DAMOCLES

DEBRISFALL ASSESSMENT IN MOUNTAIN CATCHMENTS FOR LOCAL END-USERS

Contract No EVG1 - CT-1999-00007

PERIODIC CONTRACTOR REPORT
FOR THE PERIOD
2002-2003

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SECTION 3: DETAILED REPORT OF CONTRACTOR MILANO-BICOCCA

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Summary

The activity of the third year of the project focused on the development of hazard assessment methods for debris-flows and rockfalls. 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 77%, 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 third year of the project to transfer the knowledge to the end-users: a one-day workshop and four days of courses have been organized.

3.1 Objectives of the reporting period

According to the second year report, the objectives of the third year were:

1. preparation and transfer of the GIS database on landslide distribution (rockfall, debris flow, etc.);
2. development of a new method for rock fall hazard assessment and for risk assessment both along corridors and large areas;
3. application of the rockfall model and of the hazard assessment methodologies to the Spanish Pyrenees in collaboration with the ITGE Zaragoza Team;
4. improvement of the rockfall model;
5. organization of the Damocles Training Course in collaboration with the Padova Team and the CNR CSITE sub-contractor;
6. demonstration of WP2 and WP3 workpackages links.

Section 3.2 Methodology and scientific achievements related to work packages

3.2.1. Preparation and transfer of the GIS database on landslide distribution (WP2)

The landslide inventory that was produced during the second year of the project has been implemented and updated using new photographs (taken in 2000) and digital ortho-photographs (figure 1).

In particular, debris flows have been extensively revised in order to optimise the hazard modelling procedure (figure 2). The new inventory have been introduced in a GIS environment and transferred to the Newcastle team.

A thorough collection of historical records for the study area have been completed through the analysis of several archives (Archivio di Stato di Como, Archivio del Museo Civico di Lecco – Casa di A. Manzoni, Archivio Comunale di Barzio, Archivio dell'Ufficio del CFS di Barzio, Archivio Comunale di Pasturo, Archivio Comunale di Casaro, Archivio Comunale di Primaluna, Archivio Comunale di Margno. Archivio dell'Ufficio del CFS di Margno). Data ranging from the beginning of XIX century to 1990 have been collected, recording 147 landslide events located in 97 different sites. If possible, the sites have been localized and mapped within a GIS database (figure 2).

3.2.2 Creation of the GIS-based model for debris flow hazard assessment, in collaboration with CNR CSITE sub-contractor (WP2)

A GIS-based predictive model of debris-flow occurrence was developed by using multivariate statistical techniques (Carrara 1983; Carrara and others 1995, 1999). First, 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 (Table 1a). 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 standarised 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 (Figure 3, Table 1b).

