Abstract Code: A01

The role of geographic and seasonal factors and land cover change on empirical rainfall thresholds in Italy

S.L., Gariano[(1,2)*], M.T., Brunetti[(1,2)], M., Melillo[(1)], S., Peruccacci[(1)], F., Guzzetti[(1)]

[(1)] CNR IRPI, via Madonna Alta 126, 06128 Perugia, Italy
[(2)] University of Perugia, Department of Physics and Geology, via A. Pascoli, 06123 Perugia, Italy

Corresponding author details:
* CNR IRPI, via Madonna Alta 126, 06128 Perugia, Italy, e-mail: gariano@irpi.cnr.it

Keywords:
Rainfall threshold, shallow landslide, seasonality, latitude, rainfall duration, land cover.

INTRODUCTION

In Italy, the prediction of rainfall-induced shallow landslides is a fundamental aim for civil protection purposes. In fact, severe events in the past caused economic damage and loss of human lives. For the purpose, we have investigated the rainfall conditions responsible for the occurrence of shallow landslides in Italy. Our work focused on the definition of empirical rainfall thresholds for their use in national landslide warning systems. The thresholds are based on the statistical analysis of past rainfall conditions that have resulted in landslides. However, the rainfall conditions that have resulted in landslides in the past may vary in the future due to climatic changes (i.e., changes in rainfall intensity and frequency, and patterns of the triggering events) and to landscape changes (i.e., land use and land cover changes). We have studied a catalogue of 1980 rainfall events that have resulted in 2407 shallow landslides in Italy from 1996 to 2012, and we investigated how the triggering rainfall conditions and the thresholds vary depending on geographical, seasonal and land cover factors.

DATA

The definition of reliable rainfall thresholds for possible landslide occurrence requires information on the geographical and temporal locations of landslides, and on the rainfall conditions responsible for the landslides (Guzzetti et al. 2007, 2008). We are compiling a catalogue of rainfall events that have resulted in landslides in Italy. At present, the catalogue lists 1980 rainfall events that have resulted in 2407 documented shallow landslides in the period from January 1996 to August 2012. The documented landslides are distributed in almost all the Italian regions, with the exception of Liguria, Emilia-Romagna and Tuscany. For these three regions, information on about 300 rainfall events with landslides is available and is under investigation at the date of the paper. We collected information on the rainfall-induced landslides searching chiefly online newspaper archives and fire brigade reports. Each record in the catalogue lists information on (Gariano et al. 2012): (i) the event identification (ID number, source of the information), (ii) the landslide location (place, municipality, province, region, geographical accuracy), (iii) the landslide type (where available), (iv) the temporal information of the failure (day, month, year, time, date, temporal accuracy), and (v) information on the triggering rainfall (representative rain gauge, rainfall duration D in hours, cumulated event rainfall E in mm, rainfall mean intensity I in mm/h). We attributed to each failure a level of mapping accuracy P (Peruccacci et al. 2012, Vennari et al. 2014), in four classes i.e., high ($P_1 < 1$ km^2), medium ($1 \le P_2 < 10$ km^2), low ($10 \le P_3 < 100$ km^2) and very low ($100 \le P_4 < 300$ km^2), and a level of temporal accuracy T (Peruccacci et al.

2012, Vennari et al. 2014) in three classes i.e., the day (T_3), the period of the day (T_2), and the time (T_1).

In the catalogue, 1274 landslides (52.9%) were mapped with a high geographical accuracy, 914 landslides (38.0%) with a medium accuracy, 211 (8.8%) with a low accuracy, and 8 (0.3%), with a very low accuracy. For 656 landslides (27.3%) the time of occurrence is known, for 810 (33.7%) the period of the day is known, and for 941 landslides (39.1%) only the day is known. Figure 1 shows the geographical location of the collected rainfall-induced landslides, and their monthly and yearly distributions. In the last 10 years in the catalogue (a period for which the information is more abundant) an average of 220 landslides occurred every year, with the largest number of landslides recorded in the 4-year period 2008-2011 (1323 landslides). The rainfall-induced failures mostly between November and January, and were also frequent in March. We reconstructed the triggering rainfall conditions (the rainfall duration *D* and the cumulated rainfall *E*) of each landslide using national and regional rain gauge networks. Additional information on the catalogue and the national and regional thresholds is available in Brunetti et al. (2014, 2015), Peruccacci et al. (2012, 2014), Gariano et al. (2014), and Vennari et al. (2014).

