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DAMOCLES: Debris-fall assessment in mountain catchments for local end-users

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ABSTRACT: The DAMOCLES project has developed and applied new quantitative technologies for debris flow and rockfall hazard assessment, impact prediction and mitigation studies. Three models provide an integrated approach to debris flow hazard assessment: a statistical multivariate model and GIS for mapping debris flow susceptibility at the regional scale (1000 km^2); a small basin (10 km^2) debris flow impact model for predicting fan sedimentation; and the existing SHETRAN landslide model for predicting debris flow occurrence and sediment yield at the basin scale (500 km^2). In addition the STONE model has been developed to assess rockfall hazard at scales ranging from the hillslope to the region. A supporting field programme in the Spanish Pyrenees and Italian Alps has provided new quantifications of debris flow characteristics, databases for running the models and improved techniques for assessment mapping and data analysis. The close involvement of end-users has ensured the practical relevance of the project technologies and facilitated their transfer into the public domain.

1 INTRODUCTION

Debris flows and rockfalls are a familiar hazard in European mountain areas and regularly cause loss of life, livelihood and property and disruption of communications. The potential for such losses is increasing as the mountain areas are increasingly developed and insurance claims as a result of this threat are steadily rising. Further, the development itself (e.g. construction of roads and recreational areas) can increase the incidence of debris flows by changing their topographic, soil and vegetation controls (e.g. Simons 1988, García-Ruiz & Valero 1998, Wasowski 1998). Changes in climate and land cover may have a similar impact. Hazard assessment is therefore increasingly required in land use planning in mountain environments and is aimed at three critical aspects: 1) the spatial distribution of debris flows, rockfalls and other slope failures; 2) predicting their occurrence and impact; and 3) minimizing the impact. However, while there is a great deal of expertise in hazard assessment at the national level, this is unevenly distributed between countries. Techniques have been developed as standards in some European countries: in Austria, for example, hazard mapping combines information on past events with geomorphological surveys (Aulitzky 1994). However, there is no uniformity of approach in Europe and available techniques are approximate (because of lack of data) and give only qualitative or relative estimates of hazard. Further, climate

Table 1. DAMOCLES project partners.

Partner	Role	Associated end-users
University of Newcastle upon Tyne, UK	Coordinator; Leader WP4 (Basin landslide model) and WP5 (Dissemination)	None
Università degli studi di Milano-Bicocca, Italy	Leader WP2 (GIS hazard assessment, regional scale model and rockfall model)	Servizio Geologico della Regione Lombardia; University of Bologna (subcontractor)
Consiglio Nazionale delle Ricerche-Istituto di Ricerca per la Protezione Idrogeologica, Perugia, Italy	Assistant Contractor to U. Milano-Bicocca (GIS hazard assessment, regional scale model and rockfall model; DAMOCLES website)	None
Università degli studi di Padova, Italy	Leader WP3 (Small basin debris flow model)	Servizio Azienda Speciale di Sistemazione Montana, Provincia Autonoma di Trento; Associazone Italiana di Idronomia
Consejo Superior de Investigaciones Científicas – Instituto Pirenaico de Ecologia, Zaragoza, Spain	Leader WP1 (Field studies and debris flow relationships)	Diputación General de Aragón, Zaragoza (Dirección General de Ordenación del Territorio y Urbanismo; Dirección General de Política Interior y Administración Local)
Instituto Geológico y Minero de España, Zaragoza, Spain	End-user and Assistant Contractor to CSIC-IPE (Application of project models)	None

WP: The project work is divided into five workpackages as shown

change may render unreliable techniques which have been developed from past experience and conditions.

In the light of the above, DAMOCLES (Debrisfall Assessment in MOuntain Catchments for Local End-userS) was conceived as a project to develop and apply new technologies for assessing the distribution of rapid slope failures and their hazard, for determining the physical impact of debris flows and, hence, for assessing the mitigating effects of torrent control works and land management, with these technologies being transferred to relevant end-users. (The term debrisfall is adopted here to refer collectively to debris flows and rockfalls.) To achieve the above aims, the specific project objectives were:

1) To develop and apply advanced quantitative models for debris flow and rockfall hazard assessment, impact prediction and mitigation studies, relevant at the local, river basin and regional scales. The models were to represent advances in their own right but, in addition, their integration was to provide a more coherent, unified and quantitative approach to hazard assessment than is currently available;
2) To conduct field surveys and assemble databases in support of model development and to improve mapping and data analysis techniques. Two field areas were selected in the Italian Alps and one in the Spanish Pyrenees;
3) To transfer the technologies to end-users and make the outcomes accessible through the public domain.