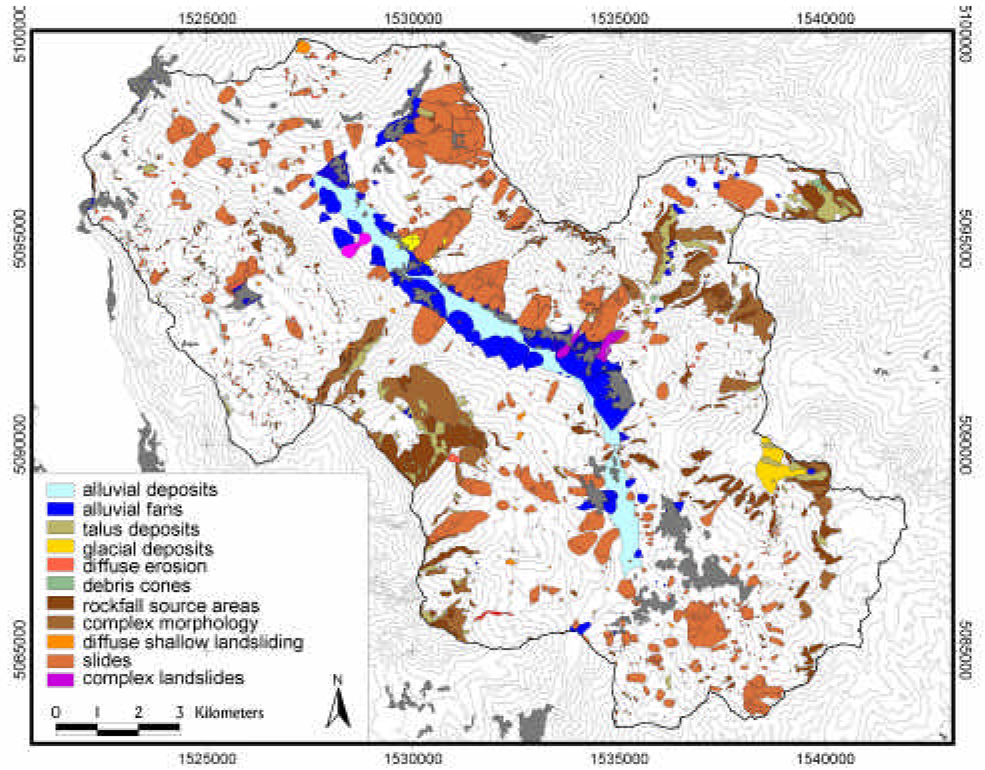

Figure 1. Map of debris flows and historical landslides in the Focus Area B (Pioverna and Esino basins)

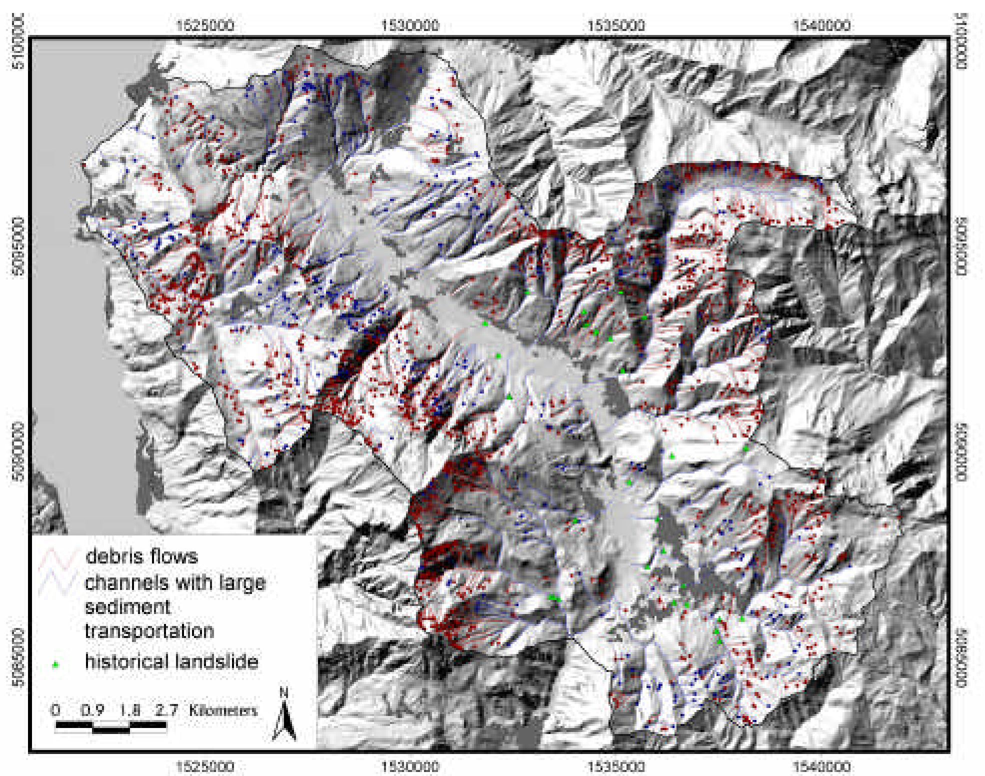

Figure 2. Map of landslide deposits in the Focus Area B (Pioverna and Esino basins)

