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The influence of the geological and geomorphological settings on shallow landslides. An example in a temperate climate environment: the June 19, 1996 event in northwestern Tuscany (Italy)

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Abstract

On June 19, 1996, an extremely heavy rainstorm hit a restricted area in the Apuan Alps (northwestern Tuscany, Italy). Its max intensity concentrated over an area of about 150 km^2 astride the Apuan chain, where 474 mm was recorded in about 12 h (21% of the mean annual precipitation, with an intensity up to 158 mm/h). The storm caused floods and hundreds of landslides and debris flows, which produced huge damage (hundreds of millions of Euros), partially destroyed villages and killed 14 people. This paper reports the results obtained from a detailed field survey and aerial view interpretation. In the most severely involved area, 647 main landslides were investigated, mapped and related to the geologic, geomorphic and vegetational factors of the source areas. This was in order to define the influence of these factors and contribute to an evaluation of the landslide hazard in the study area. An assessment was also made of the total area and volume of material mobilised by landsliding. The study area, about 46 km^2 wide, includes three typically mountainous basins, characterised by narrow, deep cut valleys and steep slopes, where many rock types outcrop. Most of the landslides were shallow and linear, referable to complex, earth and debris translational slide, which quickly developed into flow (soil slip–debris flow). Usually, they involved colluvium and started in hollows underlain by metamorphic rock (metasandstone and phyllite), often dipping downslope. Therefore, bedrock lithology and impermeability appeared to be important factors in the localisation of the landslide phenomena. The investigation of the geomorphic and land use features in the source areas also frequently highlighted a rectilinear profile of the slope, a high slope gradient (31–45°) and dense chestnut wood cover. In the area, about 985,000 m^2 (2.1% of 46 km^2) was affected by landsliding and about 700,000 m^2 of this area was covered by chestnut forest. The landslides removed about 7000 trees. The volume of mobilised material was about 1,360,000 m^3; about 220,000 m^3 remained on the slopes, while the rest poured into the streams. In addition, about 945,000 m^3 was mobilised by the torrential erosion in the riverbeds.

Keywords: Rainstorm; Shallow landslide; Triggering factor; Tuscany, Italy

1. Introduction

On June 19, 1996, a violent rainstorm hit the northwestern part of Tuscany, affecting in particular the Versilia River basin and the upper part of the

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Turrite di Gallicano basin (Serchio River basin), in the Garfagnana area (Fig. 1) (Caredio et al., 1996; D'Amato Avanzi, 1999; D'Amato Avanzi et al., 2000). These territories are located in the Apuan Alps area, one of the rainiest regions in Italy.

The climatic features of the Apuan Alps mainly derive from the interaction between their geographical/morphological factors and the characteristics of the general and local atmospheric path. The shape, altitude and location of the Apuan chain intercept the western and local perturbations of Atlantic or Mediterranean origin and produce the forced lifting of humid air masses, so favouring their rapid adiabatic cooling. Consequently, very heavy yearly meteoric affluxes are registered, with a mean annual rainfall of over 3000 mm close to the watershed. The pluviometric regime is substantially referable to the Apennine–Mediterranean type with transition to the subcoastal type, characterised by dry summers and cold winters, with a primary peak of rainfall in autumn and two secondary maximums, in winter and spring. In the Apuan Alps, intense rainstorms are particularly frequent in autumn and often cause many landslides and flash floods.

The June 1996 storm occurred after a rather dry month (17.2 mm of rainfall at the Pomezzana gauge)

