DAM/MR/0304/6

DAMOCLES

DEBRISFALL ASSESSMENT IN MOUNTAIN CATCHMENTS FOR LOCAL END-USERS

Contract No EVG1 - CT-1999-00007

FINAL REPORT

SECTIONS 1, 2, 3, 5, 6

PROJECT DURATION
1 March 2000 – 28 February 2003

Coordinator: **Dr James C Bathurst**
University of Newcastle upon Tyne, UK

Project web site: http://damocles.irpi.cnr.it/

May 2003

DAMOCLES

DEBRISFALL ASSESSMENT IN MOUNTAIN CATCHMENTS FOR LOCAL END-USERS

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FINAL REPORT

SECTION 1

COORDINATOR'S MANAGEMENT REPORT
FOR THE THIRD ANNUAL REPORT
FOR THE PERIOD
1 March 2002– 28 February 2003

Coordinator: **Dr James C Bathurst**
University of Newcastle upon Tyne, UK

Project web site: http://damocles.irpi.cnr.it/

April 2003

COORDINATOR'S MANAGEMENT REPORT

Coordinator:	University of Newcastle upon Tyne
Responsible Scientist:	Dr J C Bathurst
Address:	Water Resource Systems Research Laboratory School of Civil Engineering and Geosciences University of Newcastle upon Tyne Newcastle upon Tyne NE1 7RU UK
Telephone:	+44 191 222 6333/6319
Fax:	+44 191 222 6669
Email:	j.c.bathurst@newcastle.ac.uk

1.1 OBJECTIVES OF THE REPORTING PERIOD

This report covers the period 1 March 2002 – 28 February 2003. The main project objectives, by workpackage, were:

WP1: Analysis of the relationship between extreme rainfall events and the occurrence of debris flows in the flysch sector of the central Pyrenees. Enhancement of the debris flow logistic model to include deposition characteristics as well as debris flow occurrence. Debris flow characteristics studies in the Benasque valley (Spanish Pyrenees). Delivery of reports integrating the project's debris flow studies in the Alps and Pyrenees.

WP2: Development of a rockfall hazard assessment procedure and application of the procedure and the STONE rockfall model in the Benasque valley, in Lecco Province (Italy) and in other physiographical regions. Evaluation of rockfall hazard and risk for transport networks. Development of statistical models for debris flow hazard assessment for Valsassina (Italy) and the Benasque valley.

WP3: Hazard assessment applications of the debris flow impact model to the Rio Lenzi and Rio Rudan catchments (Italy) and Sahùn catchment (Benasque valley, Spain). Improvement of user-friendly graphics and data input-output scheme for the model.

WP4: Refining SHETRAN landslide model files for the Valsassina and Ijuez (Spain) focus sites. Revision and updating of the landslide inventory and completion of the landslide historical data record for the Valsassina focus area, Italy. Validation of the model for the focus sites. Development of scenarios for future land use and climate. Scenario applications and use of results to develop illustrative guidelines for land management. Integration with WP2 to provide basis for hazard assessment map for Valsassina for future conditions.

WP5: Transfer of project technologies to end-users through training courses on debris flow impact model at University of Padova and on landslide and rockfall hazard assessment at University of Milan-Bicocca. Workshops with the end-user community at IPE Zaragoza and University of Milan-Bicocca. Development of a demonstration of the link between WP2 and WP3 on the project website. Continued maintenance and upgrading of the website and testing of the GIS-based web technology for publishing thematic and landslide hazard maps on the internet. Preparation of publications.

1.2 SCIENTIFIC/TECHNICAL PROGRESS

1.2.1 Gantt Chart

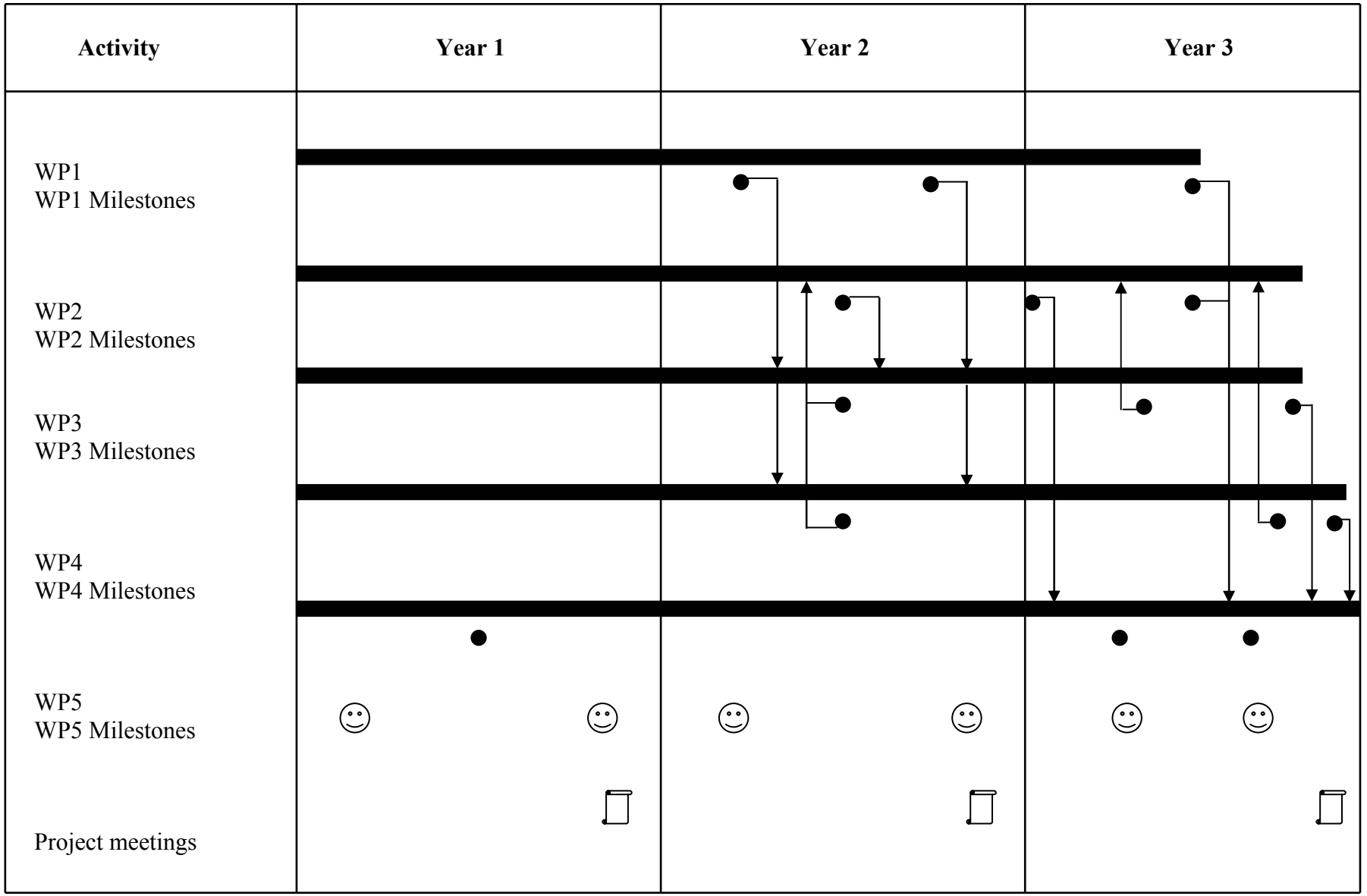
For reference purposes, the Gantt chart from the previous management report (up to October 2002) is attached.

1.2.2 Resources Used

A comparison of the originally planned and actual use of manpower resources is shown in Table 1. In general the contribution of manpower was considerably higher than originally envisaged but without requiring additional EC funding. In this sense the project represents good value for money.

A comparison of the originally planned and actual use of financial resources is shown in Table 2. Some partners have slightly exceeded their budgets while others have slightly underspent. In general, though, final expenditures are close to the original estimates and the overall project expenditure is within budget.

Gantt Chart for the DAMOCLES Project



Vertical arrows indicate exchanges between workpackages at the times indicated by the milestones.

Table 1 Manpower resources used during the full project and comparison with the originally planned use

WORK PACKAGE	RESOURCE USE IN PERSON-MONTHS FOR PARTNER									TOTAL
	1-UNEW		2-UNIBICO		3-CNR-IRPI	4-UNIPD		5-CSIC-IPE	6-IGME	
	Add*	Perm*	Add*	Perm*		Add*	Perm*			
Coordination	9.5	4								13.5
WP1	0	0	4	12.5	0	3	2.5	60.8	15.61	98.41
WP2	0	0	23.5	54	10.5	1	3	5.2	5.11	102.31
WP3	0	0	0	0	0	30.5	57	1	5.46	93.96
WP4	35	3.5	5	3	0	0	1	4.5	0	52
WP5	4.2	1	3.6	2	6.33	0	4.5	7.5	4.38	33.51
Total Use for Full Project	48.7	8.5	36.1	71.5	16.83	34.5	68	79	30.56	393.69
Original Planned Use for Full Project	43	9	25.1	21.7	6.85	51	51	76.8	5.8	290.25

*Add = additional personnel; Perm = permanent personnel

Table 2 Financial resources used during the full project and comparison with the originally planned use

EXPENDITURE TYPE	EXPENDITURE IN EUROS FOR PARTNER							TOTAL
	1-UNEW		2-UNIBICO	3-CNR-IRPI	4-UNIPD	5-CSIC-IPE	6-IGME	
	Coord*	Proj*						
Actual Total	23,472	207,777	210,694	83,112	183,700	391,468	67,984	1,168,207
Original Planned Total	21,800	227,800	202,500	74,900	190,400	391,377	63,337	1,172,114
Actual EC Claim	23,472	207,777	210,694	41,556	183,700	152,673	33,993	853,865
Original Planned EC Claim	21,800	227,800	202,500	37,400	190,400	152,637	31,669	864,206

* Coord = DAMOCLES coordination; Proj = Newcastle project

1.2.3 Highlights of Progress in Each Workpackage

The emphasis in Year 3 has been on model applications, production of deliverables, transfer of the project results to the end-users and completion of the project.

WP1 Development of functional relationships for debris flow behaviour derived from field data and existing databases

(i) Data from 37 rainfall stations for 1941-2000 in the central Spanish Pyrenees have been used to develop a technique for constructing maps of the spatial distribution of extreme rainfall events. Magnitude/frequency curves can be derived for any location in the study area and four specific maps have been constructed showing the distribution of the maximum expected daily precipitation for events with return periods of 1, 5, 25 and 100 years. (Pyreneen Institute of Ecology)

(ii) The rate of occurrence of debris flows in the Ijuez catchment has been found to be essentially constant over the last 50 years (6 debris flows/km^2/100 years), despite large scale changes in land use. This lessens the effectiveness of reforestation as a debris flow mitigation practice in the area and raises the importance of the other factors like topography or soils. Comparison with rainfall intensity/duration limit curves for debris flow occurrence in the literature suggests that the Ijuez catchment is relatively susceptible to debris flows. (Pyreneen Institute of Ecology)

(iii) A project report has been submitted to the Coordinator entitled "Comparing Debris Flow Relationships in the Alps and in the Pyrenees". This notes that confined (or valley) debris flows (observed in the Alps) tend to travel further than unconfined (or hillslope) debris flows (observed in the Pyrenees). (Pyreneen Institute of Ecology)

(iv) A methodological revision of the multivariate logistic regression model for debris flow occurrence (produced for the central Pyrenees in Year 1) has been carried out to solve problems arising from the scarcity of observed events available for model development. Without a correction, the model is likely to underpredict the probability of rare events. (Pyreneen Institute of Ecology)

(v) Empirical and semi-empirical relationships for debris flow velocity, discharge, runout and depositional area have been investigated for the upper Valtellina (central Italian Alps). The characteristics of the debris flow material has an important effect on the relationship coefficients. (University of Milan-Bicocca)

(vi) Fieldwork has been carried out to identify debris flow location and to characterize magnitude in the Benasque valley (central Spanish Pyrenees). Three-dimensional debris flow cartography has been updated (increasing the number of mapped debris flows and incorporating gully sources). (Geological and Mining Institute of Spain)

WP2 Development of a GIS hazard assessment methodology using field data, available databases and model developments

(i) A rockfall hazard assessment procedure has been developed, integrating a Rockfall Hazard Index (based on rockfall count, translational kinetic energy and flying height) and a Rockfall Hazard Vector ranking scheme, allowing the production of a hazard map. The procedure was tested for the 570-km^2 Lecco Province, Lombardy Region. (University of Milan-Bicocca, CNR-IRPI Perugia)

(ii) The STONE rockfall model and the rockfall hazard assessment procedure were applied to the Benasque valley in the Spanish Pyrenees. This work supported also the transfer of the rockfall modelling technology to the Geological and Mining Institute of Spain, as an end-user. (Geological and Mining Institute of Spain, University of Milan-Bicocca)

(iii) The STONE model was applied to Yosemite Valley (California) and the Nera River Valley in Umbria (central Italy) to verify its performance in different physiographical environments. In each case, the rockfall model was combined with a map of the local transport network so as to evaluate, on a spatially distributed basis, the rockfall hazard and risk along the network. This illustrates how the model can be used in assessing risk and planning protection measures. (CNR-IRPI Perugia)

(iv) A GIS-based predictive model of debris flow occurrence was developed for Valsassina using a multivariate statistical technique, giving a debris flow probability map. The model is capable of predicting with a reliability of 78.4% which terrain units are affected by or are free of landslides. The model shows that debris flows are strongly controlled by slope morphology and that land management (i.e. forest or non-forest cover) has relatively little effect on slope stability.