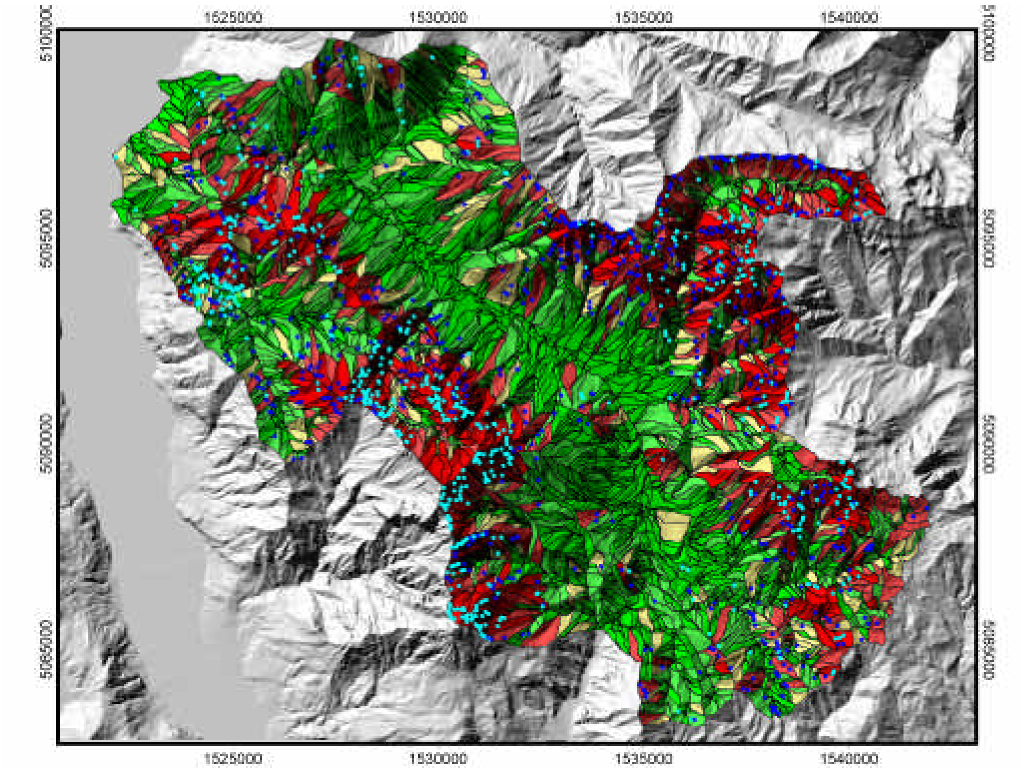

Figure 3. Predictive map of debris-flow source area based on a multivariate model that incorporates geological, morphological and land-use factors of slope units.

Among the lithological variables, the factor with the largest standardized discriminant function coefficients was the presence within the terrain unit of foliated metamorphic rocks, (MT_FL), with a negative value, in disagreement with debris-flow occurrence.

A lower mechanical resistance characterizes these rocks, giving rise to relatively gentle slopes that are poorly prone to debris flows. Thus, the influence of metamorphic rocks on debris flow susceptibility is an indirect effect of slope morphology. Among land-use variables, the presence of forest (FOR), natural vegetation (NAT_VEG), lawns and pastures (LAW_PAS), have similar negative coefficents, whereas the absence of vegetation (i.e. bare rocks and active talus; NO_VEG) shows a positive coefficient. This result indicates (1) that all kinds of vegetation cover contribute to slope stability, and (2) that no difference exists between forested and un-forested areas. As a consequence, 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 was the presence of complex morphologies (FR_Y), characterized by small scale alternations of rocky cliffs and debris deposits. In these areas, debris-flows are triggered at the base of the rocky cliffs by superficial water flow concentrated in small and very steep channels carved along the cliff. Sometimes, debris-flows are initiated by a “fire-hose” effect (Johnson & Rodine, 1984). 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 values of the standardized coefficient indicate that debris flows are strongly controlled by slope morphology. The higher the local relief and the slope angle, and the higher the energy of the slope unit and the susceptibility to debris flows. Being equal the slope energy, the density of minor channels (i.e., areas flow convergence) plays an important role in debris flow occurrence. Along minor channels, concentrated erosion occurs and pore pressure within the soil increases.

Table 1. Discriminant model of debris-flows. (a) List of the 29 variables selected by stepwise discriminant analysis as the best predictors of the occurrence in the terrain units of debris-flow source areas. The most important standardized discriminant function coefficients (SDFC) are shown in bold. (b) Classification of stable and unstable terrain units using the presence of debris-flows as the predicted variable.

a)