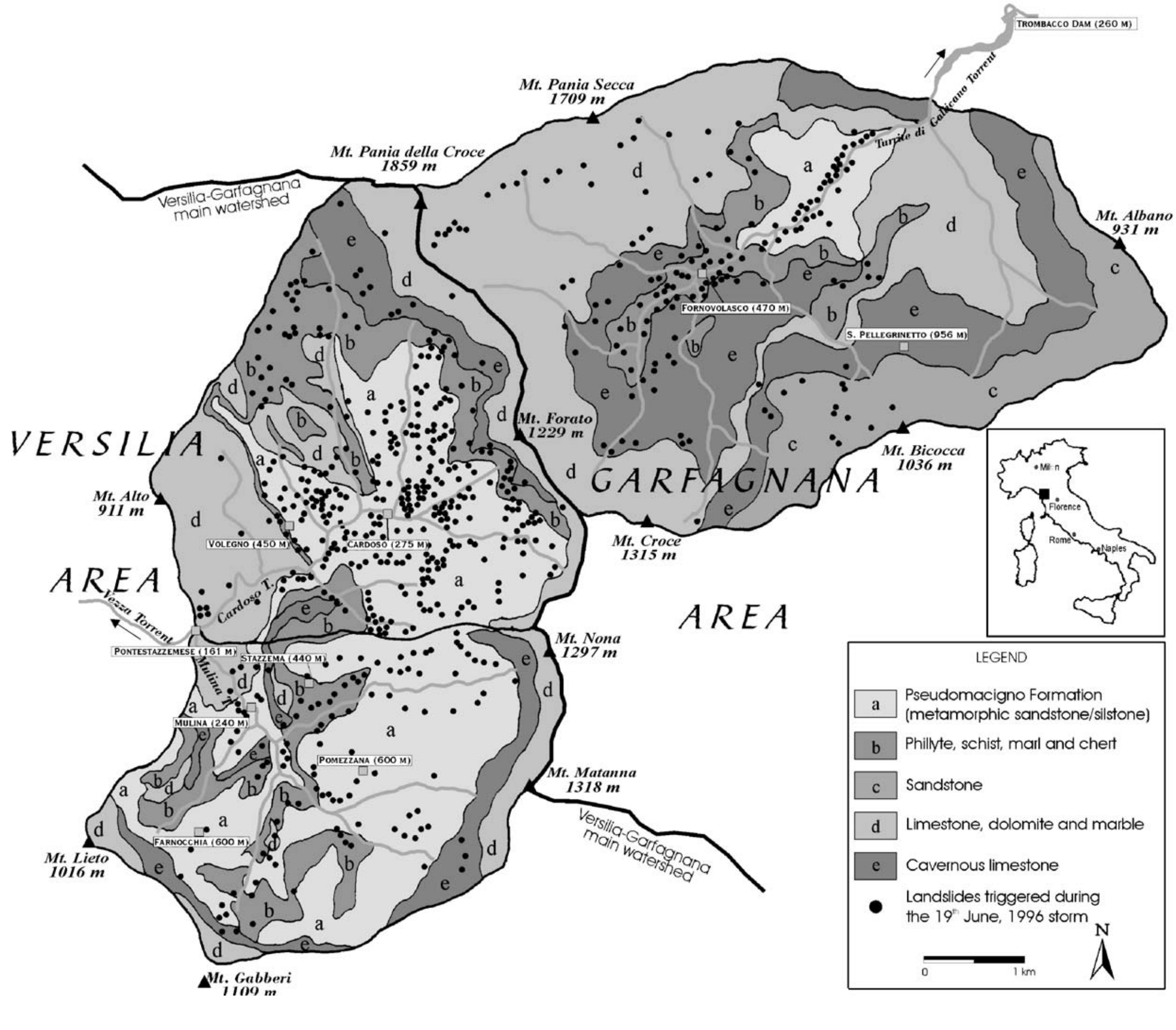

Fig. 1. Lithologic sketch map and location of the shallow landslides triggered by the June 19, 1996 rainstorm.

and hit a very limited area of the Apuan Alps. The max rainfall intensities were concentrated over an area of about 150 km^2 astride the Apuan chain (Fig. 2), where 474 mm was recorded in about 12 h (21% of the annual average amount, with max intensity of 158 mm/h) at Pomezzana, and 420 mm at Fornovolasco in almost 10 h (Fig. 3), before the instrument was destroyed by a landslide. At the Querceta and Gallicano rain gauges, about 10 and 7 km from Pomezzana and Fornovolasco, respectively, only some millimetres of rainfall was recorded. Analysing the historical records of the Fornovolasco rain gauge, Caredio et al. (1996) estimated the recurrence period of such an event to be over 100 years.

The maximum intensity area included the Cardoso basin, the Mulina basin and the upper part of the Turrite di Gallicano basin. Actually, relying on the rainfall recorded at Pomezzana and Fornovolasco and on direct eyewitness evidence, the rainstorm broke out in two violent downpours in the early morning and afternoon of June 19. During the first, which mainly hit the Pomezzana area (about 400 mm in 6 h), where only a few landslides occurred, no mass movements were triggered in the Cardoso and Turrite di Gallicano

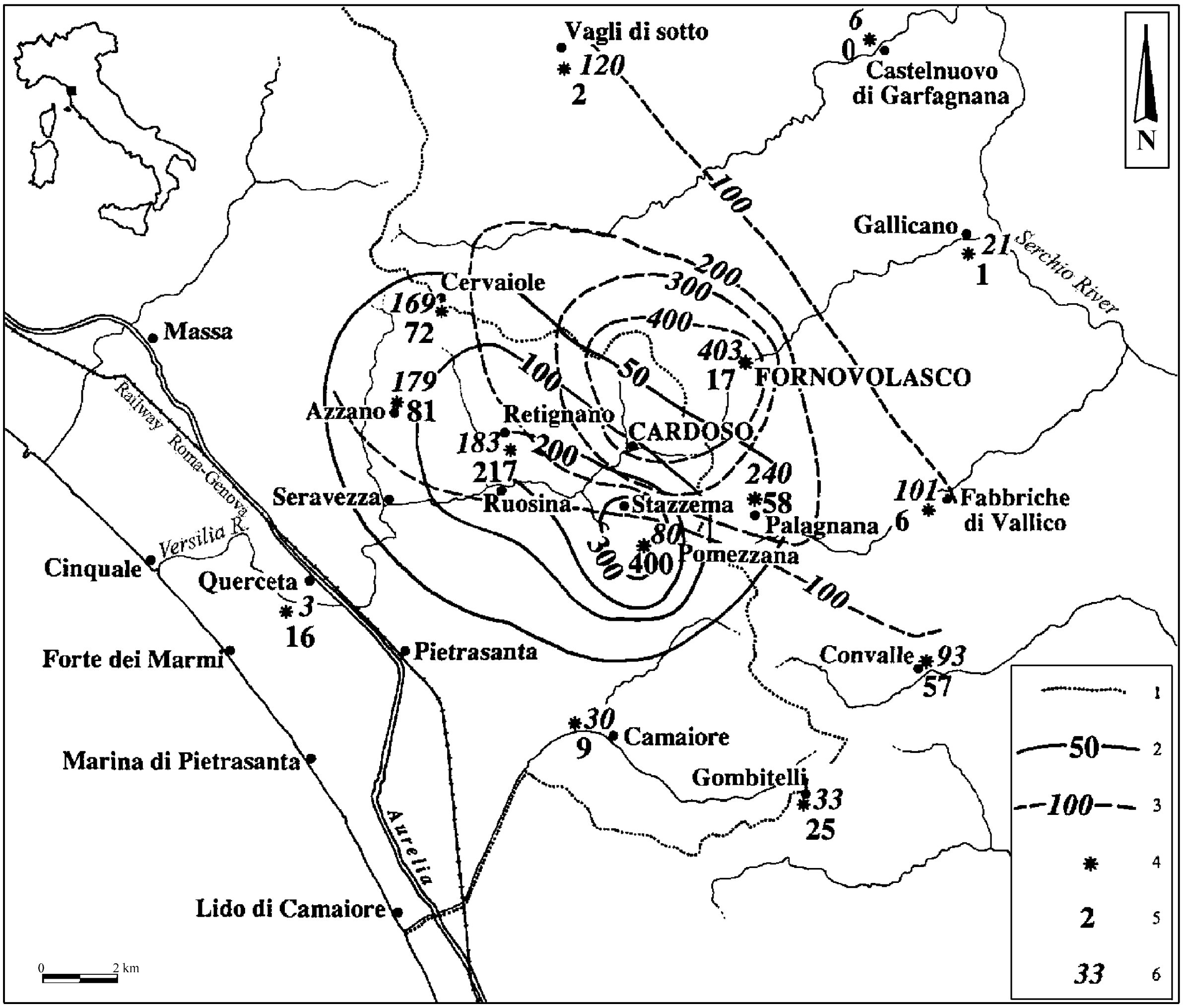

Fig. 2. Isohyet map of the June 19, 1996 storm (after D'Amato Avanzi, 1999). (1) Watershed of the Serchio River basin, (2) morning event isohyet, (3) afternoon event isohyet, (4) rain gauge, (5) total morning rainfall, (6) total afternoon rainfall.

