HAL
open science

Relationship between rainfall and shallow landslides in the southern Apuan Alps (Italy)

R. Giannecchini

To cite this version:

R. Giannecchini. Relationship between rainfall and shallow landslides in the southern Apuan Alps (Italy). Natural Hazards and Earth System Sciences, 2006, 6 (3), pp.357-364. hal-00301650

HAL Id: hal-00301650

https://hal.science/hal-00301650v1

Submitted on 18 Jun 2008

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Nat. Hazards Earth Syst. Sci., 6, 357–364, 2006
www.nat-hazards-earth-syst-sci.net/6/357/2006/
© Author(s) 2006. This work is licensed
under a Creative Commons License.

Natural Hazards and Earth System Sciences

Relationship between rainfall and shallow landslides in the southern Apuan Alps (Italy)

R. Giannecchini

Dipartimento di Scienze della Terra, Università di Pisa, Via S. Maria, 53, 56 126 Pisa, Italy

Received: 28 September 2005 – Revised: 8 February 2006 – Accepted: 15 February 2006 – Published: 11 May 2006

Abstract. The Apuan Alps region is one of the rainiest areas in Italy (more than 3000 mm/year), in which frequently heavy and concentrated rainfall occurs. This is particularly due to its geographical position and conformation: the Apuan chain is located along the northern Tuscan coast, close to the Ligurian Sea, and the main peaks reach almost 2000 m. In several cases, the storms that hit the area have triggered many shallow landslides (soil slip-debris flows), which exposed the population to serious risks (during the 19 June 1996 rainstorm about 1000 landslides were triggered and 14 people died). The assessment of the rainfall thresholds is very important in order to prepare efficient alarm systems in a region particularly dedicated to tourism and marble activities.

With the aim of contributing to the landslide hazard evaluation of the southern Apuan Alps territory (upper Versilia area), a detailed analysis of the main pluviometric events was carried out. The data recorded at the main rain gauge of the area from 1975 to 2002 were analysed and compared with the occurrence of soil slips, in order to examine the relationship between soil slip initiation and rainfall. The most important rainstorms which triggered shallow landslides occurred in 1984, 1992, 1994, 1996, 1998 and 2000.

Many attempts were made to obtain a possible correlation between rainfall parameters and the occurrence of soil slip phenomena and to identify the local rainfall threshold for triggering shallow landslides. A threshold for soil slip activity in terms of mean intensity, duration and mean annual precipitation (MAP) was defined for the study area. The thresholds obtained for the southern Apuan Alps were also compared with those proposed by other authors for several regions in the world. This emphasized the high value of the rain threshold for shallow landslide activity in the Apuan area. The high threshold is probably also linked to the high mean annual precipitation and to the high frequency of rainstorms.

Correspondence to: R. Giannecchini
(rgiannecchini@dst.unipi.it/)

1 Introduction

The Apuan Alps, well-known worldwide for their valuable marble quarrying and for their tourist attractions, is one of the rainiest areas in Italy. Frequently, the rainfall reaches or exceeds 3000 mm per year. This characteristic is particularly due to its geographical position and conformation: the Apuan chain is located along the northern Tuscan coast, close to the Ligurian Sea (from which it is only a few kilometres away), and the main peaks reach almost 2000 m (Figs. 1 and 2). This geographical-morphological situation creates a "barrier effect" for the Atlantic damp air masses, produces their adiabatic cooling 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. The last important event, the 19 June 1996 catastrophe, triggered about 1000 landslides, hyperconcentrated flows, floods in the Versilia plain, and caused 14 deaths (D'Amato Avanzi et al., 2000, 2004). Other recent significant events occurred in September 1998 and November 2000, in which hundreds of shallow landslides were triggered and many torrents overflowed. An important and destructive rainstorm also occurred on 8 June 1984 (2 deaths), on 11 July 1992 (2 deaths) and on 22 August 1992 (1 death).

Besides the high hazard represented by heavy rainfall events, the Apuan-Versilian area is characterized by a high vulnerability, especially due to the tourist industry of the area (Versilia and Apuan regions) and to the marble quarrying and working. As a consequence, the elements at risk in the area are numerous (more than 200 000 inhabitants in summer, marble laboratories and factories, tourist infrastructures, etc.) and the risk for damage and/or loss of life is high. In spite of such important aspects, only a few studies were carried out in order to understand the triggering conditions of soil slip-debris flows in this area (D'Amato Avanzi et al., 2000, 2004; Martello et al., 2000; Giannecchini and Pochini, 2003) and the critical rainfall thresholds (Annunziati et al., 2000).