(v) A debris flow probability map has been constructed for the Benasque valley (central Spanish Pyrenees). (Geological and Mining Institute of Spain, Pyreneen Institute of Ecology, University of Milan-Bicocca)

(vi) A project report has been submitted to the Coordinator entitled "Landslide Hazard Mapping by Multivariate Statistics: Comparison of Methods and Case Study in the Spanish Pyrenees". This reviews the different approaches to multivariate statistical modelling, noting in particular the advantages and disadvantages of spatially distributed (grid) and spatially lumped (e.g. topographical units) approaches for the model mapping unit. (Pyreneen Institute of Ecology)

WP3 Development of a small basin debris flow impact model using field data and a physically-based modelling approach

(i) The Debris Flow Impact Model (DEFLIMO) was applied to the 2.43-km^2 Rio Lenzi catchment in Trento Province, Italy. The aim was to compare the model-derived hazard map for the Lenzi fan with the Aulitzky method,

geomorphologically based map. Comparison was also made between the full DEFLIMO-based map and a hazard map produced using only the one-dimensional channel routing component (MODDS, Muskingum-Cunge One-Dimensional Debris-flow Simulation) coupled to a debris flow runout formula. The modelling was carried out for a debris flow volume of 30,000 m^3 and a peak discharge of 120 $m^3 s^{-1}$. (University of Padova)

(ii) MODDS was also applied to the 3-km^2 Rio Rudan catchment in Veneto Region, Italy. The aim was to identify critical sections for overflow, for input to future mitigation measures. The modelling was carried out for a debris flow volume of 64,400 m^3 and a peak discharge of 112.5 $m^3 s^{-1}$. (University of Padova)

(iii) MODDS, was applied to the 3.26-km^2 Sahùn catchment in the Benasque valley to identify critical sections for overflow, including bridges and bends, to quantify the magnitude of a large debris flow and to evaluate the debris flow hazard area within the fan. Based on formulae and field surveys, a debris flow volume of 40,000 m^3 was specified for modelling. A preliminary hazard map was derived using a runout formula to determine the area affected by material overflowing from the main channel, for a peak debris flow discharge of 197 $m^3 s^{-1}$. (University of Padova, Geological and Mining Institute of Spain)

WP4 Application of a physically-based, basin scale, landslide erosion and sediment yield model to land use and climate scenario analysis for selected sites

(i) The rainfall input data for the Valsassina focus basin have been checked and revised. The SHETRAN model grid systems and channel networks for both Valsassina and the Ijuez catchment have been revised using a 20-m and 10-m Digital Elevation Model respectively. (University of Newcastle)

(ii) The landslide inventory for Valsassina has been updated using new photographs and a historical data record of landslides from the beginning of the 19th century to 1990 has been completed (147 landslide events at 97 different sites). (University of Milan-Bicocca)

(iii) The SHETRAN hydrology model has been validated for Valsassina for the period 1/1/93 – 31/12/99. Simulated sediment yields are comparable with measured yields in the north eastern Italian Alps. A good capability has been demonstrated for bracketing the observed landslide incidence for the event of 27/28 June 1997 and for reproducing the general spatial distribution of landslides which have occurred over the last 50 years. (University of Newcastle, University of Milan-Bicocca)

(iv) The SHETRAN hydrology model has been validated for the Ijuez catchment for the period 1/1/95 – 31/12/98. Simulated sediment yields are comparable with measured yields along the Ebro valley. A good capability has been demonstrated for bracketing the observed debris flow incidence for 1990-2001 and for reproducing the general spatial distribution of landslides which have occurred over the last 50 years. (University of Newcastle, Pyreneen Institute of Ecology)

(v) A procedure has been established for generating scenarios of future climate for the two focus areas, based on data from Global Circulation Model predictions up to 2099. Simulations were carried out for land use and climate scenarios and the results were presented and compared in an electronic matrix system. This was designed to be a user-friendly means for transferring the results to the end-users. (University of Newcastle)

WP5 Dissemination of the project deliverables via training courses, workshops, implementation by end-users and placement of demonstration material on a web site

(i) A training course on the WP3 debris flow impact model was held at the University of Padova on 10 and 11 September 2002. Sixteen participants attended, largely from the end-user community. A four-day training course on the landslide and rockfall hazard assessment techniques was held for 25 staff from the Lombardy Region Geological Survey by the University of Milan-Bicocca in December 2002. (University of Padova, University of Milan-Bicocca)

(ii) Workshops for publicizing the project technologies among the end-user community were held at the Pyreneen Institute of Ecology in May 2002 and at the University of Milan-Bicocca in November 2002. The latter workshop was integrated within the EC High-level Scientific Workshop "GI and Natural Hazards" held during 18-22 November 2002. (Pyreneen Institute of Ecology, University of Milan-Bicocca)

(iii) The SHETRAN scenario simulation results for the Valsassina and Ijuez focus basins were transferred to the relevant end-users in Italy and Spain on CD, via discussion meetings. The results are available for developing guidelines for future land management to mitigate debris flow occurrence and impact.

(iv) The project website continued to be maintained and upgraded. The availability of a new release of the ArcIMS software used to publish maps and other geographical information on the web made it possible to transfer the GIS-based web site from a Windows-based system to a Linux-based system. The change, transparent to the end-user, made the system more robust and less prone to network attacks and consequent failures. (CNR-IRPI Perugia)

(vi) Several partners have prepared, or are preparing, publications on their work as described in the attached reports.

1.2.4 Workpackage Integration

Integration of modelling approaches

A demonstration link has been created for the web site, showing how the WP3 debris flow impact model can be used to examine, at the local scale, a site selected from the WP2 regional scale hazard map. (University of Milan-Bicocca, University of Padova)

A procedure for using the WP4 SHETRAN landslide model to recalibrate the WP2 hazard assessment model has been agreed. (University of Newcastle, CNR-IEIIT Bologna)

Integration of debris flow relationships with models

The WP1 data and process relationships have fed through to the model developments and applications of WP2, WP3 and WP4:

- a logistic regression for the controls on debris flows was required for the WP2 Benasque debris flow probability model;

- debris flow characteristics (e.g. volumes and runout distances) were an important component of the WP3 debris flow impact model applications;

- the survey and analysis of debris flow characteristics in the central Pyrenees carried out by the Pyreneen Institute of Ecology enabled SHETRAN's rule-based model of debris flow behaviour to be requantified for the WP4 Ijuez application.

Integration of the end-users within the project

This is covered in Section 1.2.3, WP5.

1.3 MILESTONES AND DELIVERABLES

The status of the project deliverables is as follows:

D1 Debris flow relationships and database. Reports submitted.

D2 Debris flow maps and mapping procedures. A report on landslide hazard mapping has been submitted. Details of procedures and final maps have been transferred to the end-user (Lombardy Region Geological Survey).

D3 Debris flow and rockfall database for GIS. A 5 m x 5 m DEM for Valsassina, a landslide inventory for Valsassina and thematic maps are available.

D4 Hazard and risk assessment technology. The multivariate statistical technique and the rockfall modelling methodology, together with results, have been transferred to the end-user (Lombardy Region Geological Survey).

D5 Review of rockfall and granular flow models. Report submitted.

D6 Debris flow database for impact model. Submitted.

D7 Debris flow impact model. Report and CD submitted.

D8 Debris flow impact scenario simulations. Land use and climate scenario simulations for Valsassina and the Ijuez catchment submitted on CD.

D9 Guidelines for basin management. Electronic matrices comparing the scenario simulations submitted on CDs for Valsassina and the Ijuez catchment.

D10 End-users trained in project technologies. Training courses have been held.

D11 Project technologies in the public domain. Achieved by the training courses, workshops, CDs of scenario results, website and published papers.

D12 Proposal for standard approach to zonation. Achieved with D4 and the training of end-users.

1.4 DEVIATIONS FROM THE WORK PLAN AND/OR TIME SCHEDULE

Work has generally unfolded as planned. The University of Newcastle took on additional research associate staff to compensate for the unforeseen departure of the original research associate in the middle of the project (see the Year 2 report) and to ensure that the relevant deliverables were completed by the end of the project. CNR-IRPI, Perugia, was involved in two additional, unforeseen tasks, namely the application of the STONE rockfall model in Yosemite Valley and the Nera River valley and the porting of the GIS-based web server on a Linux-based system. However, the impacts on the project were very positive and did not adversely affect CNR-IRPI's work programme.

1.5 COORDINATION BETWEEN PARTNERS AND COMMUNICATION ACTIVITIES

Progress meetings were held at Zaragoza during 16 – 17 May 2002 and Milan on 22 November 2002. Copies of the minutes have been submitted to the EC.

There has been excellent collaboration between the partners over data collection, model application and dissemination of project results, as described in the previous report.

The dissemination of project technologies within the end-use community is reported in Section 1.2.3, WP5.

Several partners have been or will be involved in conferences and other meetings as described in the attached reports. A paper, co-authored by all the project partners, has been submitted for presentation at the Third International Conference on Debris-Flow Hazards Mitigation, to be held at Davos, Switzerland, during 10 – 12 September 2003.

1.6 DIFFICULTIES IN MANAGEMENT AND COORDINATION

There are no difficulties to report.

APPENDICES

Section 3 of the Final Report contains detailed progress reports by

- University of Newcastle upon Tyne, UK

- University of Milan-Bicocca, Italy
- CNR-IRPI, Italy
- University of Padova, Italy
- Pyreneen Institute of Ecology, Spain
- Geological and Mining Institute of Spain.

DAMOCLES

DEBRISFALL ASSESSMENT IN MOUNTAIN CATCHMENTS FOR LOCAL END-USERS

Contract No EVG1 - CT-1999-00007

FINAL REPORT

SECTION 2

EXECUTIVE PUBLISHABLE SUMMARY
FOR THE THIRD ANNUAL REPORT
FOR THE PERIOD
1 March 2002 – 28 February 2003

Coordinator: **Dr James C Bathurst**
University of Newcastle upon Tyne, UK

Project web site: http://damocles.irpi.cnr.it/

April 2003

SECTION 2: Executive publishable summary, related to reporting period (12 months)

Contract n°	EVG1-CT-1999-00007	Reporting period:	1/3/2002 – 28/2/2003
Title	DAMOCLES: Debrisfall Assessment in Mountain Catchments for Local End-users		

Objectives:

(i) To carry out the work of the third year of the project, at the workpackage level and, as appropriate, with integration between workpackages. This work involves a shift from the Year 2 emphasis on model development and testing to model application and project completion.

(ii) To complete the project deliverables.

(iii) To carry out the end-user training programme and transfer the project results to the end-user community.

Scientific achievements:

WP1 Development of functional relationships for debris flow behaviour derived from field data and existing databases

Maps have been constructed of the spatial distribution of extreme rainfall events in the central Spanish Pyrenees. The rate of occurrence of debris flows in the Ijuez focus catchment was essentially constant over the last 50 years, despite large scale changes in land use, suggesting that reforestation is unlikely to be an effective debris flow mitigation practice. Fieldwork to characterize debris flows and to improve debris flow maps has been carried out in the Benasque valley (central Spanish Pyrenees). A report has been submitted to the Coordinator entitled "Comparing Debris Flow Relationships in the Alps and in the Pyrenees"; confined (or valley) debris flows tend to travel further than unconfined (or hillslope) debris flows and debris flow material has an important effect on debris flow behaviour.