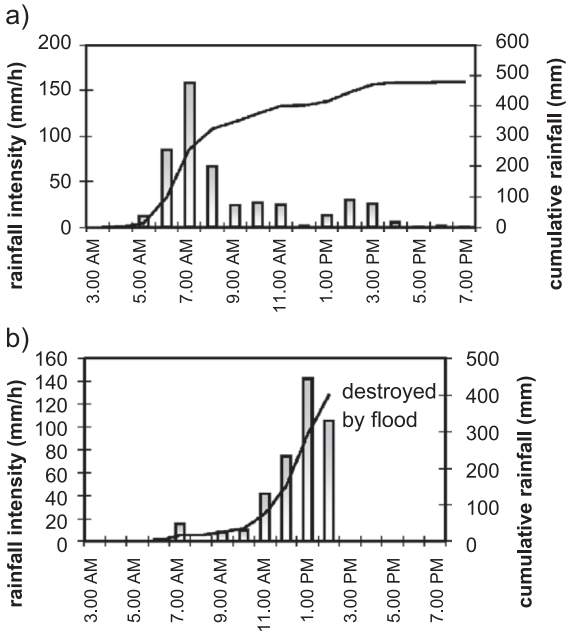

Fig. 3. Rainfall data in the study area: (a) Pomezzana (597 m asl) and (b) Fornovolasco (470 m asl) rain gauges.

basins. After a moderate rain period (2–3 h), the second storm hit the Cardoso and Turrite di Gallicano basins, with an amount of rain similar to the first one. However, in the Cardoso area, the most involved in landsliding and flooding, there was no rain gauge to record the rainfall amount and intensity.

The rainstorm had various effects on both rivers and slopes; floods, landslides and debris flows almost completely destroyed the villages of Cardoso (Fig. 4) and Fornovolasco, resulting in 14 deaths and damage to the sum of hundreds of millions of Euros. In a preliminary study, D'Amato Avanzi et al. (2000) identified and investigated the main factors of the source areas of the landslides that involved the Cardoso basin. Afterwards, this research was further developed and extended to the neighbouring basins. The main results are shown in this paper.

2. Geological and geomorphological settings

The study area is represented by three typically mountainous basins, characterised by narrow, deep cut valleys and steep slopes. The Cardoso basin, tributary of the Vezza Torrent, covers an area of about 13 km^2 at the section of Pontestazzemese. The Mulina basin, also a tributary of the Vezza Torrent, has an area of about 11 km^2 at the same point. The Turrite di Gallicano basin, right-hand tributary of the Serchio River, has an area of about 22 km^2 at the section of Trombacco. This territory is scarcely populated and there are only a few villages such as Stazzema, Fornovolasco, Pomezzana and Cardoso (Fig. 1). Typical economic resources are fundamentally based on quarrying and manufacturing of ornamental stone (metamorphic sandstone, known as Cardoso Stone) and on tourism. The road network is limited to some main roads close to the valley bottoms and to secondary roads leading to the minor villages; there are also a few narrow forest roads and trails. Therefore, most of the study area is almost uninhabited and often difficult to reach.

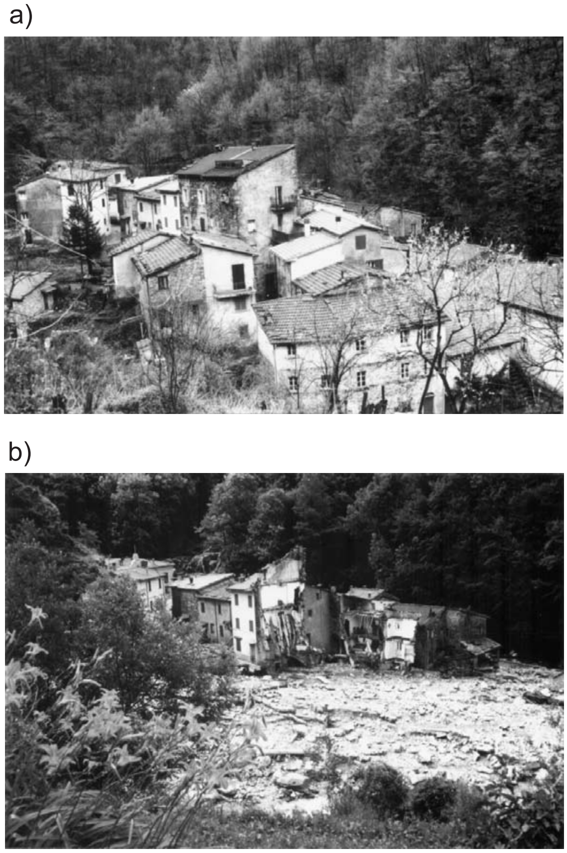

Fig. 4. View of Cardoso village before (a) and after (b) the June 19, 1996 event.

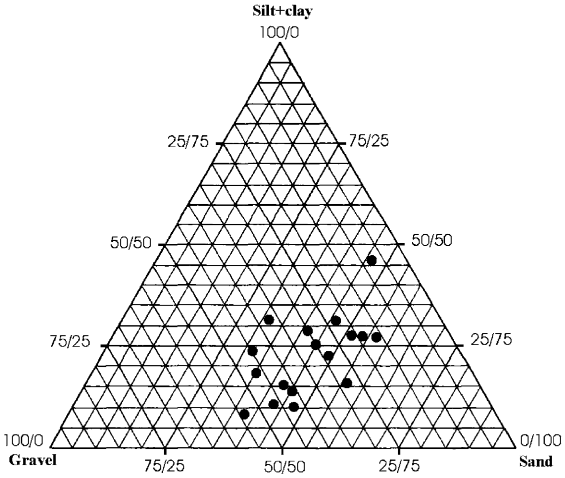

Fig. 5. Grain size composition of the samples collected in the Cardoso area (after Giannecchini and Pochini, 2003, modified).