Variable	**Description**	**SDFC**
AR_SH	% of sandstone and shale in the terrain-unit	.111
CONG	% of conglomerate in the terrain-unit	-.118
LIM_M_SH	% of limestone with interbedded shale and marls in the terrain-unit	.059
LIM_SN	% of limestone with sandstones in the terrain-unit	-.103
LIM_ST	% of stratified limestone in the terrain-unit	-.063
MT_FL	% of foliated metamorphic rocks in the terrain-unit	**-.184**
REG	% of beds dipping toward the slope free face in the terrain-unit	-.067
FR_A	% of alluvial deposit in the terrain unit	-.070
FR_C	% of alluvial fans in the terrain unit	-.069
FR_H	% of areas with diffuse erosion in the terrain unit	.088
FR_SD	% of areas with diffuse landsliding in the terrain unit	.092
FR_Y	Index of slope irregularity	**.206**
LNK_A_OR	Interaction between channel angle and order	-.111
SLO_ARE	Area of slope-unit	**-.196**
R	I° index of terrain-unit micro-relief	**.298**
ELV_M	Mean elevation of the terrain unit	.082
RELIEF	Local relief of the terrain unit	**.729**
ANG_STD	Standard deviation of slope angle	-.107
ANGLE1	Slope angle of the lower portion of the terrain unit	**.310**
DENSITY	Index of the density of minor channels in the terrain unit	**.378**
FORM	Ratio of slope-unit perimeter and area$^{0.5}$	**-.372**
DEN_FOR	Interaction between DENSITY and FORM	**-.259**
M_NNE	Interaction between elevation and N-NE aspect of the terrain-unit	-.076
M_ESE	Interaction between elevation and E-SE aspect of the terrain-unit	-.089
FOREST	% of forested area in the terrain-unit	-.129
DEGR	% of degraded forest in the terrain-unit	-.058
NO_VEG	% of area without vegetation in the terrain-unit	-.123

(continue)

Variable	**Description**	**SDFC**
LAW_PAS	% of pasture area in the terrain-unit	-.122
NAT_VEG	% of natural vegetation area in the terrain-unit	.124

b)

Actual groups	Predicted group membership	
	Group 1 (stable terrain units)	Group 2 (unstable terrain units)
Group 1 (stable terrain units)	**80.5%**	**19.5%**
Group 2 (unstable terrain units)	**27.9%**	**72.1%**

Terrain units correctly classified: ***78.4%***

3.2.4 Definition of rockfall hazard assessment methodology

A new rockfall hazard assessment procedure has been developed (Crosta and Agliardi, in press). This 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, to be translated into planning tools with little further effort. 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*. According to the method, 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. The choice of a small number of classes allows us to simplify the classification and ranking of the computed RHI values (i.e. a 3 class subdivision results in 27 RHI values) and to obtain clearer hazard maps. The three controlling parameters are classified according to standard criteria, established through the objective evaluation of the “potential destructiveness” of simulated rockfalls. Hazard assessment is usually performed for planning or mitigation purposes. From this point of view, an increasing kinetic

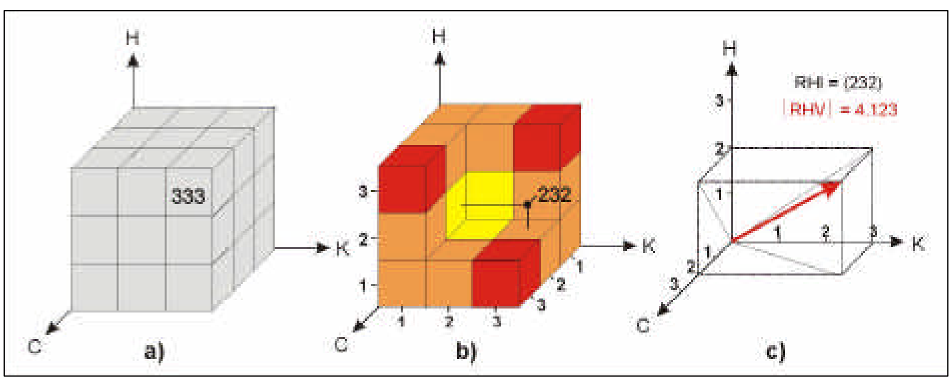

Figure 4. The three-dimensional matrix ckh, used for rockfall hazard assessment. (a) General definition of the positional Rockfall Hazard Index, RHI; (b) splitted matrix cube with ranked RHI values; (c) Rockfall Hazard Vector (RHV) concept.

energy implies higher capability of a falling rock of damaging structures (i.e. buildings, infrastructure etc.) and passive countermeasures (e.g. barriers). In addition, higher maximum fly height results in higher probability for barriers to be overcome or for higher structures to be hit. According to these considerations, we decided to reclassify the parameters *c*, *k* and *h* according to a scheme directly related with the possible final use of hazard maps for mitigation purposes.