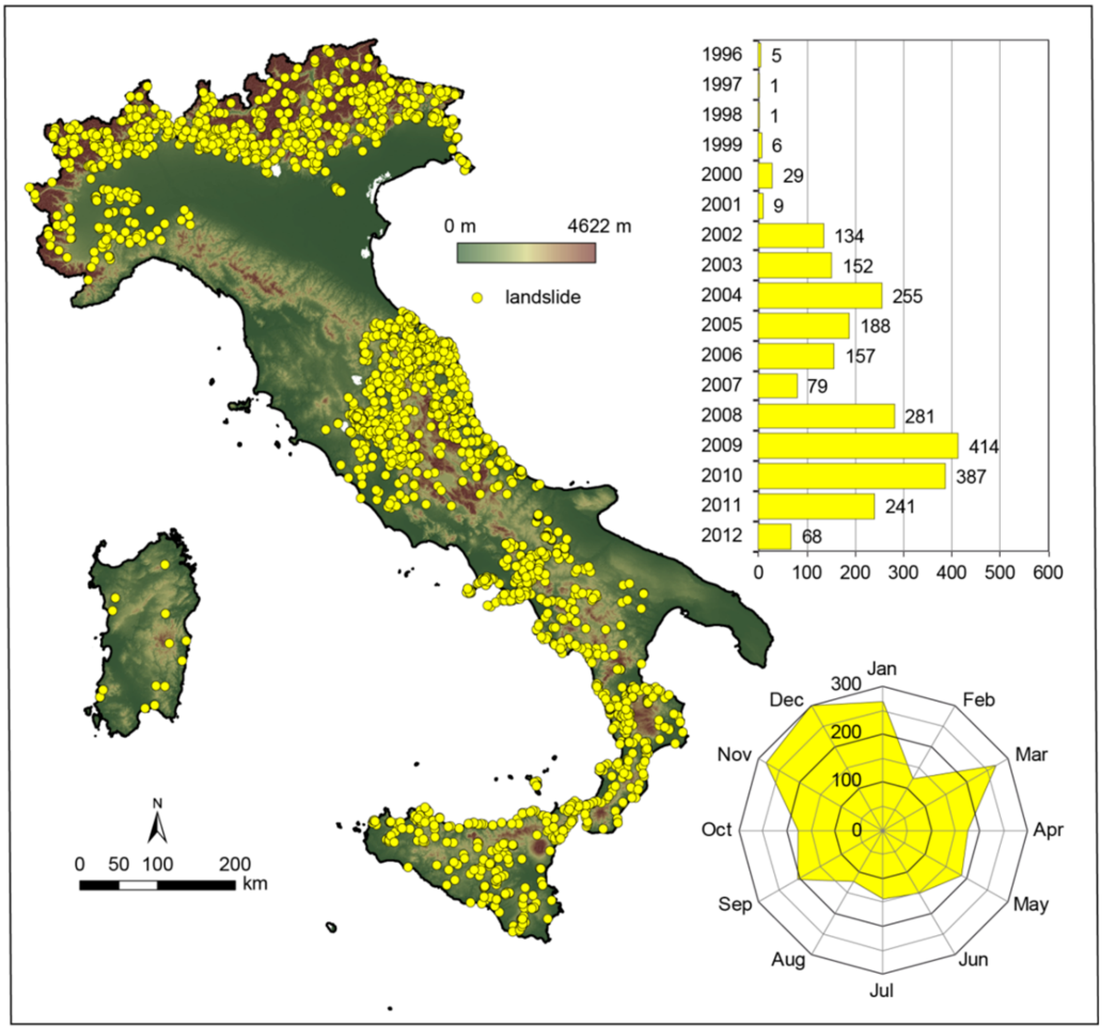

Figure 1. Map showing the location of 2407 rainfall-induced shallow landslides in Italy between 1996 and 2012. The histogram portrays the number of landslides per year. The spider chart shows the monthly distribution of the events.