Some of the main tectonic units of the Apuan area have been found in the survey area, in particular the Autochthon *Auctt*. and the Tuscan Nappe (Carmignani et al., 2000). The Autochthon (Paleozoic–Upper Oligocene), mainly cropping out in the basins of the Cardoso Torrent, Mulina Torrent and in the northwest part of the Turrite di Gallicano Torrent basin, includes metamorphic formations which, in the study area, are mainly represented by Pseudomacigno Fm. (metamorphic sandstone with interbedded metasiltite, Upper Oligocene), and Grezzoni Fm. (Norian dolomite). The Tuscan Nappe crops out in the southeastern part of the Turrite basin and includes Calcari e marne a *Rhaetavicula contorta* Fm. (limestone and marl, Norian–Rhaetian), Maiolica Fm. (limestone and calcarenite, Upper Tithonian–Lower Cretaceo), Calcareniti a Nummuliti Fm. (Eocene–Lower Oligocene) and Macigno Fm. (micaceous–quartzose–feldspathic sandstone, Upper Oligocene–Lower Miocene).

The morphology of the area is markedly influenced by the structural–geological arrangement of the Apuan area. The ridges that divide the basins are usually made up of carbonaceous rocks with slope gradients of even greater than 60°, often subvertical or vertical. These slopes are usually rocky and with discontinuous vegetation, without forest. The carbonaceous rock faces are connected to the lower parts of the slopes, composed of metamorphic sandstone 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°). There is, however, an increase in gradient in the lower slopes, as a consequence of the accentuation of erosive processes resulting from the Olocenic–Pleistocenic uplift of the Apuan metamorphic core.

The slopes are largely characterised by soils which typically cover the slopes underlain by predominantly phyllitic–schist and metamorphic–arenaceous rocks and are also mantled by dense forest (mainly chestnut). On the contrary, the calcareous and dolomitic slopes are usually rocky or with very thin soil cover. As shown below, the soils covering metamorphic sandstone and phyllite were the most involved in landsliding; these soils are rather thin (0.5–2 m thick). Preliminary laboratory tests were carried out by Giannecchini and Pochini (2003) on the soils lying on the metamorphic sandstone (Pseudomacigno Fm.). According to the USCS classification, the samples usually fall in the SM class and are characterised by a well-sorted grain size (Fig. 5), with a 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; they generally fall in the low–medium plasticity silt field (Fig. 6).

Moreover, these authors compared the soil characteristics between different sites, located both in the source areas and in some hillslopes not involved in landsliding. As first results, they found some differences; a finer grain size and a lower liquidity limit

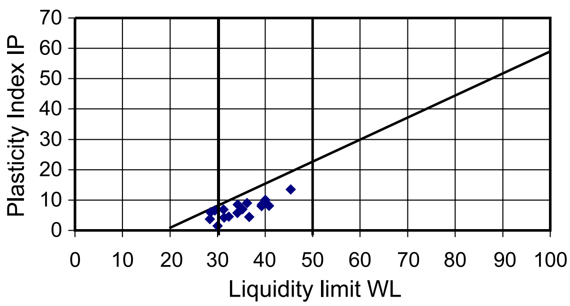

Fig. 6. Plasticity Chart of the samples collected in the Cardoso area (after Giannecchini and Pochini, 2003, modified).

emerged for the source areas. To confirm this outcome further investigations are needed.

3. Characteristics of the landslides

The heavy rainfall of June 19 caused at least 647 main landslides (Fig. 1), mostly of first generation, mainly referable to complex, earth and debris translational slides. They quickly developed into flows (Cruden and Varnes, 1996) and may be also defined as soil slip–debris flows (Campbell, 1974, 1975; Varnes, 1978; Govi and Sorzana, 1980; Ellen and Fleming, 1987; Crosta et al., 1990; Corominas et al., 1996; Crosta, 1998). These phenomena were usually superficial landslides (thickness usually from 0.5 to 2 m, Fig. 7a), mainly linear (width/length ratio 0.03–0.5, Figs. 7b and 8), and generally involved soil and sometimes portions of bedrock. These landslides mainly developed in the hollows of the slopes underlain by metamorphic sandstone and phyllitic–schist, at the top of the zero-order basins. In these hollows, the concave morphology of the slope favoured runoff,

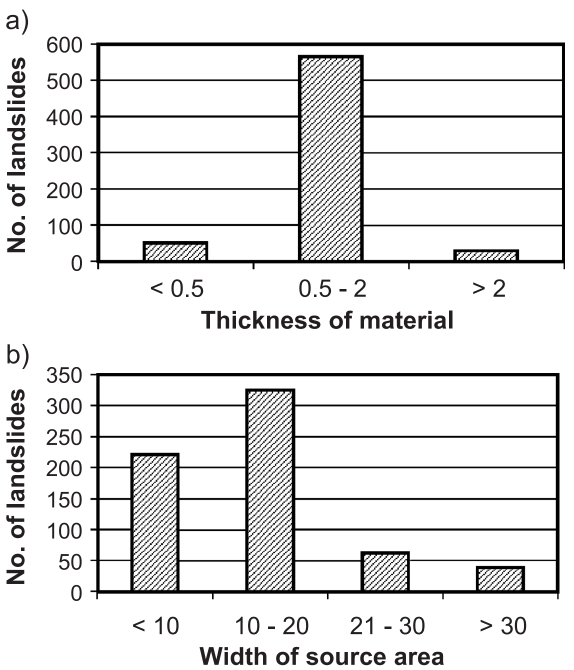

Fig. 7. Distribution of landslides compared with the thickness of material involved (a) and with the width of detachment area (b).

while the concave soil–bedrock interface could have favoured the concentration of subsurface downflow, saturation and buildup of pore pressures. These landslide phenomena are usually associated with heavy, severe rainstorms (Campbell, 1974, 1975; Wieczorek, 1987, 1996). The association of high-intensity rainfall with debris flows has been documented in Japan (Fukuoka, 1980), New Zealand (Selby, 1976; Pierson, 1980) and in many other places worldwide (Caine, 1980; Jibson, 1989). The triggering mechanism is generally characterised by the infiltration of rainwater into the soil, which may cause the buildup 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).

