DAMOCLES

DEBRISFALL ASSESSMENT IN MOUNTAIN CATCHMENTS FOR LOCAL END-USERS

Contract No EVG1 - CT-1999-00007

PERIODIC CONTRACTOR REPORT
FOR THE PERIOD
2000-2001

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SECTION 5

Two GIS-based methods for rockfall/debris flow hazard assessment have been produced during the Damocles project. A multivariate statistical approach was applied to develop a predictive model of debris flow susceptibility. Outcomes of the analysis indicate that the model is capable of predicting, with a reliability of the 78.4%, which terrain units could be either affected by or free of landslides. The hazard methodology for rockfall is founded on the 3D physically based model, STONE, that has been implemented during the Damocles project. The methodology is conceived (1) to take in account physical aspects of rockfalls, (2) to be easy to use, (3) to provide meaningful hazard maps, and (4) to be translated into planning tools with little further effort.

A strong effort was made during the project to transfer the knowledge to the end users: a one-day workshop and four days of courses have been organized.

SECTION 6

Section 6.1 Background

Debris flows and rockfalls are hazardous phenomena in mountain areas. Despite the volume involved in these phenomena are not usually very large, both debris flows and rockfalls are extremely dangerous because they are very rapid and very frequent both spatially and temporally. Numerous rockfall/debris flow events have occurred in the last years in the Italian Alps, claiming lives and causing economic losses for people living in mountain areas. In example, considering only the province of Lecco, the following rockfalls have occurred in the last years: Mt. S.Martino – Coltignone, 1969, 8 casualties; Valmadrera, July 1981, 1 casualty; Onno Lario, 1984, 1 casualty; Varenna, May 1997, 5 casualties.

Section 6.2 Scientific/technological and socio-economic objectives

The relevant hazard posed by rockfalls and debris flows makes necessary the development of hazard assessment methodologies. As previously reported, both rockfalls and debris flows are relatively small, very rapid, and spatially frequent phenomena. Thus, when modelling these processes it is necessary to develop methodologies capable to describe hazard as a diffuse problem, and to incorporate local slope morphology in the modelling. The hazard assessment methodologies must therefore rely on distributed models that are based on the use of detailed Digital Terrain Models.

On the other hand, in order to make the hazard assessment effective, it is necessary to provide methodologies that are usable for the end-users, and to co involve the end users in the development of these methodologies.

Section 6.3 Applied methodology, scientific achievements and main deliverables

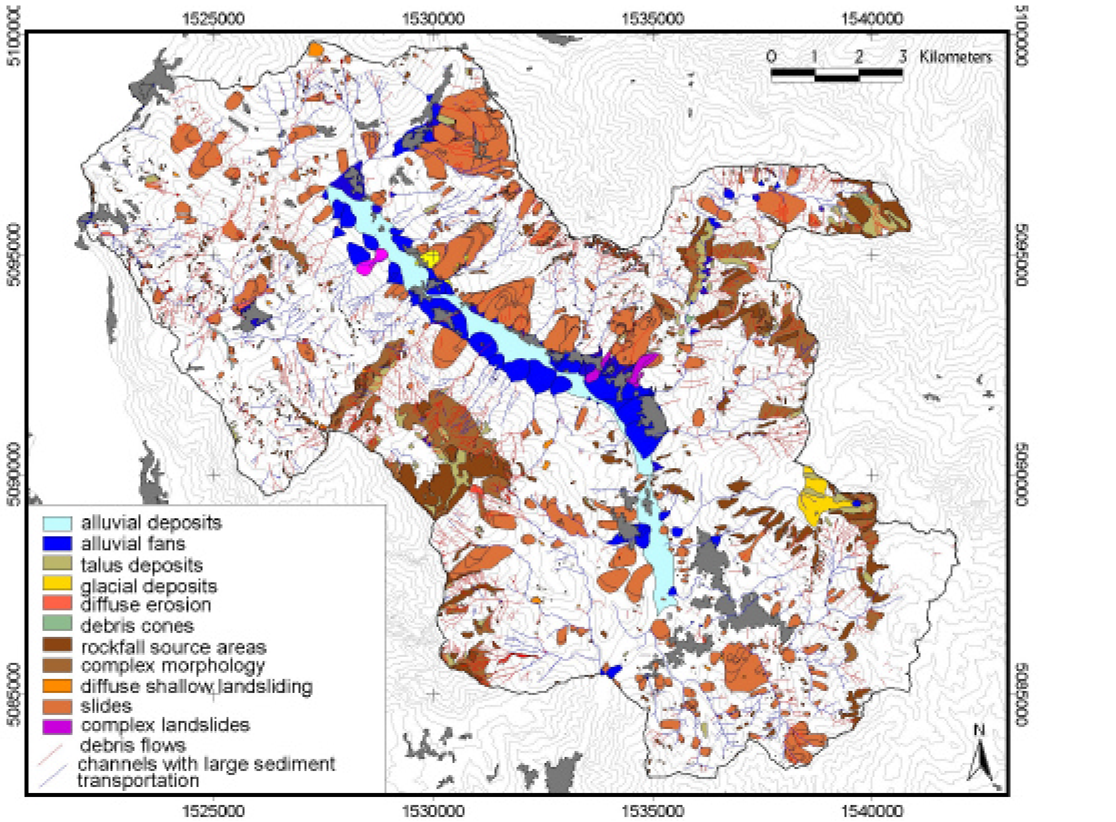
WP1. Analysis of empirical relationships for Alpine debris-flows