Published by Copernicus GmbH on behalf of the European Geosciences Union.

Fig. 1. Schematic representation of the southern Apuan Alps.

For the above reasons, for the local administrations and civil protection agencies it would be extremely important to have hazard warning systems, in order to evacuate the population in time.

With the aim of contributing to the landslide hazard evaluation of the southern Apuan Alps territory, a detailed analysis of the main pluviometric events was carried out. The data recorded at the main rain gauge of the area (Retignano station, see Figs. 1 and 2) from 1975 to 2002 were analysed and compared with the occurrence of the shallow landslides (soil slip-debris flows), in order to examine the relationship between soil slip initiation and rainfall.

This particular approach was first applied by Caine (1980) for several intense events which occurred in various parts of the world. However, the author found a threshold-curve which was too low, because he considered very different areas from a geological and climatological point of view. Here, a similar methodology is proposed for a restricted area, characterized by homogeneous geologic, geomorphologic and climatic settings.

2 Rainfall thresholds

It is well known that rainfall is the most important and frequent trigger of landslides, in general, and of shallow landslides, in particular. Commonly, it contributes to the triggering of the landslides by means of infiltration into the slope cover, which causes an increase in the pore pressure value and a decrease in the soil suction value. The consideration that some pluviometric events produce failures and others do not induced scientific research to analyse the relationship between rainfall amount and landslide initiation. This is aimed at identifying the critical rainfall thresholds (Crozier, 1986).

The rainfall amount needed to trigger a landslide can also vary considerably for adjacent slopes. Therefore, the determination of the critical threshold is very problematic over wide areas, due to the lack of homogeneity of the geological, geomorphological, hydrogeological and geotechnical characteristics of the slopes. Furthermore, another variable parameter is represented by the soil moisture, which can undergo continuous and significant changes, depending on the season and the antecedent rainfall amount. For this reason, it is extremely important to identify not a univocal threshold value for an area, but a range of thresholds that varies according to the local soil moisture conditions and therefore to the antecedent rainfall amount. From this point of view, the empirical approach can provide significant and valid results. In fact, physically-based models can analyse in detail only a few slopes, and then generalize the results over a wide area. This approach, and its subsequent generalization, could involve significant errors in the identification of the threshold values. On the other hand, we must considered that the empirical approach has a probabilistic significance and also depends on the correct functioning conditions of the rain gauge used.

The concept of pluviometric threshold was introduced by Campbell (1975) and successively theorized by Starkel (1979) as a duration-intensity relationship. Many attempts were made to determine the minimum rain height or intensity required for triggering landslides (e.g. Eyles, 1979; Caine, 1980; Fukuoka, 1980; Govi and Sorzana, 1980; Brand, 1985; Cancelli and Nova, 1985; Crozier, 1986; Cannon and Ellen, 1988; Wieczorek and Sarmiento, 1988; Jibson, 1989; Wilson, 2000; Chien-Yuan et al., 2005; etc.). Generally, in these

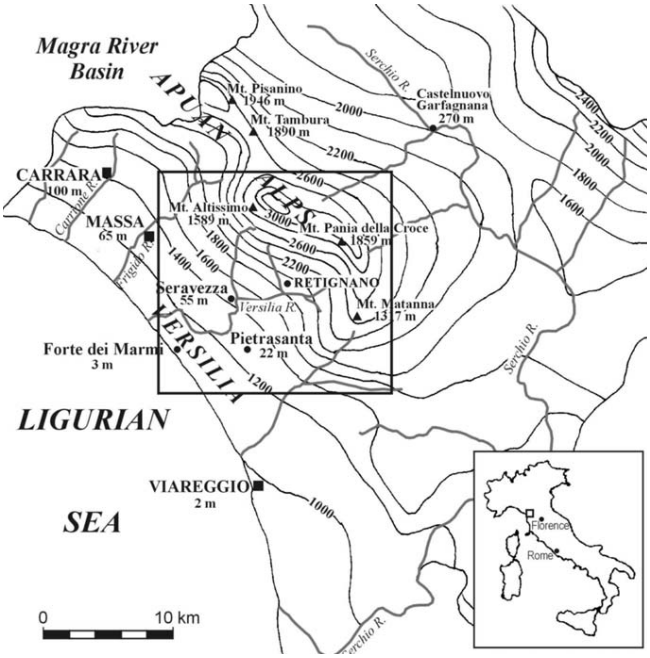

Fig. 2. Location map of the study area. The isohyets (from Baldacci et al., 1993) are also shown.

cases the rainfall thresholds are based on an empirical approach, while other authors (e.g. Wilson and Wieczoreck, 1995; Crosta, 1998; etc.) used physically-based approaches.

