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DAMOCLES

DEBRISFALL ASSESSMENT IN MOUNTAIN CATCHMENTS FOR LOCAL END-USERS

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6.1 BACKGROUND

Landsliding can play an important role in determining the sediment yield of upland river basins (e.g. Hicks et al., 2000). The incidence of shallow landsliding can be significantly affected by changes in land use and vegetation cover (e.g. Amaranthus et al., 1985; Sidle et al., 1985; Greenway, 1987). Given the dependency of shallow landsliding on rainfall and snowmelt characteristics, the incidence should also be sensitive to climate change. The economic impacts of landslide erosion and sediment yield can be immense, affecting for example forestry operations, fisheries, reservoir sedimentation and aggradation of river beds (with consequences for flooding). There is a need therefore for models which can be used predictively to explore the effects of possible future land management activities and changes in basin characteristics on landslide incidence and sediment yield. Such models need in some way to be coupled, physically based, spatially distributed, geotechnical-hydrological models, able to represent time-varying soil moisture conditions as the trigger for shallow landsliding and surface runoff (including river flow) for transporting the eroded material to the catchment outlet. Several models have been constructed in recent years but most are for small catchments (around 1 km^2 in area) and for simulating landslide occurrence but not sediment yield (e.g. Montgomery and Dietrich, 1994; Wu and Sidle, 1995; Borga et al., 2002). Takahashi and Nakagawa (1989) developed a model for landslide sediment yield which they tested at a basin scale of around 20 ha. However, only the model of Burton and Bathurst (1998) is currently available for predictive simulation of shallow landslide erosion and sediment yield (accounting for future land use and climate change effects) at basin scales relevant to a range of engineering interests (up to 500 km^2). The model is a component of the SHETRAN system for modelling flow, sediment yield and contaminant transport at the basin scale (Ewen et al., 2000).

The DAMOCLES project provided the first opportunity to test the SHETRAN landslide model with field data, in this case for the focus areas of Valsassina (Italian pre-Alps) and the Ijuez catchment (central Spanish Pyrenees). This report describes the model validations, applications to predict the impact of climate and land use changes on debris flow occurrence and thence catchment sediment yield, and the transfer of the results to the local end-users.

6.2 SCIENTIFIC/TECHNOLOGICAL AND SOCIO-ECONOMIC OBJECTIVES

The SHETRAN applications were carried out within Workpackage 4 by the University of Newcastle upon Tyne but involving also collaboration with other partners and end-users. 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. Specific objectives to achieve this requirement were:

1) Selection of focus basins and assembly of SHETRAN database;

2) Validation of SHETRAN for the current conditions of the focus basins;

3) Application of SHETRAN to model debris flow spatial and temporal occurrence and impact on basin sediment yield for land use and climate scenarios;

4) Transfer of results to the local end-users and development of guidelines for basin management to minimize impacts.

The socio-economic relevance of the work is defined by the ability of the model to provide improved estimates of basin scale sediment yield, in support of more efficient land use planning and engineering design. To ensure the practical relevance of the simulations, careful attention was paid to the interests of the end-users and to the means of transferring the results to the end-users.

6.3 APPLIED METHODOLOGY, SCIENTIFIC ACHIEVEMENTS AND MAIN DELIVERABLES

6.3.1 Focus Basins

Valsassina, Lombardy Pre-Alps

This 160-km^2 catchment was selected with the advice of the University of Milan-Bicocca team. The main river (the Pioverna) discharges into Lake Como (Lake Lario) near Bellano. The total area modelled with SHETRAN was 180 km^2, which includes the neighbouring 20-km^2 Esino catchment which also discharges directly into Lake Como. A particular reason for selecting this catchment was that it was subject to a heavy rainstorm on 28 June 1997 which triggered extensive landsliding at the lower end of the Pioverna catchment and in the Esino catchment.

Ijuez Catchment, Central Spanish Pyrenees

This 45-km^2 catchment was selected with the advice of the Pyreneen Institute of Ecology. The Ijuez is a tributary of the Aragón river in the flysch sector of the central Spanish Pyrenees, 10 km from the city of Jaca. A particular reason for selecting this catchment was that it contains 60-100 debris flow sites.