An important feature of the project is its integration of research-based model development with the direct involvement of local planning and civil protection authorities as data suppliers, advisors and recipients of the project results. In this way it aims to provide new knowledge on rapid slope failures in European mountain areas while helping to improve the efficiency and reliability of decision-making in the development of those areas.

There are six project partners from the UK, Spain and Italy, with a further six organizations associated as end-users or as a subcontractor (Table 1). The DAMOCLES project was funded by the European Commission. The project website is at http://damocles.irpi.cnr.it.

This paper summarizes the technologies which have been developed in the project and shows how they are integrated. More detailed information is given in the companion papers (Crosta et al. 2003, Lenzi et al. 2003).

2 FIELD STUDIES AND DEBRIS FLOW RELATIONSHIPS

Field data have been collected in the Central Spanish Pyrenees (the 867 km^2 flysch geological sector of the upper Aragón and Gallego river basins and the 300 km^2 Benasque valley), in the Lombardy alpine and pre-alpine area of Italy and in the Trento-Veneto-Bolzano alpine region of Italy. The field programme underpins the DAMOCLES project in four important ways.

1) As our theoretical understanding of debris flow processes is still limited in some areas, field data are needed to support empirical, or semi-empirical, developments in debris flow modelling. This is particularly so for such key features as debris flow volume and runout distance. Thus, analysis of 64 debris flows in the flysch sector of the Central Pyrenees shows that deposition begins to occur at a higher slope gradient (about 18°) than is generally reported for other sites in the literature and runout distances are then relatively longer than for other sites. An equation for runout distance in the flysch sector was determined by multiple linear regression as:

   $$D = -14.447 + 0.477H + 0.709L + 0.365S + 0.180B \quad (1)$$
   $$r^2 = 0.664$$

   where D = runout distance or length of the debris flow deposit (m); H = the difference in height between the debris flow scar or origin and the point at which runout deposition begins (m); L = travel distance of the debris flow from the upper part of the scar to the beginning of the deposit (m); S = gradient of the scar (degrees); and B = gradient of the debris flow deposit (degrees). (Since B can be determined only after the debris flow has occurred, Equation 1 is of interest for the relationships between parameters which it defines but it cannot be used predictively.) Similarly analysis of data from northeastern Italy quantifies debris flow volume as:

   $$M = 70\,A\,S^{1.28}\,GI \quad (2)$$

   where M = volume (m^3); A = catchment area (km^2); S = mean stream gradient (%); and GI = a dimensionless geological index (D'Agostino & Marchi 2001). This functional dependency has been used by others but with different coefficients and exponents. In other words the format of the derived relationships is in line with other studies but the differences indicate regional variation and a continuing need to carry out site specific field studies. One of the project outcomes is a report on Debris Flow Relationships.
2) Field data are needed to test and improve models. Within DAMOCLES, data relevant to the four main project models have been collected: for regional scale hazard assessment modelling in Lombardy and the Benasque valley; for small basin debris flow impact modelling in northeastern Italy and the Benasque valley; for basin scale sediment yield modelling in Lombardy and the Central Pyrenees; and for rockfall modelling in Lombardy.

