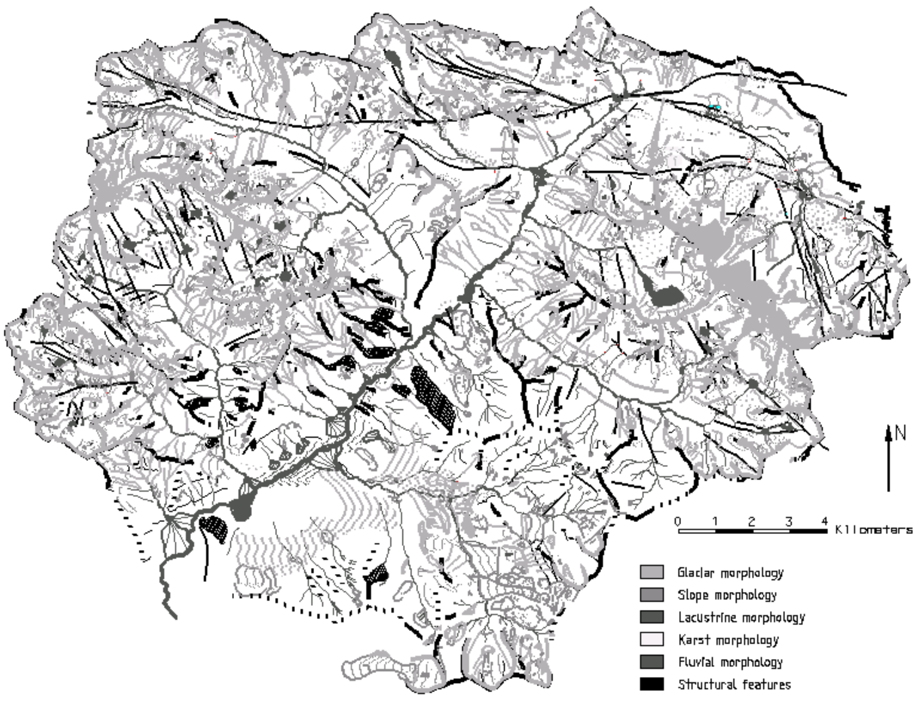


*Figure 3.- Benasque valley geomorphologic map*

Among the slope morphologies, many landslides, talus deposits, debris cones, rockfall blocks (tectonic fractures, faults and unloading joints subdivide the different lithologies inducing frequent rockfalls from major rocky cliffs) and debris flows (both hillslope debris flows, most of them on talus deposits, and canalised debris flows) have been mapped. The accumulation of these slope deposits regularize and soften the sculpted-by-the-ice valley slopes (see figure 4).

*Figure 4.- Slope deposits regularize and soften the glacial valleys U-like profile*

Some precisions about the moment when these events began to take place have been made trying to date some recent faults in relationship with the last postglacial period. Some samples of carbon (charcoal) have been picked up in some trenches dug near *Sackungen* faults and have been sent to a laboratory.

An updated 3D debris flow cartography has been done (see figure 5) from 3D topographic maps, orthophotos and aerial photos of different dates. The number of mapped hillslope debris flows is in this moment 545 (all of them in slope quaternary deposits: talus and moraines). Gullies where canalised debris flows occur have been mapped as well and a total of 71 have been identified so far. In this new cartography, every debris flow has information about the starting point, track and stopping point and as far as they are into a 3D space, they provide information about heights, gradients and real distances.

Rockfall source areas and rockfall blocks were mapped to prepare data for applying the University of Milano-Bicocca & CNR-CSITE from Perugia rockfall model in the framework of WP2 and WP5.

To complete our field information, vegetation and land use coverages of the Benasque test area have been provided kindly by the *Instituto Pirenaico de Ecología* (IPE) colleagues, to be used both in WP2 and WP3 models applications.