Llobregat, Eastern Spanish Pyrenees

While the databases for the Valsassina and Ijuez focus catchments were being compiled, an initial SHETRAN validation was made for the 500-km^2 Llobregat basin in the eastern Spanish Pyrenees, using data from a major landsliding event in November 1982. This work was carried out in collaboration with a team from the Institute of Earth Sciences (Consejo Superior de Investigaciones Cientificas), Barcelona, building on a preliminary validation from the EC MEDALUS III (Mediterranean Desertification and Land Use) project. The validation provided valuable experience in running the model, which benefitted the focus basin applications. It is reported separately in a paper currently under preparation.

6.3.2 Data Assembly

Three-day field visits were made to Valsassina in May 2001 and to the Ijuez catchment in June 2001 to collect soil samples. These visits also allowed other data to be checked (e.g. rainfall records) and a general feel for the catchments to be gained. The Newcastle team was joined by the Milan-Bicocca team for the Valsassina visit and by the Pyreneen Institute of Ecology team for the Ijuez visit.

For the precipitation input time series, gap-filling in the original records and disaggregation of the daily data to the required hourly scale were carried out using simple statistical techniques. Spatial distribution was provided by five existing raingauges in Valsassina and on the basis of three altitudinal zones in the Ijuez catchment. Potential evapotranspiration was calculated from temperature using the Blaney-Criddle equation (e.g. Dunne and Leopold, 1978, p139) (calibrated for the Ijuez with limited pan evaporation data).

Eighteen soil samples were collected for Valsassina and twelve for the Ijuez catchment. Soil properties were evaluated from field measurements and by laboratory analysis of the samples. Soil maps were produced by correlation of the property data with geology in Valsassina and with vegetation cover in the Ijuez catchment.

Land cover maps were compiled from vegetation, land use and topographic maps. The principal covers were forest, pasture/meadow and rocky outcrops in Valsassina and pasture/meadow, natural pine/oak and plantation pine in the Ijuez catchment.

No discharge or sediment yield data were available for the catchments and model validation was therefore caried out against regionally normalized or scaled data,

6.3.3 Simulation Approach

It is generally accepted that evaluation of model parameters and other inputs for complex physically based systems like SHETRAN involves uncertainty (e.g. Beven, 1989; Grayson et al., 1992). The aim of the validations, therefore, was not to reproduce the observed hydrograph and the observed occurrence of landslides as exactly as possible with one simulation but to bracket the observed responses with several simulations (e.g. Ewen and Parkin, 1996). Between them, these simulations should represent the uncertainty in the key input conditions. Similarly, the event sediment yield should be represented by an uncertainty envelope rather than a single simulation. The results are therefore presented below in terms of uncertainty envelopes with upper and lower simulation bounds.

As the first stage in the validation, the event hydrological response was simulated, so as to obtain the soil saturation and water flow data which form the input to the landslide simulation. Next the landsliding was simulated, along with the debris flows which carry the landslide material to the channel network. Finally the sediment transport component was run, accounting for additional erosion by raindrop impact and overland flow and determining the overall sediment discharge at the catchment outlet.

6.3.4 Valsassina Validation

The validation period for Valsassina was 1/1/93 – 31/12/99, selected in part because it contains the major landsliding event of 27/28 June 1997. The first year (1993) was used as a “settling down” period to minimise the effect of the initial conditions and did not contribute to the final simulation results. The full simulation area consisted of the Pioverna valley (Valsassina) (160 km^2) and the Esino valley (20 km^2). The SHETRAN model grid resolution was 500 m and the subgrid resolution for landslide modelling was 20 m.

Hydrology validation

Bounds on the simulated Pioverna mean annual peak hourly discharge of 58 – 151 $m^3 s^{-1}$ agree well with regional mean annual instantaneous peak discharges in the range 88 - 116 $m^3 s^{-1}$. Similarly, simulated mean runoff/rainfall coefficients of 0.52 – 0.64 compare well with measured runoff/rainfall coefficients of 0.59 and 0.77 for two neighbouring catchments. In addition the simulation envelope of daily flow duration curves compares well with the curves for these two catchments. On this basis the hydrology model was considered to be validated for Valsassina.