Once the input parameters have been reclassified 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 (Figue 4) are considered sufficient to represent hazard but they are not easily represented in a map. Then, further regrouping is performed to result in 3 hazard classes (low, intermediate and high). This requires a ranking criterion allowing us to translate the positional index value into a sequential value. Such a criterion is provided by the magnitude of a Rockfall Hazard Vector RHV (see Figure 4), where c, k and h are the reclassified values of the input parameters (i.e. RHI digits). 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. The mountainous area of the Lecco Province covers about 570 km^2, mainly along the eastern shore of Como Lake. Thinly bedded and massive limestone, dolostone, marl, sandstone and metamorphic rocks crop out. In this area, high and very steep rock slopes are frequent especially in limestone and dolostone. Rockfalls are also frequent, posing a severe threat to some urban areas and along roads and the railway running along Como Lake. Fatalities caused by rockfalls have occurred in the area of Mt. S.Martino – Coltignone (February 1969, 8 casualties), at Valmadrera (July 1981, 1 casualty), at Onno Lario (1984, 1 casualty) and at Varenna (May 1997, 5 casualties).

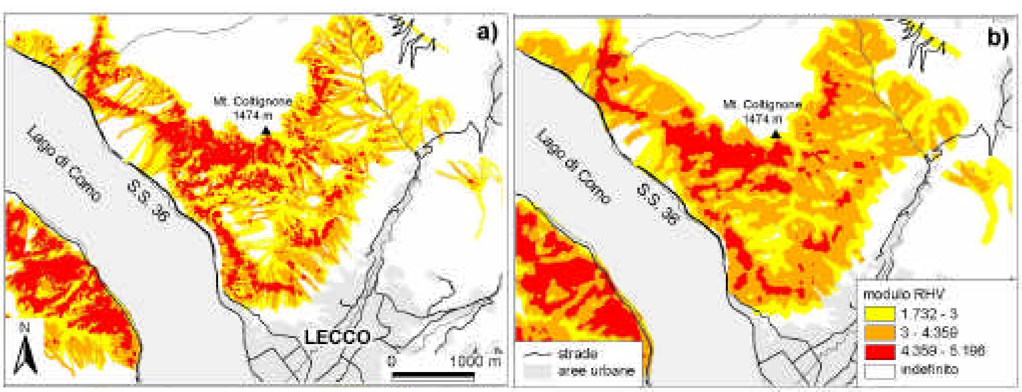

Figure 5. Close-up of the regional scale Lecco Province model (20 m ground resolution): (a) raw hazard map obtained by the application of the procedure, classified by the RHV magnitude; (b) “smoothed” hazard map obtained by averaging neighbouring cells through spatial statistics techniques. See text for explanation.

A DEM with a ground resolution of 20 metres was available for the entire area, obtained by interpolation of a subset of contour lines from the 1:10,000 scale topographic maps of the Regione Lombardia. The source areas of rockfalls were ascertained from a landslide inventory map prepared by the Regione Lombardia and the Province of Lecco. About 57 km^2 of the whole territory (10% of the total area) have been mapped as a possible “source area of rockfalls”. These areas include rocky cliffs identified on 1:10,000 topographic maps and from stereoscopic aerial photos. Minor unstable rock outcrops have been mapped through field surveys and historical rockfall reports, and 141,385 source cells were identified at the same ground resolution of the DEM. Since the experimental determination of the restitution (normal and tangential) and dynamic rolling friction coefficients across large areas is impossible both for logistic and budget limitations, initial values for such coefficients were attributed by reclassifying a “unique condition map” obtained by overlaying information about surface lithology, slope deposits, landslides, and vegetation, in order to obtain homogeneous “land units” with respect to the restitution and friction characteristics. As a consequence, unique condition areas are sectors of the study area where different features (i.e. lithology, slope deposits, landslides, vegetation, land use, etc.) are present with the same attribute (e.g., limestone, blocks, no landslide, grass, pasture, etc.). The range of values for each unique condition class has been calibrated according to the extension of scree slopes, to historic rockfall events and to the location of major boulders along the slopes. This was the most time demanding phase of the whole study because of its significance on the final results (Agliardi and Crosta, 2002).

Rockfall modelling has been performed using a probabilistic approach, by throwing 10 blocks from each source cell (for a total of 1,413,850 launched blocks) and allowing for the variability of restitution and friction coefficients into specified ranges. Cells exhibiting a very large rockfall count are located mostly along channels or in areas where the topography concentrates the falling blocks. The maximum computed velocities and heights reach 85 m/s and 500 m, respectively. A map of the translational kinetic energy, to be reclassified for hazard assessment, has been computed by considering a constant block size of 3 m^3, corresponding to about 8,000 kg, i.e. a representative size for damaging blocks in the area. Model results indicate that 328,342 cells, corresponding to about 131 km^2, (23% of the study area), are prone to rockfalls. Figure 4a shows a close-up of the computed rockfall count in the Mt. S.Martino cliff area (northern part of the Lecco urban area). The regional scale model is useful for large-scale, recognition rockfall analysis and hazard assessment, but not suitable for site-specific engineering purposes (Agliardi and Crosta, 2002).

