Available online at www.sciencedirect.com
ScienceDirect
Quaternary International 171–172 (2007) 108–117

Modelling of the initiation of rainfall-induced debris flows in the Cardoso basin (Apuan Alps, Italy)

Roberto Giannecchini[a], Duccio Naldini[b,*], Giacomo D'Amato Avanzi[a], Alberto Puccinelli[a]

[a]Dipartimento di Scienze della Terra, Università di Pisa, Via S. Maria, 53-56126 Pisa, Italy
[b]Centro di Geotecnologie, Università di Siena, Via Vetri Vecchi, 34-52027 S. Giovanni Valdarno, Italy

Available online 11 February 2007

Abstract

A case study is being carried out in relation to the event of June 19, 1996, when an intense rainstorm hit the Cardoso area in the Apuan Alps, Italy. The catastrophe triggered several gravitational movements, mainly characterized by soil slip-debris flows. A dataset coming from field and laboratory surveys allowed a complete parameterization of the event, and consequently the realization of a physically based dynamic model related to the initiation of the rainfall-induced landslides. The aim of the study is to analyze the processes involved in the light of the modelling results and to assess the spatio-temporal activity of the landslides, both in terms of location of the triggering sites and of determination of the critical rainfall conditions.

The critical rainfall input thresholds, obtained with a deterministic approach, are then compared with the thresholds obtained by an empirical analysis of the main rainfall events occurred in the southern Apuan area in the period from 1975 to 2002.

1. Introduction

The probability of occurrence of a landslide is estimated by means of several methods, such as the heuristic approach, statistical analysis or physical modelling.

The direct mapping approach identifies various degrees of landslide hazard assigned to different geomorphic units on the basis of subjective determination. Hence, it relies on the experience of the scientist with regard to the spatial and temporal framework of past events and their related triggers. This method often provides accurate results, but also contains a subjective element, which affects both the surveys and the parameterization of the elements.

Weighting factors can be assigned to selected parameters in order to rate the relative susceptibility of each terrain unit. However, since landslide susceptibility is based on the assumption that frequency and location of future landslides are related to the past activity, we can work on the hypothesis that future landslides can be expected to take place under the same conditions in which they occurred previously and at similar frequency.

In order to avoid subjectivity, it is possible to construct models starting from the input data using bivariate and multivariate techniques, which evaluate separately and simultaneously the influence of factors on landslide density, assigning weights of evidence (Soeters and Van Westen, 1993). However, the causal relationship between landslide occurrence and their related attributes is not clearly defined and the temporal activity is downplayed, as well.

Landslide hazard is often related to variations in environmental conditions: attributes like rainfall input, groundwater level or pore pressure are subjected to sudden oscillations, which constitute the triggers of landslides in most cases. In the same way, long-term variations like land-use changes often constitute the cause of landslide occurrence (Van Beek and Van Asch, 2004).

The analysis of the triggering factors of a landslide subjected to temporal changes is not fully explicated with the aid of empirical models. The introduction of dynamic modelling is needed, where the principle of spatial modelling is elaborated further by adding the concept of time (Terlien, 1996), and new attributes are calculated as a "function of attribute change over time" (PCRaster, 2000).

*Corresponding author. Tel.: +39 0335 6140029; fax: +39 055 9119439.
E-mail addresses: rgiannecchini@dst.unipi.it (R. Giannecchini), monacinald@unisi.it (D. Naldini), damato@dst.unipi.it (G. D'Amato Avanzi), pucci@dst.unipi.it (A. Puccinelli).

1040-6182/$ - see front matter
doi:10.1016/j.quaint.2007.01.011

A physically based dynamic model will allow the complete parameterization, especially considering rainfall-induced landslides where the definition of components, such as rain input, hydrological response of the soil and its geotechnical properties, is needed. The limit of this approach is constituted by the necessity of a high degree of detail in terms of land measurements, especially when an extensive area is studied. The comparison between results obtained both by empirical and deterministic approaches can supply data paucity and data errors, being a sort of reciprocal validation. A case study is being carried out in the Apuan Alps region, frequently hit by severe rainstorms. In many cases, the storms triggered shallow landslides, like the June 19, 1996 catastrophe, which triggered about a thousand events: soil slips, debris flows and floods. Detailed analyses of the event were carried out by D'Amato Avanzi et al. (2000, 2004) and Giannecchini and Pochini (2003). Furthermore, pluviometric data were analyzed and compared with the occurrence of the shallow landslides, with the aim of identifying the critical rainfall thresholds (Giannecchini, 2005, 2006).

Both geological–geomorphological surveys and field and laboratory tests were carried out to identify the various features constituting the main predisposing factors. Considering the large number of data available, a physically based dynamic model was developed in order to simulate the triggering and evolution of the debris flows, aimed at replicating the behavior of the different variables and assessing potential instability.

The physically based model allowed us to quantify the critical rainfall thresholds, and by comparing the scenarios defined by the empirical approach (Giannecchini, 2005, 2006) and the ones produced by the physically based model, we were able to validate our working hypothesis.

2. General description of the study area

The Apuan Alps chain is well known in the world for the marble quarrying and tourist attractions. Unfortunately, it is also one of the rainiest areas in Italy, where rainfall reaches or exceeds 3000 mm/year, due to its geographical position and conformation. The Apuan Alps is in fact located along the northern Tuscan coast, close to the Ligurian sea, and the main peaks reach almost 2000 m. This is a typical geographical–morphological situation that creates a "barrier effect" for the damp air masses, and consequently triggers violent rainfall events. In several cases, the storms triggered many shallow landslides (soil slip-debris flows), which exposed the population to serious risks. One of the last important events, the June 19, 1996 catastrophe, triggered about 1000 landslides, hyperconcentrated flows, floods in the Versilia plain, and caused 14 deaths (D'Amato Avanzi et al., 2000, 2004).