Landslide validation

Validation data were available in the form of landslide inventory maps for the event of 27/28 June 1997 and for the 50-year period from the 1950s. In the first case the area most affected was the Esino valley and the aim of the validation was to bracket the observed incidence of landslides with lower and higher values. For the second case the aim of the validation was to reproduce the general spatial distribution of landslide occurrence. In both cases bounds on the landslide simulation were obtained by setting upper and lower bounds on the root cohesion.

For the Esino event the simulation bounds of 277 and 10 landslides bracket the observation of 137 (Fig. 1). However, the spatial distributions of observation and simulation do not match, suggesting that representation of spatial distribution needs improvement, at least at the event scale. Such improvement may depend on more detailed or more accurate rainfall and catchment property data. Alternatively wider bounds on the simulated occurrence may be required.

The 50-year map of observed landslides was compared with the upper and lower simulated bounds for 1993-99 (Fig. 2). Considering in particular the upper simulated bound, reproduction of the observed spatial distribution is very good, accounting both for areas observed to have landslides and areas observed not to have landslides.

On the basis of these results, the landslide model was considered validated. However, at least at the event scale, wider uncertainty bounds than those used here may be appropriate.

Sediment yield validation

Data from the northeastern Italian Alps and hydraulic estimates suggested an approximate yield for the Pioverna in the range 0.5 - 10 t ha^{-1} yr^{-1}. For the simulations, uncertainty bounds were set on the soil erodibility coefficients for raindrop impact and overland flow. Without the contribution from debris flows, the sediment yield bounds simulated for 1994 - 99 were 3.05 – 4.95 t ha^{-1} yr^{-1} for the Pioverna outlet and 0.78 – 0.78 t ha^{-1} yr^{-1} (i.e. no sensitivity) for the Esino outlet. Further investigation showed that the lack of sensitivity for the Esino simulations is due to the simulated sediment yield being dominated by channel rather than hillslope sediment supply. Adding the debris flow contribution raises the Pioverna sediment yield to 3.06 – 7.59 t ha^{-1} yr^{-1} and the Esino yield to 0.85 – 5.63 t ha^{-1} yr^{-1}. For the June 1997 event, the simulated sediment yield for the Esino catchment was 1.09 t ha^{-1} without the debris flow contribution and 1.15 – 31.07 t ha^{-1} with the lower and upper bounds for debris flow contribution.

Agreement with the validation data is reasonable. Possibly the simulated Pioverna yields are a little high and the upper bound on the Esino event yield may likewise be high.

6.3.5 Ijuez Validation

The validation period for the Ijuez catchment was 1/1/95 – 31/12/98. To provide a "settling down" period for the model (so that the effect of the initial conditions was minimised), this period was preceded by the last six months of 1998. The full simulation area was 47.25 km^2. The SHETRAN model grid resolution was 500 m and the subgrid resolution for landslide modelling was 20 m.

Hydrology validation

The simulated discharges were validated against the Aragón river record at Jaca, reduced using a regionally based scaling equation. A single simulation was compared with the measured record at the monthly scale while the comparison of the envelope of simulated flow duration curves with the measured curve referred to daily discharges. In general the agreement was good: differences between simulation and observation can largely be explained by the more flashy nature of the Ijuez catchment compared with the Aragón and by the snowmelt component of the Aragón, absent from the Ijuez. On this basis the hydrology model was considered to be adequately validated.

Landslide validation

The basis for validating the landslide simulations was a map of the observed debris flow occurrence in the Ijuez catchment over the period 1956-2001. For this period 146 debris flows were identified, 21 of which occurred during 1990-2001. The principal aim of the validation was to reproduce the general spatial distribution of landslide occurrence. However, the observed incidence for 1990-2001 also provided a rough basis for testing the bounds on the simulated incidence.

