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ORIGINAL PAPER

Soil slip susceptibility assessment using mechanical–hydrological approach and GIS techniques: an application in the Apuan Alps (Italy)

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Abstract This study aims at contributing to the soil slip susceptibility assessment in a typical basin of the southern Apuan Alps, Italy. On June 1996, this basin (Cardoso Torrent, 13 km^2 large) was hit by an extremely heavy rainstorm (maximum intensity of about 160 mm/h), which caused many landslides (debris slide–debris flows) and valley bottom flows (hyperconcentrated flows), destruction and deaths. Detailed surveys provided the characterization of the main factors (geological, geomorphologic, hydrological, hydrogeological and geotechnical) which contributed in triggering landslides. In order to evaluate the soil slip susceptibility in this area, a physically based model was applied and a GIS analysis of digital elevation model was performed. This approach couples a mechanical model based on an infinite slope form of the Mohr–Coulomb failure criterion, and a steady-state hydrological one (a modified version of Shalstab, which considers the cohesion of the debris material potentially involved in landsliding). GIS techniques allowed evaluating the effects of topographic convergence and drainage area on slope failure. In this way, based on the infiltration rate, the triggering of the June 1996 landslides was simulated and the critical rainfall thresholds assessed at about 200–250 mm/24 h.

Keywords Soil slip · Landslide susceptibility · Physically based model · GIS · Apuan Alps

1 Introduction

Due to geographical position and conformation, the Apuan Alps region is one of the rainiest in Italy (up to than 3,000 mm/year) and is frequently hit by severe rainstorms. In many cases, the storms triggered shallow landslides (debris slide–debris flows), which exposed the population to serious risks (D'Amato Avanzi and Giannecchini 2003).

One of the most catastrophic events occurred on June 19, 1996, with almost 500 mm rainfall within 12 h (D'Amato Avanzi et al. 2000, 2004), which produced hundreds of

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shallow landslides and floods that devastated a small area (about 13 km^2) in the southern portion of the Apuan Alps (Fig. 1). Landslides and debris torrents destroyed some villages, causing 14 deaths and damage costing hundreds of millions of Euros (buildings, roads, bridges destroyed, work activity interrupted, rivers ruined). According to the classification suggested by Cruden and Varnes (1996), such landslides were mainly referable to complex, earth and debris translational slides, quickly developed into flows (extremely rapid debris slide–debris flow). They are generally associated with heavy rainfall and are also known 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; Jakob and Hungr 2005; Tsai 2008). The June 1996 landslides can be classified as extremely rapid debris slide–debris flow and involved almost exclusively the colluvium cover (1–2 m thick) characterized by a medium–low permeability ($K = 10^{-5}$–10^{-6} m/s). This material is underlain by impermeable and semi-permeable parent rocks (in particular, the Pseudomacigno Formation).

The Cardoso Torrent basin, a small mountain sub-basin of the Versilia River, was the most affected area. Many studies were carried out both on the landslide sites and on slopes which remained stable during the heavy rainfall (D'Amato Avanzi et al. 2000, 2004; Martello et al. 2000; Giannecchini and Pochini 2003; Giannecchini et al. 2007). Studies pointed out some characteristics, e.g. geological, geomorphologic, geotechnical, hydrogeological, that recurred in the source areas (e.g. debris cover 1–2 m thick, impermeable or semi-permeable bedrock, hollow morphology).

Besides the high frequency of intense rainfall events, the Apuan-Versilian territory is characterized by high vulnerability: many villages are located in the mountain region, while heavy urbanization occurs on the Versilia plain, towards which several torrents flow. Furthermore, the Upper Versilia is characterized by important quarrying activity, with many workers. Finally, this area has a high tourist presence both on the beaches and in the mountain area. Because the typical rainfall events are usually sudden, violent and of short duration, this could increase the risk for people and buildings. Therefore, it is extremely

