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Rainfall events with shallow landslides in the Entella catchment (Liguria, Northern Italy)

Anna Roccati[1], Francesco Faccini[2], Fabio Luino[1], Laura Turconi[1], Fausto Guzzetti[3]

[1] Istituto di Ricerca per la Protezione Idrogeologica, Consiglio Nazionale delle Ricerche, Strada della Cacce 73, 10135 Torino, Italy
[2] Department of Earth, Environment and Life Sciences, University of Genoa, Corso Europa 26, 16132 Genova, Italy
[3] Istituto di Ricerca per la Protezione Idrogeologica, Consiglio Nazionale delle Ricerche, Via della Madonna Alta 126, 06128 Perugia, Italy

Correspondence to: Anna Roccati (anna.roccati@fastwebnet.it)

Abstract. In the recent decades, the Entella River basin, in the Liguria Apennines, Northern Italy, was hit by numerous intense rainfall events that triggered shallow landslides, soil slips and debris flows, causing casualties and extensive damage. We analysed landslides information obtained from different sources and rainfall data recorded in the period 2002–2016 by rain gauges scattered in the catchment, to identify the event rainfall duration, D (in h), and rainfall intensity, I (in mm h^{-1}), that presumably caused the landslide events. Rainfall-induced landslides affected all the catchment area, but were most frequent and abundant in the central part, where the three most severe events hit on 24 November 2002, 21–22 October 2013, and 10 November 2014. Examining the timing and location of the failures, we found that the rainfall-induced landslides occurred primarily at the same time or within six hours from the maximum peak rainfall intensity, and at or near the geographical location where the rainfall intensity was largest. Adopting a Frequentist approach, we define the event rainfall intensity–event duration ID, threshold for the possible initiation of shallow landslides and debris flows in the Entella River basin. The threshold is lower than most of the thresholds proposed in the literature for similar mountain catchments, local areas and single regions in Italy. Analysis of the antecedent rainfall conditions for different periods, from 3 to 15 days, revealed that the antecedent rainfall did not play a significant role in the initiation of landslides in the Entella catchment. We expect that our findings will be useful in regional to local landslides early warning systems, and for land-planning aimed at reducing landslides risk in the study area.

1 Introduction

In the recent decades, a number of rainfall events have caused widespread landslides and inundations in Italy, resulting in serious social and economic damage (Wasowski, 1998; Alpert et al., 2002; Crosta and Frattini, 2003; D'Amato Avanzi et al., 2004; 2012; Luino, 2005; Giannecchini, 2006; Del Ventisette et al., 2012; Salvati et al., 2014). In the same period, the

Liguria region, northern Italy – one of the areas where landslide and flood risk is highest in Italy (Guzzetti, 2000; Salvati et al., 2010; Salvati et al., 2014) – was affected frequently by short duration, intense rainfall events that have triggered damaging landslides and have caused local inundations, chiefly where urban planning and land management were poor or ineffective, resulting in an increased vulnerability to geo-hydrological (landslides and flood) hazards (Bartolini et al., 2014).

In the 15-year period 2002–2015, the Liguria region suffered tens of rainfall events with local inundations, flash floods, debris flows, and shallow and deep-seated landslides (Guzzetti et al., 2004; Faccini et al., 2005; 2012; 2015a; 2015b; 2015c; 2017; Giannecchini et al., 2010; 2015; Silvestro et al., 2012; 2016; Cevasco et al., 2014; 2015a; 2015b; 2017; D'Amato Avanzi et al., 2015). Collectively, the rainfall induced landslide and flood events have claimed 37 lives, and have caused widespread and extensive damage to private and public properties, structures and infrastructures, and business. In the considered period, the Entella River basin, in eastern Liguria, was one of the most frequently affected catchments, with a total of 29 damaging rainfall events and with numerous shallow landslides and local inundations.

Here, we discuss the three largest rainfall events with abundant landslides that hit the Entella catchment in the 15-year period 2002–2016. For each event, we analyse (i) the rainfall intensity and the cumulated event rainfall, (ii) the type, number, and distribution of the event landslides, and (iii) the type and extent of the damage. We use the rainfall and the landslide information for the three events, together with additional information on 14 additional rainfall events with landslides in the same area from 2000 to 2016, to define rainfall thresholds for the possible initiation of shallow landslides in the Entella catchment.