Empirical and semi-empirical relationships for the computation of flow velocity, discharge and runout behaviour have been applied to granular debris-flows occurring both on talus slopes and in channels in the upper Valtellina (Central Alps, Northern Italy). Little differences have been observed between the debris flows that originated on calcareous slopes and those that originated in phyllites. The relationship between volume and depositional area, $A=kV^d$, was used and calibrated with different datasets from the literature. Both granular debris flows and lahars agree remarkably with the semi-empirical relationship discussed by Iverson et al. (1998): $A=kV^{2/3}$. This confirms that, for debris flows, the thickness of the deposit (and, consequently, the volume) shows a constant proportionality with the inundation area. Moreover, the power-law relationship seems scale-invariant over several orders of magnitude. The empirical coefficient, k, mainly changes in value as a function of the characteristics of the material involved in the phenomena (Crosta et al, in press).

WP2 (1). Preparation and transfer of the GIS database

Data collection for the Focus Area B (Pioverna and Esino basins) is aimed to the modelling activity of WP2 and WP5. A new high resolution DTM (5x5 m pixel size) of the study area was automatically generated by digital photogrammetry. A geological map was prepared by using all the available literature, and improved through field geological survey. Land use map was compiled by using existing maps and by field checking. A new multi-temporal inventory map for the study area was also completed (fig. 1) through the interpretation of a historical series of aerial photographs (1954, 60, 72, 83, 91, 95, 2000). The inventory has been further updated after the November 2002 rainstorm, during which several shallow and deep landslides were triggered. A thorough collection of historical records for the study area has been also completed through the analysis of several archives, with data ranging from the beginning of XIX century to 1990, recording 147 landslide events. Rainfall data, discharge data and temperature data have been collected from stations localized inside and around the study area. Finally, a set of 36 cross sections for the Pioverna river channel has been collected and prepared in a digital format.

Detailed field survey has been performed within a sub area of Focus area B, the Esino basin (fig. 1), which was hit by an intense rainstorm that triggered more than 150 shallow landslides in less than 35 km^2. This event was studied in detail because it has been used to calibrate landslide models. In-situ permeability were performed with Guelph permeameter and laboratory tests on soil samples were carried out, in order to assess the grain size distribution, Atterberg limits and, through a direct shear test, friction angle and soil cohesion. Finally, eighteen soil samples were



collected in different locations in the catchment by the Newcastle and Milan-Bicocca teams, and analysed in the laboratory by the Newcastle team.

WP2 (2). Development of GIS models for debris flow/rockfall hazard assessment

Rockfalls

A physically based distributed model for rockfall simulation was developed during the project, in collaboration with CNR-IRPI-Perugia team. The model lies on a software code called STONE, which makes use of DTMs and thematic maps to simulate rockfall propagation on 3D surfaces. Testing of the code has been performed at different scales, on different areas and both within and out of the Focus area B. The choice of the areas for a detailed testing of the model derived both by technical requirements and by specific interest of the end-users (Lombardy Region Geological Survey). A first step has been the calibration of the model at regional scale, by using available thematic maps and database of occurred rock falls. The model was able to simulate correctly some of the actual rockfall paths, as shown in figure 2. The performance of the code STONE has been tested at the local scale by using high resolution input data, in order to show its application to site-specific problems. Two case studies from the Mt. S.Martino - Coltignone (Como Lake) and the Valfurva (Central Alps) were studied (fig. 3). Models have been calibrated by back analysis, using a number of geomorphological and sedimentological field observations. For the Lecco model, the runout of blocks of different size, the extent and activity of scree slopes, the characteristics of