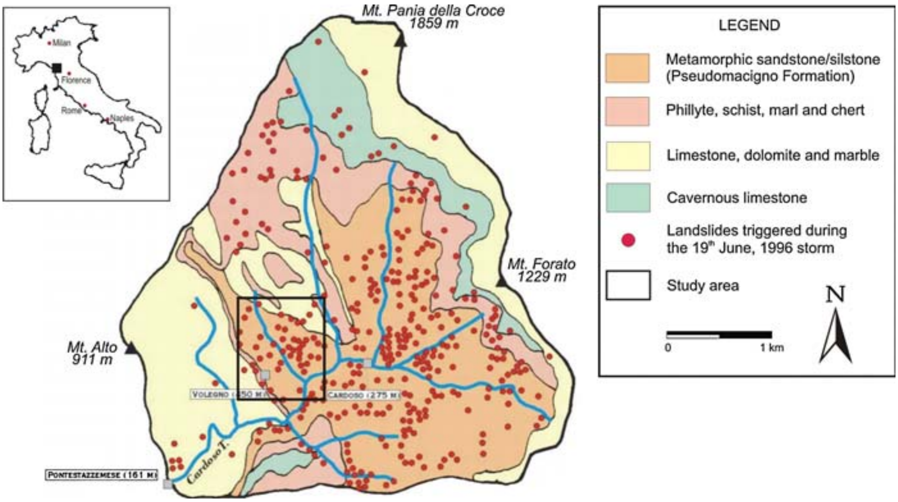

Fig. 1 Lithologic sketch map of the Cardoso Torrent basin and location of the main landslides triggered by the June 19, 1996 rainstorm (after D'Amato Avanzi et al. 2004, modified). The test area is evidenced by a *box*

important for the local municipal administrations and civil protection agencies to have efficient countermeasures and emergency plans, in order to protect the population.

During the June 1996 event, the type of landslides was mostly represented by soil slip-debris flows. In the study area, landslides with such characteristics are often associated with short duration/high intensity rainfall (duration less than 12 h and intensity between about 10 and 60 mm/h—Giannecchini 2005, 2006). In this case, the conditions for slope failure can be assessed in terms of critical amount of effective rainfall input (namely the rainfall amount which really infiltrates underground), and consequently, in a critical decreasing of frictional forces among particles in the colluvium cover (Terzaghi 1950; Carrara et al. 1995; Guzzetti et al. 1999; Giannecchini et al. 2007; Toyos et al. 2007). Thus, the landslide susceptibility evaluation of such complex landsliding process could usefully employ physically based modelling. This methodology allows for a detailed physical approach to the modelling of slope instability processes by directly applying the mechanical laws governing the shallow landslides.

2 Geomorphological setting

The Cardoso T. basin is located in the Versilian hinterland (southern Apuan Alps, north-western Tuscany—Fig. 1). The Apuan Alps chain is well known in the world for the marble quarrying and tourist attractions. Unfortunately, due to its particular geographical position and configuration, it is also one of the rainiest areas in Italy, where rainfall exceeds 3,000 mm/year. The Apuan Alps is located along the northern Tuscan coast, close to the Ligurian Sea, and the main peaks reach almost 2,000 m a.s.l. This typical geographical–morphological situation creates an "orographic effect" for oceanic 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, as during the June 1996 catastrophe.

The study area is a mountain drainage basin, characterized by narrow, deep cut valleys and steep slopes. The maximum altitude is 1,859 m (Mt. Pania della Croce); the minimum altitude is 161 m (closing section of the Cardoso T. basin). The main geological features of the area are represented by the cropping out of formations belonging to the Autochthon *Auctt.* Unit (Carmignani et al. 2000). The Autochthon *Auctt.* (Paleozoic–Upper Oligocene) includes several metamorphic formations, among which is the Pseudomacigno Fm. (meta-sandstone with interbedded shale, Upper Oligocene). This represents a key factor (Fig. 1), having a significant role in controlling the triggering sites of the soil slips: the impermeability and structural pattern (bedding dipping downslope) of this particular bedrock favoured the debris cover landsliding (D'Amato Avanzi et al. 2000, 2004).