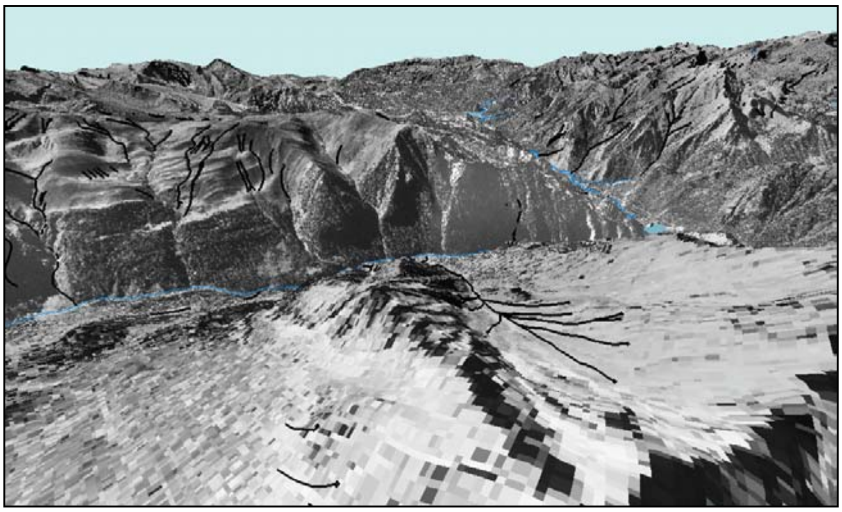

*Figure 5.- Partial view of the 3D debris flow cartography*

Thinking in applying the local scale model of WP3, a small basin with alluvial fan (Sahún catchment, 3.3 $km^2$) was selected with the help of the Padua University team. Some detail information was obtained, in particular, a detail topographic map along the fan channel was surveyed and some rain fall records from some weather stations close to the basin, obtained from the National Meteorological Institute. An assessment of the water discharge peak for several return periods was done using the Rational Method.

### 6.3.2 WP2 Development of a GIS hazard assessment technology using field data.

Knowing the characteristics of the debris flows and rock falls within our study area, we have tried to follow the gis hazard assessment methodology of some of the Damocles teams in applying some models that have been developed at regional and local scales.

As End-Users of the Damocles Project, this is an important goal for us that has to do with the WP5 objectives as it was planned at the beginning of the Project but we are referring in this paragraph and the following because of the assessment methodology applied and the maps obtained.

For doing this preliminary natural hazard assessment, an integration with the *Instituto Pirenaico de Ecología* team was necessary (see Regional analysis of debris flows) as well as with others work-packages teams: WP2, University of Milan Biccoca and CNR of Perugia (see Regional analysis of rockfalls) and WP3, for the application of a local impact model of debris-flows (referred in the next paragraph 3.2.3).

To complete our geologic and geomorphologic field knowledge, it has been necessary to get some complementary information of our study area, as for example: vegetation and land use coverages, that have been provided kindly by the IPE team, and some aspects linked to climatic data feed by the *Instituto Meteorológico Nacional.*

- **Regional analysis of debris flows**: A statistical method was applied in order to obtain a model of the probability of occurrence of hillslope debris flows in the Benasque valley at regional scale. This task was carried out along with the *Instituto Pirenaico de Ecología* (IPE) team.

The study area (300 $km^2$) was subdivided in a regular grid of 25 x 25 m cells (having a total of 465642 square slope units). This way, every cell or slope unit has information about the output variable (whether or not that cell corresponds with a debris flow starting point), and about a set of potential predicting variables or potential conditioning factors that we estimated or deduced from the DTM and from the thematic maps.

These potential factors or variables taken into account were: lithology, vegetation, land use, aspect, slope gradient, height, curvature, distance to divide and to the closest stream.

To reach to know which of these factors linked to the terrain control the spatial distribution of the starting points of hillslope debris flows, a multivariate statistical analysis was undertaken, in particular, a binary logistic regression (by means of SPSS) which builds a linear function with the more predicting variables and subsequently computes the probability of failure in every slope unit.