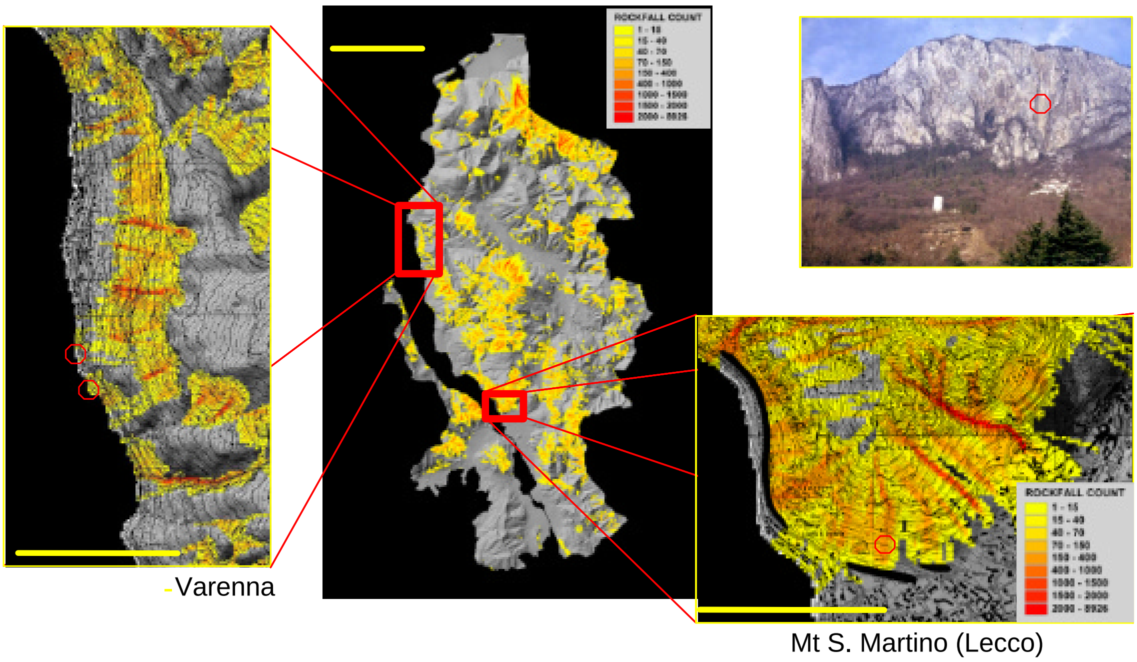
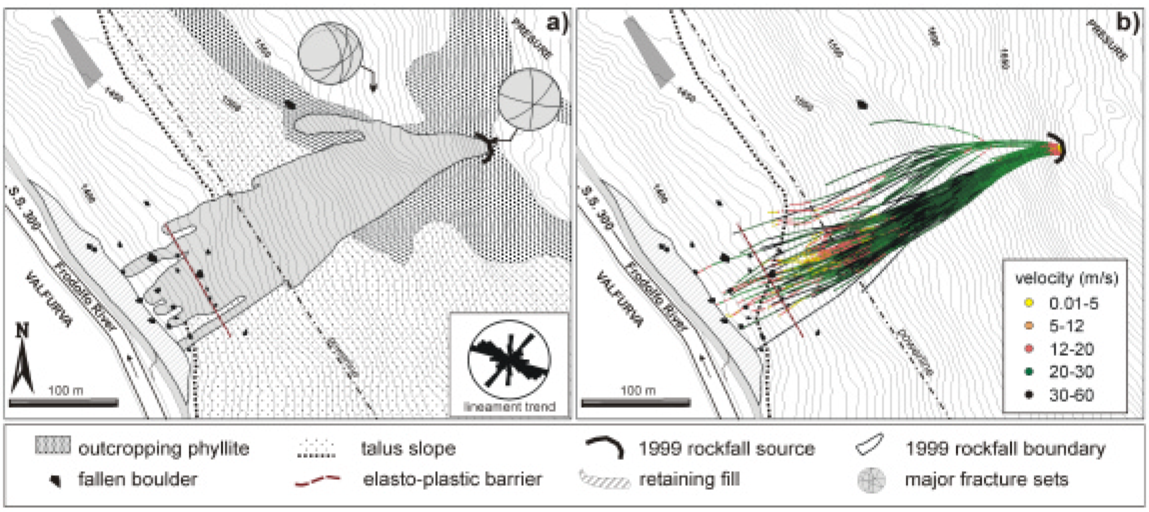
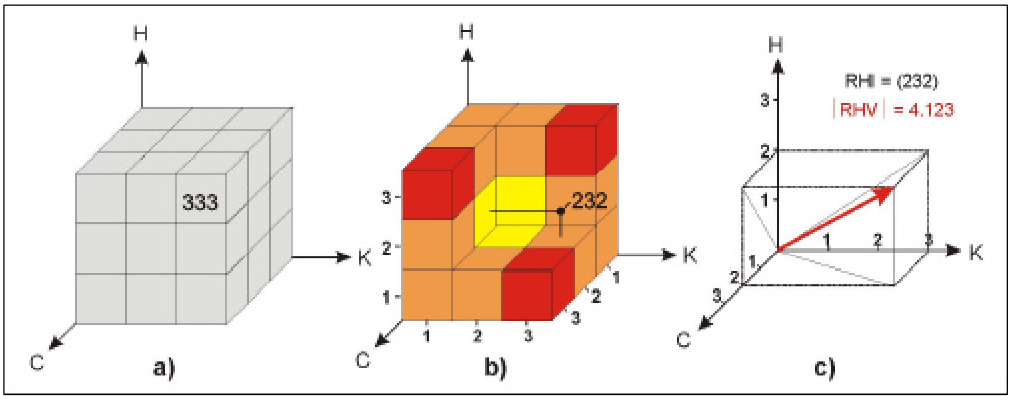


Figure 2. Enlargement of two areas adopted for the calibration of the rock fall model for the Lecco Province. Three events at Varenna and at the Mt. San Martino (Lecco) are reported. Distribution of arrest points of larger boulders has been used to calibrate the model.

earlier rockfall accumulations (e.g. 1951, 1969) and the available information about historical events have been used. Model results have been compared to experimental data available in the literature, allowing the validation of the proposed 3D kinematic modelling approach.