The morphological features are clearly influenced by the geological–structural setting of the Apuan region. The Cardoso Torrent basin is bounded by ridges made of carbonate rocks with slope gradients even greater than 60°, often subvertical or vertical. These slopes are usually rocky and nearly bare. Talus and scree deposits connect the carbonate rock faces to the lowest parts of the slopes, made of metamorphic sandstone (Pseudomacigno Fm.) and phyllitic rocks. These slopes are usually less steep, especially in the intermediate areas (steepness ranging from 25° to 40°). Soil deposits (0.5–2.0 m thick) typically cover the slopes underlain by predominantly meta-arenaceous and phyllitic rocks and are generally mantled by dense woods which are mainly formed of chestnut trees. In the 1996 catastrophe, the soils covering the meta-sandstone and phyllite were really the most involved in landsliding (D'Amato Avanzi et al. 2000, 2004; Giannecchini and Pochini 2003).

3 Soil characteristics

In order to characterize the materials involved in landsliding, in time many surveys were carried out, both on site and in laboratory, by means of penetration tests (CPT—cone penetration test and DP—dynamic penetration test), variable load permeability tests, grain size analyses and Atterberg limits (Giannecchini 2003, Giannecchini and Pochini 2003). The test area was established in a sub-basin of the Cardoso Torrent basin and shown in Fig. 1. Such area was selected because it is one of the most affected by landslides and characterized by the typical geological and geomorphologic features which recur in the soil slip areas. On site, the main morphological characteristics of soil slips were collected (D'Amato Avanzi et al. 2000, 2004), such as morphometry (length, width, thickness), geologic conditions (bedrock, bedding, colluvium), slope gradient and land use.

Further studies were carried out on the geotechnical and hydrogeological characterization of the slopes involved. Similar studies were also carried out in slopes not affected by instability processes, in order to identify significant differences between sites involved and not involved in landsliding. According to Giannecchini and Pochini (2003) and Giannecchini (2003), the landslide sites were characterized by slightly finer grain size and thinner soil covers than stable slopes.

For this purpose, penetration tests were used aimed at establishing the shear strength and the colluvium thickness of the slopes; on-site permeability tests were also carried out in order to evaluate the hydraulic conductivity (K) of colluvium; moreover, laboratory tests (grain size analyses, Atterberg limits) were carried out. According to the USCS classification (Unified Soil Classification System, U.S. Army Engineer Waterways Experiment Station 1960), the samples usually fall within the SM class (sands with fines, below A line in the Casagrande plasticity chart) 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 (2003) and 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. The results of these studies were integrated with data from the technical–scientific literature about these particular materials, as input for the model.

Therefore, the soil characteristics of the study area can be summarized as follows:

- Colluvium thickness: 0.7–2.5 m
- Unit weight (γ): 19 kN/m^3
- Grain size (average value): 26% gravel, 47% sand, 24% silt, 3% clay; uniformity coefficient: 70
- Effective shear strength angle (φ'): 28–38°
- Effective cohesion (c'): 25–38 kPa
- Saturated hydraulic conductivity (K): 5×10^{-3}–5×10^{-4} cm/s

4 Shallow rapid landslides susceptibility assessment

Several different features characterize the soil slip-debris flows in the study area. They were investigated, classified and mapped in the field or through aerial photographs and are briefly summarized below:

- high number of slides (almost 500 in the Cardoso T. basin during the June 1996 event) triggered by a single disruptive rainstorm (almost 500 mm/12 h, with mean and maximum intensity of about 40 and 160 mm/h, respectively);

- high spatial concentration (>50 slides/km^2);
- very high velocity reached by the mass movement (>5 m/s);
- very high destructive power;
- steep slopes ranging in dip from 30° to >45°;
- long distance travelled (often in a short time) by the mobilized mass until deposition;
- absence of incipient movement evidence;
- involved material mostly formed of sand with minor amount of gravel and cohesive fraction;
- low soil cover thickness (1–2 m);
- bedrock attitude dipping downslope.

The principal triggering causes of soil slip-debris flows are attributable to heavy rainstorms (Wieczorek 1996). In the study area, rainstorms are often characterized by high intensity and low duration rainfalls (usually <24 h, typically within 12 h in the study area—Giannecchini 2005, 2006).