METHOD

Definition of rainfall thresholds

To define objective and reproducible probabilistic rainfall thresholds, and their associated uncertainties, we used the approach proposed by Brunetti et al. (2010) and modified by Peruccacci et al. (2012). Following this approach, the threshold curve is a power law relationship linking the cumulated event rainfall *E* (in mm) to the rainfall duration *D* (in hours),

$$E = (\alpha \pm \Delta\alpha) \cdot D^{(\gamma \pm \Delta\gamma)},$$

where α is a scaling constant, γ defines the slope of the power law curve, and $\Delta\alpha$ and $\Delta\gamma$ represent the uncertainties of α and γ, respectively. The approach allows defining thresholds for different exceedance probabilities (e.g., 1%, 5%, 10%, etc.). As an example, a 5% threshold (T_5) leaves 5% of the (*D*,*E*) empirical points below the threshold.

Influence of environmental factors

We investigated the variations in the landslide occurrence depending on geographical and seasonal factors. In particular, we analysed the landslide latitude, the seasonal periods, and the rainfall duration. First, we selected three classes of latitude *L*, defined as follows: *North* ($L \geq 44.0°$), *Centre* ($41.5° \leq L < 44.0°$), and *South* ($L < 41.5°$). Figure 2 shows the monthly distribution of landslides as a function of the *L* classes. Next, we defined two seasonal periods (dry and wet) as a function of *L*. For the *North* class, the dry period was taken from June to September, and the wet period from October to May. For the *Centre* class, the dry period was considered from May to September, and the wet period from October to April. For the *South* class, the dry period was from April to October, and the wet period from November to March. Next, we defined two classes of rainfall duration, considering short ($D \leq 24$ h) and long ($D > 24$ h) rainfall events. Lastly, we attributed each event of the catalogue to a class on the basis of its spatial position and temporal feature (month of occurrence and rainfall duration).

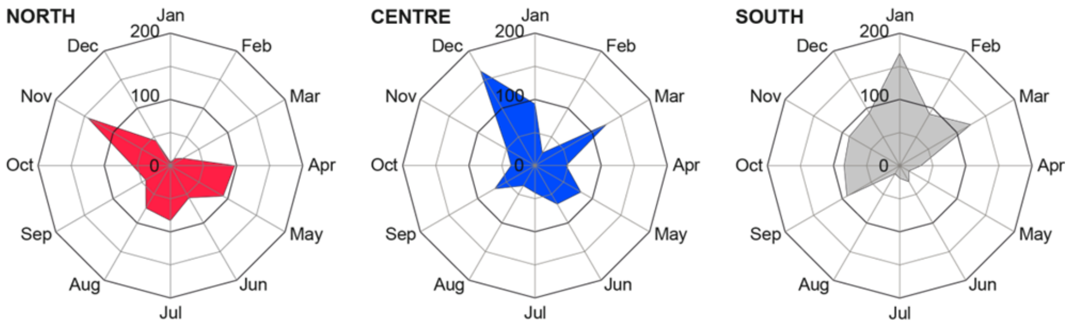

Figure 2. Number of landslides per month, for the three classes of latitude.

We also investigated the influence of land cover changes on landslide occurrence. For the purpose, we exploited two CORINE (Coordination of Information on the Environment) land cover (CLC) maps published in 2000 and 2006 (www.pcn.minambiente.it). The first level of the CORINE categories includes: (i) artificial surfaces, (ii) agricultural areas, (iii) forests and semi-natural areas, (iv) wetlands, and (v) water bodies. In the two CLC maps, the extent and geographical distribution of the different land cover classes change. In particular, agricultural areas have increased from 50.6% in 2000 to 51.1% in 2006, forest and semi-natural areas decreased from 41.4% (2000) to 40.7% (2006), and urban areas increased from 4.6% (2000) to 4.8% (2006). We attributed a specific CLC class to each landslide in the catalogue using spatial and temporal criteria and adopting the procedure proposed by Peruccacci et al. (2012). We used a circle with an areal extent dependent on the landslide mapping accuracy to represent each landslide. The size of the circle was A_1 = 0.5 km^2, A_2 = 5 km^2, A_3 = 50 km^2, and A_4 = 150 km^2 for landslides mapped with a high, medium, low and very low accuracy, respectively. Next, we intersected the circles with the layers representing the CORINE classes, and we computed the proportion of each CLC class in each circle. A CORINE class was attributed to each landslide if it covered at least 75% of the circle. To the landslides occurred in the period 1996-2003 we attributed a land cover class obtained from the 2000 CLC map, and to the landslides occurred in the period 2004-2012 we attributed a land cover class obtained from the 2006 CLC.