Considering in particular the upper simulation bound, reproduction of the observed spatial distribution is good (Fig. 3). However, as the observations refer to debris flows, it was necessary to distinguish in the model between those landslides which evolve into debris flows and those which do not. The bounds on the number of simulated landslides which evolve into debris flows for 1995-1998 are 12 and 462. These bounds enclose the number of observed debris flows (21) for 1990-2001. On the basis of these results, the landslide model was considered to be adequately validated.

Sediment yield validation

Regional long term yields of 1.5 – 4 t ha^{-1} yr^{-1} are reported for catchments along the Central Pyrenees (Ebro valley) by Avendaño Salas et al. (1997). Without the contribution from debris flows, the sediment yield simulated for 1995-98 was 0.67 t ha^{-1} yr^{-1}, there being no sensitivity to the soil erodibility coefficients. Adding the lower and upper bounds for debris flow contribution, though, raised the yield to 0.77 and 2.08 t ha^{-1} yr^{-1} respectively. On this basis the sediment yield model was considered to be validated.

6.3.6 Scenario Simulations

Climate scenarios were developed for the Valsassina and Ijuez focus basins using data from the UK Hadley Centre general circulation model HadRM3 for the period 2070-99. Relative to the current period, mean annual rainfall decreases (especially for Valsassina) but within this context winter rainfall increases slightly. Mean annual potential evapotranspiration increases.

Realistic land use changes are limited in each case. In Valsassina the likeliest change is for the hillslope meadows to be abandoned and to revert to (or be planted with) forest. In the Ijuez catchment the change of most interest is the effect of fire, i.e. removal of the tree cover. Valsassina was therefore modelled with the current hillslope meadows replaced by forest while the Ijuez catchment was modelled with a complete grass and pasture cover, representing the catchment a few years after a fire which has destroyed all the trees. These scenarios are extreme but enable the maximum impacts to be modelled and used in developing guidelines for catchment management.

The results of the scenario simulations are shown in Tables 1 and 2. Simulation uncertainty bounds are shown as appropriate. For the future climate, runoff is reduced, corresponding to the decrease in rainfall and increase in evaporation. Sediment yields derived from erosion by raindrop impact and sediment yield are likewise reduced. However, the numbers of landslides show only small decreases (Valsassina) or no decrease (Ijuez). This is because the future climate still has sufficient amounts and intensities of rainfall to cause landsliding near to the current rate of occurrence. Overall sediment yields (including the contribution from debris flows) fall more markedly for Valsassina than for the Ijuez catchment, probably because of the greater reduction in runoff for the former case.

The change to fully forested hillslopes in Valsassina produces a small reduction in landslide occurrence. Sediment yield is also reduced but this is due more to the reduction in non-landslide erosion (i.e. by raindrop impact and overland flow) and the reduction in runoff than to the reduction in landslides. Indeed, noting that conversion of pasture to forest could increase the number of landslides which evolve into debris flows, there is a possibility that the sediment yield derived from landslides may increase. This is suggested by the upper bounds on total sediment yield for the future climate (increase from 1.98 to 2.48 t ha^{-1} yr^{-1}).

The conversion of the Ijuez catchment to a full grass cover provokes an increase in landslide occurrence. However, none of the landslides develops into a debris flow, so there is a reduction in the amount of material delivered to the channel network and a corresponding decrease in sediment yield derived from landsliding. This is to some extent countered in the overall sediment yields by the increase in non-landslide erosion and in runoff.

The scenario results can all be explained in terms of model design and capability. In other words they are physically realistic, within the limitations of the model design and scenario characteristics. Comparison of the scenario results with the simulations for the current period provides an indication of the sorts of changes in catchment response which may be observed in the future and thus provides a context within which guidelines for land management can be developed to minimize debris flow impacts.