The shallow landslides assessment involves a rather complex dataset on the triggering factors and soil characteristics, which are often difficult to collect and represent in detail. Different approaches for modelling the shallow landslides were suggested by several authors (e.g. among the most adopted approaches, see Aleotti and Chowdury 1999; Crosta and Frattini 2003; Iovine et al. 2003; Campus et al. 2005, and references therein) and are briefly listed below:

- heuristic methods (index methods);
- multivariate statistical analysis techniques (black box models);
- physically based deterministic approaches (white box models).

Index methods are highly subjective and the results coming from different operators could be at variance (Carrara et al. 1995). Statistical, black box methods are essentially “data-driven” (Guzzetti et al. 1999): their reliability strictly depends on the characteristics (amount and quality) of the dataset processed by the model. On the contrary, physically based models, being “process-driven”, have the advantage of considering the geotechnical parameters that characterize the material involved and of taking into account the dynamic factors which affect the phenomenon (rainfall and soil characteristics).

Among the physically based methods, one of the well-known and tested approaches is the Shalstab model (Montgomery and Dietrich 1994; Dietrich and Montgomery 1998). This model was modified by Campus et al. (2005), in order to take into account cohesion. As summarized in Figs. 2 and 3, the essential theory of the model concerns the progressive accumulation of colluvium in the valley axis, followed by discharge and subsequent refilling. Instability conditions may depend on several factors changing in the time (progressive thickening, loading effects, hydrogeological disequilibrium) or may be suddenly triggered by intense rainfall or seismic activity.

The considered deterministic approach couples a hydrologic to a slope stability model with main assumptions listed below:

- infinite slope;
- failure plane, water table and ground surface parallel;
- failure plane at the colluvium–bedrock boundary;
- steady-state shallow sub-surface flow;
- absence of deep drainage and flow in the bedrock.

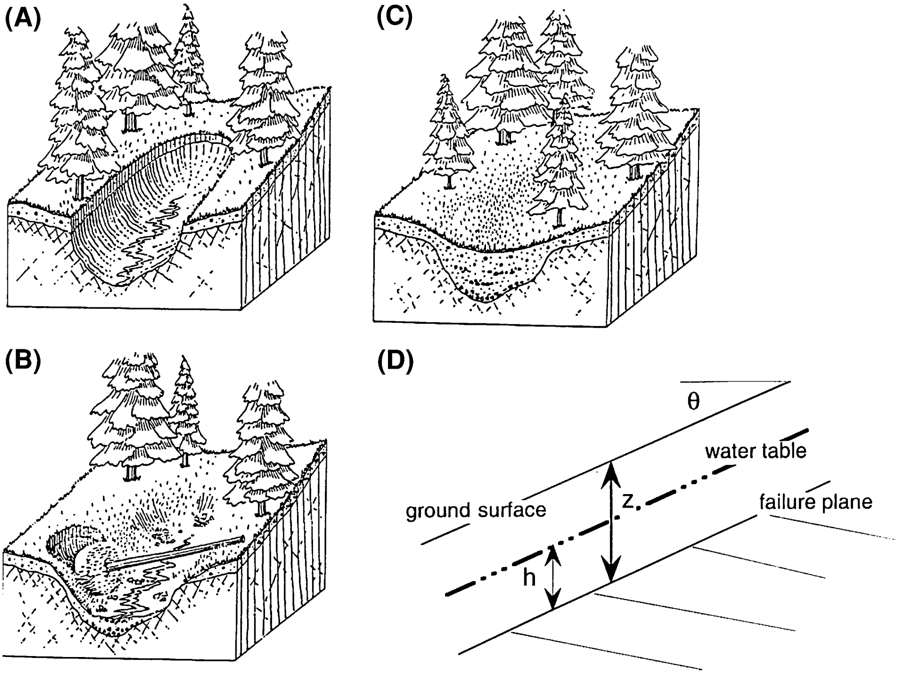

Fig. 2 Sketch of the slope stability model. **a**–**c** Cycle of accumulation and discharge of colluvium (drawing by L. Reid, after Dietrich et al. 1982). **d** Conceptual stability model: *h* thickness of the saturated subsurface flow, *z* thickness of the potential unstable mass, *θ* slope angle

The soil column that is saturated at instability ($W = h/z$) can be defined by the following expression:

$$\frac{h}{z} = \frac{q}{T} \cdot \frac{a}{b \cdot \sin\theta} = W$$

where h is the vertical depth of the saturated subsurface flow; z is the vertical depth of the failure plane (colluvium thickness $= z \cdot \cos\theta$); q is the effective steady-state precipitation; $T = K \cdot \mathrm{z} \cdot \cos\theta$ is the saturated hydraulic transmissivity, where K is the saturated hydraulic conductivity; a is the drainage area; b is the width of the outflow boundary; θ is the slope angle; W is the saturated soil column at instability.