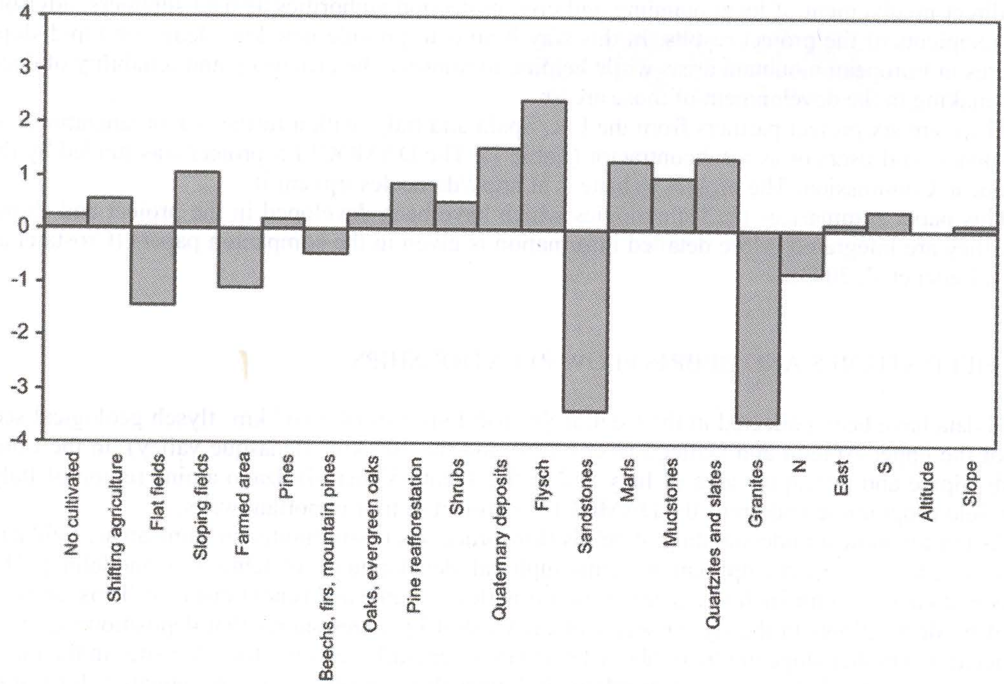

Figure 1. Discriminant analysis of factors controlling debris flow occurrence in the flysch sector of the Central Pyrenees. Positive values correlate with occurrence of debris flows. Negative values correlate with non-occurrence.

3) Field data can be used to characterize the specific field area and to provide information useful for planners and land managers. For example, discriminant analysis has defined the main factors controlling debris flow occurrence in the flysch sector of the Central Pyrenees (Lorente et al. 2002) (Fig. 1): this information could be used, for example, in protecting the more vulnerable areas from unsuitable land development programmes. Looking similarly at the rate of occurrence of debris flows in the same area, analysis has shown that rainfall variation has more influence than land use change.
4) The field programme provides an opportunity to improve and standardize mapping and data analysis techniques. A range of thematic maps have been produced, including geomorphological characteristics and hazard probability. Similarly, a standard form for recording debris flow characteristics has been implemented. Much of this output is held on the project website.

3 REGIONAL SCALE HAZARD ASSESSMENT

The particular requirement at the regional scale (hundreds to thousands of square kilometres) is to determine the spatial distribution of areas susceptible to debris flows and to quantify that susceptibility. Because of the large areas involved, the assessment technique should be limited to using generally available data (such as Digital Elevation Models and soil, vegetation and geology maps). Detailed field data (such as landslide inventories and soil property data) should not be required except for initial calibration of the technique in a limited area. A statistical multivariate model is therefore proposed as the principal DAMOCLES technology, combining relative simplicity of con-

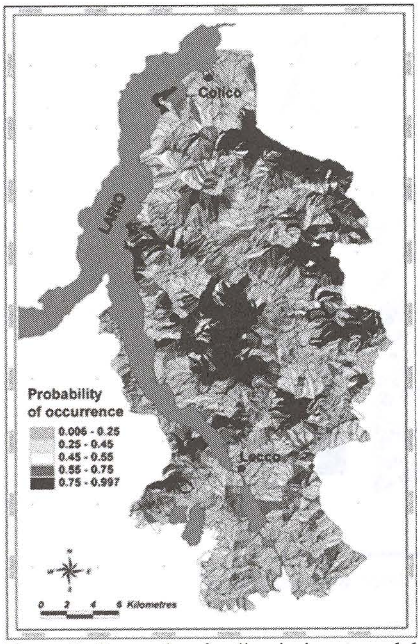

Figure 2. Example of a discriminant model of debris flow source areas, Lecco area, Lombardy, Italy.

cept with quantitative output and the capability of extending to the regional scale (e.g. Carrara et al. 1995, Guzzetti et al. 1999). Discriminant analysis is used to identify the main factors that contribute to the triggering of debris flows (e.g. land use and geology). Regression analysis between these factors and observations of debris flow occurrence then provides a model for predicting the spatial probability of debris flow occurrence as a function of the factors. This is likely to be constructed initially for a relatively small area with the necessary debris flow inventory. Application of the model within a GIS which maps the factors then enables a debris flow susceptibility map to be generated at the regional scale. Test applications of this technique have been carried out for Lecco province (Lombardy) (Fig. 2) and the Central Pyrenees.