3 Critical rainfall in the southern Apuan Alps

In the southern Apuan area, the most important problems relative to slope stability result from shallow landslides. These are triggered by very intense rainstorms (about 325 mm/4 h with maximum intensity of 158 mm/h during the June 1996 hydrogeological catastrophe). However, less intense but prolonged rainfall events are sometimes sufficient to induce the failures. With regards to this last point, it is significant to note that on 6 November 2000 the shallow landslides were triggered by 160 mm within 13 h (maximum intensity about 30 mm/h). Nevertheless, in this case a large antecedent rainfall amount was available (almost 600 mm within one month) and this drastically reduced the critical threshold tolerable by the slopes. Fortunately, the critical threshold was reached only locally, and the consequences were much less catastrophic than the June 1996 rainstorm. Generally, the type of mass movement is typical of landslides triggered by very intense rainfall on steep slopes: rapid shallow landslides (in particular soil slip-debris flows), with a width/length ratio typically less than 1, which involve the 1–2 m thick colluvial material on the bedrock. In spite of the small volume involved in sliding, the soil slip-debris flows are extremely destructive, both due to the very high speed caused by material fluidization and the high landslide concentration. The materials involved in failures (earth, debris, pebbles, trunks) usually flow into the riverbeds, increasing the load of the torrents, which provokes hyperconcentrated and destructive flows. Studies carried out after the June 1996 disaster highlighted some features of soil slip distribution (D'Amato Avanzi et al., 2000, 2004) relative to landslide susceptibility. The soil slips tend to be localized on the cover materials (1–2 m thick) of impermeable rocks, in slopes with a gradient of 30–45° and with hollow morphology. Nevertheless, there are currently very few studies aimed at identifying the temporal hazard in the Apuan area, based on the individuation of the critical rainfall values able to trigger landslides (Annunziati et al., 2000).

3.1 Work methodology

With the aim of establishing the critical rainfall thresholds for soil slip-debris flow phenomena, all the main rain events occurring in the southern Apuan area in the period from 1975 to 2002 were identified and analysed. The rain gauge taken as reference was at Retignano (Figs. 1 and 2), because it was the only station constantly equipped with pluviographic instruments from 1975 to 1996. It became an electronic rain gauge from 1996 onwards. Considering the location and the geographic and morphological features of the area, the Retignano rain gauge can reasonably be considered significant for this study. In fact, the study area is about 80 km^2 wide and the rain gauge is located in the middle of it, at 440 m. a.s.l. In this area, the soil slips usually mobilize on slopes between 200 and 800 m. a.s.l.

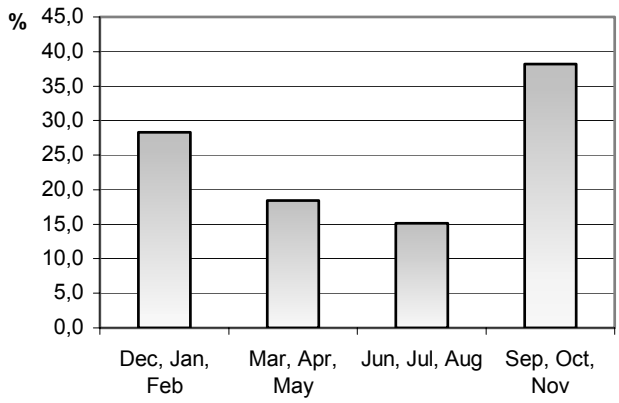

Fig. 3. Seasonal distribution of the main rainfall events which occurred in Versilia from 1975 to 2002 (Retignano rain gauge).