2 Study area

The Entella River basin extends for 375 km^2 in the Tyrrhenian sector of the Liguria Apennines, north-western Italy (Fig. 1) and encompasses the Lavagna (160 km^2), Sturla (130 km^2), and Graveglia (63 km^2) tributaries (Fig. 1A). In the area crop out different rock types, Jurassic to Paleocene in age, arranged in a complex geological setting characterized by the presence of multiple sets of tectonic discontinuities (Geological Service of Italy, 1968; Boni et al., 1969; Marini, 1992, 1993, 1994; Liguria Region, 2005) (Fig. 1B). Shale, limestone, heterogeneous marl, slate and sandstone crop out in the Lavagna and lower Sturla valleys, whereas in the Graveglia valley crop out an ophiolitic sequence, encompassing serpentine, gabbro, basalt, ophiolite breccia, chert, grey limestone and shale. In the upper part of the Sturla valley, along the Tyrrhenian–Adriatic divide, crop out marly limestone, marl, and other heterogeneous and chaotic rocks. Pliocene and Quaternary deposits cover extensively the slopes and the valley floors. The morphology of the catchment is controlled by the geological and the structural settings. Except for narrow and mostly flat plains in the Lavagna, Graveglia and Sturla valleys, steep and very steep slopes characterize the catchment, some of which host large and deep-seated landslides. Forests cover more than 70% and urban areas less than 3% of the catchment; the later chiefly along the main valley floors (Liguria Region, 2000). The remaining part is covered by olive groves, chestnut woods and fruit orchards on well-maintained or abandoned terraces, and by grassland and grazing land. Shrubs and outcropping rocks are common at high elevation.

Climate is Mediterranean, modulated by the local morphological and orographic conditions. The presence of valleys oriented E-W (Lavagna and lower Graveglia valleys) and NNE-SSW (Sturla and upper Graveglia valleys) facilitates the channelling of air masses and meteorological disturbances pushed landward by southern marine winds. The Apennines range, exceeding locally 1700 m in elevation, runs parallel to the cost of the Liguria Sea, and acts as a barrier for the low-pressure systems, facilitating the formation of thunderstorms characterized by intense and very intense rainfall. Mean annual precipitation (MAP) averages 1800 mm, and ranges from 1130 mm near the basin outlet, to more than 2300 mm in the upper Lavagna and Sturla valleys. Precipitation is most abundant from October to November, and in February.

3 Landslide and rainfall data

To define the rainfall conditions that may trigger shallow landslides in our study area, we considered 29 rainfall events occurred in the Entella catchment in the 15-year period 2002–2016 that have caused landslides and inundations (Table 1). All the events caused damage (Fig. 2), and three events (24 November 2002, 21–22 October 2013, 10–11 November 2014) resulted in loss of lives. For each event, we collected landslide and rainfall information. The landslide information included (i) the location and number of the event landslides, (ii) the time of occurrence of the slope failures, and (iii) the consequences of the landslides (i.e., type of damage, casualties). We obtained the landslide information from different sources, including scientific papers, technical and event reports, damage reports, and catalogues compiled by regional and local authorities, archives of local municipalities, newspaper articles, and interviews to local inhabitants. We obtained rainfall measurements from 15 rain gauges in the Entella catchment (Fig. 1**,** Table 2). The rain gauges operated for different periods and show gaps in their records, including a gap common to all gauges in the period 1999–2001. For each rain gauge, we calculated the mean annual precipitation (MAP) for the entire measurement record.

4 Landslide and rainfall data

Using the available landslide and rainfall information, we identified 34 rainfall conditions associated to known landslides for which the time and location of the slope failures were known with sufficient geographical and temporal accuracy (Table 3). For each rainfall condition, we estimated the cumulated event rainfall, E (in mm), the event rainfall duration, D (in h), the rainfall intensity, I (in mm h^{-1}) for 1, 3, 6, 12 and 24-hour periods, and the average rainfall intensity for the rainfall event, $\hat{I}$ (mm h^{-1}) (Table 3). For the purpose, following Peruccacci et al. (2012), for each known landslide or cluster of landslides, we selected a representative rain gauge, considering (i) the geographic distance between the rain gauge and the landslide, or the geometric centre of a cluster of landslides, (ii) the elevation of the rain gauge, compared to the elevation of the landslide(s), and (iii) the location of the rain gauge with respect to the geographical and morphological settings. For most of the landslides, the representative rain gauge was the one closest to the landslide or the cluster of landslides.