The June 1996 event (almost 500 mm of rainfall within 12 h, with a maximum intensity of about 160 mm/h) hit in particular the Cardoso Torrent basin, 13 km^2 wide, an affluent of the Versilia River. The rainstorm had various effects on both rivers and slopes: floods, landslides and debris flows almost completely destroyed the villages of Cardoso, resulting in 13 deaths and damage of hundreds of millions of Euros.

The study area is represented by a typically mountainous basin, characterised by narrow, deep cut valleys and steep slopes. The maximum altitude is 1859 m; the minimum altitude is 161 m.

From a geological point of view, in the study area the Autochthon *Auctt*. crops out, together with a small area in which the Tuscan Nappe is present (Carmignani et al., 2000). The Autochthon (Paleozoic-Upper Oligocene) includes metamorphic formations and particularly the Pseudomacigno Fm. (metamorphic sandstone with interbedded metasiltite, Upper Oligocene), and Grezzoni Fm. (Norian dolomite) (Fig. 1). The Tuscan Nappe crops out in the south-eastern part of the Cardoso Torrent basin and includes carbonatic formations.

The structural–-geological setting of the Apuan area clearly influences the morphology of the area. The Cardoso Torrent basin is bounded by ridges made of carbonaceous rocks with slope gradients even greater than 60°, often subvertical or vertical. These slopes are usually rocky and nearly bare.

The carbonaceous rock faces are connected to the lower parts of the slopes, made of metamorphic sandstone (Pseudomacigno Fm.) and phyllitic-schist, by talus and scree deposits. These slopes are usually moderately steep, especially in the intermediate areas (values ranging from 25° to 40°). These slopes are characterized by soils (0.5–2 m thick) which tipically cover the slopes underlain by predominantly phyllitic-schist and metamorphic-arenaceous rocks and are also mantled by dense forest (mainly chestnut). As shown below, the soils covering metamorphic sandstone and phyllite were the most involved in landsliding. Some laboratory tests were carried out on the soils lying on the metamorphic sandstone (Pseudomacigno Fm.) (Giannecchini and Pochini, 2003). According to the USCS classification, the samples usually fall in the SM class and are characterized by a well sorted grain size, with clay content usually less than 5% and little spatial variability on the sampled slopes. Giannecchini and Pochini (2003) also derived the Atterberg limits in order to identify the plasticity features of the colluvium, which generally falls in the low-medium plasticity silt field.

3. The shallow landslides of the June 19, 1996 catastrophe

In the Cardoso Torrent basin, the June 19, 1996 rainstorm caused about 400 first time landslides (Fig. 1). According to the Cruden and Varnes (1996) classification, the type of movement is mainly referable to complex, earth and debris translational slides, quickly developed into flows. These landslides are also known in international literature as soil slip-debris flows (Campbell, 1975; Varnes, 1978; Govi and Sorzana, 1980; Ellen and Fleming, 1987; Crosta et al., 1990; Corominas et al., 1996; Crosta, 1998).

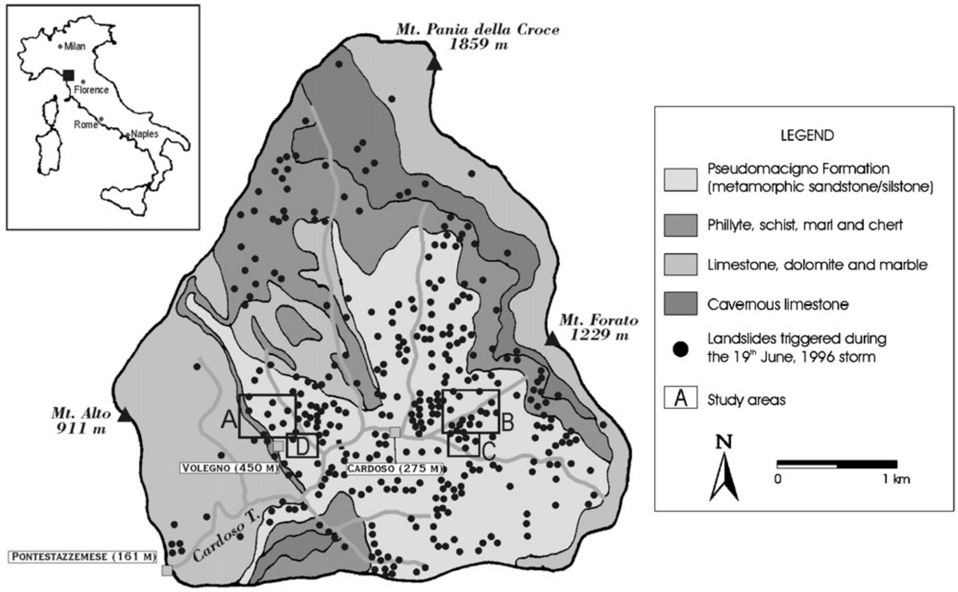

Fig. 1. Lithologic sketch map of the Cardoso Torrent basin and location of the main landslides triggered by the June 19, 1996 rainstorm (after D'Amato Avanzi et al., 2004, modified).

D'Amato Avanzi et al. (2000, 2004) carried out detailed studies about the geological and geomorphological triggering conditions of such phenomena. These mass movements were typically shallow landslides, involving the soil cover (thickness generally from 0.5 to 2 m), mainly linear (width/length ratio 0.03–0.5). They mostly developed in the hollow of slopes underlain by metamorphic sandstone (Pseudomacigno Fm.) and phyllitic-schist, at the top of the zero-order basins. In such hollows, the concave morphology of the slope favoured runoff, while the concave soil–bedrock interface could have favoured the concentration of subsurface downflow, saturation and build-up of pore pressures. The gradient of the slopes involved in sliding is usually 30–45°. As regard the land use, the chestnut woodland resulted the most involved in the shallow landslides.

Further studies on the June 1996 shallow landslides were also carried out by Giannecchini and Pochini (2003). Since not all the slopes with the same geological and geomorphological conditions, cited above, had the same behavior versus the stability, some geotechnical and hydrogeological surveys were carried out. In particular, the authors found that the slope destabilized during the rainstorm seem to have thinner debris cover, finer granulometry and lesser permeability than the slopes not involved in landslides.