Assessment of the technique is being carried out by comparison with field observations (aerial photographs covering the period 1954-1995 in the case of the Valsassina basin in Lecco province) and with physically based modelling approaches. For example, using Valsassina as the test area, three different grid-based distributed hydrological models were coupled with an infinite slope stability analysis and applied to the rainfall event of 27-28 June 1997 (which triggered a series of landslides). Using automatically generated main slope units as a common basis for representing spatial distribution, the probability of landslide occurrence in each unit given by the statistical model can be compared with the percentage of that unit which was unstable according to the physically based models. The information built up on model compatibilities in this way will be important when it comes to integrating the different project models in pursuit of objectives which cannot be achieved by one model on its own (as discussed in Section 6).

4 SMALL BASIN DEBRIS FLOW IMPACT MODEL

The regional scale hazard assessment indicates the extent to which an area is at risk from debris flows but does not quantify the effect that a debris flow would have if it occurred. A numerical

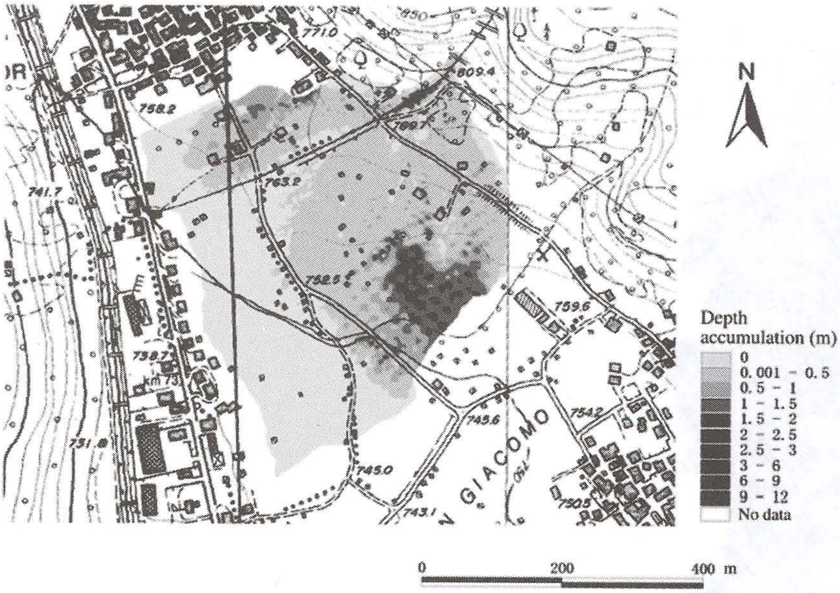

Figure 3. Debris flow depth accumulation on the Rio Lazer fan simulated with the DDPM.

model has therefore been developed to make such predictions and to explore the mitigating effects of torrent control works. It is applicable at the scale of a small catchment, typically up to 10 km^2 in area, containing a mountain torrent channel linked to a fan, and represents the channel and fan in two components.

With a user-supplied debris flow hydrograph as its input at the upstream end of the channel, the model routes the debris flow down the channel to the fan using a one-dimensional scheme called MODDS (Model One Dimensional Debris-flow Surges). This combines simplicity and a user-friendly design with an innovative ability to account for the effect of structures such as check dams and bridges, constrictions in channel cross section and overbank flow. A test comparison has shown good agreement with the well-known DAMBRK model (Singh 1996) for the case of non-Newtonian fluids (i.e. debris flows) and a successful validation has been carried out for the Rio Lenzi channel (Autonomous Province of Trento, Italy). Necessary data for the simulation include a detailed survey of the channel (Sonda 2001).

A two-dimensional model component represents debris flow propagation and sedimentation on the fan area (DDPM, Debris Flow Distribution Propagation Model). The fan is represented by a grid of square cells: transfer of debris flow material from one cell to another occurs under conditions of either uniform flow as a function of gradient or flow over a broad-crested weir. A successful test of DDPM has been completed for the debris flow deposit of 4 November 1966 on the fan of the Rio Lazer (Eastern Trento Province) (Fig. 3). Necessary data for the simulation include a high-precision survey of the fan topography.