The Rockfall Hazard Index/Vector procedure has been applied to the Lecco Province area to obtain different sets of physically-based hazard maps for local end-users and to evaluate their effectiveness. The results of low resolution modelling have been employed to obtain a preliminary recognition hazard map. Model results provided by STONE in raster format provide a conservative "worst case scenario" of hazard across an area of 570 km^2. The final map (figure 5) has been classified according to the computed magnitude of the Rockfall Hazard Vector (RHV) into three classes, namely: $1.732 \le |RHV| \le 3$ (low rockfall hazard), $3 < |RHV| \le 4.359$ (intermediate rockfall hazard) and $4.359 < |RHV| \le 5.196$ (high rockfall hazard). A fourth class has been defined representing "undefined hazard" in areas where the rockfalls are not likely to occur according to the results of numerical modelling. It must be noted that, whereas the reclassification of the parameters contributing to hazard is performed according to objective criteria, a unique way to classify the level of hazard portrayed in the final map cannot be identified, since an objective definition of "low", "moderate" or "high" hazard by means of the RHV magnitude doesn't exist. Thus, 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. In addition, hazard classification should be calibrated according to the aim of the hazard assessments (landplaning, regulation or mitigation), the spatial scale of analysis and the frequency and worth of the elements at risk.

Due to the scale of analysis, the "raw" hazard map resulting from the application of the assessment procedure (figure 5) can be excessively fragmented for practical applications. Thus, spatially distributed statistical techniques have been employed in order to obtain a smoother hazard zonation. The "raw" hazard map has been smoothed by averaging the RHV magnitude value at each cell with respect to the neighbouring cells within a radius of 20 m. Figure 6 is a close-up of the regional scale hazard model for the area north of Lecco. It clearly shows that the smoothed hazard map is much less fragmented than the "raw" one, resulting in a more effective zonation.

3.2.3 Application of the rockfall model and of the hazard assessment methodologies to the Spanish Pyrenees in collaboration with the ITGE Zaragoza Team (WP2)

A new application of the 3D numerical model for rockfall simulation was 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.

Rockfall modelling has been performed through STONE using a stochastic approach (Figure 3a, b, c). The model was calibrated using the available geomorphological information (location of mapped largest rockfall blocks and talus extent). As a result, 76% of talus areas are affected by computed trajectories and 70% of the largest blocks were along the trajectories.