The h/z ratio is made of two distinct components: the hydrological ratio (q/T, which combines the magnitude of the rainfall with transmissivity) and the topographic ratio [$a/(b \cdot \sin\theta)$: topographic effect on runoff]. The stability model is expressed as regards the Mohr–Coulomb shear strength criterion (after Skempton and DeLory 1957):

$$F = \frac{c' + (\gamma - W \cdot \gamma_{\mathrm{w}}) \cdot z \cdot \cos^2\theta \cdot \tan\varphi'}{\gamma \cdot z \cdot \sin\theta \cdot \cos\theta}$$

where F is the safety factor; c' is the effective cohesion; γ is the wet soil unit weight; γ_{w} is the water unit weight; W is the saturated soil column at instability; φ' is the effective shear strength angle; θ is the slope angle; z is the thickness of the colluvium on the failure plane.

The topographic variables were analysed by means of a digital elevation model (grid of 5 m × 5 m cells) derived from the vector format Tuscany Region technical maps, 1:5,000 and 1:2,000 scale, equipped with elevation data.

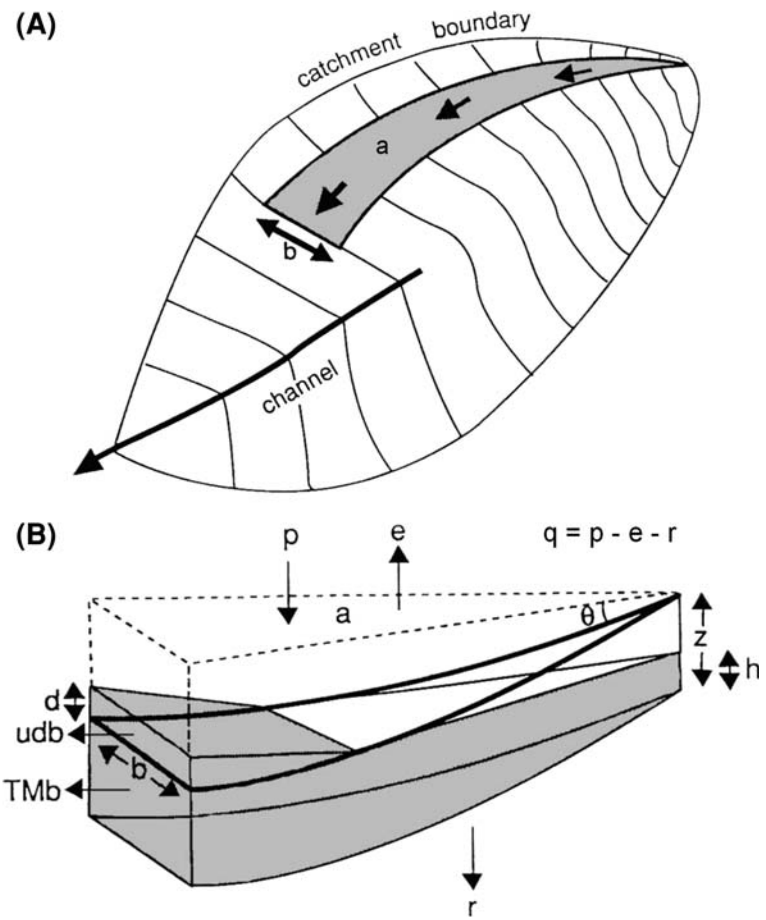

Fig. 3 **a** Hydrological model (simplified): (a) drainage area, (b) width of the outflow boundary. **b** Hydrological 3D sketch: *p* precipitation, *e* evapotranspiration, *r* deep drainage, *q* effective rainfall ($q = p - e - r$), *udb* saturation overland flow (not calculated by the model), *T* transmissivity; *M*, sin θ (after Dietrich et al. 1992)