The authors who have carried out research for the prediction of shallow landslides have followed different methodological approaches. A first approach may consist in a systematic collection of information about the time when the first movements occurred, in order to identify the critical parameters of rainfall duration and intensity capable of triggering landslides. Once the critical value of rainfall is exceeded, the shallow landslides quickly spread (Caine, 1980; Govi and Sorzana, 1980; Fukuoka, 1980; Crozier, 1986; Cannon and Ellen, 1988; Wieczorek and Sarmiento, 1988; Jibson, 1989; Cancelli and Nova, 1994; etc.).

The problem of identifying the rainfall threshold is, however, made difficult by the complex relations that exist between flow, effective infiltration and response of pore water pressure. The study of rainfall thresholds of this area was particularly difficult, because of the lack of rain gauges and information regarding the triggering time of the landslides. By means of a reconstruction of the event according to the Pomezzana and Fornovolasco gauges and eyewitness reports on the time of the start of the landslides, D'Amato Avanzi et al. (2000) estimated a threshold of about 250 mm in 8 h for the area of Cardoso. Afterwards, we obtained a value of about 325 mm in 4 h for the Pomezzana area and a value of between 170 and 240 mm in 8 h for the Fornovolasco area.

At the moment, we have not enough data to model the hydrological responses of soil to rainfall and to relate it to landsliding. The new installation of two recording stations (piezometer and rain gauge) in

Fig. 8. General view of the Cardoso basin. Many scars and tracks of the shallow, linear landslides can be recognized.

Cardoso basin will provide data to initiate a modelling of these phenomena and to better evaluate the critical rainfall thresholds for landslides.

As regards the type of movement, most of the landslides (450 of 647) are referable to soil slip–debris flows. Other typologies were found during the research; according to Cruden and Varnes (1996), they are classified as follows (Fig. 9): (a) translational slide flow, (b) flow, (c) translational slide, (d) rotational–translational slide, (e) rotational slide flow, (f) rotational–translational slide flow, (g) fall.

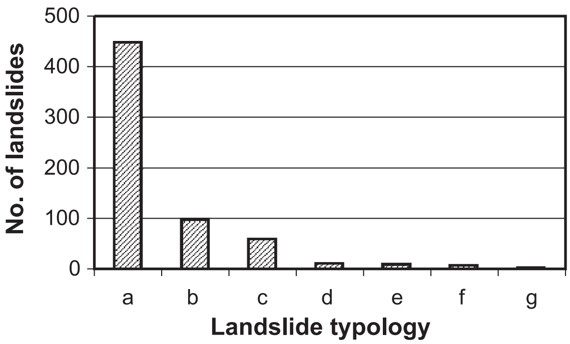

Fig. 9. Number of landslides of each typology found [(a) translational slide flow, (b) flow, (c) translational slide, (d) rotational–translational slide, (e) rotational slide flow, (f) rotational–translational slide flow, (g) fall].

4. Recurrent factors in the landslide trigger areas

Some authors have made an inventory of the debris flow distribution resulting from a single storm over a certain area (e.g., Okuda et al., 1979; Govi and Sorzana, 1980; Omura and Nakamura, 1983; Wieczorek et al., 1988; 1997), in order to obtain information about the triggering sites of landslides.

Therefore, the landslides triggered by the rainstorm of June 19 (at least 647 slope failures) were studied together with the most important geological and geomorphological parameters, in order to find common triggering conditions. The distribution of the landslides in the three study basins is reported in Table 1.

4.1. Distribution of the landslides compared to the bedrock lithology

Although the landslides involved almost exclusively the soil, a possible connection between bed-

Table 1
Landslide density due to the June 19, 1996 storm in the three basins studied

	Area (km^2)	No. of landslides/km^2
Cardoso basin	13	29.4
Mulina basin	11	10.3
Turrite di Gallicano basin	22	6.9
Whole area	46	14.1

rock permeability and landslide susceptibility was supposed.

Thus, the formations outcropping in the three basins were grouped into five main lithotypes: (a) sandstone; (b) metamorphic sandstone and siltstone; (c) phyllite, schist, marl and chert; (d) limestone, dolomite and marble; (e) cavernous limestone. For each lithotype, the extension, the number of slides and the landslide index were calculated. This index represents the percentage ratio between landslide area in each lithotype and the total surface of the lithotype studied. The results are shown in Fig. 10.

The Pseudomacigno Fm. (metamorphic sandstone and phyllite) occupies 26.9% of the area and includes 62.6% of the landslides. Considering also siliceous–phyllite schists (22.1%), it can be noted that the impermeable and semipermeable rocks, which cover an area equal to 48.4%, include 84.7% of the landslides. The sandstone (Macigno Fm.) substantially impermeable and hydrogeologically similar to the previous ones, includes a smaller number of landslides (1.4%); this is probably due to the fact that the Macigno Fm. crops out in a portion of the area where the rainfall was not very heavy. The landslide index, which is very high for the metamorphic sandstone and siltite (4.9%) and the siliceous–phyllite schists (3.2%), confirms a greater landslide predisposition of soils underlain by these rocks.

4.2. Distribution of landslides compared to the bedrock layering

Analysis of the landslide distribution compared to the layering of the bedrock was carried out on metamorphic sandstone and siltstone, where most of the landslides were triggered. A sample area (8.1 km^2, 270 landslides) of the Cardoso and Mulina basins was surveyed in detail. This area was subdivided into three classes of layering attitude (downslope, oblique, upslope). For each class, the number and surface of landslides and the landslide index were calculated.