6.3.7 Transfer to End-users

The SHETRAN model is currently too complex to be transferred to the project end-users. Instead it was used to simulate flow, sediment transport and landslide data for a range of land use and climate scenarios as described above: these data were then transferred to the end-users for use in developing land management guidelines. A matrix system was developed for presenting the simulation data in a user friendly manner. This tabulates the data for different land use scenarios for both current and future climates. Each land use/climate scenario is represented by a box in the matrix. An electronic (screen) version was produced, enabling users to access all relevant data by clicking on the relevant box. The complete DAMOCLES matrices for the two focus areas were distributed on CD to the relevant end users: Servizio Azienda Speciale di Sistemazione Montana (Trento), Lombardy Region Geological Survey, Diputación General de Aragón, and the Geological and Mining Institute of Spain. The transfers were carried out through discussion meetings at the end-user offices.

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

The economic impacts of landslide erosion and sediment yield can be immense. There is a need, therefore, for models which can be used to predict the effects of proposed basin management strategies and of possible future changes in basin characteristics on landslide incidence and sediment yield, in support of more efficient land use planning and engineering design. The application of SHETRAN in the DAMOCLES project has addressed this need:

1) Validation of the model for the focus basins has demonstrated an ability to bracket the observed spatial distribution of shallow landslides triggered by rainfall, along with their resulting debris flows, and to determine sediment yield within the range of regional observations. This is the first time that the contribution of landslides to sediment yield has been modelled as a distinct process at catchment scales relevant to a range of engineering interests (up to 500 km^2). The validation also showed an ability to account for uncertainty in model parameter evaluation, giving the results in terms of uncertainty envelopes.

2) The scenario applications have demonstrated an ability to explore the impacts of possible future changes in land use and climate on shallow landslide incidence and

sediment yield. In this way model results can contribute to the development of guidelines for future basin management.

The simulations are the first application of the SHETRAN landslide model to full-scale catchments. As such they have highlighted several areas where the model and the modelling procedure need to be strengthened, e.g. the detailed representation of landslide spatial distribution at the event scale.

More generally, the applications have demonstrated a technique for carrying out environmental impact and hazard assessments on a quantitative basis. The model is therefore a powerful tool for supporting planning decisions and the management of land use to mitigate hazard and to maintain environmental quality in mountain areas. As a catchment scale model, it is especially relevant to the Water Framework Directive, which requires the development of plans for sustainable basin management.

6.5 DISSEMINATION AND EXPLOITATION OF THE RESULTS

The principal practical form of dissemination has been the summarizing of the scenario results in the electronic matrix and their transfer to the end-users on CD. The results are thus available for developing guidelines for future land management to mitigate debris flow occurrence and impact.

The results will also be put into the public domain via the project website and through journal publications. At least three papers are envisaged, covering the Llobregat, Valsassina and Ijuez applications; these will be written jointly with the appropriate partners. The papers will also explore in more detail the options for basin management under future conditions.

6.6 MAIN LITERATURE PRODUCED

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Table 1 Results for the SHETRAN Valsassina simulations

Scenario	Mean annual rainfall	Mean annual potential evapotranspiration	Simulated mean annual runoff	Simulated sediment yield		Simulated number of landslides
				without landslides	with landslides	
	mm	mm	mm	t ha^{-1} yr^{-1}	t ha^{-1} yr^{-1}	
Current climate (1994 – 99):						
- current vegetation	1476	873	885	3.05 – 4.95	3.06 – 7.59	369 – 10661
- forested hills	1476	873	841	1.31 – 1.43	1.31 – 5.52	0 – 9923
Future climate (2070 – 99)						
- current vegetation	1001	982	470	1.10 – 1.30	1.11 – 1.98	296 – 9027
- forested hills	1001	982	420	0.43	0.43 – 2.48	0 - 8020

Table 2 Results for the SHETRAN Ijuez simulations

Scenario	Mean annual rainfall	Mean annual potential evapotranspiration	Simulated mean annual runoff	Simulated sediment yield		Simulated number of landslides
	mm	mm	mm	without landslides t ha^{-1} yr^{-1}	with landslides t ha^{-1} yr^{-1}	
Current climate (1995 – 98):						
- current vegetation	1241	950	757	0.67	0.77 – 2.08	96 – 857
- pasture	1241	950	778	0.76	0.81 – 1.54	183 – 1089
Future climate (2070 – 99)						
- current vegetation	1084	1382	624	0.52	0.58 – 1.36	
- pasture	1084	1382	638	0.60	0.66 – 1.26	96 – 857
						183 - 1089