In the 15-year period 2002–2016, the analysis revealed that rainfall that has resulted in shallow landslides exceeded 70 mm in 1 hour in five cases (26.3%), 100 mm in 3 hours in five cases (26.3%), and 200 mm in 24 hours in four cases (21.0%) (Table 3). The rainfall events affected limited sectors of the Entella catchment, where they triggered numerous landslides. We note that the five rainfall events with the largest hourly cumulated rainfall exceeding 70 mm (24 November 2002, 21-22 October 2013, 10-11 October 2014, 10-11 November 2014, and 14-15 September 2015; Fig. 1) were responsible for a large number of event landslides (tens to several tens of landslides). These events also caused severe damage to structures and infrastructures, and three casualties. With the exception of the 10–11 November 2014 rainfall event, the three events characterized by 24-hr cumulated rainfall exceeding 200 mm (26 December 2013, 10–11 October 2014, 14 September 2015; Table 1) result in less abundant landslides and less severe damage than we expected.

Visual inspection of Fig. 3 reveals that 2013 and 2014 accounted for a larger number of rainfall events, when compared to the entire period considered, with higher values of the cumulated annual rainfall and of the number of rainy days. In the entire considered period, rainfall events with landslides occurred primarily from September to December (Fig. 4a). This is in agreement with results obtained at the national (Guzzetti, 2000) and regional (Giannecchini, 2006) scales in Italy.

The event landslides occurred in all the three tributaries of the Entella catchment, but were most frequent and abundant between the medium-lower Sturla valley and the lower Lavagna valley (Fig. 4b, Table 4). In this central part of the catchment, the most severe events occurred on 24 November 2002, 21–22 October 2013, and 10 November 2014. The three events caused many shallow landslides, primarily soil-slips, slow-moving earth flows and rapid to extremely rapid debris flows, secondarily debris slides and avalanches (Cruden and Varnes, 1996; Hungr et al., 2014). The slope failures involved chiefly colluvial deposits of variable thickness, up to four meters (CNR IRPI, 2015), and the superficial layers of the highly weathered clayey bedrock. Large volumes of water mixed with mud, debris, boulders and vegetation were mobilized along the slopes and the thalwegs. Landslides occurred mainly in steep and very steep slopes, and were particularly abundant where roads, walking paths, embankments, slope cuts and other human made structures were present (Fig. 2).

4.1 The 24 November 2002 rainfall event

On 24 November 2002, a short and very intense rainfall event hit the medium-to-lower part of the Lavagna valley (Fig. 1). The convergence between a cold northern draft and wet Mediterranean currents generated a low-pressure system in the Tigullio Gulf that moved to the medium-lower Lavagna valley. The very intense rainstorm hit an area of about 50 km^2 for a period of 1–2 hours, before moving towards NNE. The event started in the afternoon on 23 November, and continued in the late morning on 24 November, with a second and more intense rainfall burst. Maximum cumulated rainfall values were measured (i) at the San Martino del Monte rain gauge, the closest to the geometric centre of clusters of event-triggered landslides, that recorded 79.4 mm of rain in one hour, and (ii) at the Piana di Soglio rain gauge, that recorded 97.2 mm in 3h, and 104.6 mm in 6h. The cumulated rainfall for the event exceeded 157.0 mm (Fig. 5a). The 1-hr maximum intensity reached 93.0 mm between 12:00 and 13:00 UTC at the Chiavari rain gauge, with the most intense rainfall measured between 09:00 and 13:00 UTC on 24 November, corresponding to the most intense phase of the event.

Figure 6a portrays the cumulated event rainfall between 08:00 and 14:00 UTC on 24 November 2002, and shows that the maximum rainfall occurred along a NNE-SSW trending line, from the medium-lower Lavagna valley (Piana di Soglio, 104.6 mm) to the upper part of the Sturla valley (Tigliolo, 124.8 mm). The rainfall field decreased gradually towards SE (San Martino del Monte, 80.0 mm; San Michele, 76.0 mm) and towards NW, with a minimum value in the upper part of the Lavagna valley (Neirone, 14 mm).