As shown in Fig. 11, in the downslope class, which covers 34.5% of the area, 45.6% of the landslides occurred. This value is even larger considering that the landslide area in the downslope class covers 57.6% of the total landslide area in the sample area. In fact, during the survey, the downslope layering emerged as a significant parameter for the widest landslides. These data are confirmed by the value of the landslide index, very high for the downslope class (8.7%).

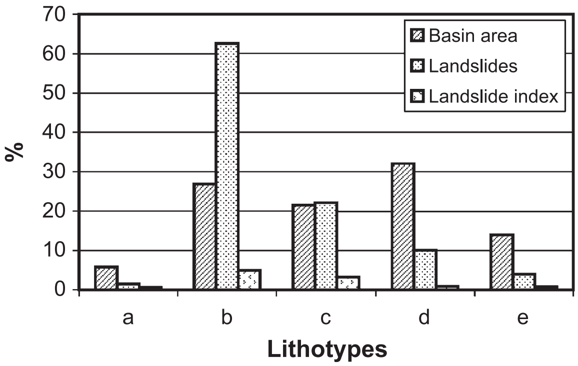

Fig. 10. Distribution of landslides compared to lithological characteristics of the bedrock [(a) sandstone; (b) metamorphic sandstone and siltstone; (c) phyllite, schist, marl and chert; (d) limestone, dolomite and marble; (e) cavernous limestone].

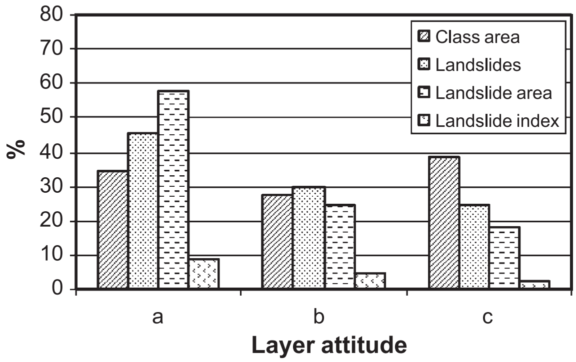

Fig. 11. Distribution of 270 landslides on a surface of 8.1 km^2 of metamorphic sandstone and phyllite compared with three classes of layer attitude [(a) downslope, (b) oblique, (c) upslope].

4.3. Distribution of landslides compared to the characteristics of the slopes

According to various authors (Pierson, 1980; Reneau and Dietrich, 1987; Ellen, 1988; Sitar et al., 1992), slope shape is important in initiating sliding phenomena. Concentration of subsurface drainage within hollows, resulting in higher pore water pressures in axial areas than on flanks, is one possible mechanism responsible for triggering soil slips (Pierson, 1980).

In order to study the morphological characteristics of the slopes, the slope profile, surface and gradient were analysed. Six classes of the slope profile were used: rectilinear, concave, convex, concave–convex, convex–concave and complex (combination of the preceding types). The distribution of the landslides compared with these conditions is shown in Fig. 12, where it can be noted how the rectilinear configuration of the slope profile is the most common (462 of 647 landslides, 71.4%). This configuration does not seem to be a reliable diagnostic element because the majority of the slopes in the basin have a rectilinear profile. At present, there is not enough data to normalize the results.

Slope surface morphology was classified as planar slope, hollow and ridge (Fig. 13).

Three hundred and fifty-eight of 647 landslides (55.3%) occurred in hollows, referable to elementary concavities or zero-order basins, while 243 landslides (37.6%) involved planar slope surfaces. A similar distribution was found by Jibson (1989) for debris flows triggered during October 5–8, 1985 in Puerto Rico. However, in some environments, Jacobson et al. (1993) found that planar slopes are more prone to failure than other slope morphological configurations.

The correlation between landslide areas and slope gradient at source areas was also analysed. Six slope gradient classes were used (Fig. 14).

The most frequent slope gradient class is between 36° and 40°. The slopes ranging from 31° to 45° include 547 landslides (84.5%) in the area; among these, 35.6% had slope gradient from 36° to 40°. The low number of instabilities on slopes with a gradient higher than 45° can be attributed to the fact that this class is relatively rare in the study area. Moreover, on such slopes the soil cover diminishes considerably.

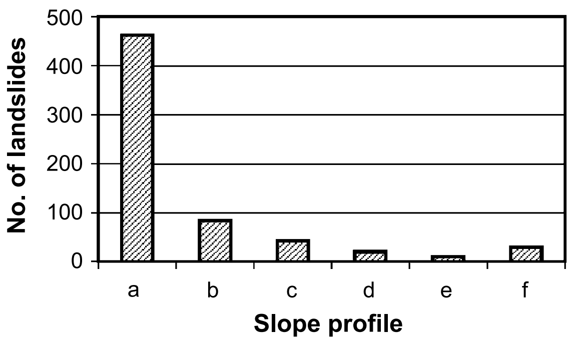

Fig. 12. Number of landslides compared to the morphological characteristics of the slope profile [(a) rectilinear, (b) concave, (c) convex, (d) concave–convex, (e) convex–concave, (f) complex].

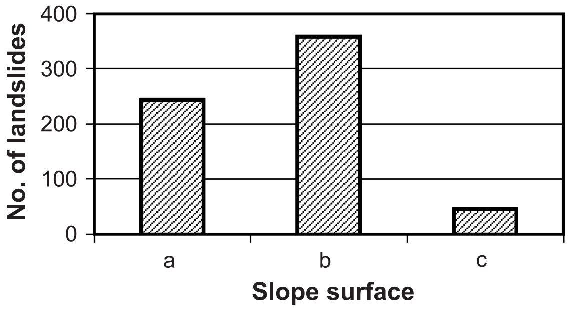

Fig. 13. Number of landslides compared to the morphological characteristics of the slope surface [(a) planar slope, (b) hollow, (c) ridge].