WP2 Development of a GIS hazard assessment methodology using field data, available databases and model developments

A rockfall hazard assessment procedure has been developed and used to develop hazard maps for Lecco Province (Italy) and the Benasque valley. The STONE rockfall model was applied to sites in California and central Italy to give, on a spatially distributed basis, the rockfall hazard and risk along local transport networks. A debris flow probability map was constructed for the Valsassina focus basin, indicating with a reliability of 78.4% which terrain units are affected by or are free of landslides. Slope morphology is found to have a much greater control on debris flow occurrence than does land management. A debris flow probability map has also been produced for the Benasque valley. A report has been submitted to the Coordinator entitled "Landslide Hazard Mapping by Multivariate Statistics: Comparison of Methods and Case Study in the Spanish Pyrenees".

WP3 Development of a small basin debris flow impact model using field data and a physically based modelling approach

The Debris Flow Impact Model (DEFLIMO) was applied to the 2.43-km^2 Rio Lenzi catchment (Trento Province, Italy) to derive a hazard map for the fan. Comparisons were made with hazard maps derived using the Aulitzky geomorphological method and using only the one-dimensional channel routing component (MODDS) of the model, coupled to a debris flow runout formula. MODDS was also applied to the 3-km^2 Rio Ruhan catchment (Veneto Region, Italy) and the 3.26-km^2 Sahùn catchment (central Spanish Pyrenees) to identify critical sections for overflow and to evaluate the debris flow hazard area within the fan.

WP4 Application of a physically based, basin scale, landslide erosion and sediment yield model to land use and climate scenario analysis for selected sites

Validation of the SHETRAN landslide sediment yield model was completed for the Valsassina and Ijuez focus catchments. The results demonstrate an ability to bracket the observed occurrence of debris flows with simulated distributions and to determine catchment sediment yield within the range of regional observations. Future land use and climate scenarios were developed for the focus catchments (with advice from the local partners and end-users): SHETRAN was applied to these scenarios to give the spatial distribution of debris flow occurrence and the sediment yield. The simulation results were summarized in electronic matrices and transferred to the end-users on CD for use in developing guidelines for future land management to mitigate debris flow occurrence and impact.

WP5 Dissemination of the project deliverables via training courses, workshops, implementation by end-users and placement of demonstration material on a web site

Training courses on the WP2 landslide and rockfall hazard assessment techniques and the WP3 debris flow impact model have been held for the project end-users. Workshops for publicizing the project technologies were held in Spain and Italy. The WP4 scenario simulation results for the Valsassina and Ijuez focus basins were transferred to the end-users on CD, using an electronic matrix system. The DAMOCLES project website (http://www.irpi.cnr.it) continued to be maintained and upgraded: a GIS-based web technology provides the basis for publishing maps and other geographical information at a range of scales.

Workpackage integration
A demonstration link has been created for the website showing how the WP3 debris flow impact model can be used to examine, at the local scale, a site selected from the WP2 regional scale hazard map. A procedure for using the WP4 SHETRAN landslide model to recalibrate the WP2 hazard assessment model is being tested. The WP1 data and process relationships have fed through to the model developments and applications of WP2 (the Benasque debris flow probability model), WP3 (the debris flow impact model applications) and WP4 (requantification of SHETRAN's debris flow behaviour model).

Socio-economic relevance and policy implications:
Every year debris flows and rockfalls cause loss of life and injury, direct damages run to tens of millions of euros and further large indirect costs arise from impacts such as road closures and insurance cover. The annual budget of the Autonomous Province of Trento alone is 20 million euros for torrent control works and debris flow management. Within this context DAMOCLES has developed modelling and mapping technologies designed to allow more accurate (and quantitative) hazard assessments from the local to the regional scale. In turn these are intended to allow more efficient land use planning and improved design of torrent control works, to the benefit of life and livelihood. The project end-users have been closely involved and are already making use of the technologies to achieve the above aims.

Conclusions:
Year 3 has seen the completion and testing of all the project modelling and mapping techniques. Notable achievements include the use of the STONE rockfall model to evaluate the hazard to transport networks, the development of a rockfall hazard assessment procedure, further productions of regional scale hazard probability maps, applications of the DEFLIMO debris flow impact model in Italy and Spain, scenario analysis with the SHETRAN basin scale model to show the impact of land use and climate change on landslide occurrence and sediment yield, and the production of maps of extreme rainfall distribution in the central Pyrenees (which can be used to recalculate design rainfalls and discharges for public works). All the project deliverables has been completed. Strong end-user involvement, including participation in training courses and model applications, and continued upgrading of the website have maximised the transfer of the project technologies into the public domain.

Keywords:
Central Spanish Pyrenees; data collection; debris flows; debris flow model; dissemination; end-users; hazard assessment maps; Italian Alps; landslide model; rockfall model; thematic maps; website.

Publications (cumulative list)

Peer Reviewed Articles:

Authors	Date	Title	Journal	Reference
Arnaez, J., Marti-Bono, C., Begueria, S., Lorente, A., Errea, M.P. & Garcia-Ruiz, J.M.	1999	Factores en la generacion de crecidas en una cuenca de campos abandonados, Pirineo Central Espanol.	*Cuadernos de Investigacion Geografica*	24: 7-24
Begueria, S. & Lorente, A.	1999	Distribucion espacial del riesgo de precipitaciones extremas en el Pirineo aragones occidental.	*Geographicalia*	37: 17-36
Garcia-Ruiz, J.M., Valero, B., Gonzalez, P., Lorente, A., Marti-Bono, C., Begueria, S. & Edwards, L.	2001	Stratified scree in the Central Spanish Pyrenees: Paleoenvironmental implications.	Permafrost and Periglacial Processes.	12: 233-242
D'Agostino, V. & Marchi, L.	2001	Debris flow magnitude in the eastern Italian Alps : data collection and analysis	Physics and Chemistry of the Earth	Part C, 26(9): 657-663
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): 1079-1093
Crosta, G.B.	2001	Failure and flow development of a complex slide: the 1993 Sesa landslide	Engineering Geology	59(1-2): 173-199
Garcia-Ruiz, J.M., Marti-Bono, C., Lorente, A. & Begueria, S.	2003	Geomorphological consequences of frequent and infrequent rainfall and hydrological events in a Mediterranean mountain area	Mitigation and Adaptation Strategies for Global Change	
Frattini, P. & Crosta, G.B.	2002	Modelling the impact of forest management changes on landslide occurrence	Int. Conference on Instability – Planning and Management, Ventnor, Isle of Wight	In press
Lenzi, M.A.	2001	Step-pool evolution in the Rio Cordon: Northeastern Italy	Earth Surface Processes and Landforms	26: 991-1008
Bathurst, J.C., Crosta, G., García-Ruiz, J.M., Guzzetti, F., Lenzi, M. & Ríos Aragüés, G	2003	DAMOCLES: Debrisfall Assessment in Mountain Catchments for Local End-users	Proc. 3rd Intl. Conf. Debris-flow Hazards Mitigation, Davos, Switzerland, 10-12 September	In press
Lorente, A., Begueria, S, Bathurst, J & García-Ruiz, J.M.	Submitted	Debris flow characteristics and relationships in the Central Spanish Pyrenees	Natural Hazards and Earth System Sciences	-

Begueria, S., Lopez-Moreno, J.I., Lorente, A., Seeger, M. & García-Ruiz, J.M.	2003	Assessing the effect of climate oscillations and land use changes on streamflow in the Central Spanish Pyrenees.	Ambio	-
Lorente, A. & Begueria, S.	2002	Variation saisonniere de l'intensité des precipitations maximales dans les Pyrenées Centrales: Analyse spatiale et cartographique	Publ. de l'Ass. Intern. Climatologie	
Lorente, A., García-Ruiz, J.M., Begueria, S. & Arnaez, J.	2002	Factors explaining the spatial distribution of hillslope debris flows. A case study in the Flysch Sector of the Central Spanish Pyrenees.	Mountain Research and Development	22(1): 32-39
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Lenzi M.A.	2002	Nuevos modelos para la predicción de riesgos geomorfológicos en abanicos aluviales; un ejemplo de los Alpes Dolomíticos	Workshop "Métodos para la predicción de riesgos de movimientos de ladera en áreas de montaña » ; Zaragoza, May 14-15 2002.		Oral presentation

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Moretti, G. & Bathurst, J.C.	2002	Physically based modelling of landslide sediment yield at Valsassina, Italian pre-Alps	ECO-GEOWATER "GI and Natural Hazards" Euroworkshop, 18-22 November, Univ. Milan-Bicocca	Website	Oral Presentation and Abstract
Moretti, G. & Bathurst, J.C.	2003	Physically based modelling of landslide sediment yield at Valsassina, Italian pre-Alps	EGS-AGU-EUG Joint Assembly, 6-11 April	Geophysical Research Abstracts, 5	Oral Presentation and Abstract
Bathurst, J.C., Carrara, A., Crosta, G., Frattini, P. & Moretti, G.	2003	An integrated apporach for assessing debris flow hazard at regional scale	EGS-AGU-EUG Joint Assembly, 6-11 April	Geophysical Research Abstracts, 5	Abstract

Planning of future publications: (type, date, contents, …)

Burton, A., Bathurst, J.C., Clarke, B.G. & Gallart, F. Validation of a basin scale, landslide sediment yield model, Llobregat Basin, Spanish Pyrenees. Journal.

Bathurst, J.C., Moretti, G., El-Hames, A., Moaven-Hashemi, A., Crosta, G. & Frattini, P. Application of SHETRAN landslide sediment yield model, Valsassina, Italian pre-Alps. Journal.

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Participants information:

N°	Institution/Organisation	Street name and number	Post Code	Town/City	Country Code	Title	Family Name	First Name	T
1	University of Newcastle upon Tyne	School of Civil Engineering and Geosciences	NE1 7RU	Newcastle upon Tyne	UK	Dr	Bathurst	James C	+4
2	Dip Scienze Geol. & Geotecnol. Univ. Studi di Milano-Bicocca	Piazza della Scienza 4	20126	Milano	Italy	Prof	Crosta	Giovanni	+3
3	CNR-IRPI Perugia	via della Madonna Alta 126	06128	Perugia	Italy	Dr	Guzzetti	Fausto	+3
4	University of Padova Department of Land and Agroforest Environment	Agripolis via Romea	35020	Legnaro (PD)	Italy	Prof	Lenzi	Mario	+3
5	Instituto Pirenaico de Ecologia (CSIC)	Avda Montañana 177, Campus de Aula Dei, Apartado 202	50080	Zaragoza	Spain	Dr	Garcia-Ruiz	José M	+3
6	Instituto Geológico y Minero de España	c/Fernándo El Católico, 59, 4ºC	50006	Zaragoza	Spain	Mr	Ríos	Santiago	+3

DAM/MR/0304/6

DAMOCLES

DEBRISFALL ASSESSMENT IN MOUNTAIN CATCHMENTS FOR LOCAL END-USERS

Contract No EVG1 - CT-1999-00007

FINAL REPORT

SECTION 3

DETAILED REPORTS OF CONTRACTORS AND ASSISTANT CONTRACTORS FOR THIRD ANNUAL REPORT
1 March 2002 – 28 February 2003

Coordinator: **Dr James C Bathurst**
University of Newcastle upon Tyne, UK

Project web site: http://damocles.irpi.cnr.it/

April 2003

DAM/MR/0304/6

DAMOCLES

DEBRISFALL ASSESSMENT IN MOUNTAIN CATCHMENTS FOR LOCAL END-USERS

Contract No EVG1 - CT-1999-00007

FINAL REPORT

SECTION 5

EXECUTIVE PUBLISHABLE SUMMARY
RELATED TO THE OVERALL PROJECT DURATION
FOR THE PERIOD
1 March 2000 – 28 February 2003

Coordinator: **Dr James C Bathurst**
University of Newcastle upon Tyne, UK

Project web site: http://damocles.irpi.cnr.it/

May 2003

SECTION 5: Executive publishable summary, related to the overall project duration

Contract n°	EVG1-CT-1999-00007	Reporting duration:	1/3/2000 – 28/2/2003
Title	DAMOCLES: Debrisfall Assessment in Mountain Catchments for Local End-users		

Objectives:

(iv) 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;

(v) To conduct field surveys and assemble databases in support of model development and to improve mapping and data analysis techniques;

(vi) To transfer the technologies to end-users and make the outcomes accessible through the public domain.