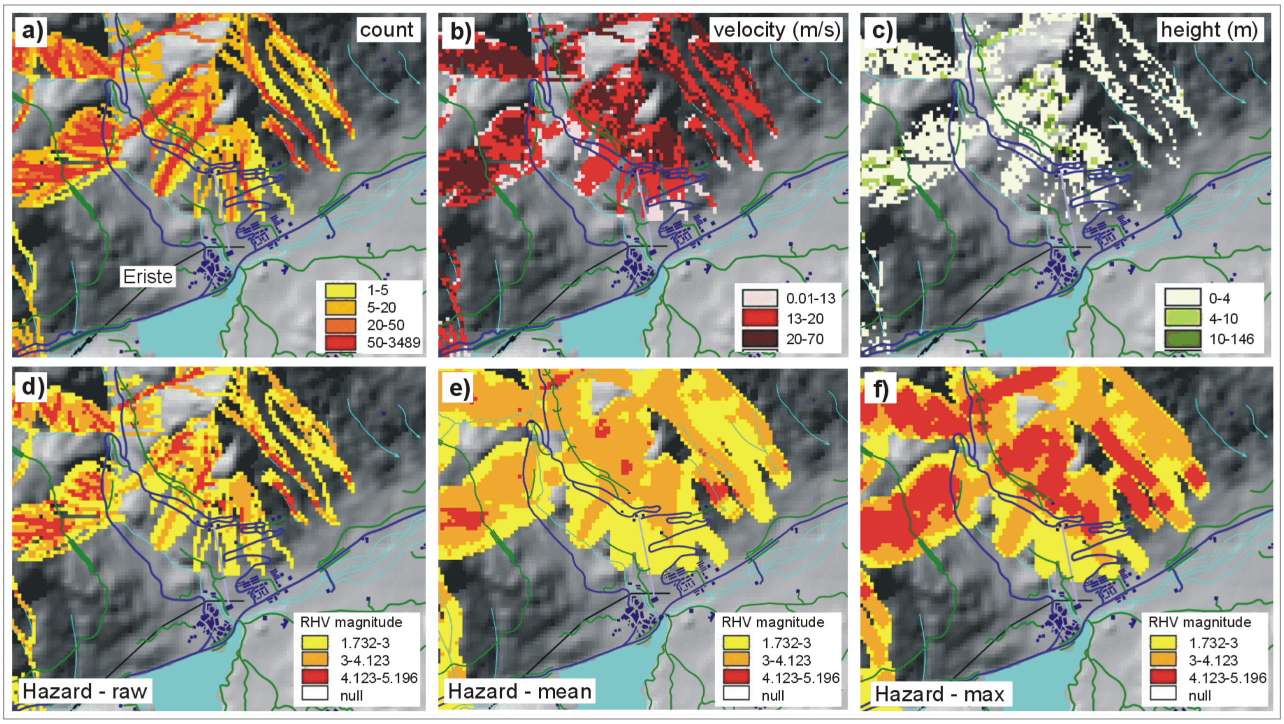
Full scale tests performed by Broili (1973) in the Mt. S.Martino area have been reproduced numerically by performing stochastic modelling Model results in terms of computed velocity have been statistically analysed and compared to the experimental data. The comparison proved that the proposed approach is able to reproduce both the kinematics and implicitly some aspects of rockfall dynamics, if used with high resolution input data.





The effects of grid resolution on model results have been evaluated by performing multi-scale modelling for both the Mt. S.Martino area and the Valfurva area (Agliardi & Crosta, in press). The DEMs have been resampled in order to simplify the description of topography. Model results have been analysed through distributed statistical techniques, and partially agree with those obtained by other authors with 2D modelling. Nevertheless, 3D analysis outlined that large deviations from the simple general rules outlined in 2D can occur when considering 3D slopes. This is due both to the effects of topographic description and to the influences of local slope geometry (occurrence of ridges, upslope-facing slope sectors, etc.). Lateral dispersion phenomena have been quantitatively evaluated at different scales as function of the model resolution, outlining the importance of 3D modelling in designing countermeasures, assessing hazard and solving site-specific rockfall problems.