The variables in the equation were only three: Lithology (specially slope quaternary deposits), Slope gradient and Curvature of the slopes. The probability values computed by the logistic regression for every pixel were grouped in four intervals and four colours were assigned in order to draw the final map (see figure 6).

Overlapping the starting points of the 188 observed hillslope debris flows, we have seen that the 70% of them are predicted by the model. That is to say, they fall within the reddish (higher probability) areas.

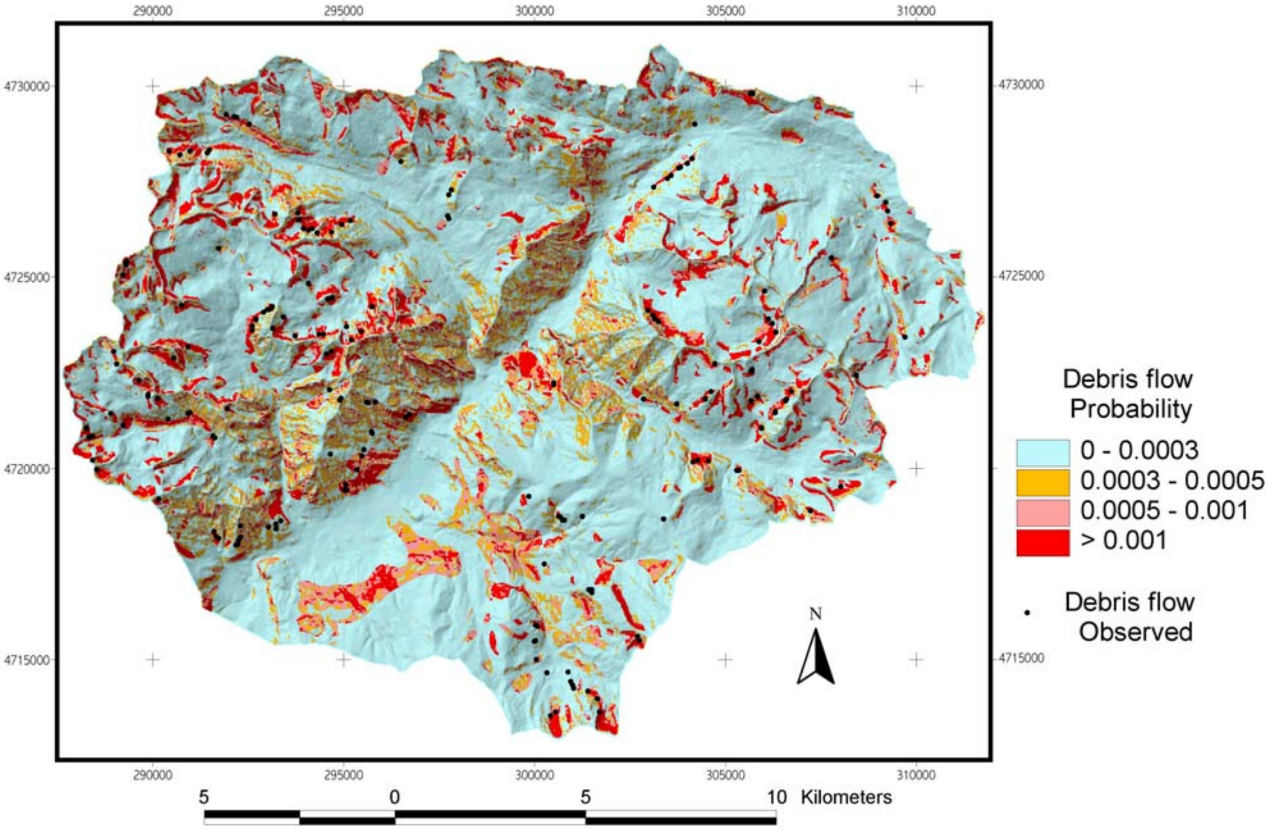


*Figure 6.- Hillslope debris flow probabilistic map of the Benasque valley*

**- Regional analysis of rockfalls**: A 3D rockfall simulation program (named STONE) developed by the *Dipartimento di Scienze Geologiche e Geotecnologie*, University of Milano-Bicocca, Italy, together with the *CNR-CSITE* from Perugia, Italy (Agliardi & Crosta 2002; Guzzetti et al., 2002), has been applied in the Benasque valley.