Scientific achievements:

WP1 Development of functional relationships for debris flow behaviour derived from field data and existing databases

Predictive relationships for key debris flow characteristics, such as runout distance, were derived and used to refine the WP3 and WP4 models. Discriminant analysis defined the main factors that contribute to the triggering of debris flows in the flysch sector of the Central Spanish Pyrenees, providing the basis for a logistic model of the spatially-varying probability of occurrence of debris flows. Maps were constructed of the spatial distribution of extreme rainfall events in the Central Spanish Pyrenees, to support predictions of debris flow occurrence and the design of public works for mitigating debris flow impact.

WP2 Development of a GIS hazard assessment methodology using field data, available databases and model developments

Using statistical multivariate regression models, regional scale debris flow susceptibility maps were generated for Lecco Province (Lombardy pre-Alps, Italy) and the flysch sector and the Benasque Valley field areas in the Central Spanish Pyrenees. Within Lecco Province a debris flow probability map constructed for the Valsassina focus basin, showed a prediction reliability of 78.4%. A new three-dimensional rockfall model was developed for scales ranging from the hillslope to the regional. A rockfall hazard assessment procedure containing the model was also developed and used to construct hazard maps for Lecco Province and the Benasque valley. Model applications in California and central Italy gave the rockfall hazard along local transport networks.

WP3 Development of a small basin debris flow impact model using field data and a physically based modelling approach

A debris flow impact model, DEFLIMO, applicable at the scale of a small catchment (typically up to 10 km^2) containing a mountain torrent channel linked to a fan was developed. With a user-supplied debris flow hydrograph as input, the model routes the debris flow along the channel using a one-dimensional scheme. This has the innovative ability to account for the effect of structures such as check dams and bridges, constrictions in channel cross section and overbank flow. A two-dimensional scheme then represents debris flow propagation and sedimentation on the fan area on a time-varying basis. Applications to catchments in the North-eastern Italian Alps and the Central Spanish Pyrenees showed a good ability to identify critical sections for overflow and to evaluate the debris flow hazard area within the fan.

WP4 Application of a physically based, basin scale, landslide erosion and sediment yield model to land use and climate scenario analysis for selected sites

The existing SHETRAN model was applied to determine debris flow spatial and temporal occurrence and impact on sediment yield for focus basins in the Italian pre-Alps and Spanish Pyrenees. Validation of the model for present-day conditions demonstrated an ability to bracket the observed spatial occurrence of debris flows with simulated distributions and to determine catchment sediment yield within the range of regional observations. Future land use and climate scenarios were developed for the focus catchments. Comparison of the scenario and present-day simulation results showed the sorts of changes in landslide incidence and sediment yield response which may be observed in the future and thus provide a context within which guidelines for land management can be developed to minimize debris flow impacts.

WP5 Dissemination of the project deliverables via training courses, workshops, implementation by end-users and placement of demonstration material on a web site

Training courses on the WP2 landslide and rockfall hazard assessment techniques and the WP3 debris flow impact model and workshops for publicizing the project technologies were held for the project end-users. The WP4 scenario simulation results for the Italian and Spanish focus basins were transferred to the end-users on CD. The DAMOCLES project website http://damocles.irpi.cnr.it was set up at the start of the project and

maintained and upgraded throughout the project. A GIS-based web technology was installed for the internet distribution of landslide inventory and hazard maps generated by the project, at a range of scales.

Workpackage integration
A demonstration link was created for the website showing how the WP3 debris flow impact model can be used to examine, at the local scale, a site selected from the WP2 regional scale hazard map. A procedure for using the WP4 SHETRAN landslide model to recalibrate the WP2 hazard assessment model for possible future conditions is being tested. The WP1 data and process relationships fed through to the model developments and applications of WP2 (the Benasque debris flow probability model), WP3 (the debris flow impact model applications) and WP4 (requantification of SHETRAN's debris flow behaviour model).

Main deliverables:
D1 Debris flow relationships and database. Reports submitted.
D2 Debris flow maps and mapping procedures. Report submitted. Procedures transferred to end-user.
D3 Debris flow and rockfall database for GIS. Valsassina DEM, landslide inventory and maps available.
D4 Hazard and risk assessment technology. Methodology, together with results, transferred to end-user.
D5 Review of rockfall and granular flow models. Report submitted.
D6 Debris flow database for impact model. Submitted.
D7 Debris flow impact model. Report and CD submitted.
D8 Debris flow impact scenario simulations. Scenario simulations for focus basins submitted on CD.
D9 Guidelines for basin management. Matrices comparing the scenario simulations submitted on CDs.
D10 End-users trained in project technologies. Training courses have been held.
D11 Project technologies in the public domain. Training courses, workshops, website and papers.
D12 Proposal for standard approach to zonation. Achieved with D4 and the training of end-users.

Socio-economic relevance and policy implications:
Every year debris flows and rockfalls cause loss of life and injury, direct damages running to tens of millions of euros and further large indirect costs arising from impacts such as road closures and insurance cover. The DAMOCLES project therefore achieves its relevance through the development of modelling and mapping technologies designed to allow more accurate (and quantitative) hazard assessments from the local to the regional scale. In turn these are intended to allow more efficient land use planning and improved design of torrent control works, to the benefit of life and livelihood. The project end-users have been closely involved and are already making use of the technologies to achieve the above aims. EU policies which could benefit from the project results include the Water Framework Directive and the Cohesion and Agriculture Policies.

Conclusions:
DAMOCLES has developed a suite of quantitative and spatially distributed models for debris flow and rockfall hazard assessment, impact prediction and mitigation studies. 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. They improve upon previously existing techniques through their ability to quantify hazard on a spatially distributed basis, to explore the mitigating effects of torrent control works and land management for present and future conditions and, in the case of the rockfall model, to determine hazard in a three-dimensional setting. 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. Strong end-user involvement, including participation in training courses and model applications, and continued upgrading of the website have maximised the transfer of the project technologies into the public domain.

Dissemination of results:

The principal dissemination activities are described under WP5 above. The end-users are already actively exploiting the project technologies and form the primary route by which the technologies will enter the user community. Publication in the scientific literature is already extensive, with further publications still to come.

Keywords:
Central Spanish Pyrenees; data collection; debris flows; debris flow model; dissemination; end-users; hazard assessment maps; Italian Alps; landslide model; rockfall model; thematic maps; website.

DAM/MR/0304/6

DAMOCLES

DEBRISFALL ASSESSMENT IN MOUNTAIN CATCHMENTS FOR LOCAL END-USERS

Contract No EVG1 - CT-1999-00007

FINAL REPORT

SECTION 6

COORDINATOR'S DETAILED REPORT
RELATED TO OVERALL PROJECT DURATION
FOR THE PERIOD
1 March 2000 – 28 February 2003

Coordinator: **Dr James C Bathurst**
University of Newcastle upon Tyne, UK

Project web site: **http://damocles.irpi.cnr.it/**

May 2003

COORDINATOR'S SUMMARY REPORT FOR THE FINAL REPORT

Coordinator:	University of Newcastle upon Tyne
Responsible Scientist:	Dr J C Bathurst
Address:	Water Resource Systems Research Laboratory School of Civil Engineering and Geosciences University of Newcastle upon Tyne Newcastle upon Tyne NE1 7RU UK
Telephone:	+44 191 222 6333/6319
Fax:	+44 191 222 6669
Email:	j.c.bathurst@newcastle.ac.uk

REPORT STRUCTURE

Section 6 of the project Final Report consists of two parts: the first part (this report) is the Coordinator's summary of the project work and its achievements; the second part consists of detailed reports submitted by each of the partners.

6.1 BACKGROUND

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 and 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 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.) It was a project aimed at improving the efficiency and reliability of decision-making in the development of European mountain areas, with implications for the quality of life of both mountain dwellers and lowland inhabitants. Its innovative aspects included: a quantitative approach; an emphasis on user-friendliness; the direct involvement of end-users; consideration of debris flow and rockfall impacts at a range of scales; and provision of new databases.

6.2 SCIENTIFIC/TECHNOLOGICAL AND SOCIO-ECONOMIC OBJECTIVES

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. Field areas were selected in the Italian Alps and pre-Alps and 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 was 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 aimed 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 were 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 work was divided into five workpackages (WP), with objectives as follows:

WP1: Development of Functional Relationships for Debris Flow Behaviour Derived from Field data and Existing Databases. The workpackage was closely concerned with the spatial distribution of debris flows, their periodicity, their relationships with intense precipitations and their modelling using past evidences of debris flows, GIS procedures and field work. Required outcomes were improved means of predicting debris flow occurrence as a function of climate and land use and improved techniques for mapping debris flow characteristics.

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 Cientificas – 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

*WP2: Development of a GIS Hazard Assessment Methodology Using Field Data, Available Databases and Model Developments***.** The workpackage was based on the development of the multivariate statistical, GIS-based approach to regional hazard assessment. Required outcomes were quantitative hazard and risk modelling technologies for rockfalls and debris flows.

*WP3: Development of a Small Basin Debris Flow Impact Model Using Field Data and a Physically Based Modelling Approach***.** The workpackage was aimed at improving hazard assessment along debris flow channels and on the debris flow fan. The required outcome was a user-friendly model for use by end-users in assessing debris flow impact and the effect of mitigation measures.

*WP4: Application of a Physically-based Basin Scale, Landslide Erosion and Sediment Yield Model to Land Use and Climate Scenario Analysis for Selected Sites***.** The workpackage concerned the use of the SHETRAN model to provide estimates of sediment yield derived from landsliding, at the basin scale and for various scenarios of land use and climate. Required outcomes were a demonstration of debris flow impact assessment (i.e. sediment yield) for current and scenario conditions for two focus basins up to 500 km^2 in area and guidelines on basin management for the end-users.

WP5: Dissemination of the Project Deliverables via Training Courses, Workshops, Implementation by End-users and Placement of Demonstration Material on a Website. This workpackage defined the practical aspect of the DAMOCLES project in terms of technology transfer. It was important that the project should not only advance our knowledge of rapid slope failures but also put that understanding at the disposal of the end-users. The principal requirement, therefore, was transfer of the project technologies to end-users and to the public domain.

Integration of the modelling technologies of WP2, WP3 and WP4 was to provide a coherent approach to hazard assessment. Similarly the output from WP1 was to support the model developments of the other workpackages.

6.3 APPLIED METHODOLOGY, SCIENTIFIC ACHIEVEMENTS AND MAIN DELIVERABLES

The methodologies and achievements are described by workpackage.