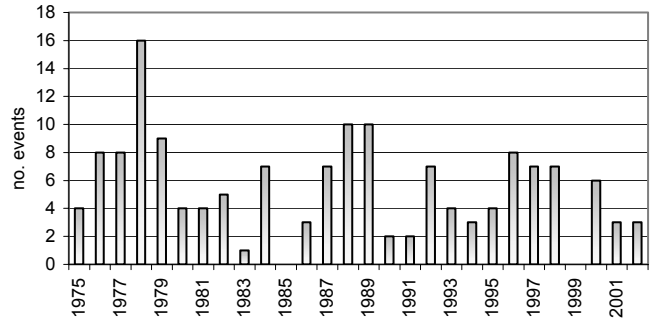

Fig. 4. Yearly distribution of the main rainfall events in Versilia from 1975 to 2002 (Retignano rain gauge).

During this research 152 significant rainfall events were identified and analyzed. The importance of a single event was evaluated on the basis of the response of the pluviographic graph: for example, events with low duration (1–2 h) and high intensity (20–30 mm/h), or high duration (40–50 h) and low intensity (2–4 mm/h). For all the rainfall events collected, a detailed archive research was carried out in order to verify the effects produced on the slopes. In fact, the scars produced by the shallow landslides are usually reabsorbed by vegetation within 4–5 years, without leaving significant geomorphological tracks, which could be observed during the on-site survey. If landslide maps of the single rainfall events are not available, the historical research represents a valid contribution in order to individualize the entity of the effects produced on the slopes (in particular for the past events).

The archive research was done by means of data verification of the local Municipal Administrations, technical and scientific articles, newspapers, and on the basis of evidence provided by local inhabitants. Among the recorded events, at least 12 rainstorms triggered a certain number of shallow landslides. In particular, as cited above, the most important events that triggered shallow landslides occurred in 1984, 1992, 1994, 1996, 1998 and 2000.

With reference to the seasonal distribution, all the events analysed preferentially occurred in autumn (almost 40% in the three-month period of September–November), when the polar front transits at the Apuan latitude. Figure 3 shows the seasonal distribution of the most important rain events which occurred in the study area in the 1975–2002 period. Guzzetti (2000) obtained similar results on a national scale. However, the graph shows that significant meteorological events can occur in all the seasons. In fact, one of the most catastrophic rainstorms (the cited 19 June 1996 catastrophe) in the history of the upper Versilia area struck the territory precisely in the period of lowest probability. Figure 4 shows the yearly distribution of the recorded events. A certain variability emerges; we can note years such as 1978, in which 16 important rainstorms occurred, and years in which only a few events or nothing occurred. For each event analyzed, the following parameters were collected: rainfall amount (mm), duration (h), mean intensity (mm/h), mean annual precipitation (MAP–mm). The 152 events investigated were subdivided into three groups on the basis of the extent of the effects caused by the rainstorms: events which induced several shallow landslides and floods (A events in the following table and graphs); events which locally induced some shallow landslides and small floods (B events); no information about effects induced (C events). For the first group the information about the effects produced were very clear: many landslides and floods and, in some cases, also deaths. This category included the following rainstorms: 8 June 1984 (2 deaths), 11 July 1992 (2), 22 August 1992 (1), 6 November 1994, 19 June 1996 (14) and 6 November 2000. Nevertheless, the 1984 event was anomalous considering the rain gauge data of the Retignano station. In fact, the rainstorm triggered numerous shallow landslides in a zone 6–7 km from the rain gauge. The instrument recorded only 26.0 mm in 4.5 h, an absolutely common value of rainfall and without effects for the study area. Therefore, the Retignano station was probably not suitable to describe the event correctly, or it was out of order. Unfortunately, extremely concentrated and localized events are frequent in the area and furthermore the other stations close to the area were simple rain gauges (registration of the 24-h rainfall amount, without any indication of intensity within 24-h) and thus insufficient to describe the event. As a consequence, the 1984 event was indicated in the graphs with the Retignano rain gauge values, but was not considered for the definition of the critical threshold curves.