The rainfall event triggered numerous shallow landslides and debris flows, which caused serious damage chiefly to the road network (Faccini et al., 2005). Based on evidences provided by local inhabitants, landslides occurred in the 30-minute period between 14:00 and 14:30 LT (13:00–13:30 UTC), following the most intense phase of the rainfall event, and within 1 to 4 hours from the hourly maximum peak rainfall intensity recorded by the San Martino del Monte rain gauge in the 48-hour period between 00:00 UTC on 23 November and 00:00 UTC on 25 November.

4.2 The 21–22 October 2013 rainfall event

On 21–22 October 2013, heavy rainfall hit the medium-to-lower part of the Sturla valley, and marginally the lower Lavagna valley and the town of Chiavari (Fig. 1). The convergence between the cold northern air flow and wet currents from the S generated several storm cells that were channelled from the Liguria Sea in front of Chiavari to the inland valleys, in particular in the Sturla valley (ARPAL, 2013). A very intense and persistent rainstorm stood over a very small area for a period of 1 to 2 hours, favoured by the orientation of the valley and the local “barrier effect” of the Apennines range.

The rainfall event started on the evening of 21 October and ended on the morning of 22 October, 2013. The maximum cumulated rainfall was measured by the Borzone rain gauge – located 1 km N of the area where event landslides were most abundant – which recorded 86.0 mm in 1h and 173.2 mm in 3h, and a cumulated rainfall for the 2-day period that exceeded 188.0 mm (Fig. 5b). At this rain gauge, the 1-hr maximum intensity reached 86.6 mm between 21:00 and 22:00 UTC. The most intense phase of the event took place between 21:00 and 23:00 UTC on 21 October, and coincided with the maximum peak of the rainfall intensity.

Figure 6b shows the cumulated event rainfall between 18:00 and 24:00 UTC on 21 October 2013. The rainfall field exhibits a NE–SW trend that coincides with the direction of the medium-lower part of the Sturla valley. The maximum cumulated rainfall was recorded along the valley (Borzone, 185.2 mm), with the rainfall totals decreasing gradually towards the main watershed (Giacopiane, 67.0 mm) and the lateral valleys (Cichero, 76.6 mm), up to minimum values at the outlet of the Sturla basin (Panesi, 36.2 mm).

The heavy rainfall event triggered widespread shallow landslides, which caused serious damage to structures and infrastructures (Faccini et al., 2017). Eyewitness evidence provided by local residents confirmed that the shallow landslides occurred in the 30-minute period between 23:00 and 23:30 LT (00:00 and 00:30 UTC), shortly after the most intense phase of the rainfall event, and within 2 to 3 hours from the hourly maximum peak intensity recorded by the Borzone rain gauge in the 24-hour period between 12:00 UTC on 21 October, and 12:00 UTC on 22 October 2013.

4.3 The 10 November 2014 rainfall event

On 10 November 2014, a very short, intense rainfall hit the town of Chiavari and the inland areas between the lower Lavagna valley and the medium-lower Sturla valley (Fig. 1). The heavy rainfall was caused by the convergence of humid air masses coming from SE and colder northerly currents over the Tigullio Gulf (ARPAL, 2015). Favoured by the local orography, the convective system remained for several hours on the area, producing intense and persistent precipitations. The event began with a light rainfall in the evening of 9 November and ended on 11 November. The maximum cumulated rainfall was recorded by the Panesi rain gauge, located about 2 km E from the centre of the cluster of the event landslides, with 70.4 mm in one hour, 130.6 mm in 3h, 169.4 mm in 6h, and a cumulated rainfall in the 3-day period that exceeded 250.0 mm (Fig. 5c). At the Panesi rain gauge, the 1-hour maximum intensity reached 66 mm between 20:00 and 21:00 UTC. The most intense phase occurred between 17:00 and 23:00 UTC on 10 November, with a maximum intensity peak between 21:00 and 22:00 UTC.