The shallow landslides are frequently associated with severe rainstorms (Campbell, 1975; Wieczorek, 1987, 1996). The association of high-intensity rainfall with debris flows was documented in Japan (Fukuoka, 1980), New Zealand (Selby, 1976; Eyles, 1979; Pierson, 1980) and in many other places worldwide (Caine, 1980; Cancelli and Nova, 1985; Crozier, 1986; Wieczorek and Sarmiento, 1988; Jibson, 1989; Wilson and Wieczorek, 1995; Wilson, 2000; Chien-Yuan et al., 2005). The triggering mechanism is generally characterised by infiltration of rainwater into the soil, which may cause the build-up of pore pressures and deterioration of slope stability. The sliding surface usually corresponds to the soil–bedrock interface or to a textural-granulometric discontinuity within the soil, which drastically changes the infiltration rate (Wieczorek, 1987).

Aiming at establishing the critical rainfall thresholds for soil slip-debris flow phenomena, Giannecchini (2005, 2006) analyzed the main rain events (152) occurring in the southern Apuan area in the period from 1975 to 2002. For each event analyzed, the following parameters were collected: rainfall amount (mm), duration (h), mean intensity (mm/h), mean annual precipitation (MAP, mm). By means of an archive research, the 152 events investigated were subdivided into three groups on the basis of the extent of the effects caused by the rainstorms: events that induced several shallow landslides and floods; events that locally induced some shallow landslides and small floods; no information about effects induced. Then, the pluviometric data of all the events were compared in order to individuate possible differences between events which produced landslides and events which did not produce landslides.

Significant results emerged from the rainfall duration/intensity, rainfall intensity/normalized storm rainfall (NSR) and rainfall duration/NSR relationships (NSR, Corominas, 2001, namely the rainfall event/MAP ratio).

Giannecchini (2005, 2006) individuated two threshold curves for triggering shallow landslides in the southern Apuan Alps (Figs. 2–4). Such limits could reasonability delimit three fields of stability: certain stability (under the lower curve), uncertain stability (between the two curves), instability (above the upper curve).

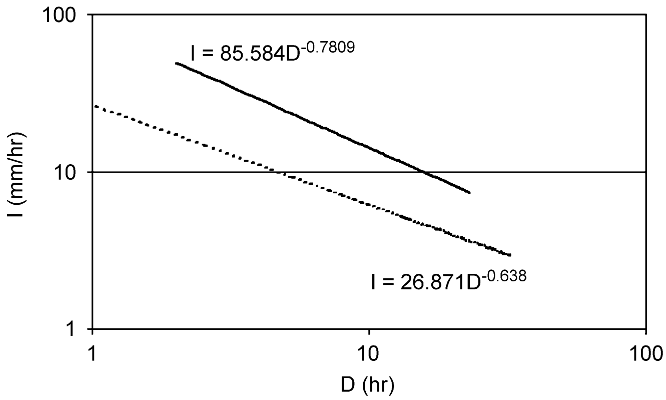

Fig. 2. Rainfall duration/intensity relationship for triggering shallow landslides in the southern Apuan Alps. A lower and an upper threshold curves are recognizable (after Giannecchini, 2006, modified).

4. Model description

There are always several processes contributing to the initiation of a landslide. These are related either to preparatory factors, directly influencing the intrinsic properties of the materials involved and almost constant over time, or to extrinsic, transient factors that influence such properties indirectly (Carrara et al., 1995). The latter are often represented by the rainfall as demonstrated during the June 1996 event, when an intense rainstorm triggered several mass movements.

The effective precipitation indeed constitutes the water supply to the soil that percolates downward to the unsaturated soil matrix.

If we consider that more rainfall must be accumulated to trigger a deep landslide than to trigger a shallow one, a leading role with regard to infiltration processes is played by the presence of a contact between the bedrock and a shallow soil cover. Under such conditions, the lithological boundary can constitute an impermeable limit that restricts

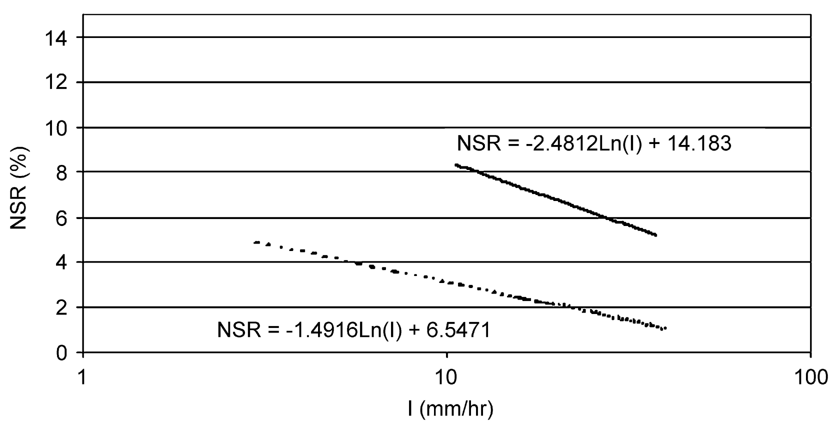

Fig. 3. Rainfall intensity/NSR relationship for triggering shallow landslides in the southern Apuan Alps. A lower and an upper threshold curves are recognizable (after Giannecchini, 2006, modified).