3.2 Duration/intensity threshold curves

A significant result emerged from the duration/intensity relationship of the 152 events collected (Fig. 5). Using a manual fitting and separating events which triggered several soil slips (events A), events which triggered a few soil slips (events B) and events which did not cause significant effects (events C), two curves (threshold curves) are reasonably recognisable (Fig. 5a):

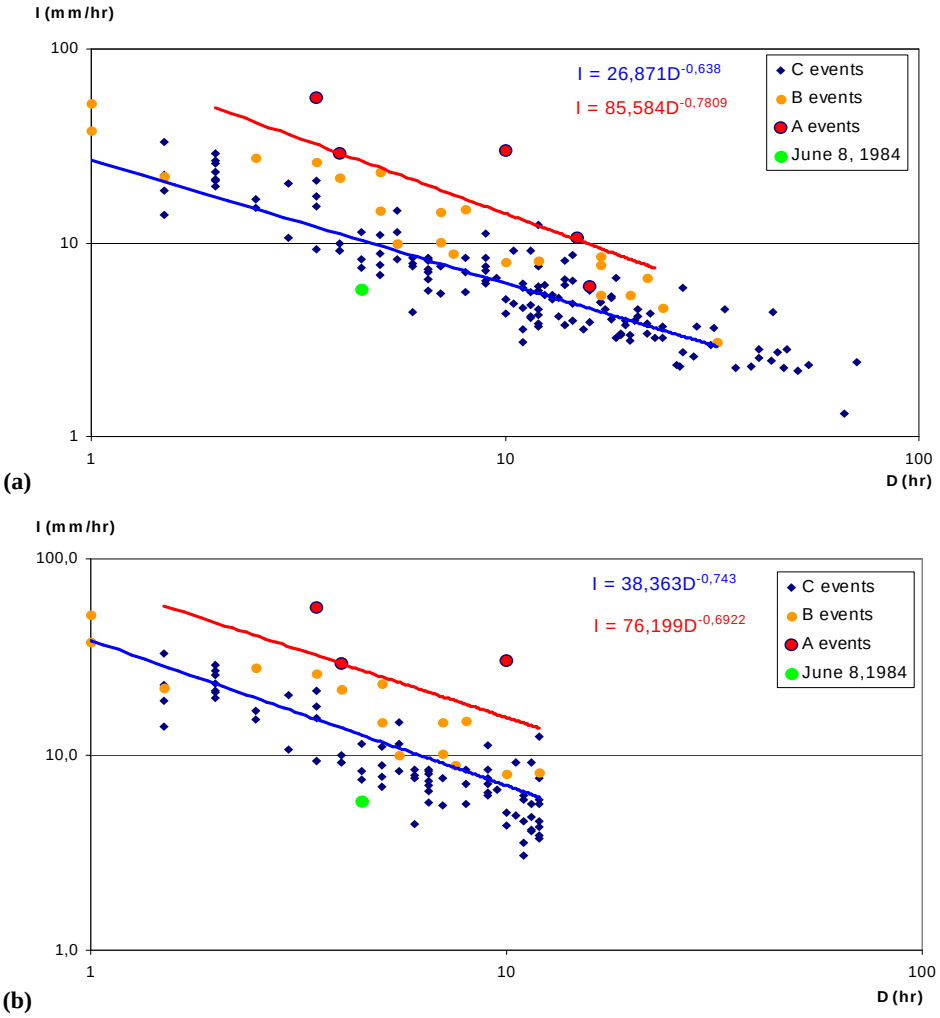

Fig. 5. Duration/intensity relationship for all 152 events collected **(a)** and for events with a duration less than or equal to 12 h **(b)**. A lower threshold curve (blue) and an upper one (red) are recognizable. The anomalous position of the 1984 event is emphasized.

$I = 26.871\ D^{-0.638}$ (lower threshold curve).

$I = 85.584\ D^{-0.7809}$(upper threshold curve).

The curves are sufficiently definite for D≤30–35 h and I≤40–50 mm/h (lower curve) and for D≤20–25 h and intensity I≤50–60 mm/h (upper curve). As noted above, the anomalous position of the 1984 event is emphasized. Considering only the events with a duration less than or equal to 12 h (Fig. 5b), which are rather typical in the Apuan area, the curve equations become:

$I = 38.363\ D^{-0.743}$ (lower threshold curve)

$I = 76.199\ D^{-0.6922}$ (upper threshold curve).

In the definition of the threshold curves there are obviously some exceptions, perhaps due to the utilization of a single station. Furthermore, the scarcity of A events from 1975 to 2002 does not allow a better definition of the upper curve, which, on the other hand, represents the most important limit. In fact, beyond this curve, the landslide hazard increases considerably.