The software was conceived to perform a large number of simulations of 3D rockfall paths using a simple cinematic modelling approach rather than a dynamic one. The energy lost at each impact or during rolling depends on a variety of factors. These parameters are difficult to determine at any spatial scale. Thus, "contact functions" relating the kinematics of the block or its dynamics before and after each impact, are used by STONE to model the energy loss. These functions are expressed as restitution and friction coefficients. The 3D nature of actual slope geometry strongly affects the trajectories and the partition of kinetic energy into translational and rotational components. Pseudo-random stochastic modelling is allowed and a scaling relationship for evaluation of restitution coefficients has been implemented within the code.

Input data are in a spatially distributed form: lithology, geomorphology, land use, vegetation, outcropping areas, rock fall source areas, rockfall blocks, talus deposits, water, snow and ice covered areas, and topography is provided as a raster Digital Elevation Model with a ground resolution of 25 m.

Both 2D (raster) and 3D (vector) outputs are provided. Raster maps portray at each cell: the cumulative count of rockfall transits, the maximum computed velocity and the largest flying height. Vector outputs provide instantaneous velocity and fly height at each point sampled along the computed fall paths.

The simulation of the rockfall blocks motion was calibrated through a geomorphologic approach checking that talus limits and largest mapped blocks felt directly within the invasion areas as computed by the code. Overlapping the mapped blocks, we see that 70% of them are along the trajectories predicted by the model. Overlapping the talus limits, we see that the 76% of the taluses extent are affected by trajectories.

Once STONE was applied and its outputs provided, the next step was to assess the rockfall hazard by means of the three variables we have obtained for every cell: number of blocks that pass over each square slope unit (counter), velocity (now the mass of the falling blocks is introduced and their kinetic energy obtained), and height.

With these 3 variables, a Rock Hazard Vector (*RHV)* is built for each slope unit. The RHV modulus allows an easy classification and ranking of the hazard. The higher these three values, the higher the modulus, and thus, the higher the hazard level.

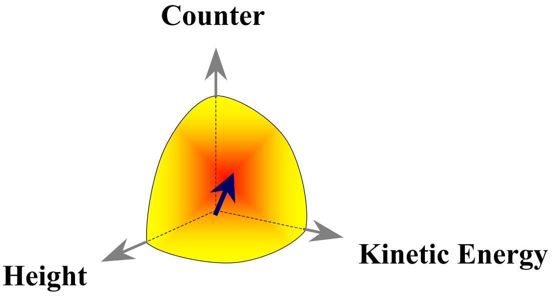


*Figure 7.- Obtaining the RHV in one cell*

The value of this modulus representing the rockfall hazard level in each cell can be visualized by means of a GIS in figure 8.