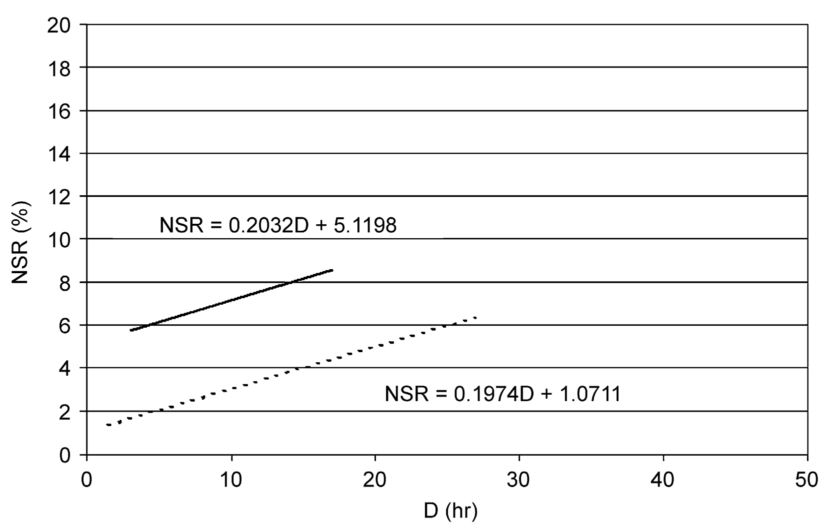

Fig. 4. Rainfall duration/NSR relationship for triggering shallow landslides in the southern Apuan Alps. A lower and an upper threshold curves are recognizable (after Giannecchini, 2006, modified).

drastically the loss of water to the deeper strata, resulting in the generation of a perched ground water table and subsequently in a lateral ground water outflow (Hungr et al., 2001). As a consequence, this contact can constitute a predisposing factor for shallow landslide activity, acting as a potential slip surface, as verified also by D'Amato Avanzi et al. (2000, 2004).

Weathering processes taking place on the bedrock often lead to these lithological characteristics, which are also found in the Cardoso basin, where the contact is located at a depth ranging from 0.5 to 2.0 m. In fact, during the June 1996 event, the triggered landslides were almost exclusively shallow movements. Landslides with such characteristics can be triggered even by short duration rainfall, but with high intensity.

A rise in pore water pressure, which is the direct consequence of the presence of a ground water table, is effectively the triggering factor, considering its effect in terms of weight acting on the potential sliding surface and of decreasing frictional forces among particles. Thus, the threshold of slope failure can be analysed in terms of critical amount of rainfall input, or consequently, in a critical increase of pore pressure.

In order to quantify these critical rainfall thresholds and understand the causal relationship among the processes involved, and test the predefined hypotheses postulated with the empirical approach, as well, a physical dynamic model was realized in cooperation with Dr. T.W.J. van Asch of the Department of Physical Geography of the Utrecht University.

This physical model, aimed at a full simulation and comprehension of the phenomenon, needs to simulate all the variables at stake; therefore, considering the described initiation mechanism, the model relates generated pore pressures to induced instability conditions, coupling a hydrological and a stability analysis functional part.

After having assessed the exact values of the single variables, the data are added on the basis of the discretisation of the space in information cells in a raster based system, where each cell can be regarded as a set of attributes defining its properties (PCRaster, 2000).

We implemented the model with the PCRaster Environmental Modelling language, developed at the Faculty of Geosciences of the Utrecht University, with the aim of constructing iterative spatio-temporal environmental models. This method allows the bond of spatial data in a raster GIS environment with physically based dynamic models using a script; moreover, its high-level computer language uses spatio-temporal operators with intrinsic functionality especially meant for construction of spatio-temporal models, such as map operations combined with time series and process equations (PCRaster, 2000).

The digital elevation model (DEM) constitutes a preliminary point for the modelling since drainage system and slope angle of the catchment are both derived from it. The digital maps obtained are then combined with thematic maps therefore defining the different attributes of the landscape stored in spatial data. Tables combined by specifying keys can define relations between maps.

The hydrological module requires as input the effective rainfall, which is the gross precipitation minus the loss of water through interception and evapotranspiration. In fact, the model includes losses caused by vegetation effects.

The rainfall time series is related to the duration of the event, which bounds also the temporal scale of the model.

Unsaturated percolation to the groundwater is assumed to take place by gravity when the soil moisture content is above the field capacity. The soil water pressure in the unsaturated zone is not taken into account; in fact, fluxes under the gradient of matric potential can be ignored due to the availability of freely draining water and are indeed small if compared to vertical and lateral gravitational flows (Millington and Quirk, 1961).

The soil profile is subdivided in different soil layers because of the various degree of weathering with regard to the depth of the profile, leading to decreased soil properties.

Percolation depends on saturated hydraulic conductivity and is given in units of waterslice in terms of maximum storage into relative degree of saturation (Van Genuchten, 1980). The actual volumetric moisture content, the residual volumetric moisture content and the saturated volumetric moisture content define the latter.

The bedrock underlying the soil cover constitutes an impermeable or semi-impermeable lithological boundary that constrains the loss of water to the deeper strata. The model in fact allows the estimation of the percolation to the bedrock. If the contact is assumed to be impermeable, a perched groundwater will develop at the lower boundary of the soil layer in consequence of percolation processes. The influence of net rainfall input on the groundwater is direct, since the saturated and unsaturated zones are freely draining.

The perched ground water flow is calculated according to the local drain direction imposed by the topographical relief, depending on saturated hydraulic conductivity, height of the water table and width of the flow. Changes in height of the water table directly relates to a change in pore pressures, which are estimated for the stability module.

The stability conditions are estimated in terms of a safety factor, which is the ratio between the resisting and the driving forces of the slope. The driving forces include the downslope component of the soil weight and any additional loads lying on it, while the resisting forces correspond to the reaction force of the mobilized shear strength. The latter decreases when a rise of pore water pressure occurs. Instability conditions are expected when the factor of safety is below unity.

To this end, the infinite slope model is used, in which the slip surface is assumed to be parallel to the slope. This choice allows stability assessment from the attributes of each individual cell, as required for models implemented in a GIS environment.

Moreover, the morphologic characteristics of the surveyed landslides agree with the assumption of parallelism between the slip surface and the topographical surface.

5. Model implementation

Most of the initial assumptions and values needed for the parameterization are supplied by the study carried out by D'Amato Avanzi et al. (2000, 2004) and Giannecchini and Pochini (2003). The laboratory and in situ tests (grain size analyses, Atterberg limits, penetrometer tests, permeability tests) in fact provided a good data set with regard to the characterization of the different properties of the soil, and the analysis of the main rainfall events furnished an adequate description of the climatic factors influencing the stability of the slopes.