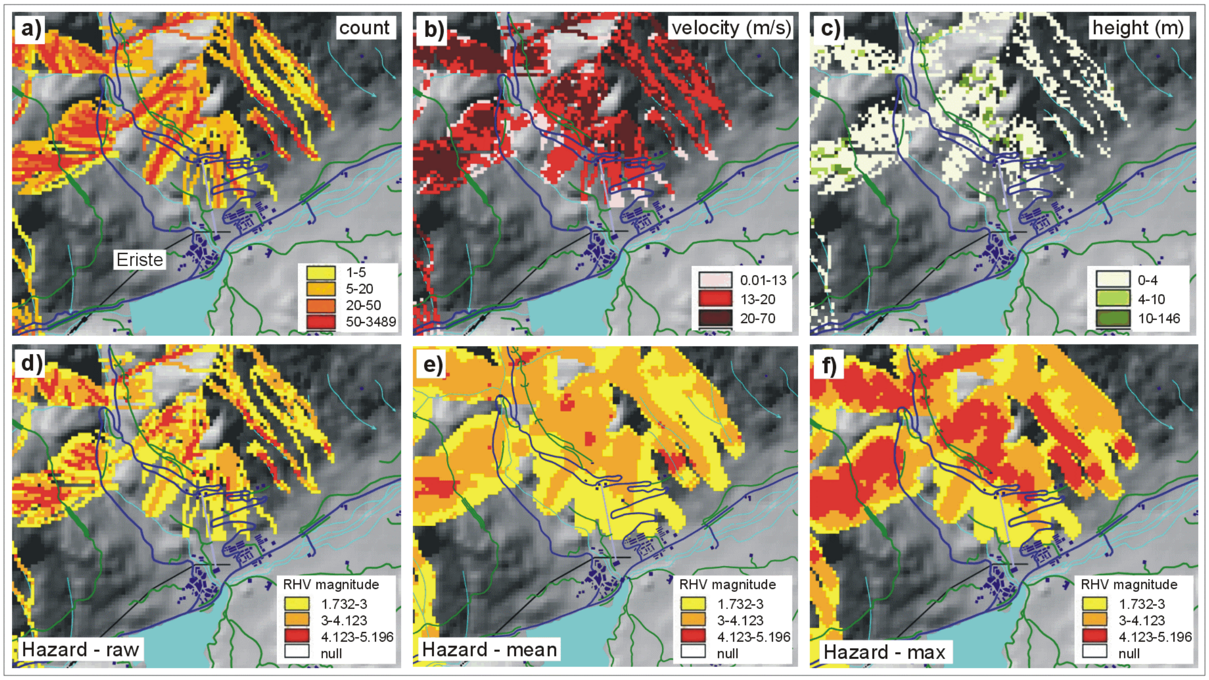

Figure 3. Close-up of the rockfall model in the Eriste area: a) rockfall count raster map; b) maximum computed velocity raster map; c) maximum computed height raster map. Hazard maps obtained through the proposed methodology: d) raw map, directly computed; b) map smoothed by the mean value (50 m neighbourhood); c) map smoothed by the maximum value (50 m neighbourhood).

The proposed new rockfall hazard assessment methodology (Crosta & Agliardi, in press) has been applied, based on the results of numerical modelling. As mentioned, STONE provides raster maps portraying the maximum frequency of transit, velocity and height of blocks at each model cell (Figure 3a, b, and c). The methodology is based on a 3D matrix with rockfall count (C), translational kinetic energy (K) and fly height (H) along the axes, providing a positional Rockfall Hazard Index (RHI), which simply includes a reference to each class value into a three digit number (Figure 2a), and a Rockfall Hazard Vector (RHV) magnitude value for each DEM cell (Figure 2b). The Rockfall hazard Vector (RHV) doesn't allow to separate the different contribution of each controlling parameters to rockfall hazard, but it points out the level of hazard allowing a simpler and more objective ranking. The input parameters (i.e. the rockfall count, the maximum kinetic energy and the highest fly height, computed at each cell) are reclassified according to the scheme proposed in Figure 2c. The reclassification is based on the evaluation of different levels of destructivity with respect to structures (buildings) and passive countermeasures (retaining fills, rockfall barriers), and allows to combine the parameters in a RHI index and to compute the magnitude of the RHV vector, required to rank hazard. Different hazard maps have been obtained using raster maps computed by STONE (Figure 3a, b and c). Hazard computation according to the proposed methodology allowed to obtain a "raw" hazard map (figure 3d). 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.

3.2.4 Improvement of the rockfall model (WP2)

Due to administrative difficulties, the project funds that were dedicated to the Lombardia Region end-user have been used to pay another sub-contractor for the improvement of the rockfall model. The new algorithm that has been implemented allows a hydrid modelling of rock motion along three-dimensional surfaces. With this improvement rock mass and rock shape can be directly incorporated within the simulation, with large benefits for the rockfall modelling. The new algorithm is used at the moment for testing and will be fully operative in few months.

3.2.7 Organization of the Damocles Training Course (WP5)

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

A full-day workshop have been organized at University of Milano Bicocca to present Damocles activities to the end-users. The workshop was organized in collaboration with the EC-project ECO-GEOWATER, a project aimed to educate young European researchers to GIS application on Natural Hazard studies. Chairman of the workshop was Dr. James Bathurst, who held an introductory speech to present the Damocles project. During the morning Dr. Alberto Carrara (CNR-IEIIT-Bologna), Prof. Giovanni B. Crosta (University of Milano Bicocca) and Dr. Greta Moretti (University of Newcastle) presented the results of statistical and physically–based modelling of rockfalls and debris flows. A first general discussion was chaired by Dr. Dario Fossati (Regione Lombardia). During the afternoon Prof. Mario Lenzi (University of Padova) showed the application of 2D and 3D modelling of debris flows on alluvial fans, and Dr. José M. Ruiz, Santiago Begueria and Enrique Acosta presented results of debris-flow and rockfall hazard assessment in the Pyrenees. A final general discussion was chaired by Paolo Campedel (Provincia Autonoma di Trento). The participants of the workshop were: 25 young researcher from several European contries (Italy, UK, Spain, Poland, Hungary and Check Republic); more than 50 end-users coming from different Italian administrations: Lombardia Region, Piemonte Region, Friuli-Venezia Giulia Region, Valle d'Aosta Province, Trento Province, Lecco Province, Verbano Province, CNR-IRPI of Torino and the Italian Geological Survey. All speeches were held in English, and a simultaneous translation service has been provided to the end-users. During the discussions, which were held mostly in Italian, the translation service was very useful for young researchers and Damocles partners, otherwise unable to participate to the discussion.