RESULTS AND DISCUSSION

We exploited the catalogue of rainfall events with landslides in Italy, and segmented it in subsets to define rainfall thresholds for possible landslide occurrence for different latitude zones, for the wet and dry seasons, for two ranges of rainfall duration, and for different land cover classes. Table 1 lists, for each subset of latitude, season, and rainfall duration, statistics for the rainfall events with landslides, and the corresponding 5% thresholds with their associated uncertainties. For the same subsets, Figures 3, 4 and 5 show the distribution of the (D,E) rainfall conditions responsible for landslides, and the associated 5% thresholds, in log-log coordinates (left graphs). The Figures also show the same thresholds in linear coordinates, in the range $1 \le D \le 120$ h (right graphs), a typical range of rainfall durations used to forecast rainfall-induced landslide in Italy (Peruccacci et al. 2012).

Table 1. Summary statistics and 5% threshold equations for rainfall events with landslides for different latitudes, seasons, and rainfall duration ranges. Legend: #REL, number of rainfall events with landslides; D, event duration (h); E, cumulated event rainfall (mm).

Classes	#REL	*D* (h) min	*D* (h) mean	*D* (h) max	*E* (mm) min	*E* (mm) mean	*E* (mm) max	Threshold equation
Entire catalogue								
Italy	1980	0.5	82.1	1212.0	4.2	104.9	751.6	$T_{5,I} : E = (7.2 \pm 0.3) \cdot D^{(0.40 \pm 0.01)}$
Latitude								
North	638	0.5	89.3	684.0	4.2	125.1	751.6	$T_{5,N} : E = (6.3 \pm 0.4) \cdot D^{(0.46 \pm 0.02)}$
Centre	637	1.0	103.6	1212.0	7.0	91.8	457.2	$T_{5,C} : E = (7.4 \pm 0.4) \cdot D^{(0.39 \pm 0.01)}$
South	705	1.0	64.7	451.0	7.6	93.4	542.0	$T_{5,S} : E = (8.3 \pm 0.5) \cdot D^{(0.36 \pm 0.02)}$
Season								
Wet	1304	1.0	110.4	1212.0	7.2	119.3	751.6	$T_{5,W} : E = (6.4 \pm 0.4) \cdot D^{(0.43 \pm 0.01)}$
Dry	676	0.5	36.3	684.0	4.2	71.8	542.0	$T_{5,D} : E = (7.1 \pm 0.4) \cdot D^{(0.39 \pm 0.02)}$
Rainfall Duration								
D ≤ 24 h	623	0.5	10.3	24.0	4.2	50.5	466.6	$T_{5,D \le 24} : E = (6.7 \pm 0.4) \cdot D^{(0.40 \pm 0.03)}$
D > 24 h	1357	25	119.5	1212.0	19.8	127.2	751.6	$T_{5,D > 24} : E = (7.3 \pm 0.6) \cdot D^{(0.41 \pm 0.02)}$

Latitude

In the South latitude zone (705 rainfall events with landslides, 36%) the mean duration of rainfall events is shorter than the mean duration found for the other two latitude zones (Table 1), with the largest mean cumulated event rainfall found the North zone (638 rainfall events with landslides, 32%). Inspection of Figure 3 reveals that the $T_{5,N}$ is the steepest threshold. As a result, for $D > 100$ h and $L \ge 44.0°$ a larger amount of rainfall is required to trigger landslides. Considering the uncertainties, the $T_{5,C}$ and $T_{5,S}$ thresholds are indistinguishable, statistically.