4.4. Distribution of landslides compared to the type of cover

The landslides that occurred in the study basins involved almost exclusively the soil, which can be

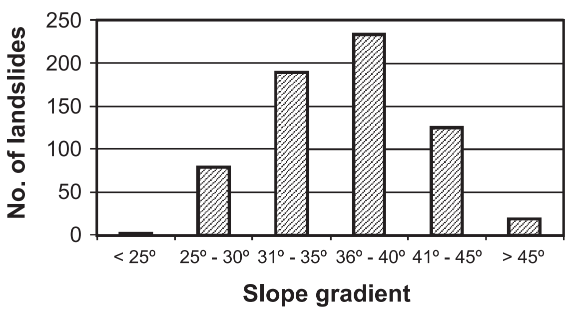

Fig. 14. Number of landslides compared to slope gradient.

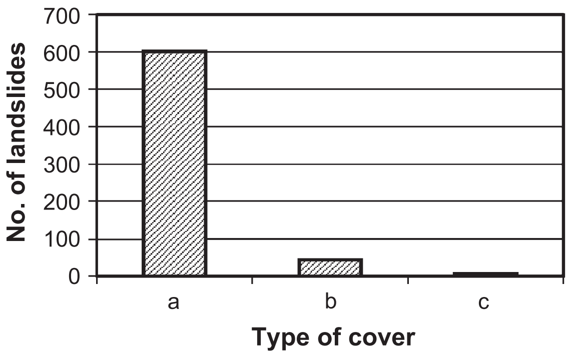

Fig. 15. Number of landslides compared to the type of cover [(a) colluvium, (b) talus, (c) filling and quarry dump].

classified into colluvium (loose material, heterogeneous, incoherent, deposited either by superficial rainwash or by gravity, matrix-supported) and talus (debris material usually coarse and angular, deposited at the base of the slopes by gravity, clast-supported). Quarry dump and filling were also taken into account, but they were only involved in three landslides.

The colluvial cover was the most subject to landsliding (601 of 647 landslides, 92.9%—Fig. 15). The scarcity of landslides on talus cover could be attributable to a smaller extension of this cover compared to colluvial in the area; better geotechnical properties and drainage conditions; location on permeable rocks. However, further data are necessary to improve these preliminary remarks.

4.5. Distribution of landslides compared to land use

The characteristics of the vegetation in the area affected by landslides were analysed. The influence of vegetation on the landslide distribution is, however, difficult to assess, at least in part, because geology, slope morphology and soil characteristics can influence vegetation, as well as the distribution of soil slips (Wieczorek et al., 1988).

The analysis of land use related to landslide distribution was performed only in the Cardoso basin, where a lot of information was available. Furthermore, this basin was the most involved by soil slips. Using the on site survey and aerial photo interpretation, seven main land use classes were identified: (a) chestnut (*Castanea sativa*); (b) ash (*Ostrya carpinifolia*, *Fraxinus ornus*, ecc.) and beech (*Fagus sylvatica*); (c) grassland of *Brachypodium genuense*; (d) no vegetation land; (e) terraced agricultural, either cultivated or neglected area; (f) inadequate data (a 2.1 km^2 area, 16.2% of the whole Cardoso T. basin).

The chestnut woodland, covering 36.9% of the Cardoso basin, is the vegetation with the highest landslide area (83% of the landslide area in the basin) and landslide index (9.3%) (Fig. 16). On the other hand, this coenosis is often associated with impermeable rock, such as the Pseudomacigno Fm. and its soil cover. Thus, it is difficult to establish the role of the chestnut woodland (introduced in the Apuan Alps centuries ago) in the sliding events of June 19.

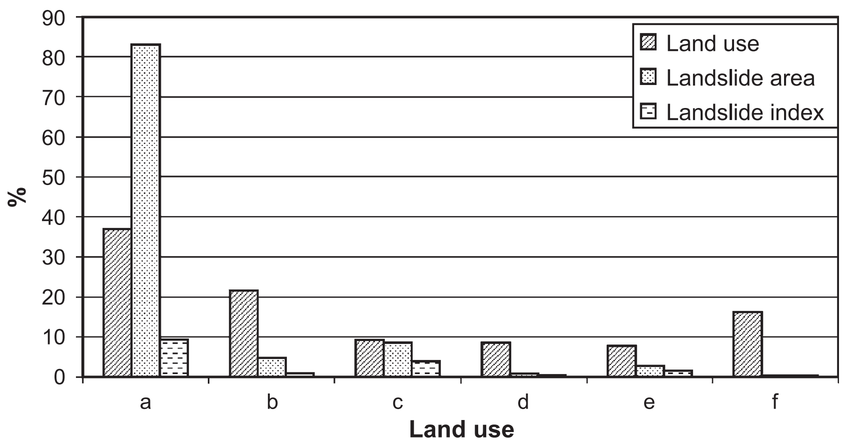

Fig. 16. Distribution of landslides compared to land use [(a) chestnut wood, (b) ash and beech wood, (c) grassland, (d) no vegetation land, (e) terraced agricultural area, (f) inadequate data].

Many authors have emphasized the importance of woodland in slope stability, which is commonly believed to be helpful to stability. For example, Crozier et al. (1980) noted an increase of shallow landslide phenomena after the conversion from indigenous podocarp-broadleaved to pasture-covered areas in Wairarapa region, New Zealand; Wieczorek and Sarmiento (1988) observed that more debris flows began on grass-covered slopes than in brush-covered and forested areas. On the other hand, in some cases, the woodland does not seem to be so favourable to stability. During the intense rainstorm of June 27, 1995, more than 1000 debris flows occurred on forested hillside in Madison County, CA (Wieczorek et al., 1996).

Furthermore, according to some authors (DeGraff, 1991; Strunk, 1997), changes in forest cover on the slopes (as occurred in the study area few centuries ago, when the chestnut was introduced) may increase the frequency of debris flows. For example, Corominas (2001) highlighted a deterioration of stability in many areas where native trees had been replaced by cultivated species with a superficial root system (like the chestnut tree), which is less effective in slope reinforcement (Ziemer, 1981).