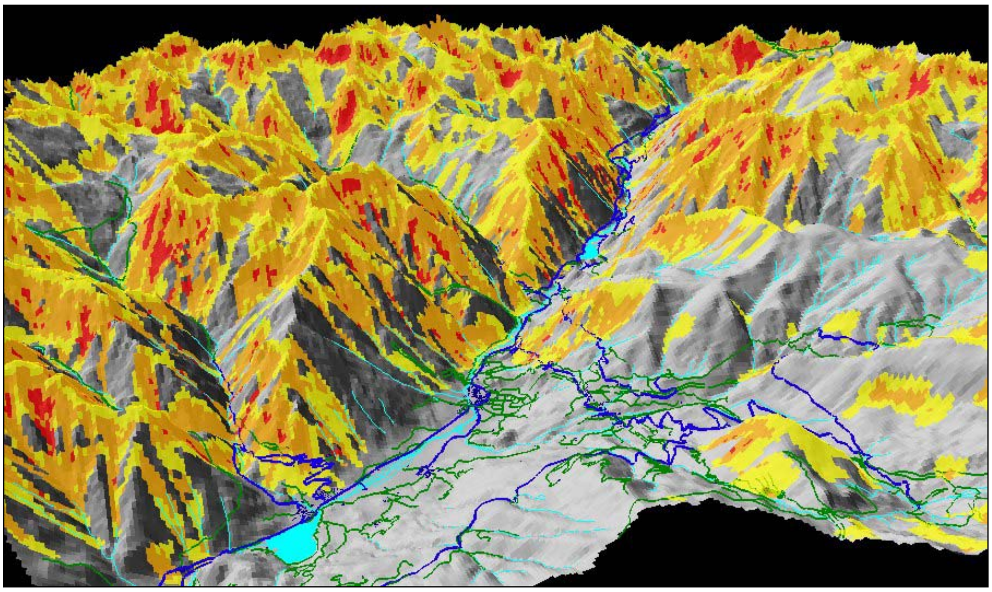

*Figure 8.- 3D partial view of the rockfall hazard assessment in the Benasque valley*

### 6.3.3 WP3 Development of a small basin debris flow impact model

A local analysis of canalised debris flows was undertaken in the Sahún area applying the model MODDS developed by the *Department of Land and Agro-forest Environment, Water Resource Division, University of* Padua, Italy*.*

The *Muskingum One Dimensional Debrisflow Simulation* (MODDS) was applied to compute those points or sections along the fan channel where an hypothetical debris flow would overflow.

To estimate the magnitude of an hypothetical debris flow great event, it was necessary to assess the potential volume of sediment yield in the basin (3.3 km$^2$). For that, a variety of empirical equations were applied and different values obtained, from which, the mean value was taken. These equations take into account the morphology, land use, vegetation, lithology and geomorphology of the basin. All this information is represented in the formulas by means of parameters such as the basin area, mean gradient of the main channel in the basin, geological index and transport index. According with the climatic scenario, it was also necessary to know the water flow peak at the exit of the basin. For a return period of 50 years, a water discharge peak of 24.6 m$^3$/s was obtained. From this value, the peak of an hypothetical debris flow was calculated by multiplying this water peak by a variable factor (Hashimoto, 1978). For the Sahún torrent, considering the degree of entrenching and the general conditions of the basin, a value of 8 was chosen by the experts and therefore, the resulting debris flow peak for that return period was 197 m$^3$/s.

To simulate the impact of this 197 $m^3/s$ debris flow in terms of sediment deposition on the alluvial fan, the morphology of the fan channel was surveyed in detail. Cross sections along the fan channel were built (see figure 9a) as MODDS required. After running MOODS, those sections where a total overflow would occur were coloured in red (in the reach of the channel corresponding to sections 14, 15 and 16, there is a bend and a small bridge). Those sections represented as green and red lines (20-23, 27-29 and 33-35) show lateral overflow. A re-entry of the overflowed material upstream has been supposed.

Figure 9b would be the preliminary map of the areas affected by the 197 $m^3/s$ debris flow event, obtained after applying the Ikeya (1984) stopping distance formula.