Instability condition for each cell was obtained using the expression below, which combines the hydrological model and slope stability model (Dietrich and Montgomery 1998):

$$\frac{a}{b} \geq \left[\frac{c'}{\gamma_w \cdot z \cdot \cos^2\theta \cdot \tan\varphi'} + \frac{\gamma}{\gamma_w} \cdot \left(1 - \frac{\tan\theta}{\tan\varphi'}\right)\right] \cdot \frac{T}{q} \cdot \sin\theta$$

GIS-supported spatial analysis allowed calculation of the slope gradient and the width of the outflow boundary (Table 1). Taking into account the divergence between the grid and the slope aspect (measured azimuth of the downslope direction), the width of the outflow boundary is defined as follows:

$$b = \frac{L}{\cos\beta}$$

where L is the width of the cell; β is the slope aspect.

Table 1 List of parameters/variables and their ranges considered in the model

Parameter/variable	Extraction technique	Data format	Range
Saturated hydraulic conductivity (*K*)	On-site permeability tests	Vector	5×10^{-3}–5×10^{-4} cm/s
Colluvium thickness (*z*)	Static–dynamic penetration test, on-site survey	Vector	0.7–2.5 m
Effective cohesion (c')	Technical–scientific literature	Vector	25–38 kPa
Shear strength angle (φ')	Static–dynamic penetration test Technical–scientific literature	Vector	28–38°
Unit weight (γ)	Static–dynamic penetration test	Vector	19 kN/m^3
Dip slope (θ)	Digital elevation model	Raster (GRID)	–
Drainage area (*a*)	Terrain analysis using DEM (TAUDEM—Tarboton 2002)	Raster (GRID)	–
Width of the outflow boundary (*b*)	Terrain analysis using DEM (TAUDEM—Tarboton 2002)	Raster (GRID)	–

The computation of the flow direction and, consequently, the drainage area required the use of a free application developed in ArcGIS (ESRI) environment, named terrain analysis using DEM (TAUDEM, Tarboton 2002). The approach applied in this study (*DInf* approach) assigns a flow direction based on the steepest slope of each triangular facet.

As shown in Fig. 4, the flow direction angle is determined as the direction of the steepest downward slope on the eight triangular facets formed in a 3 × 3 grid cell window centred on the grid cell of interest (Tarboton 2002).

The area contributing to flow is calculated using a recursive procedure (Mark 1988): for each grid cell, it is taken as its own contribution plus the contribution from upslope neighbours draining into it.

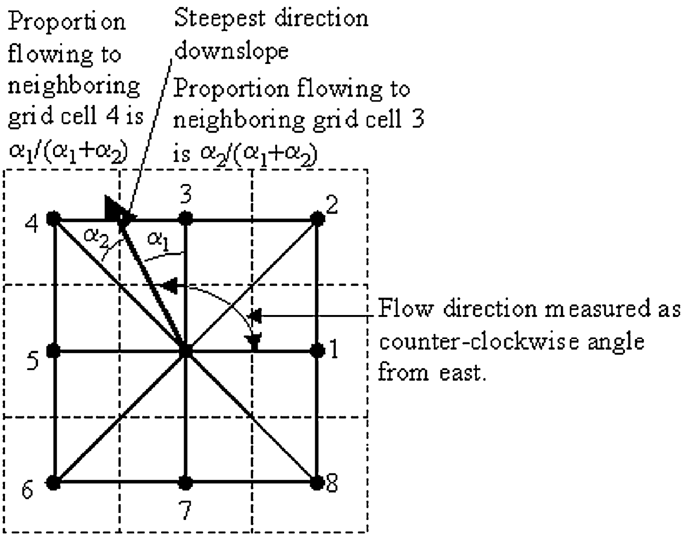

Fig. 4 Flow direction defined as steepest downward slope on planar triangular facets on a block centred grid (after Tarboton 2002)