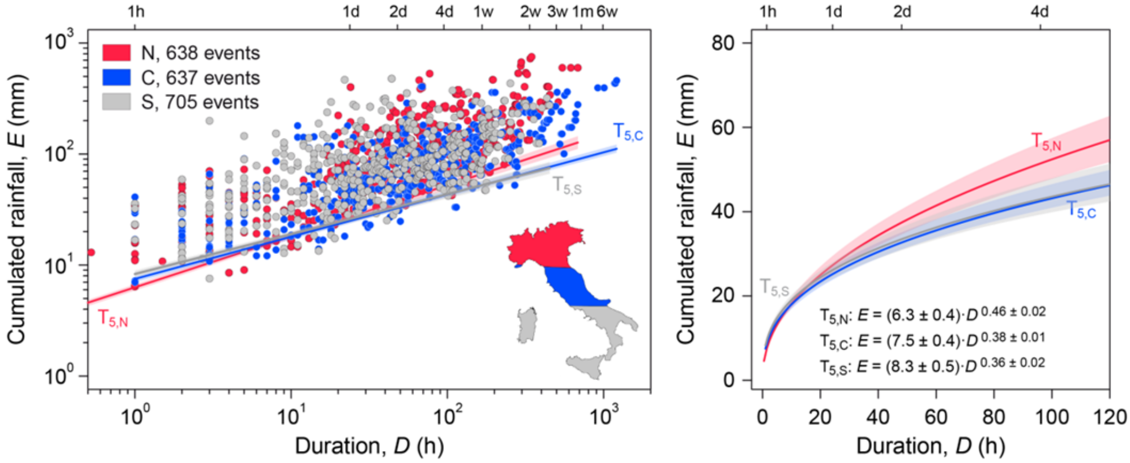

Figure 3. Left: Rainfall (D,E) conditions (log-log coordinates) that have resulted in shallow landslides in the North (red dots), Centre (blue dots) and South (grey dots) latitude zones, and corresponding 5% thresholds ($T_{5,N}$, $T_{5,C}$, and $T_{5,S}$). Inset shows subdivision of Italy in the three latitude zones. Right: $T_{5,N}$, $T_{5,C}$, and $T_{5,S}$ thresholds in the range 1 ≤ D ≤ 120 h (linear coordinates). Shaded areas show uncertainty in the thresholds.

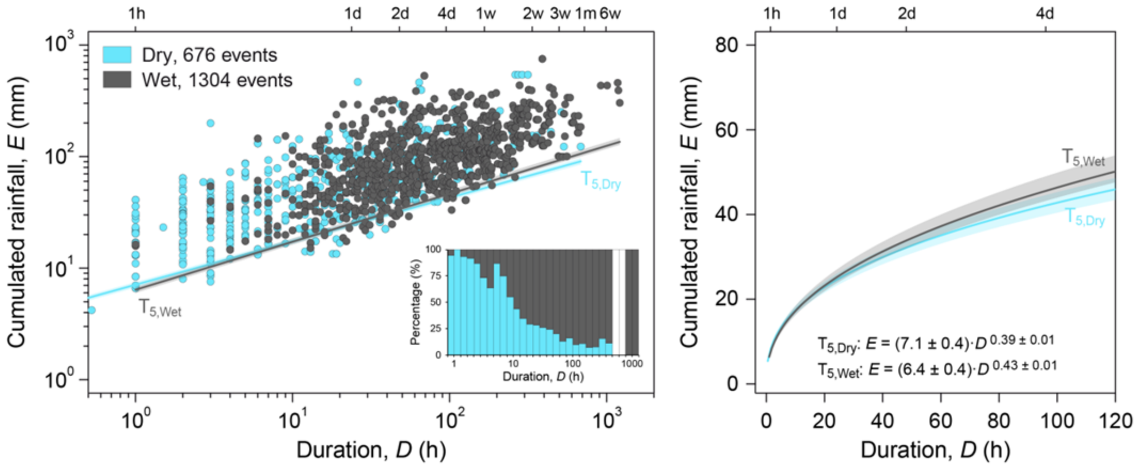

Figure 4. Left: Rainfall (D,E) conditions (log-log coordinates) that have resulted in shallow landslides in the wet (grey dots) and dry (blue dots) periods, and corresponding 5% thresholds ($T_{5,W}$ and $T_{5,D}$). Inset shows the percentage of events of different durations in the two seasonal periods. Right: $T_{5,W}$ and $T_{5,D}$ thresholds in the range 1 ≤ D ≤ 120 h (linear coordinates). Shaded areas show uncertainty in the thresholds.

Seasonal period

Rainfall events in the dry season (676 events, 34%) have a mean rainfall durations lower than the events in the wet season (Table 1). In Figure 4 the light blue dots (dry period) predominate for *D* < 20 hours, and the grey dots (wet period) are more abundant for *D* > 20 h. The $T_{5,Dry}$ threshold is less steep than the $T_{5,Wet}$ however, considering the uncertainties, the two thresholds are statistically indistinguishable for *D* < 200 h.