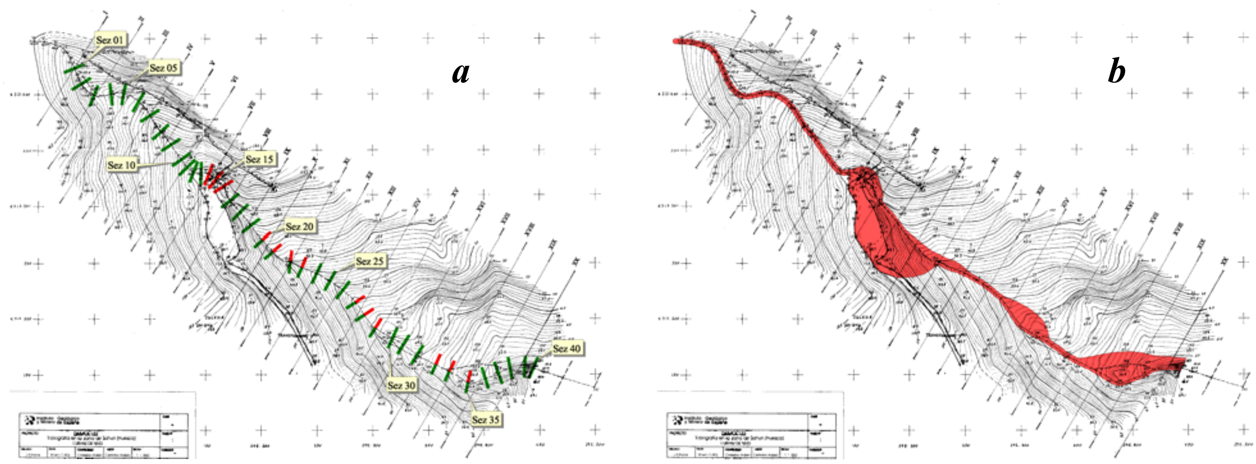


*Figure 9.- (a) Cross sections along the Sahún fan channel. The red ones indicate total overflow, the red and green ones indicate lateral overflow. (b) Debris flow affected areas*

### 6.3.4 WP5 Dissemination of the project deliverables via training courses, workshops

These have been the contributions in the objectives of WP5:

- Inclusion of the meetings, progress and annual reports in the Damocles web site.
- Participation in workshops held in Spain and Italy with other potential end-users.
- Attendance together with other potential end-users to the Damocles training course held in Italy on September 2002.
- Two papers about debris flows and rockfall presented in a congress held in Zaragoza (Spain) and in a conference held in Mallorca (Spain).

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

As end-users of the models developed in the course of the Damocles Project, we have applied on our test area of Benasque, regional and local models for predicting debris flows and rockfall prone areas. These models have allowed us to make a first hazard assessment of these rapid slope movements, and a preliminary classification of the territory according to the hazard level. This is an important goal that a good land use planning ought to take into account in order to avoid possible losses that these processes could produce in the assets of the study area.

This policy would imply convenient prediction, prevention and protection measures to try to mitigate their effects. A first step in doing a good use of the land is to know predictability that means knowing the occurrence of these natural hazards in a given space-time scenario. For doing that, the application of the models is also a first step.

We hope that in the future, we will enhance our understanding about the conditioning factors, triggering factors and behaviour of these slope phenomena and thus, improve our prediction capabilities.

## Section 6.5 Dissemination and exploitation of the results

Apart from the contributions in the objectives of WP5 aforementioned in 6.3.4, our works in the framework of the Damocles project have been presented in the *Instituto Geológico y Minero de España* in its headquarters of Madrid.

## Section 6.6 Main literature produced


- Acosta, E., Lorente, A. and Ríos, S. (2002) - Application of a regional model for the prediction of debris flows hazard areas in the Esera upper basin (Central Spanish Pyrenees). In: *XI International congress on Industry, Mining & Metallurgy*. Zaragoza, Spain.

- Acosta, E, Agliardi, F., Crosta, G. B. and Ríos, S. (2002) - Regional rockfall hazard assessment in the Benasque valley (Central Pyrenees) using a 3D numerical approach. In: *4th European Geophysical Society Plinius Conference, Mallorca, Spain.*

- Acosta, E. and Ríos, S. (2002) - Geomorphological mapping and hazard assessment in the Benasque area, Pyrenees. In: "*Tecnologie GIS nella previsione, monitoraggio e mitigazione dei rischi idrogeologici" Workshop* organised by the GISIG (Geographical Information System International Group). Milan, Italy.