These attributes are consequently stored in thematic maps in a raster format, in order to include the data inside the model. In particular, the model needs a lithological map and a vegetation map, through which the saturated conductivity, moisture content, interception by vegetation, geotechnical properties and soil thickness are also categorized. The relationship between these properties and the associated maps are defined by tables and specifying keys. A time series is used to define the rain input values. The rainfall amount is reported hourly on the basis of the duration and intensity of the studied event, with values deriving from the interpolation of two rain gauges located in close proximity to the catchment.

Potential evapotranspiration and interception by vegetation are the only parameters not obtained in the field. The first is assumed to be irrelevant considering the temporal characteristics of the event studied. In Mediterranean environments indeed the rainfall distribution is erratic and often characterized by extreme, short duration and high-intensity events, which lead to sudden fluctuations in soil moisture content. This case study refers to a 14 h duration event, thus the evapotranspiration can be neglected.

Hence, the temporal scale of the model is defined by the duration of the event, which consequently involves time increments of 1 h.

Interception by vegetation is provided as input by the users on the basis of literature values (Skidmore, 2002).

The spatial resolution is defined by the DEM and has a raster size of 20 m.

The calibration set contemplated the problems due to the divergence between the model scale and the sample support. Although the good quality and density of the available set of parameter values, the high variability of the natural processes determines the unfeasibility of obtaining an exact parameterization in a deterministic way. A spatial interpolation of the sampled data is needed to achieve a complete definition of the attributes of the catchment, involving the possibility of losing the physical meaning of the parameters in terms of predictive capability.

An extensive testing of the model constitutes a solution for this problem, especially in case of simulations of past events, where the real occurrence can be compared with the simulated occurrence of the processes. With this aim, some of the values of the parameters subjected to high variability were modified.

The percolation of groundwater to the unweathered bedrock, assumed to be irrelevant due to the characteristics of the contact with the overlying soil, was afterwards modified, admitting a certain amount of percolation and consequently modifying the development of the ground water that turns from perched to freely draining.

The thickness of the slopes, determined by several in situ tests by Giannecchini and Pochini (2003), was also found to be subjected to variability. The interpolated values, stored in a map defining polygons characterized by similar thickness, were subsequently readapted in the light of the observations made on the first model runs.

The model was also tested with altered values of the angle of internal friction and saturated conductivity, according to the range of values obtained in the field.

Finally, a new DEM with a raster size of 10 m was introduced, in order to check the sensitivity of the model to a higher spatial resolution.

6. Simulation of landslide activity

The model simulates landslide activity in the form of maps where the safety factor is reported. The location of the sites where the landslides are triggered is therefore represented in raster maps in terms of unstable cells. Besides a spatial prediction, the dynamic section of the model also provides a temporal prediction, by means of the observation of landslide occurrence at a fixed time interval.

In the hydrological module, the model requires as input an effective precipitation, which causes a rise of a ground water and consequently a rise in pore pressures leading to instability conditions. Thus, the occurrence of a landslide at a fixed time interval can be related to a definite rainfall amount, allowing an assessment of a critical rain threshold for landslide initiation.

The calibration of the model with a different input of data, based on the range of uncertainty of the parameter values, allowed an analysis of the results under several scenarios, constituting an efficient test for the definition of the most suited script. At the same time, the trial phase allowed a sensitivity analysis comparing the various model outcomes with those coming from the reference parameterization.

The included modifications showed a particular sensitivity to the spatial attributes characterizing both the hydrological and geotechnical properties of the soil. These values were often found to be subjected to high variability, like the thickness of the soil, ranging from 0.5 to 2 m but mostly oscillating around 1.5 m. In fact, initially a simple classification of the soil thickness was introduced, subdividing the catchment into a few classes with a definite prevalence for one class. On the basis of the observation of the first results, some anomalies were encountered because of the presence of large sectors of slopes without landslide occurrence. These outcomes, together with a revision of the data coming from the field surveys, helped to review the classification of these sectors, introducing more classes. Considering these remarks, a good sensitivity to the thickness of the soil was found, since a lower depth of the contact between weathered material and bedrock directly induced a higher occurrence of landslides. At the same time, these outcomes confirm the reliability of the hydrological module, since faster saturation and consequently instability conditions are expected with a decrease of the soil thickness. In fact, by in situ tests Giannecchini and Pochini (2003) found that the slopes, destabilized during the rainstorm, seemed to have a thinner debris cover, finer granulometry and lesser permeability than the slopes not involved in landslides.

These remarks induced the authors to test also an alteration in the saturated conductivity parameter, which lead, as expected, to a higher degree of destabilization with lower values of the parameter.

The hydrological module was furthermore tested admitting a certain amount of percolation of ground water to the unweathered bedrock. Unlike the above-mentioned parameters, no significant differences in the model results were observed.

With regard to the geotechnical properties, a modification of the angle of internal friction demonstrates that the parameter values are in inverse relation to the number of unstable cells, as expected by the stability module, which applies the infinite slope model.

A particular case is represented by the determination of the interception by vegetation. Initially interception values were entered on the base of literature values depending on the different land use classes (chestnut wood, mixed wood, cultivated areas, grassland, bare soil), without obtaining an improvement of the model. At the moment, an in situ determination of such interception coefficients, in order to demonstrate the effectiveness of the literature values, is not present. The model can be afterwards improved introducing values determined in the field able to assign accurately the different degrees of interception. For the time being, the model furnishes better results not considering the interception component and not introducing differences in the infiltration rates.

This assumption is quite consistent with the process activity since the low duration and high intensity of the meteoric event have induced a fast saturation of the soil and have limited the effectiveness of the interception component.

The landslides in fact mostly occurred in a short space of time, between 1 p.m. and 2 p.m., and after that time the sediment load in the main watercourses decreased, showing that the erosional phenomena had essentially ceased. Hence, the saturation processes and the pore pressure rise which lead to instability conditions took place after the same time interval for the whole basin corresponding to only 7 h of rain input.