Duration range

The histogram in Figure 5 confirms that short duration events (*D* ≤ 24 h, 623 events, 31%) occurred mainly in the period from June to October, and that long duration events (*D* > 24 h, 1357 events, 69%) are more abundant from November to May. The $T_{5,D\leq24h}$ and $T_{5,\ D>24h}$ thresholds exhibit similar slopes (Table 1, Figure 5) and, considering the uncertainties, the short and the long duration rainfall events have the same triggering conditions.

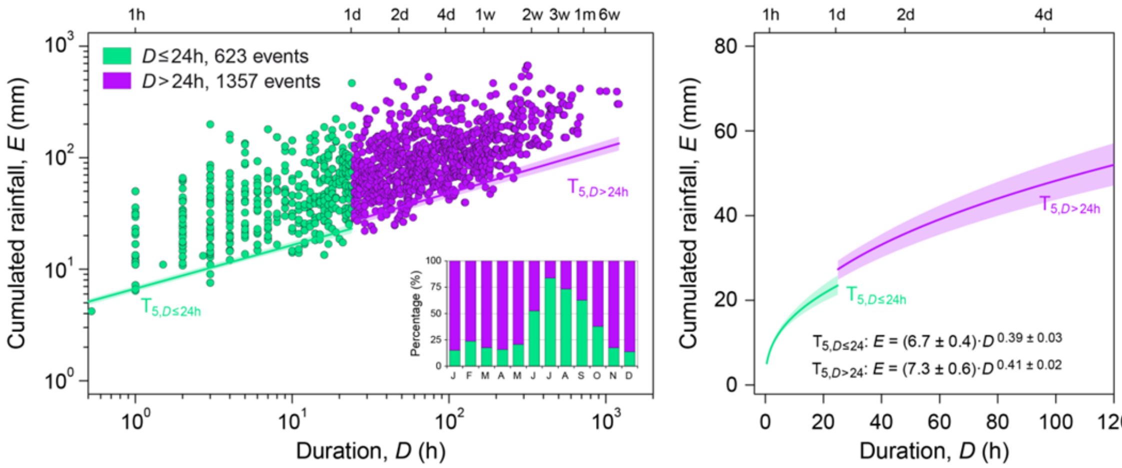

Figure 5. Left: Rainfall (D,E) conditions (log-log coordinates) that have resulted in shallow landslides for D ≤ 24 h (green dots) and > 24 h (purple dots), and corresponding 5% thresholds ($T_{5,D\leq24}$ and $T_{5,D>24}$). Histogram shows monthly distribution of rainfall events with landslides for the two duration ranges. Right: $T_{5,D\leq24}$ and $T_{5,D>24}$ thresholds in the range 1 ≤ D ≤ 120 h (linear coordinates). Shaded areas show uncertainty in the thresholds.

CORINE Land Cover

We prepared thresholds for two subsets corresponding to the "agricultural" and the "forest and semi-natural" classes in the 2006 CLC map. No landslides were attributed to the "wetlands" and "water" classes. For the subsets corresponding to the 2000 CLC map, and for the "artificial" area in the 2006 map, the number of events was insufficient to determine the thresholds.

Table 2. Summary statistics and 5% threshold equations for rainfall events with landslides for different CORINE land cover classes. Legend: #REL, number of rainfall events with landslides; D, event duration (h); E, cumulated event rainfall (mm).

Classes	#REL	D (h)			E (mm)			Threshold equation
		min	mean	max	min	Mean	max	
CORINE Land Cover 2000 Level 1								
Artificial	5	1.0	24.4	55.0	23.6	73.5	167.2	-
Agricultural	67	1.0	55.3	558	7.0	80.5	541.0	-
Forest	52	1.0	108.1	182.1	11	182.1	722.2	-
CORINE Land Cover 2006 Level 1								
Artificial	42	1.0	93.1	450.0	7.2	108.3	282.9	-
Agricultural	460	1.0	78.3	1008.0	10.8	89.5	436.2	$T_{5,A2006}: E = (8.2 \pm 0.6) \cdot D^{(0.35 \pm 0.02)}$
Forest	365	1.0	75.5	513.0	4.2	106.9	530.1	$T_{5,F2006}: E = (6.4 \pm 0.5) \cdot D^{(0.45 \pm 0.02)}$
CORINE Land Cover 2000 + 2006 Level 1								
Artificial	47	1.0	85.8	450.0	7.2	104.6	282.9	-
Agricultural	527	1.0	75.4	1008.0	7.0	88.4	539.5	$T_{5,A}: E = (8.4 \pm 0.6) \cdot D^{(0.36 \pm 0.02)}$
Forest	417	1.0	79.5	513	6.4	116.5	723.1	$T_{5,F}: E = (6.5 \pm 0.5) \cdot D^{(0.46 \pm 0.02)}$