Figure 6c portrays the cumulated event rainfall between 18:00 and 24:00 UTC on 10 November 2014, and shows that the maximum rainfall occurred along a N-S trending line, from the mouth of Entella River (Panesi, 183.2 mm) to the medium-lower Sturla valley (Borzone, 154.2 mm). Large cumulated rainfall amounts also characterize the lateral valleys (Cichero, 135.8 mm), and the upper Graveglia valley (Statale, 130.6 mm), whereas rainfall totals decrease towards W, to the medium (Pian dei Ratti, 82.4 mm) and upper (Ognio, 18.4 mm) Lavagna valley.

The heavy rainfall produced widespread shallow landslides, which caused serious damage to structures and infrastructures, and two casualties (Cevasco et al., 2015a, 2017; Faccini et al., 2015a). Based on eyewitness evidences provided by local inhabitants, and on information obtained from newspaper articles, shallow landslides occurred in the 1-hour period between 20:00 and 21:00 LT (21:00 and 22:00 UTC), during the most intense phase of the rainfall event, and within one hour from the hourly maximum peak rainfall intensity recorded by the Panesi rain gauge in the 96-hour period between 00:00 UTC on 9 November, and 00:00 UTC on 13 November.

5 Discussion

Intense and very intense, geographically limited rainfall events generated by local convective thunderstorms, including the 10 November 2004, the 21–22 October 2013, and the 24 November 2002 rainfall events (Fig. 6, Table 1), have affected repeatedly the Entella catchment, triggering shallow landslides, soil-slips, slow-moving earth flows and rapid to extremely rapid debris flows. We found that very high intensity rainfall events with cumulated rainfall exceeding 50 mm per hour are frequent in the area, including e.g. 93.0 mm in 1 hour recorded by the Chiavari rain gauge on 24 November 2002, 86.6 mm in 1 hour recorded by the Borzone rain gauge on 22 October 2013, and 66.0 mm in 1 hour recorded by the Panesi gauge on

10 November 2014. An analysis of the available rainfall records between 2002 and 2016 revealed that hourly cumulated rainfall exceeding 50 mm were recorded 42 times in the 15-year investigation period. In the records, very intense rainfall brought by local convective thunderstorms occurred chiefly in the autumn and winter, and were favoured by the motion of air masses from the Liguria Sea, where warm and moist air from the S and cold air from the N collide, generating convective systems; and by the orographic setting of the Apennines, that form a barrier for the convective cells moving inland from the Liguria Sea (Fig. 1).

Analysis of three, particularly severe rainfall events in the Entella catchment between 2002 and 2016 (Table 1) revealed that the rainfall-induced landslides triggered by the intense or very intense rainfall occurred primarily (i) at the same time, or in a period from one to six hours from the maximum recorded peak rainfall intensity, and (ii) at or near the geographical location where the measured rainfall intensity was highest. Shallow landslides and debris flows initiated chiefly from steep slopes in the range from 30° to 40°, primarily in forested and uncultivated areas, and on well maintained and abandoned terraced slopes with olive and chestnuts trees. Roads, trails, embankments, trenches and other man-made structures were often present in the source areas of the shallow landslides (Fig. 2). This finding may be useful in catchment-scale landslide early warning systems, and for land planning aimed at reducing landslide risk in the study area.

Analysis of the rainfall conditions that have resulted in shallow landslides in the Entella catchment between 2002 and 2016, allowed to define a new event rainfall intensity–event duration, ID empirical rainfall threshold for the possible initiation of shallow landslides (Guzzetti et al., 2007; 2008) in the catchment. To define the threshold, we used the rainfall duration (*D*) and intensity (*I*) conditions listed in Table 3. The rainfall duration (*D*, in hour) was determined measuring the period between the end-time of the rainfall event, set to coincide with the time of the landslide(s), and the start-time of the rainfall event, set to coincide with the time when the rain started in the rainfall record. For landslides for which the rainfall end-time s known accurately, the end-time coincides with the time of the last rainfall measurement in the hour when the slope failure occurred. For landslides for which only the date of occurrence is known, the rainfall end-time is taken to coincide with the time of the last rainfall measurement in the day when the slope failure occurred.

When the accurate identification of the rainfall start-time was problematic in the rainfall record, we considered a minimum period without rain (“dry period”) to separate two subsequent rainfall events. To account for the seasonal variability, we considered a dry period of 12 hours between April and September, and a dry period of 24 hours between October and March. For each rainfall event, the corresponding event rainfall intensity (*I*, in mm h^{-1}) was calculated dividing the cumulated event rainfall in the considered period (*E*, in mm) by the length of the rainfall period (*D*, in h). For the rainfall events listed in Table 1 for which the date of occurrence of the landslides was unknown, the reconstruction of the rainfall event was not possible; and the events were not used to define the ID rainfall threshold.