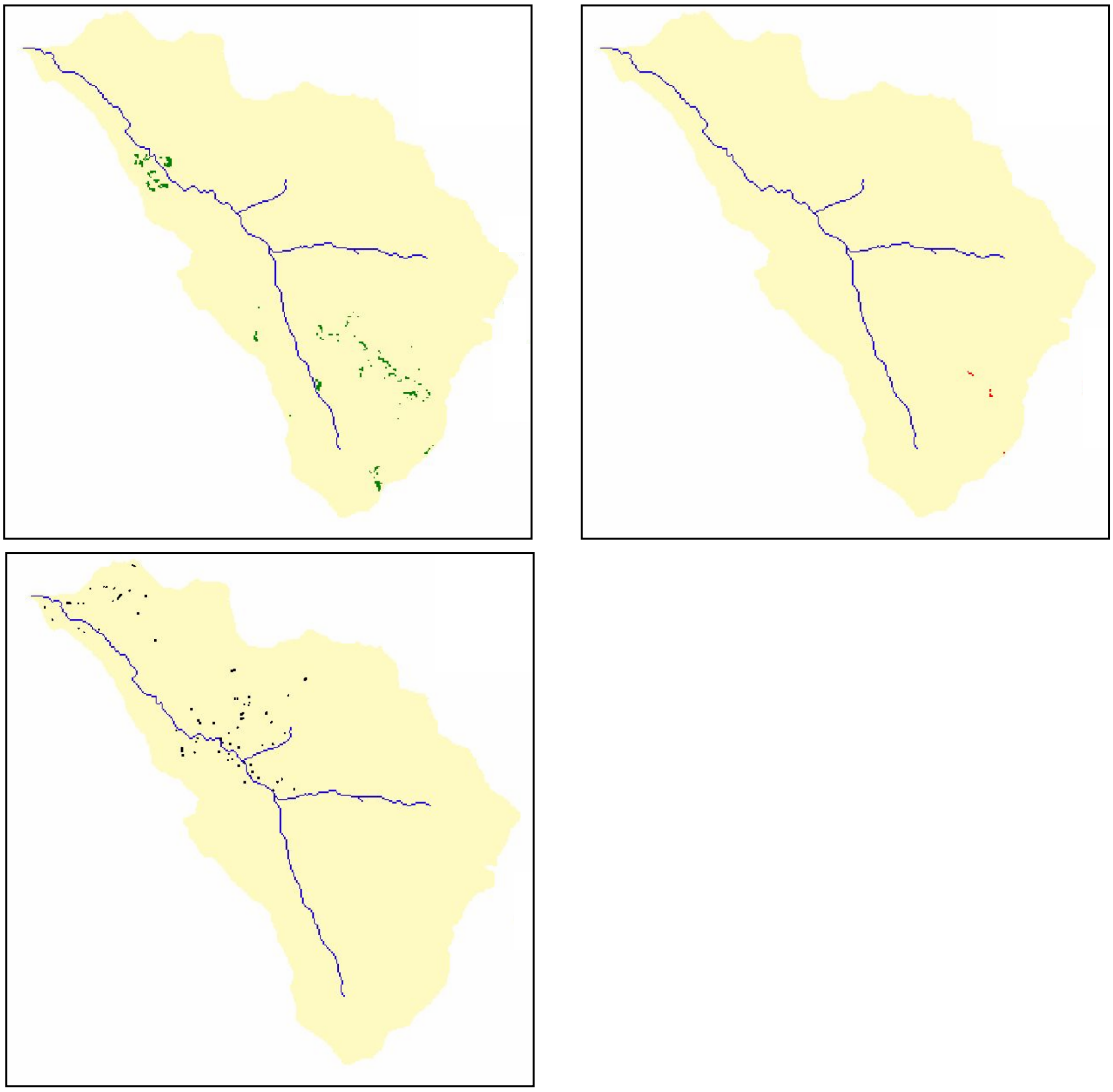

Figure 1. Comparison of uncertainty bounds for SHETRAN simulation (upper diagrams) with observed locations (lower diagram) of landslides in the Esino Catchment. Landslide locations are shown as dots