6.3.1 Development of Functional Relationships for Debris Flow Behaviour Derived from Field Data and Existing Databases

The main field area for data collection and analysis was 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). However, data in support of the modelling developments were also collected in the Lombardy pre-Alpine area of Italy and in the Trento-Veneto-Bolzano Alpine region of Italy. The field programme underpinned 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. Analysis of 64 debris flows in the flysch sector of the Central Pyrenees was therefore carried out to establish the relationships between the key debris flow parameters. The results show, for this region, that deposition begins to occur at a higher slope gradient (about 18°) than is generally reported for other sites in the literature. Runout distances are then relatively longer than for other sites (equal on average to 60% of the elevation difference between the landslide scar and the point at which debris flow deposition begins. Similarly analysis of data from northeastern Italy quantifies debris flow volume as:

$$M = 70\ A\ S^{1.28}\ GI \qquad (1)$$

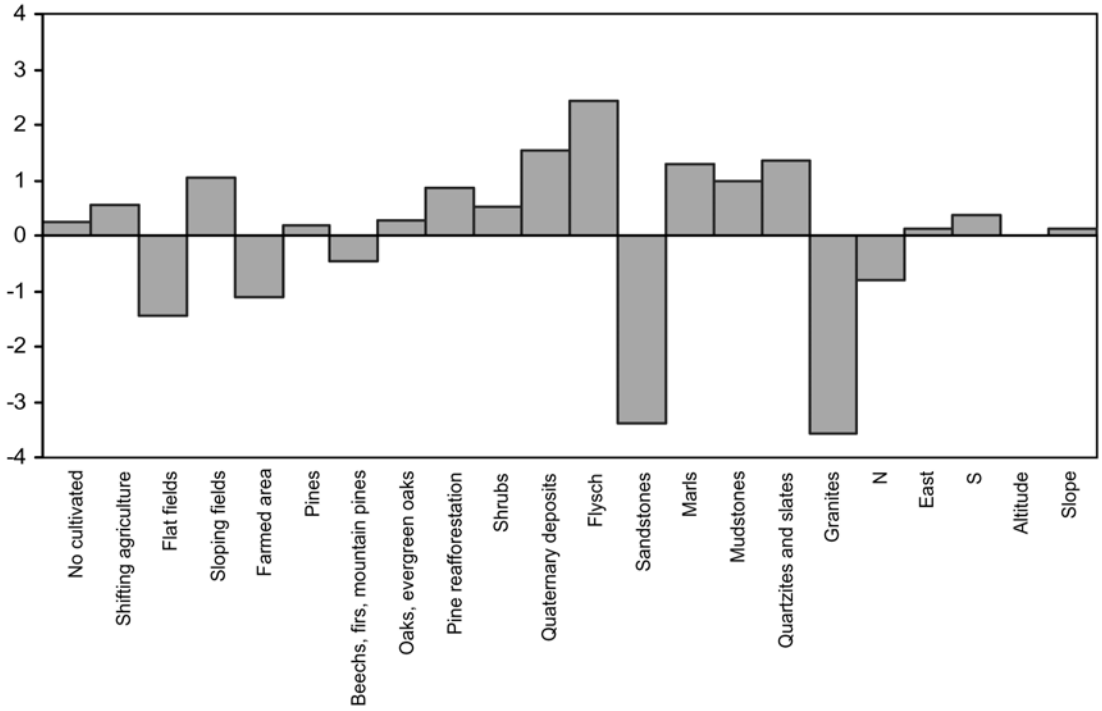

Figure 1. Discriminant analysis of factors controlling debris flow occurrence in the flysch sector of the Central Pyrenees. Positive values correlate with occurrence of debris flows. Negative values correlate with non-occurrence

where M = volume (m^3); A = catchment area (km^2); S = mean stream gradient (%); and GI = a dimensionless geological index (D'Agostino and 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 and additional analysis is reported in Crosta et al. (2003).

(2) Field data are needed to test and improve models. Within DAMOCLES, data relevant to the four main project models were collected: for regional scale hazard assessment modelling in Lombardy and the Central Pyrenees; 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, Umbria, the Central Pyrenees and California.

(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 showed that rainfall has more influence than land use change. Maps of the spatial distribution of extreme (maximum daily) rainfall were therefore constructed corresponding to events with return periods of 1, 5, 25 and 100 years: in addition to supporting predictions of debris flow occurrence these maps could be of use in improving the accuracy of design storm rainfalls and discharges for public works.

(4) The field programme provided an opportunity to improve and standardize mapping and data analysis techniques. A range of thematic maps was produced, including geomorphological characteristics and hazard probability,

in both two- and three-dimensional form. Similarly, a standard form for recording debris flow characteristics was implemented. Much of this output is held on the project website.

6.3.2 Development of a GIS Hazard Assessment Methodology Using Field Data, Available Databases and Model Developments

Hazard assessment methodologies based on Geographical Information Systems (GIS) and applicable at scales up to regional were produced, separately, for debris flows and rockfalls.

Regional Scale Debris Flow 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 was therefore proposed as the principal DAMOCLES technology, combining relative simplicity of concept 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 (or probability) map to be generated at the regional scale. Applications of this technique were carried out for Lecco province (Lombardy) (Fig. 2) and the Central Pyrenees. Within Lecco Province a separate application was carried out for the Valsassina focus basin. The resulting model was capable of predicting with a reliability of 78.4% which terrain units are affected by or are free of landslides. The model also showed that debris flows are strongly controlled by slope morphology and that land management (i.e forest or non-forest cover) has relatively little effect on slope stability.

Assessment of the technique was carried out by comparison with field observations (aerial photographs covering the period 1954-1995 in the case of the Valsassina basin)

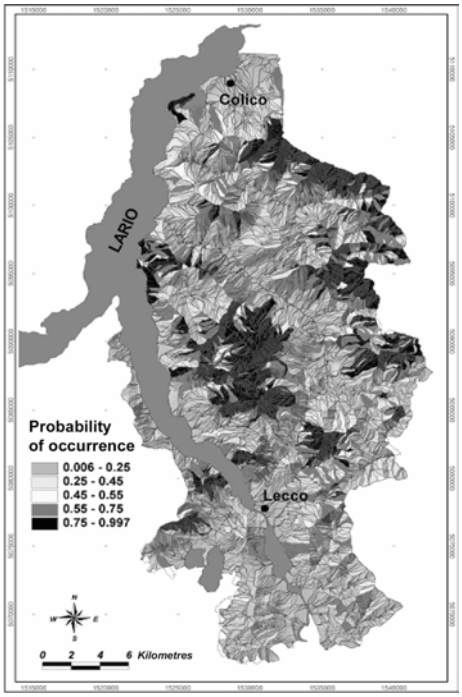

Figure 2. Example of a discriminant model of debris flow source areas, Lecco area, Lombardy, Italy

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 could be compared with the percentage of that unit which was unstable according to the physically based models (Crosta and Frattini, 2003). The information built up on model compatibilities in this way will be important for integrating the different project models in pursuit of objectives which cannot be achieved by one model on its own.

Further assessment of the multivariate statistical technique concerned the method of representing spatial distribution. The geomorphological unit, such as a small basin, (used in Italy) was compared compared with the pixel (a convenient approach, used in Spain).

Rockfall Model

The computer model STONE was developed for the simulation of rockfall trajectories in three dimensions (Guzzetti et al., 2002). It 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

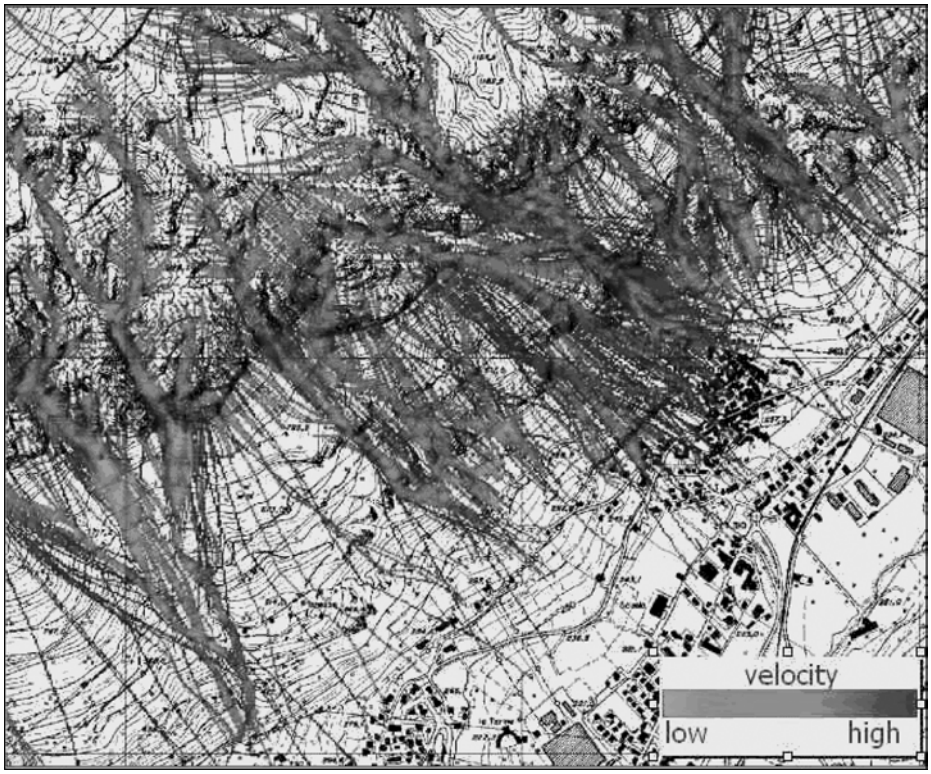

Figure 3. Example of application of the STONE rockfall model

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. 3).

Accurate calibration of the model parameters has been successfully accomplished using thematic maps and a database of observed rockfalls. Model applications were completed at different spatial scales and with different data availabilities within the 600-km^2 Lecco province in the Lombardy pre-Alps, in the Nera valley in Umbria (central Italy), in the Central Pyrenees (Acosta et al., in press) and in Yosemite Valley, California (Guzzetti et al., in press). A rockfall hazard map was produced for Lecco province, as a contribution to planning protection measures. For the applications in Umbria and California the rockfall model was combined with a map of the local transport network so as to evaluate, on a spatially distributed basis, the rockfall hazard and risk along the network. This illustrates how the model can be used in assessing risk and planning protection measures.

A rockfall hazard assessment procedure was developed, integrating a Rockfall Hazard Index (based on rockfall count, translational kinetic energy and flying height provided by the STONE model) and a Rockfall Hazard Vector ranking scheme, allowing the production of a hazard map (Agliardi and Crosta, 2002). The procedure was tested for Lecco Province. The STONE model and the rockfall hazard assessment procedure were also applied to the Benasque valley, supporting the transfer of the technology to the Geological and Mining Institute of Spain, as an end-user (Acosta et al., in press).

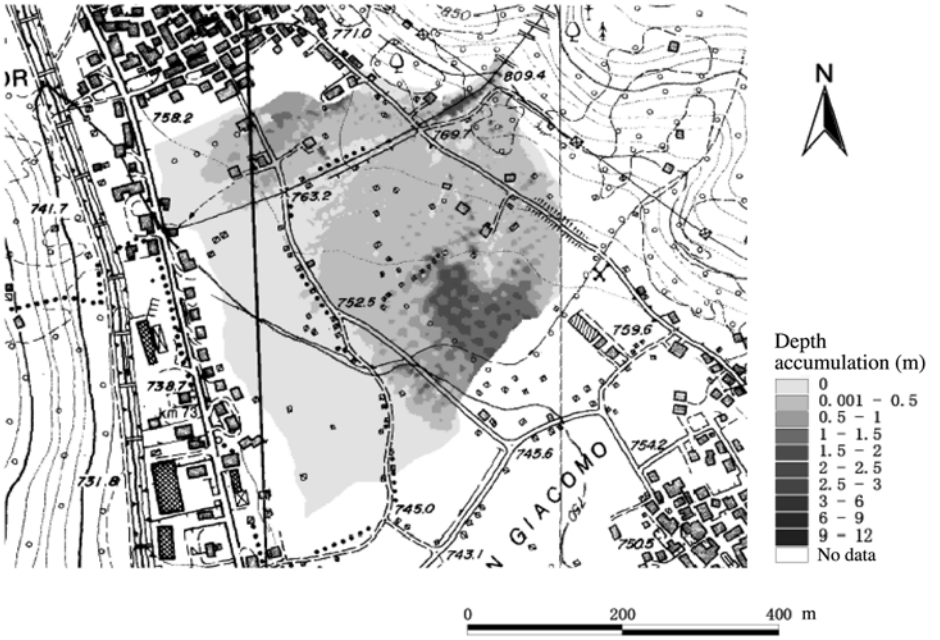

Figure 4. Debris flow depth accumulation on the Rio Lazer fan simulated with the DDPM

6.3.3 Development of a Small Basin Debris Flow Impact Model Using Field Data and a Physically Based Modelling Approach

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 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 theeffect 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. An application of DDPM for the debris flow deposit of 4 November 1966 on the fan of the Rio Lazer (Eastern Trento Province) is shown in Fig. 4. 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 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 applied to the 2.43-km^2 Rio Lenzi catchment to compare the model-derived hazard map for the fan with the Aulitzky method, to the 3-km^2 Rio Rudan catchment (Veneto Region, Italy) to identify critical sections for overflow (for planning mitigation measures) and to the 3.26-km^2 Sahùn catchment in the Benasque valley to identify critical sections and to evaluate the debris flow hazard on the fan.

6.3.4 Application of a Physically Based Basin Scale, Landslide Erosion and Sediment Yield Model to Land Use and Climate Scenario Analysis for Selected Sites

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 focus basins in the Italian pre-Alps (Valsassina, 180 km^2) and Spanish Pyrenees (Ijuez, 45 km^2), for scenarios of possible future land use and climate. The scenario results were transferred to the local end-users for use in developing guidelines for land management to mitigate debris flow occurrence and impact.