With regard to Fig. 5a and excluding the June 1984 event, the probability of each kind of event (A, B, C) falling within each defined stability region could be estimated. The results are shown in Table 1, obtained by counting the percentage of the A, B, C events which fall in the instability, intermediate and stability fields, respectively. In particular, good results are obtained for A and B events, while a more significant error concerns C events (39.8% falls in the intermediate field). The threshold curve obtained for the southern Apuan Alps was also compared with threshold curves

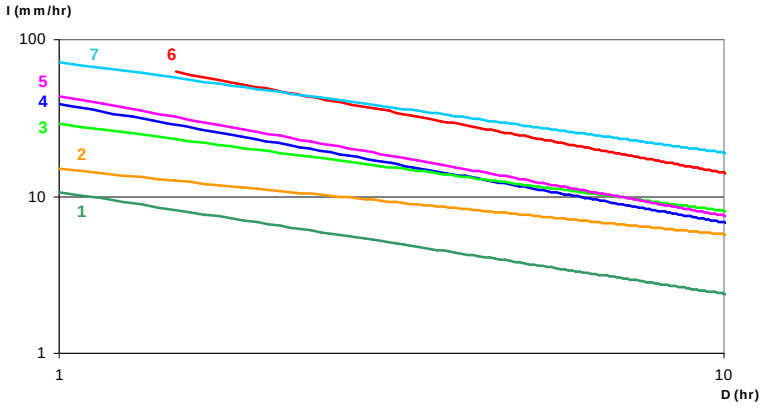

Fig. 6. Comparison among duration/intensity curves for shallow landslides of the southern Apuan Alps and other areas in the world (events with a duration less than or equal to 10 h): 1) California (Wieczorek and Sarmiento, 1988); 2) general (Caine, 1980); 3) general (Jibson, 1989); 4) Apuan lower curve; 5) Valtellina (Cancelli and Nova, 1985); 6) Apuan upper curve; 7) Porto Rico (Jibson, 1989).

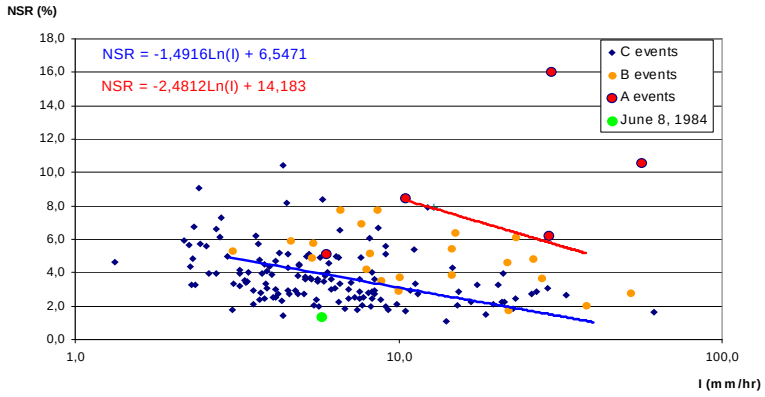

Fig. 7. Semi-logarithmic intensity/NSR relationship for all 152 events recorded. A lower threshold curve (blue) and an upper one (red) are recognizable. The anomalous position of the 1984 event is emphasized.

Table 1. Distribution of the events (A, B, C) in each defined stability field.

	Stability field	Intermediate	Instability field
A event (%)	0	20.0	80.0
B event (%)	0	100.0	0
C event (%)	59.5	39.8	0.7

proposed by other authors for several regions of the world (Fig. 6). In comparison with the other results, a higher value of the rainfall threshold for shallow landslide activity in the Apuan area emerges. This is probably linked to the high mean annual precipitation and to the high frequency of rainstorms.

As is well recognized, the Caine (1980) relationship, which, in theory, should have general validity because it was obtained with events occurred in several parts of the world, is often exceeded by the other threshold curves. Consequently, this is a further demonstration that each area (with its geological, geomorphological, hydrogeological and geotechnical features) is in equilibrium with its ordinary climatic conditions. Therefore, this type of research acquires importance only if carried out in a restricted area in which the cited characteristics can be reasonably considered homogeneous.