To define the rainfall duration–rainfall intensity threshold, we adopted the statistical Frequentist approach proposed by Brunetti et al. (2010). We plotted the 34 event rainfall duration–rainfall intensity (*D*, *I*) conditions that have resulted in shallow landslides and debris flows in the period 2002–2016, and we found the best-fit to the cloud of empirical (*D*, *I*) data points, adopting a power law model. To avoid problems associated with the fitting of data spanning multiple orders of magnitude, we log-transformed the empirical data, and we fitted the distribution of rainfall conditions (log(D), log(I)) that resulted in landslides with a linear equation,

$$\log(I) = \log(\alpha) - \beta \log(D) \tag{1}$$

which is entirely equivalent to the power law curve $I = \alpha\ D^{-\beta}$ in linear coordinates commonly adopted to represent ID thresholds in the literature (Guzzetti et al., 2007; 2008), where I is the rainfall intensity (mm hr^{-1}), D is the duration of the rainfall event (h), α is the intercept, and β defines the slope of the power law curve. The black line in Fig. 7a represents the best-fit line T_{50}:

$$I\ = 31.88\ D^{-0.60} \tag{2}$$

Next, for each event (D, I) we calculated the difference $\delta(D)$ between the logarithm of the event intensity log[I (D)] and the corresponding intensity value of the fit log[$I_f(D)$], $\delta(D)$ = log[I (D)] − fit log[$I_f(D)$]. Then we estimated the probability density of the distribution of δ and model the distribution through least square fitting using the Gaussian function:

$$G(\delta) = \frac{1}{\sqrt{2\pi\sigma^2}} * \exp\left\{-\frac{[\delta - \mu]^2}{2\sigma^2}\right\} \tag{3}$$

where μ is the mean value, and σ is the standard deviation. The black line in Fig. 7b represents the Gaussian model of the empirical distribution of the δ values around the central value, $\mu = 0$, measured by the standard deviation, $\sigma = 0.26$. Lastly, the threshold corresponding to the 5% exceeding probability, is defined, based on the fitted distribution of $\delta(D)$. The red vertical line represents the 5% threshold (T_5), the grey vertical line portrays the mean of the distribution, corresponding to the 50% threshold (T_{50}), and the distance δ^* between the red and the grey lines is used to calculate the intercept of the 5% threshold curve. The 5% threshold T_5, is the curve parallel to the best-fit line T_{50}, with intercept $\alpha_5 = \alpha_{50} - \delta^*$ and slope β = 0.60. Assuming the available set of rainfall events is sufficiently complete and representative for the study area, we can state that the probability of experiencing landslides triggered by rainfall below the obtained threshold is less than 5%. Rainfall events that have resulted in slope failures in the Entella catchment considered for the determination of the thresholds, are in the range of rainfall duration 4 h < D < 169 h and in the range of mean intensity 0.5 mm $\text{h}^{-1} < I <$ 4.9 mm h^{-1}.

Peruccacci et al. (2012) have argued that empirical rainfall thresholds for possible landslide occurrence are inherently affected by uncertainty, and that the uncertainty needs to be quantified. In an attempt to define the uncertainty associated to our threshold, we calculated the mean values $\overline{\alpha}$ and $\overline{\beta}$ and the associated uncertainty $\Delta\alpha$ and $\Delta\beta$ in terms of standard deviation of the α, β values obtained after sampling the D, I conditions considered to define the threshold. First, out of the N(D, I) population, we selected a single (D, I) value, and we calculated the α and β values using the remaining (N-1) population of (D,I) value. When the selected (D, I) values was returned to the population N, a second (D, I) value was selected, and new α, β values calculated. We repeated the procedure for all the n=34 (D,I) conditions, and calculated the standard deviation of the α (1.04) and the γ (0.02) values. The red curve in Fig. 7c is the 5% ID threshold (T_5) for the study area:

$$I\ = (11.28\ \pm 1.04) D^{(-0.60\ \pm 0.02)} \tag{4}$$

and the grey pattern shows a proxy for the uncertainty associated to the threshold, in the range 4 h <*D*< 170 h. The T_5 threshold should Eq. (4) leave 5% of the (*D*, *I*) empirical points below the power law curve; in Fig. 7c, two points (5.9%) are below the curve, approaching the number of data points expected below the threshold line. We note that the rainfall conditions that have resulted in landslides in the three severe events analysed in this work i.e., the 10 November 2014, the 21–22 October 2013, and the 24 November 2002 events, all plot above the established ID threshold curve.