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 and 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 (Section 6.3.1). 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.

Before the scenario runs, SHETRAN was validated for the two focus basins. An initial validation of the landslide model was also completed for the November 1982 landsliding event in the 500-km^2 Llobregat basin in the eastern Spanish Pyrenees, in a

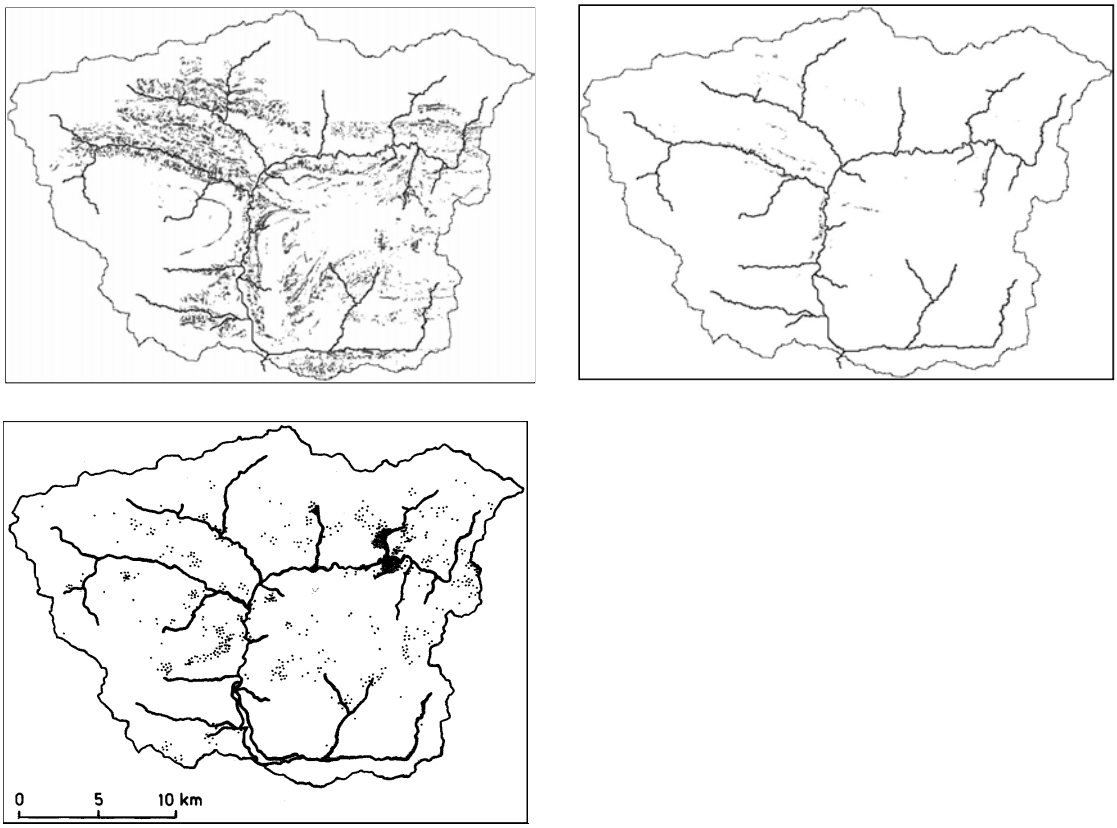

Figure 5. Comparison of uncertainty bounds for SHETRAN simulation (upper diagrams) with observed locations (lower diagram) of landslides in the Llobregat Basin. Landslide locations are shown as dots.

study originally started in the earlier EC MEDALUS project. Because of uncertainty in evaluating the model parameters and other inputs, the aim was not to reproduce the observed hydrograph and the observed occurrence of debris flows as exactly as possible with one simulation. Instead the aim was to bracket the observed responses 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 and Parkin (1996).). Similarly the sediment yield should be represented by an uncertainty envelope rather than a single simulation. The results demonstrate the required ability: Figure 5 shows the simulated spatial distribution of debris flows for the Llobregat basin, with the bounds in this case being set as a function of vegetation root cohesion. 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 event sediment yield (2500 – 15,000 t km^{-2}) which bracket measurements for extreme events elsewhere in the Pyrenees. A similar ability to bracket the observed spatial distribution of debris flows (according to 50-year inventories) and to determine annual sediment yield within the range of regional observations was demonstrated for the Valsassina and Ijuez basins.

Climate scenarios for 2070-99 were generated using data from a General Circulation Model. Land use scenarios were selected according to the likely trends in the basins.

Comparison of the scenario simulation results with the validation simulations for the current period provide an indication of the sorts of changes in catchment response (landslide incidence and sediment yield) which may be observed in the future and thus provide a context within which guidelines for land management can be developed to minimize debris flow impacts. The simulation results were summarized on an electronic matrix and transferred to the local end-users on CD.

6.3.5 Integration Of Modelling Approaches

The above three debris flow 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 and land use conditions characterizing the period of record. If the conditions change, 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 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).

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 and land use)
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

6.3.6 Dissemination of the Project Deliverables via Training Courses, Workshops, Implementation by End-users and Placement of Demonstration Material on a Website

The actions from this workpackage supporting dissemination are described in Section 6.5. An important development in its own right, though, was a GIS-based web technology for distributing thematic, landslide inventory and landslide hazard maps in digital form over the internet.

In recent years GIS-based web technology has improved substantially and has been made available at reasonably low costs. As a result many attempts have been made to exploit the potential of the new technology to publish geographical information (i.e. maps) on the web. The technology allows interested users to find and browse through digital maps directly on the web, using standard Internet applications (e.g. Netscape©, Internet Explorer© and Opera©). Users can also customize the way the geographical information is portrayed and they can pose simple geographical queries, in addition to traditional text-based queries. The technology is designed to facilitate the dissemination and use of geographical information amongst very large communities.

In the DAMOCLES project CNR-IRPI applied GIS-based web technology to disseminate the project results and, in particular, to publish on the Internet the landslide inventory maps, the landslide hazard maps and the other thematic maps prepared by the project partners. The software selected for the experiment was ESRI® Arc Internet Map Server, or ArcIMS™: in its final project configuration, as Release 4.0, it was mounted on a personal computer running RedHat® Linux 7.2. In addition to the ArcIMS™ GIS software, the system uses the Apache web server release 1.3.22-6 and Jakarta-Tomcat Release 3.1.1.

The functionalities and capabilities of the system were tested using landslide inventory and landslide hazard maps, and other thematic maps (including topographic, geological and land-use maps), provided by the University of Milan-Bicocca for the Pioverna river basin, Valsassina. Development of the GIS-based web site proved cumbersome but demonstrated that a significant amount of geographical information showing landslides and landslide hazards can be delivered to interested parties, including concerned citizens, using innovative web-based technologies. A versatile system is provided in which the number and type of thematic layers that can be accessed changes with spatial scale.

6.3.7 Deliverables

All the contracted project deliverables have been achieved, as noted in Table 3.

Table 3 DAMOCLES Deliverables

WORKPACKAGE		DELIVERABLE		STATUS
WP1	Field studies and debris flow relationships	D1	Debris flow relationships and database	Reports submitted
		D2	Debris flow maps and mapping procedures	Report on landslide hazard mapping submitted. Details of procedures and final maps transferred to end-user (Lombardy Region Geological Survey)
WP2	Regional scale hazard assessment	D3	Debris flow and rockfall database for GIS	A 5 m x 5 m DEM for Valsassina, a landslide inventory for Valsassina and thematic maps are available
		D4	Hazard and risk assessment technology	The multivariate statistical technique and the rockfall modelling methodology, together with results, transferred to end-user (Lombardy Region Geological Survey)
		D5	Review of rockfall and granular flow models	Report submitted
WP3	Small basin debris flow model	D6	Debris flow database for impact model	Database submitted
		D7	Debris flow impact model	Report and CD submitted
WP4	Basin scale landslide modelling	D8	Debris flow impact scenario simulations	Land use and climate scenario simulations for Valsassina and Ijuez basins submitted on CD
		D9	Guidelines for basin land management	Electronic matrices comparing the scenario simulations submitted on CDs for Valsassina and Ijuez basins
WP5	Dissemination of project deliverables	D10	End-users trained in project technologies	Training courses have been held
		D11	Project technologies in public domain	Achieved by training courses, workshops, CDs of scenario results, website and published papers
		D12	Proposal for standard approach to zonation	Achieved with D4 and the training of end-users

6.4 CONCLUSIONS, INCLUDING SOCIO-ECONOMIC RELEVANCE, STRATEGIC ASPECTS AND POLICY IMPLICATIONS

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. They improve upon previously existing techniques through their ability to quantify hazard on a spatially distributed basis, to explore the mitigating effects of torrent control works and land management for present and future conditions and, in the case of the rockfall model, to determine hazard in a three-dimensional setting. 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.

Every year debris flows and rockfalls cause loss of life and injury, direct damages run to tens of millions of euros and further large indirect costs arise from impacts such as road closures and insurance cover. The annual budget of the Autonomous Province of Trento alone is 20 million euros for torrent control works and debris flow management. The DAMOCLES project therefore achieves its relevance through the development of modeling and mapping technologies designed to allow more accurate (and quantitative) hazard assessments from the local to the regional scale. In turn these are intended to allow more efficient land use planning and improved design of torrent control works, to the benefit of life and livelihood. Examples where the project technologies may support improved practice include:

- use of discriminant analysis, logistic models and hazard probability maps to delineate the more vulnerable areas and to protect them from unsuitable land management programmes;

- use of the relationships between rainfalls of different return periods and debris flow occurrence to improve the design of public works for mitigating debris flow impacts;

- use of the rockfall hazard and risk assessment procedure to evaluate the risk to transport networks;

- use of DEFLIMO to design torrent control works and to quantify hazard on the debris flow fan;

- use of SHETRAN to select land management plans to minimize debris flow occurrence and sediment yield in the context of possible future changes in land use and climate.

The means of ensuring that the project realised its socio-economic potential was the direct involvement of end-users. These organizations (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 had practical relevance and fitted 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 training courses and workshops. Some of the end-users were also data suppliers.

In general, the project has developed and demonstrated techniques for carrying out environmental impact and hazard assessments on a quantitative basis. The models are therefore powerful tools for supporting planning decisions and the management of land use to mitigate hazard and to maintain environmental quality in mountain areas. 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. EU policies which could benefit from the DAMOCLES results include the Water Framework Directive and the Cohesion and Agriculture Policies.

6.5 DISSEMINATION AND EXPLOITATION OF THE RESULTS

Dissemination of the project results and technologies within the end-user community and the wider public domain was an important project objective, assigned its own workpackage (WP5). As noted above, end-users were actively involved in the project and form the primary route by which the project technologies will enter the user community. Specific dissemination activities were as follows:

(1) A training course on the small basin debris flow impact model was held at the University of Padova on 10 and 11 September 2002. Sixteen participants attended, largely from the end-user community. A four-day training course on the landslide and rockfall hazard assessment techniques was held for 25 staff from the Lombardy Region Geological Survey by the University of Milan-Bicocca in December 2002. In each case the relevant software and other material were given to the end-users.

(2) Workshops for publicizing the project technologies among the end-user community were held at the Pyreneen Institute of Ecology in May 2002 and at the University of Milan-Bicocca in November 2002. The latter workshop was integrated within the EC High-level Scientific Workshop "GI and Natural Hazards" held during 18-22 November 2002 and attracted over 50 participants including end-users and young researchers. The workshops provided an opportunity for demonstration and discussion of the technologies.

(3) The SHETRAN scenario simulation results for the Valsassina and Ijuez focus basins were transferred to the relevant end-users on CD. These were: in Italy, the Servizio Azienda Speciale di Sistemazione Montana (Trento) and the Lombardy Region Geological Survey; and in Spain, the Diputación General de Aragón and the Geological and Mining Institute of Spain. The transfers took place via extended demonstration and discussion meetings. The results are available for developing guidelines for future land management to mitigate debris flow occurrence and impact and such development will be taken further in journal publications on each of the focus basin applications.

(4) The project website was set up in the first six months of the project (by CNR-IRPI) and was maintained and upgraded throughout the project. It has been an

easy to use and efficient way of distributing information among the partners and of disseminating the project results to a wide audience over the internet. The site will be maintained for three years from the end of the project.

(5) A large number of journal publications and conference presentations have been prepared during the project (as listed in Section 6.6) and more are on the way.