3.3 Normalization by MAP value

Several authors (e.g. Govi and Sorzana, 1980; Cannon and Ellen, 1988) asserted that each area is in equilibrium with its usual climatic and pluviometric conditions, and related the rainfall events to the mean annual precipitation (MAP), in order to normalize the rainfall data. The MAP was calculated at the Retignano rain gauge from 1936 to 2002 and resulted 1869.9 mm. For the Apuan area, the results of this normalization were interesting. Introducing the parameter NSR (Normalized Storm Rainfall–Corominas, 2001), namely the rainfall event/ MAP ratio, the relationship

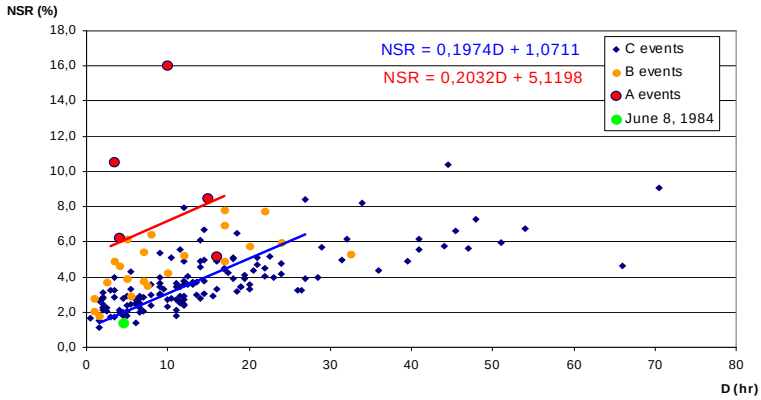

Fig. 8. Duration/NSR relationship for all 152 events recorded. A lower threshold curve (blue) and an upper one (red) are recognizable. The anomalous position of the 1984 event is emphasized.

intensity/NSR (Fig. 7) and duration/NSR (Fig. 8) were analysed. Also in these graphs two threshold curves are recognizable with a good approximation (on the basis of an empirical approach). In the first case (Fig. 7) the equations are respectively:

I = -1.4916 ln(NSR)+6.5471 (lower threshold curve)

I = -1.4812 ln(NSR)+14.183 (upper threshold curve).

In the second graph (Fig. 8) the equations are respectively:

D = 0.1974 NSR+1.0711 (lower threshold curve)

D = 0.2032 NSR+5.1198 (upper threshold curve).

In all the previous cases, the two threshold curves could reasonability delimit three fields of stability: certain stability (under the lower curve), uncertain stability (between the two curves), instability (above the upper curve).

4 Conclusions

In a region particularly subject to severe rainstorms, such as the Apuan Alps, and characterized by numerous elements at risk, the knowledge of the minimum rainfall amount necessary for shallow landslide (soil slip-debris flow) initiation is extremely important. With the aim of contributing to the landslide hazard evaluation of the southern Apuan Alps territory, a detailed analysis of the main pluviometric events was carried out. The data recorded at the chief rain gauge of the area in the period from 1975 to 2002 were analysed and compared with the occurrence of shallow landslides. Many attempts were made to obtain a possible correlation between rainfall parameters and the occurrence of soil slip-debris flow phenomena and to identify the local rainfall threshold for triggering shallow landslides.

Due to the lack of a close pluviometric network in the study area, characterized by a significant recording period, the rainfall data used to obtain the critical thresholds must be considered with caution (the 1984 event is a meaningful example). However, important results emerged from the duration/intensity, intensity/NSR and duration/NSR relationships, identifying two threshold curves, which could separate fields with different degrees of stability: stability, uncertain stability and instability.

The critical thresholds obtained for the southern Apuan Alps were also compared with those proposed by other authors for several regions in the world, to emphasize the high value of the rain threshold for shallow landslide activity in the Apuan area. The high value is probably linked to the high mean annual precipitation and to the high frequency of rainstorms in the study area.

This research is still in progress. Similar studies have been started in an adjacent area, and seem to provide analogous results. This fact should confirm the validity of the empirical approach in the Apuan area. At present, two monitoring stations, equipped with pluviometers and piezometers, are set up to verify and improve the critical threshold found and to comprehend the infiltration model using the proposed rainfall values. Further studies will also be carried out to obtain more information about the role of the antecedent rainfall in the initiation of shallow landslides.