A new rockfall hazard assessment procedure has been developed (Agliardi & Crosta, 2002). procedure is conceived to take in account as many physical aspects of rockfall as possible, to be easy to use and to provide meaningful hazard maps. The method considers three main parameters which are computed directly or indirectly by STONE, namely: the rockfall count *c*, the translational kinetic energy $k = 0.5\ m\ v^2$, and the fly height *h*. Rockfall hazard is expressed by a “Rockfall Hazard Index” RHI = (ckh). Since the three parameters are characterised by different physical meanings and orders of magnitude, their values are conveniently reclassified in three classes, according to standard criteria, established through the objective evaluation of the “potential destructiveness” of simulated rockfalls. Then, they are combined to obtain a value of the 3-digit positional Rockfall Hazard Index (RHI), portraying on the map a specific level of hazard and retaining in each digit the information about the contribution of each parameter. The resulting 27 classes (fig. 4) are considered sufficient to represent hazard but they are not easily represented in a map. As a consequence, further regrouping is performed to result in 3 hazard classes (low, intermediate and high), according to the magnitude of a Rockfall Hazard Vector RHV (see fig. 4). The magnitude of the RHV vector allows us to rank the hazard level in classes and to obtain an



objective and clear hazard map. The Rockfall Hazard Index/Vector method has been tested at regional scale in the study area of the Lecco Province. Rockfall modelling has been performed using a probabilistic approach, by throwing 10 blocks from each source cell and allowing for the variability of restitution and friction coefficients into specified ranges. The regional scale model is useful for large-scale, recognition rockfall analysis and hazard assessment, but not suitable for site-specific engineering purposes. The final classification of hazard has been calibrated using available information about documented rockfall events causing fatalities and damage to infrastructures and lifelines (S. Martino, 1969; Valmadrera, 1981; Onno Lario, 1984; Varenna, 1997; etc.) and geomorphological data.

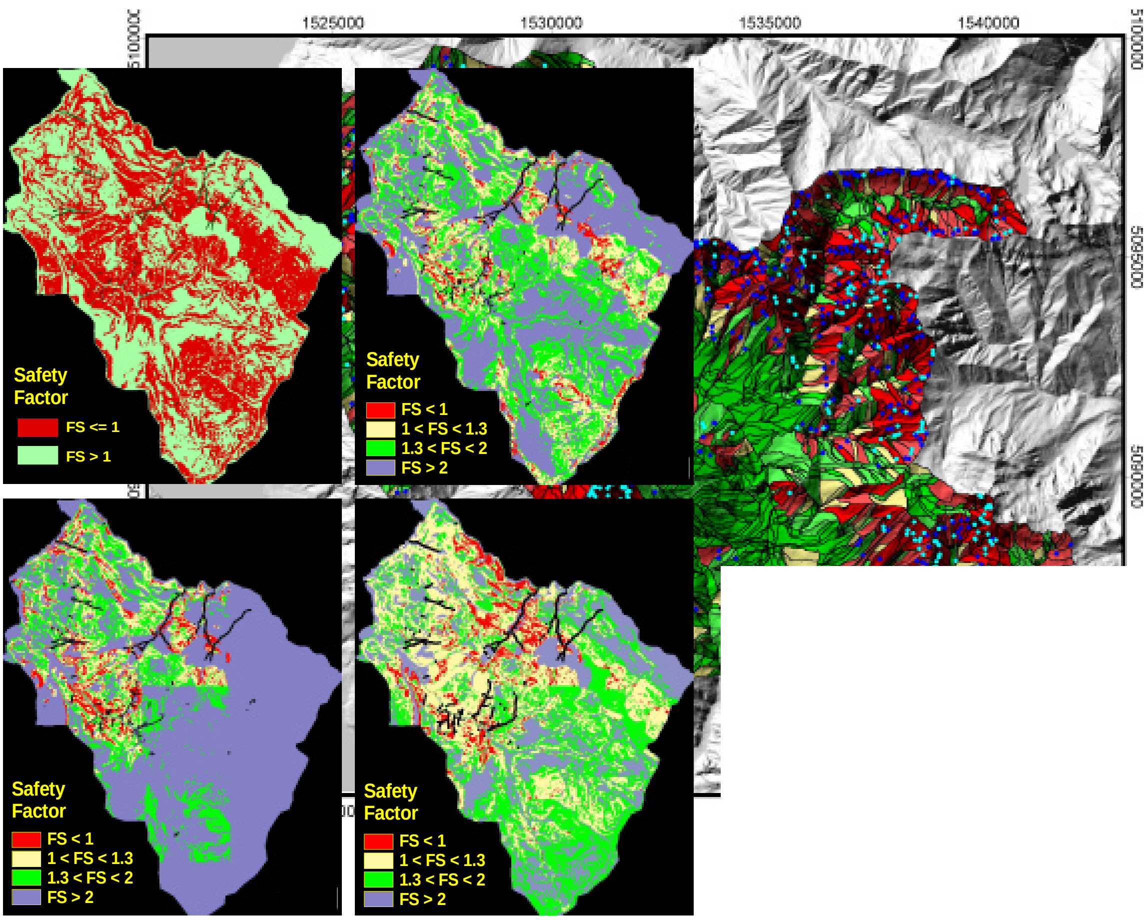
An application of the 3D numerical model for rockfall simulation was also performed in the Benasque valley, Spanish Pyrenees (Acosta et al, in press). The model was developed using geomorphological and geological data collected and provided by the Saragoza ITGE team. A 25*25 m DEM has been prepared as well as two different rockfall source maps. Rockfall sources have been outlined according to two different approaches: a first rockfall source map has been obtained starting from simple morphometric assumptions (slope > 43° in outcropping rock areas) and a second map from direct aerial photo interpretation. Different hazard maps have been obtained using raster maps computed by STONE (Figure 5a, b and c). Hazard computation according to the proposed methodology allowed to obtain a “raw” hazard map (figure 5d). In order to achieve a more effective hazard zonation, the raw hazard map has been “smoothed” by the mean and the maximum RHV magnitude, respectively computed in a 50 m neighbourhood.