Integration of MODDS, DDPM and a Digital Terrain Model for the fan forms the overall Debris Flow Impact Model, DEFLIMO. The integration is carried out using the ArcView GIS framework, which enables the one-dimensional channel model (based on vector elements) to be linked with the two-dimensional fan model (based on raster cells). The component models can be run independently or integrated together.

DEFLIMO improves upon existing impact assessment techniques such as the Aulitzky (1994) index in that it accounts for obstructions to debris flow movement along the channel (including the effect of torrent control works) and provides a quantitative and time-varying simulation of debris

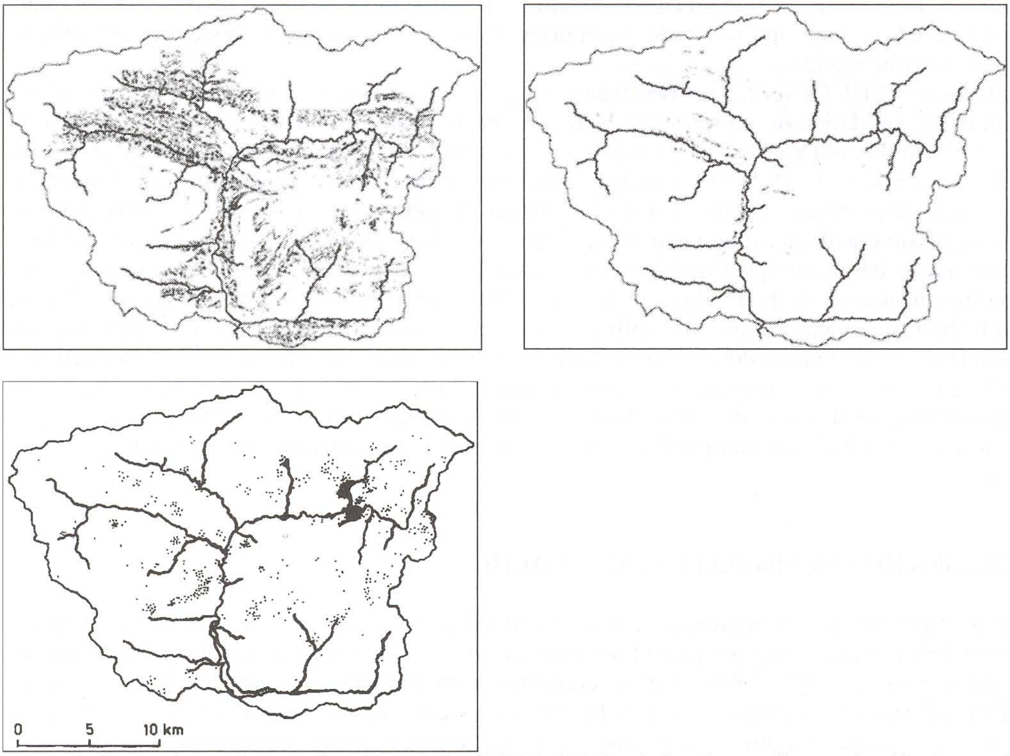

Figure 4. Comparison of uncertainty bounds for SHETRAN simulation (upper diagrams) with observed locations (lower diagram) of landslides in the Llobregat Basin. Landslide locations are shown as dots.

flow propagation and deposition on the fan. It also represents an improvement in user-friendliness and can be easily mastered in a short training course. Full details of the model, including data requirements and limiting assumptions, are given in Lenzi et al. (2003).

Within the DAMOCLES project, DEFLIMO was tested at sites in the Italian Alps and in the Spanish Pyrenees.