Edited by: F. Guzzetti
Reviewed by: S. Simoni and two other referees

References

Annunziati, A., Focardi, A., Focardi, P., Martello, S., and Vannocci, P.: Analysis of the rainfall thresholds that induced debris flows in the area of Apuan Alps, Tuscany, Italy (June 1996 storm), Proc. EGS Plinius Conference Mediterranean Storms, Maratea, Italy, 485–493, 2000.

Baldacci, F., Cecchini, S., Lopane, G., and Raggi, G.: Le risorse idriche del Fiume Serchio ed il loro contributo all'alimentazione

dei bacini idrografici adiacenti, in Italian, Mem. Soc. Geol. It., 49, 365–391, 2003.

Brand, E. W.: Predicting the performance of residual soil slopes, Proceedings 11th Int. Conf. Soil Mech. & Found. Engineering, San Francisco, United States, 5, 2541–2578, 1985.

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

Campbell, R. H.: Soil slips, debris flows and rainstorms in the Santa Monica Mountains and vicinity, Southern California, U.S. Geological Survey Professional Paper, 851, 51 , 1975.

Cancelli, A. and Nova, R.: Landslides in soil and debris cover triggered by rainfall in Valtellina (Central Alps – Italy), Proc. 4th International Conference & Field Workshop on Landslides, Tokyo, Japan, 267–272, 1994.

Cannon, S. H. and Ellen, S. D.: Rainfall that resulted in abundant debris flows activity during the storm, Landslides, floods, and marine effects of the storm of 3–5 January , 1982, in the S. Francisco Bay Region, California, edited by: Ellen, S. D. & Wieczorek, G. F., U.S. Geological Survey Professional Paper, 1434, 27–33, 1988.

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

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

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

Crozier, M. J.: Landslides: causes, consequences and environment, Routledge, London-New York, 252, 1986.

D'Amato Avanzi, G., Giannecchini, R., and Puccinelli A.: Geologic and geomorphic factors of the landslides triggered in the Cardoso T. Basin (Tuscany, Italy) by the 19 June 1996 intense rainstorm, Proc. 8th International Symposium on Landslides, Cardiff, Galles, 381–386, 2000.

D'Amato Avanzi, G., Giannecchini, R., and Puccinelli A.: 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), Eng. Geology, 73(3–4), 215–228, 2004.

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

Fukuoka, M.: Landslides associated with rainfall, Geotechnical Eng., 11, 1–29, 1980.

Giannecchini, R. and Pochini, A.: Geotechnical influence on soil slips in the Apuan Alps (Tuscany): first results in the Cardoso area; Proc. Int. Conf. Fast Slope Movements-prediction and prevention for risk mitigation (IC-FSM 2003), Naples, 241–245, 2003.

Govi, M. and Sorzana, P. F.: Landslide susceptibility as function of critical rainfall amount in Piedmont basin (North-Western Italy), Studia Geomorphologica Carpatho-Balcanica, Krakow, 1980, 14, 43–60.

Guzzetti, F.: Landslide fatalities and the evaluation of landslide risk in Italy, Eng. Geology, 58, 89–107, 2000.

Jibson, R. W.: Debris flows in Southern Puerto Rico, Geological Soc. Amer., 236, 29–55, 1989.

Martello, S., Catani, F., and Casagli, N.: The role of geomorphological settings and triggering factors in debris flow initiation during the 19 June 1996 meteorological event in Versilia and Garfagnana (Tuscany, Italy), Proc. 8th Int. Symp. Landslides, Cardiff, Galles, 1017–1022, 2000.

Starkel, L.: The role of extreme meteorological events in the shaping of mountain relief, Geographica Polonica, 41, 13–20, 1979.

Wieczorek, G. F. and Sarmiento, J.: Rainfall, piezometric level and debris flows near La Honda, California, in storms between 1975 and 1983, Landslides, floods, and marine effects of the storm of 3–5 January, 1982, in the S. Francisco Bay Region, California, edited by: Ellen, S. D. and Wieczorek, G. F., U.S. Geological Survey Professional paper, 1434, 43–62, 1988.

Wilson, R. C.: Climatic variations in rainfall thresholds for debris-flow activity, Proc. EGS Plinius Conf. Mediterranean Storms, Maratea, Italy, 415–424, 2000.

Wilson, R. C. and Wieczorek, G. F.: Rainfall thresholds for the initiation of debris flows at La Honda, California, Environ. Eng. Geosci., I, 1, 11–27, 1995.