Finally, the utilization of a DEM using a higher spatial resolution, with a raster size of 10 m instead of 20 m, furnished more reliable results.

Though there was a relative degree of sensitivity to the described parameters, the model showed mostly that the morphological features influence the results. Most of the unstable cells in fact are dependent on the slope angle, since instability conditions are triggered in a range of values that oscillate from 25° to 45°. Moreover, the simulated landslides mostly occur in the presence of hollows, as expected by the hydrological module, in which the infiltration processes promote the development of a ground water in case of concave sectors of the slopes.

The spatial distribution of the simulated landslides was compared to the real occurrence related to the event. Even though a total consistency was not obtained, the model provided valuable results, considering that the most influent factors identified in the field were also significant in the simulation. In fact, during the June 19, 1996 catastrophe, the landslides mostly developed in the hollows of slopes and in slopes with a gradient of 30–45° (D'Amato Avanzi et al., 2000, 2004). These conditions, as described previously, were also met by the modelling results.

These remarks are easily achievable simply through the projection on three-dimensional models of the results obtained, where it is possible to examine the morphological features of the areas corresponding to unstable sectors of the slopes. However, the model was validated overlapping on a raster base the simulated and actual failures, comparing the pixels having the same values both in the simulation raster and in the real occurrences raster, therefore deriving the success rate. The 4% of the modelled failures, reported in terms of unstable cells, correspond to actual failures, but a certain degree of error was induced by the process of conversion on a raster base of the areas representing the real occurrences, both because of the approximation made by the surveyor mapping the landslides, and because of the conversion in shape of cells of the landslides polygons. Considering this degree of error, the spatial association between the point patterns was measured also buffering the cells at a certain distance, in order to enlarge the unstable areas and to examine the trend of the success rate for cells of bigger dimensions, obtaining a considerable increasing of the success for cells of doubled dimensions (success rate: 32%).

The model replicates with good reliability the process activity observed during the field surveys.

The direct influence of parameters like soil thickness or saturated conductivity demonstrates that the infiltration and percolation processes are properly simulated in the hydrological module. Moreover, the latter also provides appreciable results in terms of temporal activity, since the occurrence of a landslide at a fixed time interval refers to a definite amount of rainfall, which can be related to a critical rain threshold.

These critical values are quite consistent with those coming from the empirical approach; in effect the model shows increasing values in the landslide initiation after 6 h, with a cumulative rain input of about 255 mm, which is a likely scenario if compared to the processes occurred during the studied event (Fig. 5).

7. Discussion and conclusions

A good quality of data constitutes an essential component for the proper parameterization of a catchment. The available dataset for this study in fact allowed the realization of a physically based model, reproducing the processes involved and evaluating the factors with sufficient detail.

In physical models, an extensive parameterization is needed, while a completely characterizing collection of data in the field is not always possible because of the high spatial variability of the natural processes.

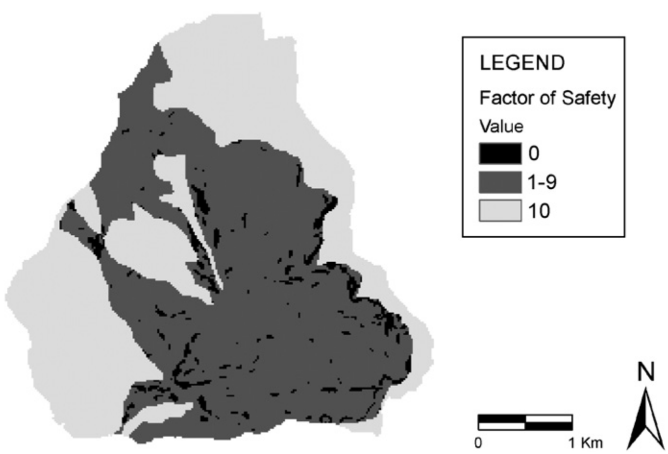

Fig. 5. Landslides activity reported in terms of unstable cells (factor of safety < 1) after the first 6 h of the simulation.

Indeed it is quite impossible, in a catchment reproduced in a raster system, to characterize every single cell with all the attributes defining the environmental properties. For model scales that exceed the sample scale, an interpolation is needed, which could well cause the physical meaning of the parameters to be lost.

An extensive testing of the model, which highlights the weak points of the simulation, constitutes a fundamental part of the modelling itself, allowing the calibration of the parameters that lead to less reliable results. At the same time, the authors' knowledge of catchment systems and processes becomes of fundamental importance, in order to compensate the lack of sample support or the low spatial correlation. Some values based on an expert knowledge approach can be introduced.

In this case study, some parameters like the thickness of the soil cover had to be redefined in the light of the first model results, on the basis of heuristic determinations arrived at through a good level of awareness of the geological and geomorphological processes, since the number of in situ tests were not sufficient to characterize every single sub-catchment.

From a general point of view, the modelling results are consistent with the real occurrence of the landslides, since the real process activity is respected. The main triggering conditions for the development of landslides during the event are also met by the model.

The lack of consistency in terms of exact location of the triggered landslides can be ascribed to the discrepancy between the model scale and the sample scale.

In the field of natural hazard assessment, at a catchment scale, it is not always necessary to give predictions in terms of the precise location of the hazard inferred. A general evaluation in terms of temporal activity is often sufficient.