5 BASIN SCALE LANDSLIDE SEDIMENT YIELD

In addition to predicting the local impact of a debris flow (i.e. on the fan), there is interest in the effects of debris flows at larger basin scales. In particular the contribution of debris flows to sediment yield is important in basins large enough to feed reservoirs. The existing SHETRAN landslide erosion and sediment yield model was therefore applied to model debris flow spatial and temporal occurrence and impact on basin sediment yield, for scenarios of possible future land use and climate. The scenario results will be used to develop guidelines for land management to mitigate debris flow occurrence and impact, for focus areas in the Italian pre-Alps (Valsassina) and Spanish Pyrenees (Ijuez). SHETRAN is a physically-based, spatially distributed modelling system for water flow and sediment transport, valid at the basin scale (Ewen et al. 2000). Its landslide component takes soil moisture data from the hydrological model to simulate shallow landslide occurrence using infinite slope (factor of safety) analysis and transfers the landslide material to the channel network as a debris flow (Burton & Bathurst 1998). SHETRAN then routes this material to the basin outlet using its channel sediment transport component. The relationships used in the model to simulate the transfer of material by debris flow were modified and enhanced using the results of the field studies. Data needs include precipitation and evaporation records, runoff records, topographic, soil and vegetation maps and landslide inventories. Typically the landslide model is applicable to basins up to about 500 km^2.

Validation of SHETRAN for the two focus areas was not complete at the time of writing. However, an initial validation of the landslide model has been completed for the November 1982 landsliding event in the 500 km^2 Llobregat basin in the eastern Spanish Pyrenees, in a study originally started in the earlier EC MEDALUS project. Because of uncertainty in evaluating the model parameters and other inputs, the aim is not to reproduce the observed occurrence of debris flows as exactly as possible with one simulation. Instead the aim is to bracket the observed pattern with several simulations based on upper and lower bounds for the more important model parameters, reflecting the uncertainty in their values. (The basis of this technique is described by Ewen & Parkin (1996).) The results demonstrate this ability, in this case using bounds set on the vegetation root cohesion (Fig. 4). The upper debris flow bound is a considerable overestimate of the observed pattern but, crucially, it reproduces several of the principal clusters in the observed pattern. The results also demonstrate an ability to determine bounds on the landslide sediment yield for the event (1000 – 10,000 t km^{-2}) which are comparable with measurements for extreme events elsewhere in the Pyrenees.

6 INTEGRATION OF MODELLING APPROACHES

The above three modelling approaches are summarized in Table 2. They provide complementary outputs and their integration both provides a more coherent approach to debris flow hazard assessment and widens the applicability of each, compared with using them separately. Because the regional hazard assessment model is essentially based on a correlation between recorded debris flow occurrence and geomorphological and land use characteristics, its relevance is limited to the climatic conditions characterizing the period of record. If the climate changes, the model correlation may no longer apply. SHETRAN, however, by virtue of its physical basis, can investigate patterns of debris flow occurrence for possible scenarios of future climate and land use. It can therefore provide a new "virtual ground truth" of debris flow occurrence, which can be used to calibrate the hazard assessment model for the future conditions. The regional hazard assessment model is also limited to providing the probability of occurrence of debris flows. The small basin debris flow

Table 2. The DAMOCLES debris flow models and their integration.

Model	Model output	Role in integrated application
Regional hazard Assessment	Debris flow probability map	Provide hazard map based on correlation between recorded debris flow occurrence and gemorphological and land use characteristics (for past climate)
Local debris flow Impact	Fan sedimentation as function of debris flow characteristics	Investigate in detail the hazard at sites of interest, including sites identified in the regional scale map
Basin scale impact	Sediment yield as function of climate and land use	Investigate landslide erosion and sediment yields for climate and land use scenarios, including revised basis for regional hazard assessment for future altered conditions