Another important parameter needed for modelling is the effective rainfall amount infiltrated. In this study, due to the lack of knowledge about the effective infiltration rate during intense rainstorms, on the basis of authors' experience about this particular material, it was reasonably supposed as the 30% of the critical rainfall of the area. Two approaches were followed: first, an infiltration rate of 60 mm within 24 h was used according the studies on critical threshold curves carried out for this area by Giannecchini (2005, 2006); then, an infiltration rate of 80 mm within 24 h was considered on the basis of the rainfall recorded during the June 1996 event in the pluviometric network close to the study area. The model was applied to two different conditions of effective rainfall, while the geotechnical parameters of each cover remained obviously constant. Table 1 summarizes the general ranges of the parameters/variables used for the modelling.

5 Discussion and conclusion

This study was focused on the application of a physically based instability model for assessing soil slip susceptibility in a heavy rainstorms prone area of the Apuan Alps.

Figure 5 shows the results obtained by the model elaboration, namely the unstable areas predicted by the slope instability model on the basis of the data collected: Fig. 5a shows the instable slopes for an effective rainfall of 60 mm, while Fig. 5b indicates results under an effective rainfall of 80 mm.

The comparison of the instability models with the landslide inventory maps highlights a good correspondence, in particular with reference to the application of an effective infiltrated rainfall of 80 mm within 24 h. A simple neighbourhood statistical method to assess the prediction capability (success %) of the instability model was also performed. This method aims at considering the inaccuracy rate involved in the landslides mapping, especially when it is made by photo-interpretation, and in the georeferencing operation of geomorphologic maps. This method is based on a 10-m cell-centred circular radius neighbourhood that provides a success when at least one unstable cell calculated by the model matches with a circular neighbourhood of 10 m radius centred on a real unstable cell. The calculated success percentage is about 60% as regards the effective rainfall of 60 mm within 24 h and rises up to 71% of real unstable cells for the considered effective rainfall of 80 mm within 24 h.

Giannecchini et al. (2007) recently simulated the initiation of the debris flows in the Cardoso T. basin applying a deterministic model based on the safety factor analysis and related to the pore pressure building-up. Their results give the spatial distribution of the calculated safety factor for the whole Cardoso T. basin, showing a rather good consistence with the real landslide occurrence. Moreover, they assess the rainfall threshold for starting debris flows at 255 mm/6 h.

This study was focused on a well-defined area, where many geotechnical and hydrogeological data on the colluvial material are available and couple the safety factor with topographical and hydrogeological components. It allowed assessing the effective infiltrated rainfall in 24 h (as the model requires) and a critical threshold for triggering landslides at about 60–80 mm/24 h, corresponding to a 200–266 mm/24 h precipitation. These results seem to agree with the critical threshold curves obtained by Giannecchini (2005, 2006) using an empirical approach (Fig. 6).

This apparent disagreement between the two models is mainly due to the different assumptions of the considered models with respect to the event duration. In particular, the Dietrich and Montgomery (1998) approach considers rainfall events with duration of 24 h