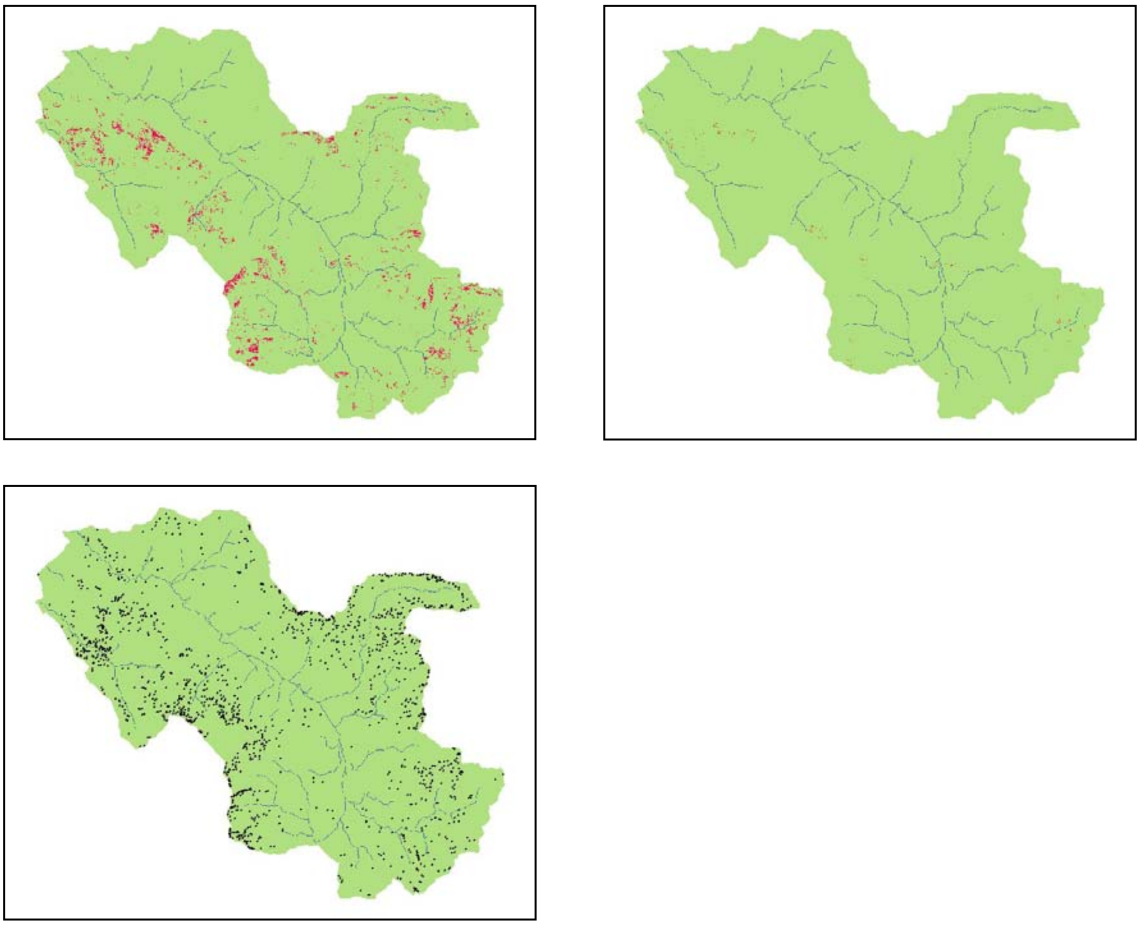

Figure 2. Comparison of uncertainty bounds for SHETRAN simulation (upper diagrams) with observed locations (lower diagram) of landslides in Valsassina. Landslide locations are shown as dots