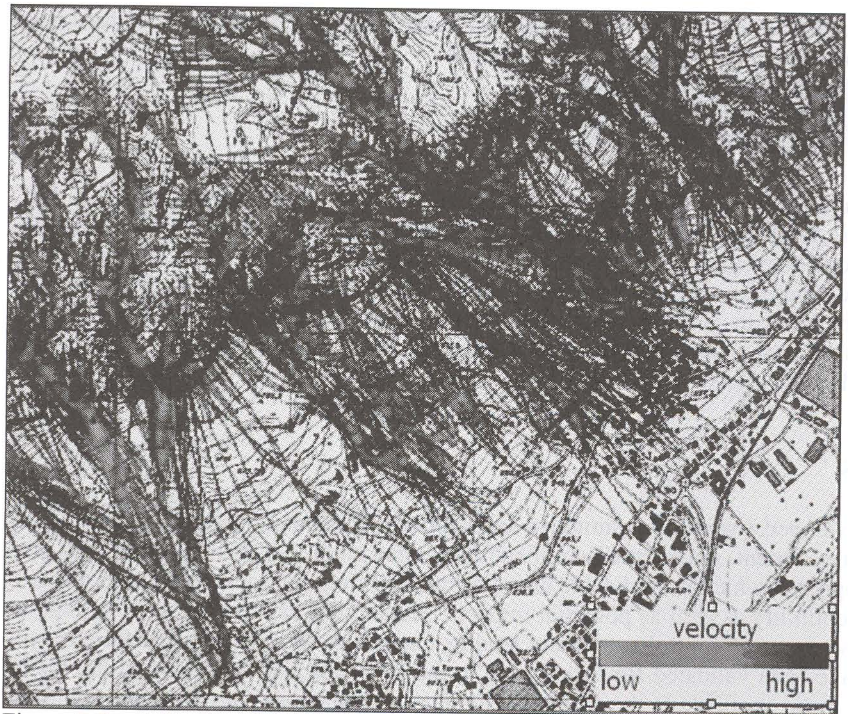

Figure 5. Example of application of the STONE rockfall model.

impact model therefore provides the means of investigating in detail the hazard (in terms of sediment deposition) at sites identified from the regional scale analysis as requiring attention (e.g. where it is planned to build a road or new infrastructure). Similarly SHETRAN can be used to predict the basin scale sediment yield as a function of debris flow occurrence (e.g. to determine reservoir sedimentation).

7 ROCKFALL MODEL

The computer model STONE has been developed for the simulation of rockfall trajectories in three dimensions (Guzzetti et al. 2002). This uses generally available thematic data and GIS technology to generate simple maps useful for assessing rockfall hazard at scales ranging from the hillslope to the region. STONE simulates rock movement by free fall, bouncing and rolling. The trajectories are calculated as a function of the starting point, topography and coefficients used for determining loss of velocity in impacts or in rolling. It is acknowledged that evaluation of these coefficients involves uncertainty and a capability is therefore provided for random evaluation within a user-specified range. Further capability for accounting for natural variability is provided by allowing more than one boulder to be launched from a site. Output includes frequency of rockfall, three-dimensional display of rockfall trajectories and information such as velocity of fall and height of the trajectory above the ground (Fig. 5).

Accurate calibration of the model parameters has been successfully accomplished using thematic maps and a database of observed rockfalls. Model performance has also been investigated at different spatial scales and with different data availabilities within the 600 km^2 Lecco province in the Lombardy pre-Alps, in an area in the Apennines in central Italy, in the Central Pyrenees (Acosta et al. 2002) and in Yosemite Valley, California. A rockfall hazard map has been produced for Lecco province, as a contribution to planning protection measures.

8 INTEGRATION OF END-USERS

The end-users (regional planning authorities and geological surveys) had an important role in DAMOCLES. On the one hand they contributed advice to the project, helping to ensure that the technologies being developed have practical relevance and will fit their needs. On the other, by receiving the project technologies, they are the primary route by which these technologies will enter the public domain and be used in practice. Familiarity with use of the technologies was achieved through participation in applications and through a training course and workshops. Some of the end-users were also data suppliers.

9 CONCLUSIONS

DAMOCLES has developed a suite of quantitative and spatially distributed models for debris flow and rockfall hazard assessment, impact prediction and mitigation studies. Taken together they provide an integrated approach which is applicable at scales ranging from the local to the regional and which indicates susceptibility as well as potential impacts. The models can also be used to explore the mitigating effects of torrent control works and land management, for present and future conditions. The models have been validated for focus areas in the Pyrenees and the Alps and the methodologies have been made available to the end-user community. The model development has been supported by a field programme which has provided new quantifications of debris flow characteristics, databases for running the models and improved techniques for assessment mapping and data analysis. Through the advances which the individual models represent in their own right and through their integrated approach, the DAMOCLES technologies provide an improved basis for hazard assessment. Through the emphasis on practical application and the involvement of end-users, and through the European nature of the project, DAMOCLES also provides an important opportunity for the adoption of a more uniform approach to hazard assessment in Europe. Further publicity and training will be devoted towards this aim.

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