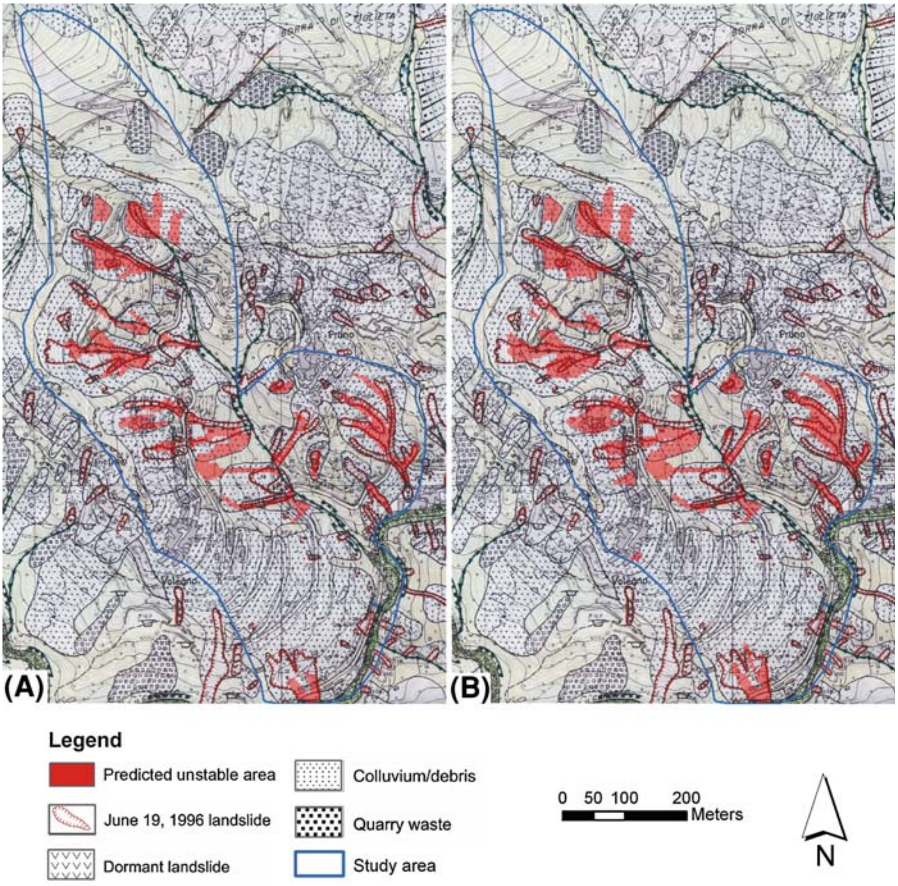

Fig. 5 Unstable areas predicted by the slope instability model (**a** effective rainfall = 60 mm; **b** effective rainfall = 80 mm) versus the June 1996 landslide inventory map (after Giannecchini 2003, modified). Filtering operation, based on simple neighbourhood spatial analysis (majority filter and nibble), was applied in order to eliminate unstable cells dispersion

at least, in order to reasonably consider a steady-state flow in each grid cell. Therefore, a next step in the research could be a more detailed characterization of the infiltration model, in order to better quantify the critical effective rainfall threshold, together with application of other different modelling approaches.

However, as already highlighted by Giannecchini (2005, 2006), the critical rainfall needed to trigger shallow landslides in the study area is very high. This is probably due to the high rainfall annual amount that characterizes the Apuan Alps, which is one of the rainiest regions in Italy (more than 3,000 mm/year); moreover, this area often experiences intense, short-duration rainstorms. In time, the slopes of this area have probably reached equilibrium with the local climatic conditions. As a consequence, heavy rainfalls that in many other landscapes trigger landslides, in this area do not.

At present, the research needs more investigation to better characterize the cover materials and the infiltration model. Further data will be collected by means of penetration tests, permeability tests and undisturbed sampling of the cover materials, in order to better

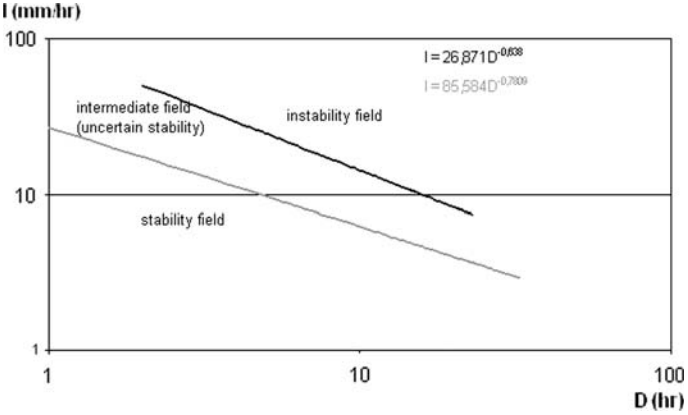

Fig. 6 Rainfall duration/intensity relationship for triggering shallow landslides in the southern Apuan Alps. A lower and an upper threshold curves are shown, which individuate three different fields: a stability field (under the lower curve); an intermediate field (between the two curves); an instability field (above the upper curve) (after Giannecchini 2006, modified)

define their geotechnical features. Moreover, the setting-up of monitoring stations equipped by pluviometer, piezometer and inclinometer is also foreseen.

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