For each CLC class, Table 2 lists summary statistics for the rainfall events with landslides and (where defined) the equations of the 5% thresholds and their associated uncertainties. Figure 6 shows the distribution of the rainfall (*D*,*E*) conditions responsible for the landslides in the “agricultural” and the “forest and semi-natural” classes in the 2000 and 2006 CLC maps, together with the 5% thresholds for the two classes in the 2006 CLC map. Inspection of Figure 6 and Table 2 reveals that the number and the distribution of the events in the 2000 and 2006 CLC maps have changed. In the 2006 CLC map, the 5% threshold for the “forest and semi-natural” class is steeper than the threshold for the “agricultural” class. For rainfall duration < 12 h more rain is needed to trigger landslides in “agricultural” than in “forest and semi-natural” areas. For predicting purposes, considering the uncertainties, the thresholds are statistically indistinguishable for 8 < *D* < 30 h.

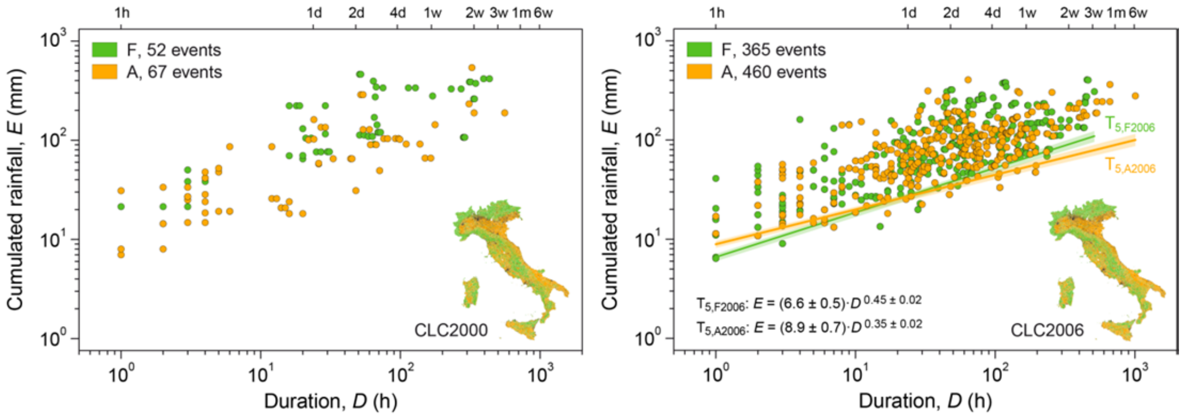

Figure 6. Rainfall duration vs. cumulated event rainfall (D,E) conditions (log-log coordinates) that have resulted in shallow landslides in “agricultural” (orange dots) and “forest and semi-natural” (green dots) classes of the first level CORINE land cover (CLC) map (insets), in 2000 (left) and 2006 (right). The 5% thresholds for the 2006 classification ($T_{5,A2006}$, $T_{5,F2006}$) are also shown.