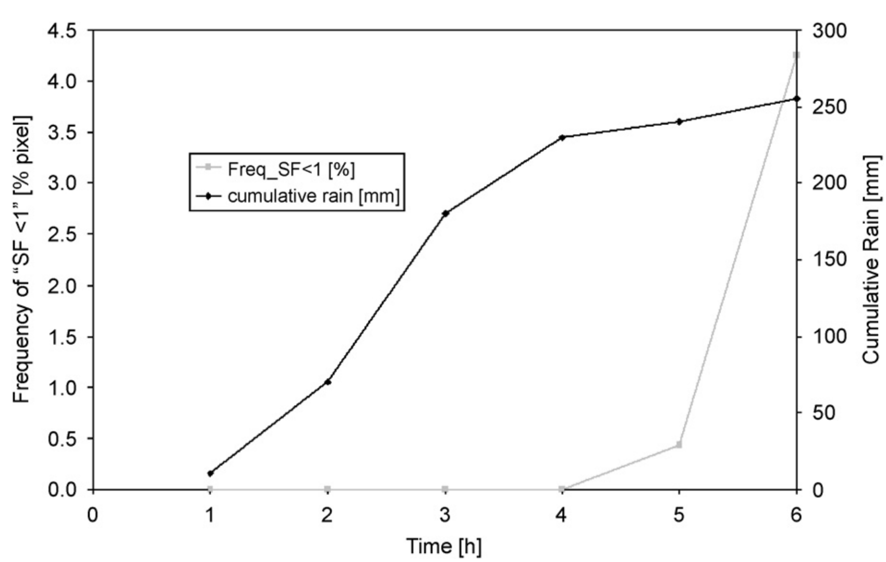

Fig. 6. Number of unstable cells and cumulative rainfall for the first 6 h of the simulation.

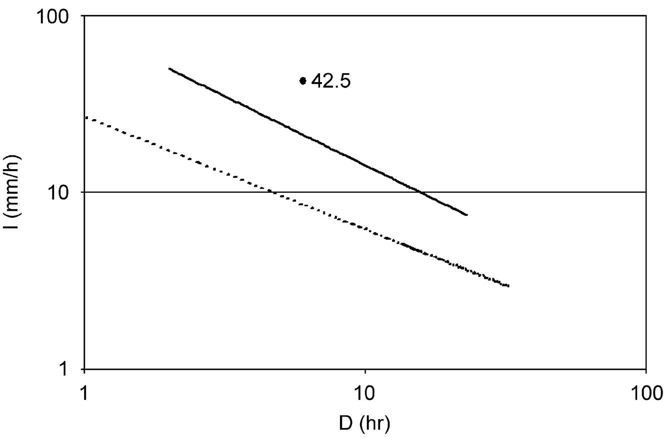

Fig. 7. Mean precipitation per hour (for the first 6 h) plotted in the graph. Rainfall intensity/NSR for triggering shallow landslides in the southern Apuan Alps.

Nevertheless a validation of the model was implemented, which produced low values of overlapping (success rate: 4%) considering the same spatial resolution used during the modelling.

Then, in order to reduce the error induced by the process of mapping and conversion on a raster base of the landslide areas, cells of increased dimensions were used, obtaining a considerable increase of the success rate.

The comparison between a physically based dynamic approach and an empirical approach constitutes a valid test for the reciprocal effectiveness of the results.

To this end, the critical rainfall input thresholds calculated by Giannecchini (2005, 2006) were compared with those obtained by the model. The results are rather consistent with the characteristics of the empirical critical thresholds; in fact, during the simulation, the first occurrence of landslides is observed after 5 h of rainfall with a mean of 48 mm/h, referred to a cumulative amount of 240 mm. Under these conditions, the number of pixels in which the safety factor reports a value less than 1 is the 0.4% of the whole area. Subsequently, a higher amount of landslides is registered, with a number of unstable pixels of 4.3% and with a mean of 42.5 mm/h after 6 h.

Therefore, these results yielded by the deterministic approach deal with the empirical thresholds of instability. Indeed, plotting the mean of 42.5 mm/h for the first 6 h in the rainfall duration/intensity graph of Fig. 2, the value lies above the upper threshold of instability proving the consistency between the two methods (Figs. 6 and 7).

References

Caine, N., 1980. The rainfall intensity-duration control of shallow landslides and debris flows. Geografiska Annaler 62A (1–2), 23–27.

Campbell, R.H., 1975. Soil slips, debris flows and rainstorms in the Santa Monica Mountains and Vicinity, Southern California. USGS Professional Paper 851, 51pp.

Cancelli, A., Nova, R., 1985. Landslides in soil and debris cover triggered by rainfall in Valtellina (Central Alps-Italy). In: Proceedings of the IV International Conference and Field Workshop on Landslides. Tokyo, pp. 267–272.

Carmignani, L., Conti, P., Disperati, L., Fantozzi, P.L., Giglia, G., Meccheri, M., 2000. Carta geologica del Parco delle Alpi Apuane. Parco Regionale delle Alpi Apuane e Università degli Studi di Siena. S.El.Ca. (Eds)., Firenze, in Italian.

Carrara, A.M., Cardinali, F., Guzzetti, F., Reichenbach, P., 1995. Gis based techniques for mapping landslide hazard. In: Carrara, A.M., Guzzetti, F. (Eds.), Geographical Information Systems in Assessing Natural Hazards. Kluwer, Dordrecht, pp. 135–176.

Corominas, J., 2001. Landslides and climate. Keynote lecture from the 8th International Symposium on Landslides in Cardiff, Galles, 4, pp. 1–33

Chien-Yuan, C., Tien-Chien, C., Fan-Chieh, Y., Chun-Chieh, T., 2005. Rainfall duration and debris-flow initiated studies for real-time monitoring. Environmental Geology 47, 715–724.

Corominas, J., Remondo, R., Farias, P., Estevao, M., Zezere, J., Diaz De Teran, J., Dikau, R., Schrott, L., Moya, J., Gonzalez, A., 1996. Debris flow. In: Dikau, R., Brundsen, D., Schrott, L., Ibsen, M.-L. (Eds.), Landslide Recognition. Identification, Movement and Causes. Wiley, pp. 161–180.

Crosta, G., 1998. Regionalization of rainfall thresholds: an aid to landslide hazard evaluation. Environmental Geology 35 (2–3), 131–145.

Crosta, G., Guzzetti, F., Marchetti, M., Reichembach, P., 1990. Morphological classification of debris-flow processes in South-Central Alps (Italy). In: Proceedings of the Sixth International IAEG Congr. Balkema, Rotterdam, pp. 1565–1572.