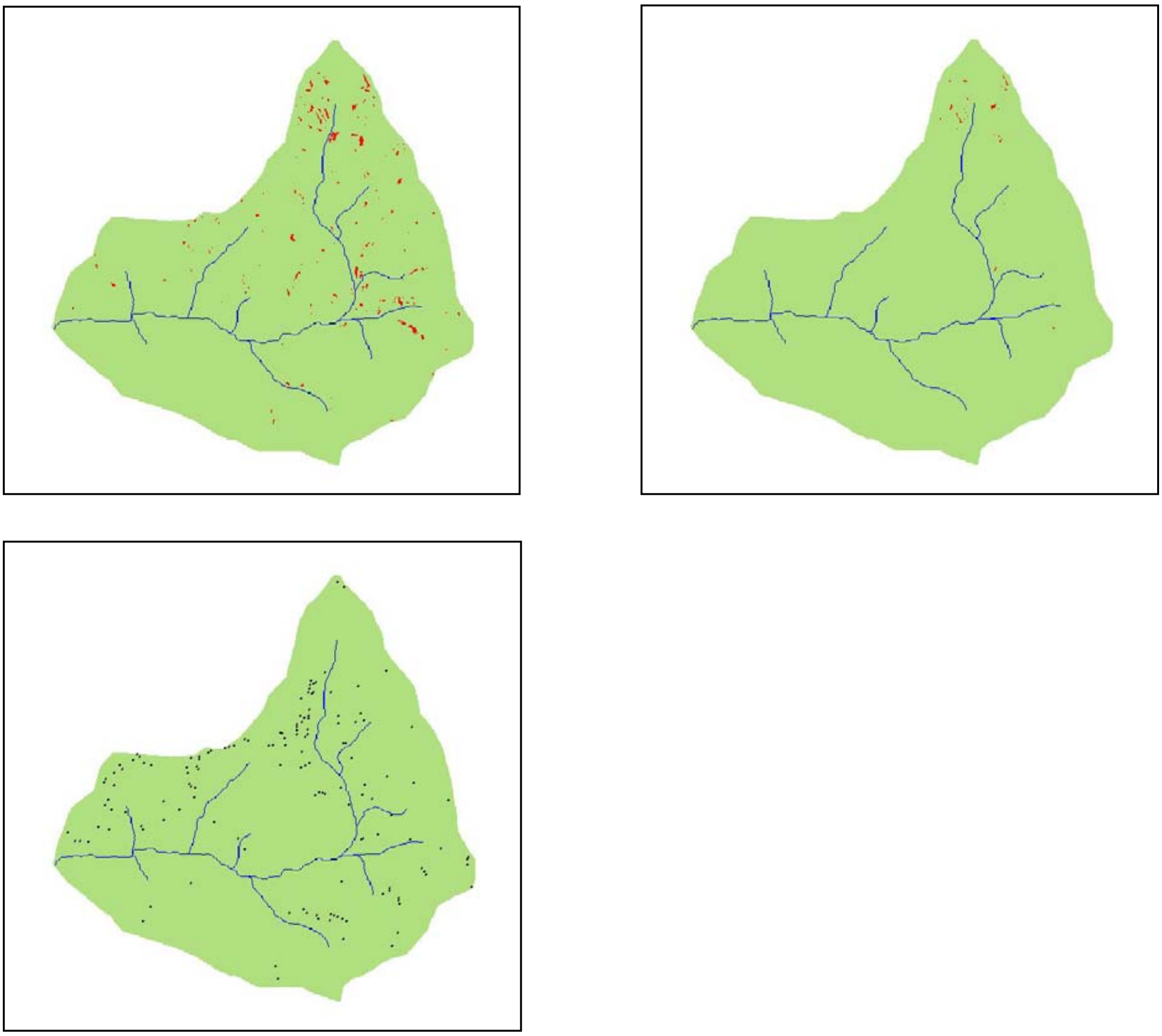

Figure 3. Comparison of uncertainty bounds for SHETRAN simulation (upper diagrams) of landslides with observed locations (lower diagram) of debris flows in the Ijuez Catchment. Landslide and debris flow locations are shown as dots