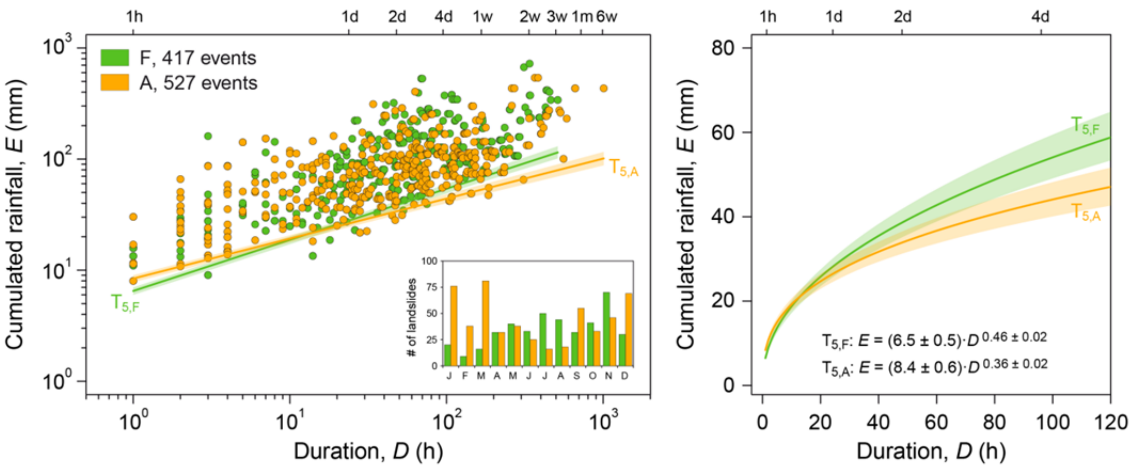

Figure 7. Left: Rainfall (D,E) conditions (log-log coordinates) that have resulted in shallow landslides in the “agricultural” (orange dots) and “forest and semi-natural” (green dots) classes of the first level CORINE land cover (CLC) map, and corresponding 5% ($T_{5,A}$, $T_{5,F}$). Histogram shows number of landslides per month, for the two classes. Right: $T_{5,A}$, and $T_{5,F}$ thresholds in the range $1 \leq D \leq 120$ h (linear coordinates). Shaded areas show uncertainty in the thresholds.

Considering all the rainfall events with landslides in the 2000 and the 2006 CLC maps, we defined 5% thresholds for the “agricultural” and the “forest and semi-natural” classes (Figure 7). The distributions of the (*D*,*E*) rainfall conditions that have resulted in landslides in the two CLC classes are not significantly different than the conditions observed using the 2006 CLC map. The 5% threshold for the “forest and semi-natural” areas remains steeper than the threshold for the “agricultural” areas. However, considering their uncertainties, the $T_{5,F}$ and $T_{5,A}$ thresholds are indistinguishable, statistically, for 8 < *D* < 80 h. The abundance of landslide events varied in the two CLC classes (histogram in Figure 7), with landslides attributed to the “agricultural” class more abundant between September and March, and landslides attributed to the “forested and semi-natural” class more abundant between July and November.

CONCLUSIONS

We analyzed a catalogue of 1980 rainfall events that have resulted in 2407 landslides in Italy in different geographic areas, seasonal periods, and land cover classes and scenarios and we defined rainfall thresholds, with associated uncertainties, for each considered factor. We found that: (i) the 5% threshold for the “North” latitude zone is steeper than the thresholds found for the “Centre” and the “South” zones; (ii) the 5% threshold for the dry seasonal period is less steep and has a shorter range of duration than the threshold for the wet season; (iii) the 5% threshold for short and long rainfall durations exhibit a similar slope, indicating that the triggering conditions for the two durations are similar; and (iv) the 5% threshold for the “agricultural” CLC class are steeper than the threshold for the “forested and semi-natural” CLC class. Therefore, the main conclusion of this work is that latitude, season and land cover affect the triggering conditions of rainfall-induced landslides in Italy. In particular, for very short rainfall durations (D ≤ 10 h), lower amounts of cumulated event rainfall are required to trigger landslides in the North latitude zone and in “forest and semi-natural” areas than in the Centre and South latitude zones and in “agricultural” areas.
Analysing the considered factors is important to define rainfall thresholds in homogenous areas, and to investigate how possible changes in the factors may lead to variations in the landslide triggering conditions.
Future developments of this work will concern the increase of the catalogue, the definition of thresholds for different classes of elevation, morphology, soil type, and climate, and the evaluation of the variation of triggering condition considering several global change scenario.
We expect that the new thresholds can be implemented in a nationwide landslide warning system, improving the forecasting of landslides at national scale.

ACKNOWLEDGEMENTS

L. Antronico, D. Bartolini, A.M. Deganutti, G. Iovine, S. Luiciani, F. Luino, M.R. Palladino, M. Parise, M. Rossi, O. Terranova, L. Turconi, C. Vennari, G. Vessia and A. Viero contributed to collecting information on landslides and to reconstructing the rainfall events. The research was financed by the Italian National Department for Civil Protection.

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