Crozier, M.J., 1986. Landslides: Causes, Consequences and Environment. Routledge, London–New York, 252pp.

Cruden, D.M., Varnes, D.J., 1996. Landslide types and processes. In: Turner, A.K., Schuster, R.L. (Eds.), Landslide Investigation and Mitigation, Special Report 247, Transportation Research Board, National Research Council, National Academy Press, Washington, DC, pp. 36–75.

D'Amato Avanzi, G., Giannecchini, R., Puccinelli, A., 2000. Geologic and geomorphic factors of the landslides triggered in the Cardoso T. Basin (Tuscany, Italy) by the June 19, 1996 intense rainstorm. In: Proceedings of the eighth International Symposium on Landslides, Cardiff, Galles, pp. 381–386.

D'Amato Avanzi, G., Giannecchini, R., Puccinelli, A., 2004. The influence of the geological and geomorphological settings on shallow landslides. An example in a temperate climate environment: the June 19, 1996 event in north-western Tuscany (Italy). Engineering Geology 73 (3–4), 215–228.

Ellen, S.D., Fleming, R.W., 1987. Mobilization of debris flows from soil slips, San Francisco Bay Region, California. In: Costa, J.E., Wieczorek, G.F. (Eds.), Debris Flows/Avalanches: Process, Recognition, and Mitigation. Reviews in Engineering Geology, vol. 7. Geological Society of America, Boulder, CO, pp. 31–40.

Eyles, R.J., 1979. Slip-triggering rainfalls in Wellington City, New Zealand. New Zealand Journal for Science 22 (2), 117–121.

Fukuoka, M., 1980. Landslides associated with rainfall. Geotechnical Engineering 11 (1), 1–29.

Giannecchini, R., 2005. Rainfall triggering soil slips in the southern Apuan Alps (Tuscany, Italy). In: Sixth Plinius Conference on Mediterranean Storms (European Geosciences Union), Mediterranean Sea, 17–24 October 2004. Advances in Geosciences, vol. 2, pp. 21–24.

Giannecchini, R., 2006. Relationship between rainfall and shallow landslides in the southern Apuan Alps (Italy). Natural Hazards Earth System Science 6, 357–364.

Giannecchini, R., Pochini, A., 2003. Geotechnical influence on soil slips in the Apuan Alps (Tuscany): first results in the Cardoso area. In: Proceedings of the International Conference on Fast Movements-Prediction and Prevention for Risk Mitigation (IC-FSM2003), Napoli (Italy). 11–13 May 2003, pp. 241–245.

Govi, M., Sorzana, P.F., 1980. Landslide susceptibility as a function of critical rainfall amount in Piedmont basins (north-western Italy). Studia Geomorphologica Carpatho-Balcanica 14, 43–61.

Hungr, O., Evans, S.G., Bovis, M., Hutchinson, J.N., 2001. Review of the classification of landslides of the flow type. Environmental and Engineering Geosciences 7 (3), 1–18.

Jibson, R.W., 1989. Debris flows in Southern Puerto Rico. Geological Society of America 236, 29–55.

Millington, R.J., Quirk, J.M., 1961. Permeability of porous solids. Transactions of the Faraday Society 57, 1200–1207.

PCRaster, 2000. PCRaster Environmental Software, Manual version 2. Faculty of Geographical Sciences, Utrecht University, Utrecht, 367pp.

Pierson, T.C., 1980. Piezometric response to rainstorms in forested hillslope drainage depressions. Journal of Hydrology, New Zealand 19 (1), 1–10.

Selby, M.J., 1976. Slope erosion due to extreme rainfall: a case study from New Zealand. Geografiska Annaler 58A (2), 131–138.

Skidmore, A., 2002. Environmental Modelling With Gis and Remote Sensing. Taylor & Francis, London, 286pp.

Soeters, R., Van Westen, C.J., 1993. Slope instability recognition, analysis and zonation. In: Turner, A.K., Schuster, R.L. (Eds.), Landslides, Investigation and Mitigation. Special Report 247, Transport Research Board. National Academy Press, Washington, DC, pp. 129–177.

Terlien, M.T.J., 1996. Modelling spatial and temporal variations in rainfall triggered landslides. Ph.D. Thesis, ITC Publ. 32, Enschede, 254pp.

Van Beek, L.P.H., Van Asch, Th.W.J., 2004. Regional assessment of land-use change on landslide hazard by means of physically based modelling. Natural Hazards 31, 289–304.

Van Genuchten, M.Th., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal 44, 892–898.

Varnes, D.J., 1978. Slope movements. Types and processes. In: Schuster, R.L., Krizker, R.J. (Eds.), Landslide: Analysis And Control. Natural Academy of Sciences, Trasp. Res. Board, Washington, Special Report, 176, pp. 11–35.

Wieczorek, G.F., 1987. Effect of rainfall intensity and duration on debris flows in central Santa Cruz Mountains, California. In: Costa, J.E., Wieczorek, G.F. (Eds.), Debris Flows/Avalanches: Process, Recognition and Mitigation. Geological Society of America, Reviews of Engineering Geology 7, 93–104.

Wieczorek, G.F., 1996. Landslide triggering mechanisms. In: Landslide: Investigation and Mitigation, Special Report 247, Transp. Res. Board, National Academy of Sciences, Washington, pp. 76–90.

Wieczorek, G.F., Sarmiento, J., 1988. Rainfall, piezometric level and debris flows near La Honda, California, in storms between 1975 and 1983. In: Ellen, S.D., Wieczorek, G.F. (Eds.), Landslides, Floods, and Marine Effects of the Storm of January 3–5, 1982, in the S. Francisco Bay Region, California, US Geological Survey Professional Paper, 1434, pp. 43–62.

Wilson, R.C., 2000. Climatic variations in rainfall thresholds for debris-flow activity. In: Proceedings of the EGS Plinius Conference Mediterranean Storms, Maratea, Italy, pp. 415–424.

Wilson, R.C., Wieczorek, G.F., 1995. Environmental and Engineering Geoscience, I 1, 11–27.