5. Area and volume of material involved in landsliding

Rapid shallow landslides are destructive and sometimes formidable phenomena in mountainous areas, but generally mobilise relatively small quantities of debris. In the study basins, the area and volume affected by landslides was assessed based on the data collected during survey and aerial photo interpretation. To calculate the mobilised area, all the landslides were mapped on a 1:5000 scale map and each area was computed by a planimeter. To obtain the mobilised volume, the area of each landslide was multiplied by the average thickness of the material involved, measured at the relative landslide site.

Thus (Table 2), in the Cardoso basin, the total area affected by landslides was calculated at about 550,000 m^2 (4.2% of the whole basin), while in the Mulina basin it was about 190,000 m^2 (1.7%) and in the

Table 2
Area involved in landsliding and volume of material mobilized by the June 19 event in the study area

	Cardoso basin	Mulina basin	Turrite di Gallicano basin	Total
Basin area (km^2)	13	11	22	46
Number of landslides	382	113	152	647
Landslide density (No./km^2)	29.4	10.3	6.9	14.1
Landslide area (m^2)	550,000	190,000	245,000	985,000
% of basin	4.2	1.7	1.1	2.1
Landslide area in chestnut woodland (m^2)	450,000	160,000	90,000	700,000
No. of chestnut trees uprooted by landslides	4500	1600	900	7000
Total volume of material mobilized by landslides (m^3)	850,000	290,000	220,000	1,360,000
Volume of material mobilized by landslides and remained on the slopes involved (m^3)	95,000	45,000	80,000	220,000
Volume of material mobilized by landslides and poured into the riverbeds (m^3)	755,000	245,000	140,000	1,140,000
Total volume of material mobilized during the June 19, 1996 rainstorm (m^3)	1,400,000	600,000	–	–
Volume of material mobilized by stream erosion in the riverbeds (m^3)	645,000	355,000	–	–

Turrite di Gallicano basin it was calculated at about 245,000 m^2 (1.1%). Altogether, the total surface affected by landslides in the area was about 985,000 m^2, equivalent to 2.1% of the total area of the three basins (46 km^2).

The total area of landslides occurring in chestnut forest was about 700,000 m^2 (71.1% of the total affected surface). From this data, we assessed the number of fallen chestnut trees involved in sliding phenomena, a great number of which ended up in the main watercourses, contributing to the destructive force of debris flows and streams. During the on-site survey, an average number of about 100 trees per ha (10,000 m^2) was assessed. Consequently, the total number of fallen chestnut trees was about 7000; as in a few cases, the landslide area was not totally deprived of its vegetation, the number of chestnuts uprooted by the landslides may be slightly lower. A large number of uprooted trees left the study basins and were carried down river by the flood; in the Versilia area, they were mainly deposited along the Vezza Torrent, in the Versilia River valley or carried out into the sea. In the Garfagnana area, they were mostly intercepted by the Trombacco dam (42 m high with a 940,000 m^3 storage capacity) located just after the closing section considered for the Turrite di Gallicano basin.

The volume of material mobilised by the landslides in the Cardoso basin was calculated at about 850,000 m^3, while for the Mulina and Turrite di Gallicano basins it was evaluated at about 290,000 and 220,000 m^3, respectively. Thus, the volume mobilised by the landslides in the three basins was about 1,360,000 m^3 in all. One portion (evaluated during the survey at about 220,000 m^3) remained on the slopes, while the rest poured into the hydrographic network.

By means of technical surveys commissioned by the Tuscany Regional Administration, the quantity of solid material mobilised along slopes and streams during the 1996 event in the Cardoso and Mulina basins was evaluated at about 1,400,000 and 600,000 m^3, respectively. Therefore, given the volumes mobilised by the landslides and ending up in the hydrographic network (about 755,000 and 245,000 m^3, respectively, for the two basins), we can conclude that the volume of solid material mobilised by the torrential erosion in the river beds was about 645,000 m^3 in the Cardoso basin and about 345,000 m^3 in the Mulina basin (Table 2).

6. Conclusions

After analysing the distribution of 647 shallow landslides occurred on June 19, 1996 in Cardoso, Mulina and Turrite di Gallicano basins, we can draw some conclusions regarding the typical slopes susceptible to landsliding. The results supply further confirmation of what had already come out from the research by D'Amato Avanzi et al. (2000) for the Cardoso basin only.

The bedrock lithology appears to be an important factor in the localisation of landslide phenomena. In fact, it was observed that the majority of the landslides (84.7%) occurred on slopes characterised by impermeable and semipermeable rocks (metasandstone, phyllite, schist, etc.) and, among these rocks, the Pseudomacigno Fm. (metasandstone and phyllite) showed the highest landslide index (4.9%). As regards the layering of the bedrock, a detailed investigation performed on the Pseudomacigno Fm. showed that 45.6% of the landslides were in the downslope class, which covers 57.6% of the total landslide area investigated. The downslope class shows the highest landslide susceptibility, as confirmed by the landslide index (8.7%).

The analysis of the landslide distribution according to the slope morphology revealed that hollows and a rectilinear configuration of the slope profile were the most frequently observed situations in the source areas (55.3% and 71.4% of the landslides, respectively). Furthermore, 84.5% of the landslides occurred on slopes with a steepness of 31–45°. The type of superficial slope cover was also important for the localisation of the source areas; 92.9% of the landslides involved colluvium and only 6.6% occurred in talus deposits.

Finally, the chestnut woodland, which covers 36.9% of the Cardoso basin, is the coenosis with the highest landslide area (83.0% of the landslide area in the basin) and landslide index (9.3%).

Further investigations are currently being performed in order to quantify the main geotechnical parameters of the soil slope cover. Furthermore, a monitoring phase has been launched with the installation of two stations equipped with rain gauges and piezometers. This investigation phase is aimed at obtaining adequate intensity/duration curves of rainfall events and at determining and quantifying the relationship between rainfall and pore water pressure in the soil, for the modelling of the infiltration process. The purpose is fundamentally to produce landslide-triggering models and identify the possible critical thresholds for the investigated area.

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