Exploitation of the results will continue in two directions: application of the technologies by the end-users and publication by the research teams.

All the project end-users are interested in improving their hazard assessment procedures by exploiting the DAMOCLES technologies. The Lombardy Region Geological Survey is using the project outcomes to design new policies for mitigating geo-hydrological hazards at the regional scale. The Civil Protection office of Perugia Province in Italy is considering using the rockfall modelling results to identify the areas where rockfall risk is high in the Nera River valley, despite the presence of extensive defensive structures. The U.S. National Park Service might consider adopting the modelled rockfall hazard assessment for Yosemite Valley as an alternative to, or in combination with, the existing rockfall hazard maps. The small basin debris flow impact model DEFLIMO has been installed at and is being used by the Torrent Control Agency of Trento Province, by the Avalanche Centre at Arabba, Veneto Region, (ARPAV) and by the Associazione Italiana di Idronomia. The Torrent Control Agency of the Valle d'Aosta Region is using the MODDS component of DEFLIMO to design new open check dams for mitigating debris flow hazards at the small catchment scale; the Soil Defence Agency of the Fiuli-Venezia Region is considering using DEFLIMO to identify the areas where debris flow risk is high on the Rio Moscardo fan; and the Soil Defence Agency of the Veneto Region might consider using DEFLIMO for a hazard assessment of several fan areas located in the Piave and Cordevole Valleys. Model results have also been presented to the Torrent Control Agency of the Tucumán Province of Argentina. It is expected that such use of the project technologies will continue and may thus lead to a standard quantitative procedure for hazard assessment, as a basis also for uniformity in land use planning.

Publication of the project's achievements is important to the research teams as a means of enhancing their scientific reputation and maintaining their knowledge base and competitive position. Further publications are therefore planned, especially in the international refereed literature. An excellent opportunity for publicizing the project results is provided by the Third International Conference on Debris-flow Hazards Mitigation being held at Davos, Switzerland, in September 2003, and three (refereed) papers will be presented on the project (see Section 6.6.1 for the references).

6.6 MAIN LITERATURE PRODUCED

6.6.1 Peer Reviewed Articles

Authors	Date	Title	Journal	Reference
Arnaez, J., Marti-Bono, C., Begueria, S., Lorente, A., Errea, M.P. & Garcia-Ruiz, J.M.	1999	Factores en la generacion de crecidas en una cuenca de campos abandonados, Pirineo Central Espanol.	Cuadernos de Investigacion Geografica	24: 7-24
Begueria, S. & Lorente, A.	1999	Distribucion espacial del riesgo de precipitaciones extremas en el Pirineo aragones occidental.	Geographicalia	37: 17-36
Garcia-Ruiz, J.M., Valero, B., Gonzalez, P., Lorente, A., Marti-Bono, C., Begueria, S. & Edwards, L.	2001	Stratified scree in the Central Spanish Pyrenees: Paleoenvironmental implications.	Permafrost and Periglacial Processes	12: 233-242
D'Agostino, V. & Marchi, L.	2001	Debris flow magnitude in the eastern Italian Alps : data collection and analysis	Physics and Chemistry of the Earth	Part C, 26(9): 657-663
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): 1079-1093
Crosta, G.B.	2001	Failure and flow development of a complex slide: the 1993 Sesa landslide	Engineering Geology	59(1-2): 173-199
Garcia-Ruiz, J.M., Marti-Bono, C., Lorente, A. & Begueria, S.	2003	Geomorphological consequences of frequent and infrequent rainfall and hydrological events in a Mediterranean mountain area	Mitigation and Adaptation Strategies for Global Change	
Frattini, P. & Crosta, G.B.	2002	Modelling the impact of forest management changes on landslide occurrence	Int. Conference on Instability – Planning and Management, Ventnor, Isle of Wight	In press
Lenzi, M.A.	2001	Step-pool evolution in the Rio Cordon:	Earth Surface Processes and Landforms	26: 991-1008

		Northeastern Italy		
Bathurst, J.C., Crosta, G., García-Ruiz, J.M., Guzzetti, F., Lenzi, M. & Ríos Aragüés, G	2003	DAMOCLES: Debrisfall Assessment in Mountain Catchments for Local End-users	Proc. 3rd Intl. Conf. Debris-flow Hazards Mitigation, Davos, Switzerland, 10-12 September	In press
Lorente, A., Begueria, S, Bathurst, J & García-Ruiz, J.M.		Debris flow characteristics and relationships in the Central Spanish Pyrenees	Natural Hazards and Earth System Sciences	In press
Begueria, S., Lopez-Moreno, J.I., Lorente, A., Seeger, M. & García-Ruiz, J.M.	2003	Assessing the effect of climate oscillations and land use changes on streamflow in the Central Spanish Pyrenees.	Ambio	-
Lorente, A. & Begueria, S.	2002	Variation saisonniere de l'intensité des precipitations maximales dans les Pyrenées Centrales: Analyse spatiale et cartographique	Publ. de l'Ass. Intern. Climatologie	
Lorente, A., García-Ruiz, J.M., Begueria, S. & Arnaez, J.	2002	Factors explaining the spatial distribution of hillslope debris flows. A case study in the Flysch Sector of the Central Spanish Pyrenees.	Mountain Research and Development	22(1): 32-39
Lopez-Moreno, J.I., Begueria, S. & Garcia-Ruiz, J.M.	2002	Influence of the Yesa reservoir on floods of the Aragon river, Central Spanish Pyrenees	Hydrology and Earth System Sciences	6(4):753 -762.
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. & Dal Negro P.	2003	Observations and modelling of soil slip-debris flow initiation processes in pyroclastic deposits: the Sarno 1998 event	Natural Hazards and Earth System Sciences	3:53-69

Crosta G.B. & Frattini P.	2003	Distributed modelling of shallow landslide triggered by intense rainfall	Natural Hazards and Earth System Sciences	3:81-93
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
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	-
Crosta G.B. & Agliardi F.	In press	A new methodology for physically-based rockfall hazard assessment.	Natural Hazards and Earth System Sciences	
Agliardi F.& Crosta G.B.	In press	High resolution three-dimensional numerical modelling of rockfalls	International Journal of Rock Mechanics and Mining Sciences	
Crosta, G.B., Cucchiaro, S. & Frattini P.	2003	Validation of semi-empirical relationships for the definition of debris-flow behaviour in granular materials	Proc. 3rd Intl. Conf. Debris-flow Hazards Mitigation, Davos, Switzerland, 10-12 September.	
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	Proc. of the 4th EGS Plinius Conf., Mallorca, Spain, Oct. 2002	
Crosta , G.B., Cucchiaro, S.& Frattini, P.	In press	Determination of the inundation area for debris flows through semiempirical equations	Proc. of the 4th EGS Plinius Conf., Mallorca, Spain, Oct. 2002	
Guzzetti F., Reichenbach P. & Wieczorek G.F.		Rockfall hazard and risk assessment in the Yosemite Valley, California, USA	Natural Hazards and Earth System Sciences	In press
Guzzetti F., Reichenbach P. & Ghigi S.		Rockfall hazard and risk assessment in the Nera River Valley, Umbria Region, central Italy	Environmental Management	Submitted

Lenzi M.A. & Mao L	2003	Analisi del contributo del trasporto solido in sospensione alla produzione di sedimento del bacino del Rio Cordon nel periodo 1986-2001.	Quaderni di Idronomia Montana	Vol. 21 (in press)
Lenzi M.A.	2002	Stream bed stabilization using boulder check dams that mimic step-pool morphology features in Northern Italy.	Geomorphology	Vol 45, 243-260.
Lenzi M.A.		Debris-flow hazard assessment using numerical models and GIS: case studies in central Italian Alps and Spanish Pyrenees	Environmental Science and Environmental Computing	Submitted
Lenzi M.A., Mao L. & Comiti F.		Inter-annual variation of suspended sediment load and total sediment yield in an instrumented alpine catchment over 16 years	Hydrological Sciences Journal des Sciences Hydrologiques	Submitted
Lenzi M.A., D'Agostino V. Gregoretti C. & Sonda D.	2003	A simplified numerical model for debris flow hazard assessment: DEFLIMO.	Proc. 3rd Intl. Conf. Debris-flow Hazards Mitigation, Davos, Switzerland, 10-12 September	In press

6.6.2 Non Refereed Literature

Authors / Editors	Date	Title	Event	Reference	Type
Burton, A., Bathurst, J.C., Clarke, B.G. & Gallart, F.	2000	Validation of a basin scale, landslide sediment yield model	European Geophysical Society XXV General Assembly, 24-29 April	Geophysical Research Abstracts, 2	Oral Presentation & Abstract
Garcia-Ruiz, J.M. & Marti-Bono, C.	2000	Check-dam failures as sediment source during an extreme event.	European Geophysical Society XXV General Assembly, 24-29 April	Geophysical Research Abstracts, 2	Oral Presentation & Abstract
Garcia-Ruiz, J.M. & Marti-Bono, C.	2000	Different perspectives in studying an extreme event: The Biescas campsite disaster as a case study.	European Geophysical Society XXV General Assembly, 24-29 April	Geophysical Research Abstracts, 2	Oral Presentation & Abstract
Garcia-Ruiz, J.M., Lorente, A., Gonzalez, P., Valero, B., Marti-Bono, C. & Begueria, S.	2002	El mega-slump de Biescas-Arguisal y su posible contexto temporal.	VI Reunion Nacional de Geomorfologia, Madrid, 17-20 September, 2000	pp 227-234	Oral Presentation & Proceedings
Lorente, A., Begueria, S., Arnaez, J. & Garcia-Ruiz, J.M.	2000	Distribucion de coladas de piedras de ladera (hillslope debris flows) en el Pirineo Central español.	VI Reunion Nacional de Geomorfologia, Madrid, 17-20 September	-	Oral Presentation

Antonini, G., Ardizzone, F., Cardinali, M., Carrara, A., Detti, R., Galli, M., Guzzetti, F., Reichenbach, P., Sotera, M. & Tonelli, G.	2000	*Rapporto Finale. Novembre 2000.*		Convenzione fra il CNR, IRPI di Perugia e CSITE di Bologna, e la Regione Lombardia, Direzione Generale al Territorio ed Edilizia Residenziale, per lo sviluppo di tecniche e metodologie idonee alla produzione di carte della pericolosità e del rischio da frana in aree campione rappresentative del territorio della Regione Lombardia. 120 pp. (in Italian)	Report
Guzzetti, F., Detti, R., Crosta, G. & Agliardi, F.	2000	STONE. A computer program to evaluate rock-fall hazard at the regional scale.	Interreg IIC Falaises Meeting, Alagna, Italy, November 13-14, 2000.		Oral Presentation
Guzzetti, F., Detti, R., Crosta, G. & Agliardi, F.	2001	A computer program to evaluate rockfall hazard and risk at the regional scale. Examples from the	European Geophysical Society XXVI General Assembly 25-30 March	Geophysical Research Abstracts, 3	Oral Presentation & Abstract

		Lombardy region.			
Crosta, G.B., Frattini, P. & Siena, L.	2001	Shallow landslide triggered by rainfall: the 27th –28th June 1997 event in Lecco Province (Lombardy, Italy)	European Geophysical Society XXVI General Assembly 25-30 March	Geophysical Research Abstracts, 3	Oral Presentation & Abstract
Crosta, G.B. & Dal Negro, P.	2001	Triggering of soil slips and rapid mudflows in pyroclastic soils. The event of Sarno, 1998	European Geophysical Society XXVI General Assembly 25-30 March	Geophysical Research Abstracts, 3	Oral Presentation & Abstract
Crosta, G.B. & Frattini, P.	2000	Rainfall thresholds for soil slips and debris flow triggering	European Geophysical Society Topical Conferences, 2nd Plinius Conference on Mediterranean Storms, Siena, Italy, 16-18 October		Proceedings
Burton, A., Bathurst, J.C., Clarke, B.G. & Gallart, F.	2002	Validation of a basin scale, landslide sediment yield model, Llobregat Basin, Spanish Pyrenees	European Geophysical Society XXVII General Assembly, 21-26 April	Geophysical Research Abstracts, 4	Poster & Abstract
Lorente, A., Begueria, S. & Garcia-Ruiz, J.M.	2002	Assessing the hazard of sediment yield from debris flows. A case study in the central Spanish Pyrenees	European Geophysical Society XXVII General Assembly, 21-26 April	Geophysical Research Abstracts, 4	Oral Presentation & Abstract