Debris flows

A GIS-based predictive model of debris-flow occurrence was developed by using multivariate statistical techniques (Carrara 1983; Carrara and others 1995, 1999). The basin area was automatically partitioned into main slope-units (i.e. the left and right sides of elementary sub-basins), starting from a DTM of high accuracy (5x5 m). By defining a slope-unit minimum size of 10000 m^2, 4179 units were generated, with an average area of 42000 m^2. Under the assumption that both the mapping errors and the uncertainty decrease with the size of the terrain unit, all the discriminant analyses were weighted by the square root of the terrain unit area. Likewise, debris-flows were weighted according to their estimated degree of activity and the degree of certainty associated with their identification and mapping. Using a stepwise procedure, 29 geological-morphological factors were selected as predictors, and the presence or absence of debris-flow source areas within each terrain unit was used as the predicted or dependent variable of a discriminant function. Since discriminant scores at the group centroids of stable and unstable terrain units have values equal to -0.371 and 1.121, negative and positive discriminant standardized coefficients (SDFC) indicate variables that contribute to the stability or instability of the slope-unit, respectively.

Outcomes of the analysis indicate that the model is capable of predicting, with a reliability of the 78.4%, which terrain units could be either affected by or free of landslides. Among the lithological variables, the factor with the largest standardized discriminant function coefficients is the presence within the terrain unit of foliated metamorphic rocks, (MT_FL), with a negative value, in disagreement with debris-flow occurrence. Among land-use variables, the presence of forest (FOR), natural vegetation (NAT_VEG), lawns and pastures (LAW_PAS), have similar negative coefficients, whereas the absence of vegetation (i.e. bare rocks and active talus; NO_VEG) shows a positive coefficient. This indicates that all kinds of vegetation cover contributes to slope stability, and that no significant difference exists between forested and un-forested areas. As a consequence, we can expect that the role of land use management (forest cutting, grazing, etc.) is poorly significant for slope stability within the study area. Of the geomorphological variables, the most relevant is the presence of complex morphologies (FR_Y), which are areas characterized by small-scale alternations of rocky cliffs and debris deposits. Among the morphometric variables of the terrain units, the local relief (RELIEF), the density of minor channels (DENSITY), the ratio of perimeter and $(area)^{0,5}$ (FORM) and the slope angle of the lower portion (ANGLE1), have large coefficients. The high values of their coefficients indicate that debris flows are strongly controlled by slope morphology.

An important issue for Damocles Project is the comparison between statistical multivariate models and physically based models. Three simple grid-based distributed hydrological models have been



therefore implemented in ArcInfo Macro Language (Crosta & Frattini, 2003): a steady state model (Montgomery and Dietrich, 1994), a transient “piston-flow” wetting front model (Green and Ampt, 1911), and a transient diffusive model (Iverson, 2000). These models have been coupled with an infinite slope stability analysis and applied to simulate the triggering of shallow landslides due to the rainfall event of June 27th-28th (figure 7). The calibration was performed on the basis of prior information about soil and vegetation, with adjustments made to improve the distribution of computed Safety Factor with respect to the actual distribution of triggered landslides. In order to compare develop a common environment that allows a comparison between models, automatically generated main slope units were used. These units were reclassified according both to the percentage of unstable areas modelled by physically based models and to the probability of landslide presence modelled by statistical models. A direct confrontation of these reclassified units permits to outline similarities and differences of the models.

WP1 (3). Preparation of a short review on granular flows

The review on granular flows, entitled “GRANULAR FLOWS AND NUMERICAL MODELLING OF LANDSLIDES”, has been produced (Month 18 deliverable). The document (71 pp) includes a short revision of existing theories on granular flows and it especially includes some applications produced by the Milano-Bicocca team: distinct element modelling for rapid dry granular flows, depth averaged modelling of gravitational mass flows, finite element modelling of landslides with large runout, empirical relationships for the assessment of debris flow runout distances.