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

Four full-day (from 9.30 a.m to 18 p.m) training courses have been organized at Università Milano Bicocca. The courses were held by Prof. Giovanni B. Crosta, Dr. Alberto Carrara, Dr. Paolo Frattini and Dr. Federico Agliardi. The participants were 25 people from the Regione Lombardia end-user. During the first day the course was focalised on general topics related to landslides: classification, on field recognition, aerial photo interpretation and mapping. The landslide inventory produced during the Damocles project was presented and discussed. During the second day, the methods for the production and the updating of a digital landslide inventory were discussed. A part of the day was dedicated to a practical training on aerial photo-interpretation for the production of a landslide cartography. The third day was devoted to landslide hazard. Different methods for hazard and susceptibility assessment were reviewed and the results of the Damocles project were presented. The possible application of these results was discussed with the end-users. During the fourth day, the 3D rockfall model was presented, showing the theory, the results and the possible applications to rockfall hazard assessment.

3.2.7 Demonstration of WP2 and WP3 workpackages links (WP5)

In order to demonstrate the links between WP2 and WP3 for integrated debris flow hazard assessment on alluvial fan, a demonstrative presentation was prepared in collaboration with the University of Padova team. This presentation shows the methodological approach for alluvial fan hazard assessment that was developed during the Damocles project. This approach is based on the coupling of a regional scale statistical modelling and a small scale physically based modelling. The regional scale analysis is conducted by using the GIS-based model for debris flow hazard assessment (see paragraph 3.2.5). This analysis allows the identification of both the debris flow susceptibility of the slope terrain unit and the hazardous basins. The identification of a hazardous small basin (high probability of debris flow occurrence), leads to the small-scale analysis. This analysis is conducted by using the models developed by the University of Padova to simulate the propagation of the debris flow on the fan area (DEFLIMO).

Section 3.3. Socio-economic relevance and policy Implication

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).

During the project, many results have a socio-economic relevance. The data that have been acquired and organized within a GIS database provide a detailed knowledge of the territory. Landslide inventory, especially, have been acquired by the Lombardia Region end-user and applied as a tool for the planning regulation.

At the same time, 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 hazard modelling allows defining hazard over large areas, taking in account the large variability of environmental factors that characterize the alpine landscape.

Section 3.4. Discussion and conclusion

The main expected results have been realized during the third year of the project. Two GIS-based methods for hazard assessment have been produced, one for debris flows and one for rockfalls. The statistical approach for debris-flow susceptibility assessment was realized by using techniques and tools developed, tested and refined during almost 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 therefore a severe need for hazard assessment of debris flows.

The physically-based approach for rockfall hazard modeling is based on a 3D model (STONE) that was developed and tested during the Damocles 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. A further improvement of the rockfall model with a hybrid algorithm will enhance the potentiality of this hazard methodology.

Section 3.5. Recommendations arising from the Project

Hazard assessment has a strategic importance for land management in alpine areas. A strong effort is necessary for (1) the acquisition and management of data, (2) the improvement of the capability of the models, (3) the inclusion of hazard assessment methods in policy regulations.

1. Data acquisition is a major issue for the analysis and the modelling of natural hazards. Both the quantity and the quality of data must be improved, with the help of the end-users themselves. The management, manipulation and transfer of data are other important issues. The availability of Geographic Information Systems, nowadays, allows building easy-to-access geographic databases. These databases should become a high quality standard for geographical data treatment.

2. The improvement of predictive models is an important task in studying natural hazards. Again, Geographic Information Systems are valuable tools for modelling natural hazards, especially for processes that are spatially distributed, such as rockfalls and debris flows. Thus, newly improved models should be integrated in a GIS environment. An important issue that must be furthered is the evaluation of model quality, through quantitative, objective and reproducible analyses.

3. The inclusion of hazard assessment methodologies in policy tools is another primary issue. Both researchers and policy-makers should contribute to this task. The firsts should understand the needs of end-users and make the research compatible with these needs. The seconds should feed

the researchers with incentives and requirements. Finally, it is necessary that researchers and policy-makers meet each others frequently to exchange their know-out.

3.6 References

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