Begueria, S.	2002	Identification and mapping of eroded lands in mountain areas by remote sensing	European Geophysical Society XXVII General Assembly, 21-26 April	Geophysical Research Abstracts, 4	Oral Presentation & Abstract
Bathurst, J.C., El-Hames, A.S., Moretti, G., Crosta, G. & Frattini, P.	2001	Application of a basin scale, landslide sediment yield model, River Pioverna, Valsassina (Lake Como)	Conference "Prevenzione del Rischio Idrogeologico Attraverso la Conoscenza del Territorio". Regione Lombardia, Milan, 26-27 September		Oral Presentation and Proceedings
Crosta, G.B. & Frattini, P.	2001	Coupling empirical and physically based rainfall thresholds for shallow l andslides forecasting.	EGS Topical Conferences, 3rd Plinius Conference on Mediterranean Storms, Baia Sardinia, Italy, 1-3 November		Poster and Proceedings
Crosta, G.B. & Frattini, P	2001	Physically based distributed modelling for shallow landslide hazard zonation	EGS Topical Conferences, 3rd Plinius Conference on Mediterranean Storms, Baia Sardinia, Italy, 1-3 November		Oral Presentation and Proceedings
Crosta, G.B., Dal Negro, P., & Frattini, P.	2002	Distributed modelling of shallow landsliding in volcaniclastic soils.	European Geophysical Society XXVII General Assembly, 21-26 April	Geophysical Research Abstracts, 4	Oral Presentation & Abstract
Crosta, G.B., Imposimato, S. & Roddeman, D.	2002	Numerical modelling of large landslide stability and runout.	European Geophysical Society XXVII General Assembly, 21-26 April	Geophysical Research Abstracts, 4	Oral Presentation & Abstract

Agliardi, F. & Crosta, G.B.	2002	High resolution 3D numerical modelling of rockfalls.	European Geophysical Society XXVII General Assembly, 21-26 April	Geophysical Research Abstracts, 4	Oral Presentation & Abstract
Ghigi, S., Guzzetti, F., Reichenbach, P. & Detti R.	2002	Preliminary assessment of rock fall hazard and risk in the central part of the Nera Valley, Umbria Region, Central Italy	European Geophysical Society XXVII General Assembly, 21-26 April	Geophysical Research Abstracts, 4	Poster Presentation & Abstract
Guzzetti, F., Reichenbach, P. & Wieczorek, G F.	2002	Rock-fall hazard in the Yosemite Valley, California	European Geophysical Society XXVII General Assembly, 21-26 April	Geophysical Research Abstracts, 4	Poster Presentation & Abstract
Agliardi, F., Crosta, G. B., Guzzetti, F. & Marian, M.	2002	Methodologies for a physically based rockfall hazard assessment	European Geophysical Society XXVII General Assembly, 21-26 April	Geophysical Research Abstracts, 4	Oral Presentation & Abstract
D'Agostino, V., Sonda, D., & Piccoli, E.	2000	Delimitazione su coniode delle aree soggette a pericolo di debris flow medianti indagini di campo, pp 16	"Taller sobre degradación ambiental en cuencas torrenciales", Universidad Nacional de La Plata, Argentina, La Plata, 9-10 November 2000.		Paper

Lenzi, M.A.	2001	Fluvial geomorphology and biological-ecological analysis to planning and designing torrent control and restoration works.	4th Inter-Regional Conference "Environment and Water: Competitive use and conservation strategies for water and natural resources, Fortaleza, Brazil, August 2001.	Alves Soares A. and Mattana Saturnino H. (eds.), Competitive use and conservation strategies for water and natural resources, pp. 56-66.	Paper
D'Agostino, V.	2001	Elementi per la progettazione delle briglie aperte	Università Europea d'Estate sui Rischi Naturali, Cemagref. Post-graduate Training Course on "Rischi torrentizi", Serre Chevalier, September 10-15, 2001, France		Proceedings
Lenzi, M.A.	2002	Valutazione della pericolosità e del rischio idraulico sui conoidi alpini	Convegno La Gestione Forestale nel Veneto; "Le esperienze maturate come supporto per l'ammodernamento legislativo e normativo del settore", Padova, February 23, 2002		Oral presentation

D'Agostino, V.	2002	La difesa idrogeologica e le sue implicazioni territoriali	Convegno La Gestione Forestale nel Veneto; "Le esperienze maturate come supporto per l'ammodernamento legislativo e normativo del settore", Padova, February 23, 2002		Oral presentation
Begueria, S.	2002	Revisión de metodos parametricos para la estimacion de la probabilidad de ocurrencia de eventos extremos en climatologia e hidrologia.	Meeting	pp 83-92	Proceeding
Lorente, A., Begueria, S., Arnaez, J. & Garcia-Ruiz, J.M.	2002	Distribucion de coladas de piedras de ladera (hillslope debris flows) en el Pirineo Central español.	Meeting	pp 227-234	Proceeding
Begueria, S.	2002	Debris flow modelling in the Pyrenees.	ECO-GEOWATER "GI and Natural Hazards" Euroworkshop, 18-22 November, Univ. Milan-Bicocca	-	Oral
Begueria, S., Lopez-Moreno, J.I. & Garcia-Ruiz, J.M.	2002	Different evolution of precipitation and discharge extremes in	Paleoflood	-	Oral

		the Pyrenees.			

Begueria, S.	2002	Modelizacion estadistica espacial de debris flows en el Pirineo como base para cartografia de riesgos	Damocles workshop, Zaragoza, May	-	Oral
Lopez-Moreno, J.I., Begueria, S., Valero, B. & Garcia-Ruiz, J.M.	2002	Intensidad de avenidas y aterramiento de embalses en el Pirineo Central español	Eria	(in press)	Spanish Journal
Lorente, A. & López-Moreno, J.I.	2002	Efectos del abandono de tierras y la revegetacion en el desencadenamiento de deslizamientos superficiales en el Pirineo Central español	Workshop Frankfurt	-	Oral
Agliardi F., Crosta G.B.	2002	High resolution three-dimensional numerical modelling of rockfalls	Geophysical Research Abstracts	volume 4. Abstract EGS02-A-04594.	
Guzzetti F.	2002	Spatial rock fall hazards and risk assessment: applications of the computer program STONE	Geography Depart., University of Bonn, November 2002		Oral presentation

Guzzetti F., Reichenbach P. Crosta G.B., Agliardi F. & Detti R.	2002	Spatial assessment of rock fall hazard and risk	Sediment Disaster Prevention Technology Conference, Tokyo and Hiroshima, 7-14 April 2002.	5pp	Extended Abstract and Oral presentation
Ghigi S.	2002	Un approccio sperimentale in Valnerina (Umbria sud-orientale)	University of Perugia	Unpublished Thesis	Thesis
Acosta, E., Lorente, A. & Ríos, S.	2002	Application of a regional model for the prediction of debrisflows hazard areas in the Esera upper basin (Central Spanish Pyrenees).	XI Congreso Internacional de Industria, Minería y Metalurgia. 4-7 June 2002. Zaragoza.		
Acosta, E. & Ríos, S.	2002	Geomorphological mapping and hazard assessment in the Benasque area, Pyrenees	ECO-GEOWATER "GI and Natural Hazards" Euroworkshop, 18-22 November, Univ. Milan-Bicocca	Website	Oral Presentation and Abstract
Lenzi M.A., D'Agostino V. Gregoretti C. , Sonda D. , Guarnirei A., Comiti F. & Mao L.	2002	Modellistica della propagazione delle colate detritiche e della sedimentazione nei conoidi alluvionali: guida metodologica, casi di studio ed applicazioni.	DAMOCLES Training Activities, September 10-11, 2002, University of Padova.	University of Padova, 74 pp.	Report
Sonda D.	2002	Valutazione della	University of Padova	University of Padova, PhD	PhD. thesis

		pericolosità idrogeologica sui conoidi alpini		"in Idronomia", 256 pp.	
Lenzi M.A.	2002	Nuevos modelos para la predicción de riesgos geomorfológicos en abanicos aluviales; un ejemplo de los Alpes Dolomíticos	Workshop "Métodos para la predicción de riesgos de movimientos de ladera en áreas de montaña » ; Zaragoza, May 14-15 2002.		Oral presentation
Lenzi M.A.	2002	Valutazione della pericolosità e del rischio idraulico sui conoidi alpini	Seminario "Gestione integrata dei bacini idrografici", Bari, October 2, 2002; University of Bari and "Associazione Italiana di Idronomia"		Oral presentation
Lenzi M.A.	2002	Debris flow hazard assessment using numerical models and GIS	ECO-GEOWATER "GI and Natural Hazards" workshop, 18-22 Novembre, Univ. Milan-Bicocca	Website	Extended Abstract and Oral presentation
Lenzi M.A.	2002	Bedload and sediment budget in the instrumented catchment of the Rio Cordon (Northeastern Italy).	XXVII EGS General Assembly, Nice, April, 21-26, 2002	Geophysical Research Abstracts, Vol. 4, 2002, ISSN 1029-7006	Abstract and Poster presentation
Lenzi M.A.	2002	Suspended sediment load and sediment yield during floods and snowmelt in the Rio	XXVII EGS General Assembly, Nice, April, 21-26, 2002	Geophysical Research Abstracts, Vol. 4, 2002, ISSN 1029-7006	Abstract and Oral presentation

		Cordon (Northeastern Italy).			

Mao L. & Lenzi M. A.,	2002	Impact of limitation in sediment supply on bed load transport in the instrumented catchment of the Rio Cordon, Italy	AGU Fall Meeting, S. Francisco, USA, December 6-10, 2002	*Eos. Trans. AGU, 83(47), Fall Meet. Suppl., Abstract H11C-0851*, 2002.	Abstract and Poster presentation
Bathurst, J.C.	2002	DAMOCLES	1st EU-MEDIN Workshop on Natural and Technological Hazards, 15-17 November, 2002	EUR 20199, K. Fabbri & M Yeroyanni (eds.), Office for Official Publications of the European Communities, Luxembourg, 106-115	Book
Bathurst, J. C.	2002	DAMOCLES	Meeting of EC FP5 Coordinators in Seismic and Landslide Risks, 8-9 July	-	Oral presentation
Bathurst, J. C.	2002	DAMOCLES	Meeting of EC FP5 Coordinators in Seismic and Landslide Risks, 12-13 November	-	Oral presentation
Bathurst, J.C.	2002	DAMOCLES	ECO-GEOWATER "GI and Natural Hazards" Euroworkshop, 18-22 November, Univ. Milan-Bicocca	Website	Oral Presentation and Abstract
Moretti, G. & Bathurst, J.C.	2002	Physically based modelling of landslide sediment	ECO-GEOWATER "GI and Natural Hazards" Euroworkshop,	Website	Oral Presentation and Abstract

		yield at Valsassina, Italian pre-Alps	18-22 November, Univ. Milan-Bicocca		

Moretti, G. & Bathurst, J.C.	2003	Physically based modelling of landslide sediment yield at Valsassina, Italian pre-Alps	EGS-AGU-EUG Joint Assembly, 6-11 April	Geophysical Research Abstracts, 5	Oral Presentation and Abstract
Bathurst, J.C., Carrara, A., Crosta, G., Frattini, P. & Moretti, G.	2003	An integrated approach for assessing debris flow hazard at regional scale	EGS-AGU-EUG Joint Assembly, 6-11 April	Geophysical Research Abstracts, 5	Abstract

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APPENDICES

Detailed final reports by

- University of Newcastle upon Tyne, UK
- University of Milan-Bicocca, Italy
- CNR-IRPI, Italy
- University of Padova, Italy
- Pyreneen Institute of Ecology, Spain
- Geological and Mining Institute of Spain

DAM/MR/0304/6

DAMOCLES

DEBRISFALL ASSESSMENT IN MOUNTAIN CATCHMENTS FOR LOCAL END-USERS

Contract No EVG1 - CT-1999-00007

FINAL REPORT

SECTION 6

APPENDICES

DETAILED REPORTS OF CONTRACTORS AND ASSISTANT CONTRACTORS RELATED TO OVERALL PROJECT DURATION 1 March 2000 – 28 February 2003

Coordinator: Dr James C Bathurst
University of Newcastle upon Tyne, UK

Project web site: http://damocles.irpi.cnr.it/

May 2003