WP5. Dissemination of the projects results

The results of the project has been transferred to the other partners and to the end-users by means of different strategies. First, thematic maps for the Focus area B, detailed metadata, and the granular flows review document were provided to CNR-IRPI of Perugia to be published on the web site (http://damocles.irpi.pg.cnr.it). Then, a full-day workshop have been organized on November 21, 2002, at Milano-Bicocca University to present Damocles activities to the end-users. Finally, 25 people from the Lombardia Region end-user were trained in the methodologies for debris-flow and rock-fall hazard assessment during a four-day training course that was held at Milano-Bicocca University, on December 10-12-17-19, 2002 .

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

Two GIS-based methods for rockfall/debris flow hazard assessment have been produced during the Damocles project. The physically based approach for rockfall hazard modelling is based on a 3D model (STONE) that was developed and tested during the project. The model simulates the energy and the probability of rockfalls propagating on complex surfaces. By combining this information, a quantitative, reproducible and objective hazard assessment methodology has been developed. The statistical approach for debris-flow susceptibility assessment was realized by using techniques and tools developed and tested during twenty years of studies in Apennine settings (Carrara 1983; Carrara and others 1995). The application of these techniques to alpine environment was a new challenge, and good results were obtained. The predictive model is strongly dependent on the morphometric variables, with minor control of land-use and geological parameters. The availability of a high resolution DTM is a severe need for hazard assessment of debris flows.

Hazard assessment has a direct and important socio-economic relevance. Both rockfalls and debris flows are causes of casualties and loss for people living in mountainous areas, as testified by numerous events that occurred in the Italian Alps in the last years (e.g., Lecco - Mt.S.Martino, 1968; Valtellina, 1987, Lecco province, 1997; Lower Valtellina, 2000 and 2002). Thus, the regional and basin scale hazard assessment methodologies for debris flows and rockfalls are important tools for land management and planning in alpine areas. Moreover, the distributed approach that was used for landslide hazard modelling allows defining hazard over large areas, taking in account the large variability of environmental factors that characterize the alpine landscape.

The inclusion of hazard assessment methodologies in policy tools is a primary issue. Since this issue requires that both researchers and policy-makers give a contribute, a strong effort has been made during the project to transfer the project results and to exchange know-out with the end-users.

Section 6.5 Dissemination and exploitation of the results

- WEB publication

Updated thematic maps and detailed metadata were provided to CNR-IRPI of Perugia to be published on the web site (http://damocles.irpi.pg.cnr.it). The granular flows review document, was also provided to the CNR-IRPI of Perugia for publication on Web.

- Damocles workshop with end-users, Milano, 21 November 2002

A full-day workshop have been organized at Università Milano-Bicocca to present Damocles activities to the end-users. During the workshop, all the Damocles partners presented the results of their activities. More than 50 end-users participated to the workshop, coming from different Italian administrations: Lombardia Region, Piemonte Region, Valle d'Aosta Province, Trento Province, Lecco Province, Italian Geological Survey, and others.

- Damocles training course for the Lombardia Region end-user: 10-12-17-19 December 2002

Four full-day training courses have been organized at Università Milano-Bicocca. 25 people from the Lombardia Region end-user have been trained in the methodologies for debris-flow and rock-fall hazard assessment developed during the Damocles Project.

Section 6.6 Main literature produced

Peer Reviewed Articles:

Authors	**Date**	**Title**	**Journal**	**Reference**
Crosta G.B.	2001	Failure and flow development of a complex slide: the 1993 Sesa landslide.	*Engineering Geology*	59(1-2): 173-199
Crosta G.B. & Frattini P	2001	Rainfall thresholds for the triggering of soil slips and debris flows.	Proc. of EGS 2nd Plinius Conference 2000, Mediterranean Storms, Siena.	pp. 463-488
Guzzetti F., Crosta G.B., Detti R. & Agliardi F.	2002	Stone: a computer program for the three dimensional simulation of rockfalls	*Computers & Geosciences*	28 (9), 1081-1095
Frattini P., Ceriani M. & Crosta G.	2002	A statistical approach for hazard assessment on alluvial fans.	*Quaderni di Geologia Applicata - Serie AIGA*	**1**:1-20.
Frattini P. & Crosta G.B.	2002	Modelling of impact of forest management changes on landslide occurrence.	In: McInnes & Jakeways (eds), *Instability, planning and management*, Thomas Telford, London.	pp. 257-264
Agliardi F. & Crosta G.B.	2002	3D numerical modelling of rockfalls in the Lecco urban area (Lombardia Region, Italy)	Proc. EUROCK 2002, I.S.R.M, Madeira, Portugal, Nov. 2002	**vvvvv**
Crosta G.B., Dal Negro P. & Frattini P.	2003	Soil slips and debris flows on terraced slopes.	*Natural Hazards and Earth System Sciences*	**3**:31-41
Crosta G.B. & Frattini P.	2003	Distributed modelling of shallow landslide triggered by intense rainfall	*Natural Hazards and Earth System Sciences*	**3**:81-93
Agliardi F. & Crosta G.B.	In press	High resolution three-dimensional numerical modelling of rockfalls	*International Journal of Rock Mechanics and Mining Sciences*	In press
Crosta G.B. & Agliardi F.	In press	A new methodology for physically-based rockfall hazard assessment.	*Natural Hazards and Earth System Sciences*	In press
Crosta G.B., Cucchiaro S. & Frattini P.	In press	Validation of semi-empirical relationships for the definition of debris-flow behaviour in granular materials	Proc. 3rd Int. Conf. Debris-Flow Hazard Mitigation, Davos, Switzerland, Sept. 2003	In press

Non refereed literature:

Authors / Editors	Date	Title	Event	Reference	Type
Agliardi F., Cardinali M., Crosta G. Guzzetti F., Detti R., & Reichenbach P.	2001	A computer program to evaluate rockfall hazard and risk at the regional scale. Examples from the Lombardy region	EGS XXVI General Assembly, 25-30 March 2001	Geophysical Research Abstracts, 3	Oral Presentation and Abstract
Crosta G.B., Frattini P. & Siena L.	2001	Shallow landslide triggered by rainfall: the 27th –28th June 1997 event in Lecco Province (Lombardy, Italy)	EGS XXVI General Assembly, 25-30 March 2001	Geophysical Research Abstracts, 3	Oral Presentation and Abstract
Dal Negro P. & Frattini P.	2001	Shallow landslides triggered by prolonged rainfall: the November 2000 event in Valtellina (Central Alps, Italy).	EGS XXVI General Assembly, 25-30 March 2001	Geophysical Research Abstracts, 3	Poster and Abstract
Crosta G.B. & Frattini P.	2001	Coupling empirical and physically based rainfall thresholds for shallow landslides forecasting.	EGS Topical Conf., 3rd Plinius Conf. on Mediterranean Storms, Baia Sardinia, Italy, 1-3 Nov. 2001	Proc. of EGS 3rd Plinius Conf. 2001, Mediterranean Storms, 375-378	Poster and Proceedings
Crosta G.B. & Frattini P.	2001	Physically based distributed modelling for shallow landslide hazard zonation	EGS Topical Conf., 3rd Plinius Conf. on Mediterranean Storms, Baia Sardinia, Italy, 1-3 Nov. 2001	Proc. of EGS 3rd Plinius Conf. 2001, Mediterranean Storms, 371-374	Oral presentation and Proceedings
Agliardi F., Crosta G.B., Guzzetti F. & Marian M.	2002	Methodologies for a physically-based rockfall hazard assessment	EGS XXVII General Assembly, 20-25 April 2002	Geophysical Research Abstracts, 4	Oral Presentation and Abstract
Agliardi F. & Crosta G.B.	2002	High resolution three-dimensional numerical modelling of rockfalls	EGS XXVII General Assembly, 20-25 April 2002	Geophysical Research Abstracts, 4	Oral Presentation and Abstract
Crosta G.B., Frattini P. &	2002	Distributed modelling of shallow landsliding in	EGS XXVII General Assembly, 20-25	Geophysical Research	Oral Presentation

Dal Negro P.		volcaniclastic soils	April 2002	Abstracts, 4	and Abstract
Acosta E., Agliardi F., Crosta G.B. & Rìos S	In press	Regional rockfall hazard assessment in the Benasque Valley (Central Pyrenees) using a 3D numerical approach	EGS Topical Conf., 4th Plinius Conf. on Mediterranean Storms, Mallorca, Spain, Oct. 2002	Proc. of the 4th EGS Plinius Conf., 2002, Mediterranean Storms, in press	Oral presentation and Proceedings
Crosta G.B., Cucchiaro S. & Frattini P.	In press	Determination of the inundation area for debris flows through semi-empirical equations	EGS Topical Conf., 4th Plinius Conf. on Mediterranean Storms, Mallorca, Spain, Oct. 2002	Pr Proc. of the 4th EGS Plinius Conf., 2002, Mediterranean Storms, in press	Oral presentation and Proceedings

Section 6.6 Literature cited

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Agliardi F. & G.B. Crosta. In press. High resolution three-dimensional numerical modelling of rockfalls. International Journal of Rock Mechanics and Mining Sciences.

Agliardi F. & G.B. Crosta. 2002. 3D numerical modelling of rockfalls in the Lecco urban area (Lombardia Region, Italy). Proceedings EUROCK 2002, I.S.R.M. International Symposium on Rock Engineering for Mountainous Regions and Workshops on Volcanic Rocks. Madeira, Portugal, 8 pp.

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Crosta G.B. & P. Frattini. 2003. Distributed modelling of shallow landslide triggered by intense rainfall *Natural Hazards and Earth System Sciences,* **3**:81-93.

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