We compared the new rainfall threshold determined for the Entella catchment to similar ID empirical threshold curves (Table 5) proposed in the literature for mountain catchments, local areas, or single regions in Italy (Fig. 8). In the range of validity for the threshold (4h < *D* < 170h), the new threshold for the Entella catchment is lower to significant lower than other thresholds proposed for mountain catchments in Italy. In particular, the threshold is lower than the curves proposed for (i) the Champeyron mountain catchments in the Susa Valley, Piedmont, NW Italy (Bolley and Olliaro, 1999), (ii) the Moscardo mountain catchment, Friuli, NE Italy (Marchi et al., 2002), and (iii) the Valzangona area, Marche, central Italy (Floris et al., 2004); and it is significantly lower than the threshold curves proposed by Giannecchini (2005) for the Apuane Alps, and by Giannecchini et al. (2012) for the Serchio Basin, Tuscany. The obtained threshold is similar to the curves proposed by Bolley and Olliaro (1999) for the Rho and Perilleux mountain catchments, in Piedmont.

The new threshold for the Entella catchment is also significantly lower than the local threshold proposed by Cancelli and Nova (1985) for the Valtellina valley, in the southern Italian Alps, and the regional thresholds proposed e.g., by (i) Ceriani et al. (1994) for the Lombardy region, northern Italy, (ii) Paronuzzi et al. (1998) for the NE Alps, (iii) Calcaterra (2000) for the Campania region, southern Italy, and by (iv) Aleotti (2004) for the Piedmont region, northern Italy. The new threshold is instead higher than the regional thresholds proposed by Peruccacci et al. (2017) for physiographic, climatic and meteorological regions in Italy that are similar to the Entella River basin; and in particular, (i) the high mean annual precipitation region (1600mm < MAP < 2000mm), (ii) the Apennines mountain province, and (iii) the region characterized by a temperate climate with dry and hot summer (Csa, in the Köppen-Geiger climate classification system). We attribute the result to the peculiar orographic and meteorological conditions that characterize the Entella catchment, with a high MAP and the frequent occurrence of convective thunderstorms whose formation is favored by the local orographic setting.

To investigate the possible role of the antecedent rainfall conditions in the initiation of the rainfall-induced landslides in the Entella catchment, for each rainfall event in the 15-year period 2002–2016, we confronted the MAP-normalised cumulated event rainfall E_{MAP}, to the MAP-normalised antecedent rainfall, $A_{(d)MAP}$ for four antecedent periods – $A_{(3)MAP}$, $A_{(5)MAP}$, $A_{(15)MAP}$ and $A_{(30)MAP}$ – for periods of 3, 5, 15, and 30 days before the rainfall events. For the analysis, we used the rainfall measurements obtained by the Panesi, Borzone and Pian dei Ratti rain gauges (Fig. 1) i.e., the rain gauges nearest to the central portion of the Entella catchment where the considered rainfall events that have resulted in abundant and widespread landslides have occurred. Inspection of Fig. 8 reveals that the scattering of the empirical data is very high, and the event cumulated rainfall and the antecedent rainfall for the different periods that have resulted (red triangles) and have not resulted in landslides, or for which the occurrence of landslides is unknown (black squares), cannot be separated. Significant correlation between the event cumulated rainfall and the antecedent rainfall does not exist, based on the results of a Pearson correlation test (Table 6). We conclude that antecedent rainfall conditions do not play a significant role in the initiation of landslides in the Entella catchment.

6 Conclusion

Between 2002 and 2016, numerous intense rainfall events hit the Entella River basin, in the Liguria Apennines, northern Italy. The intense to very intense rainfall events were produced by local thunderstorms, and caused abundant and widespread shallow landslides, soil-slips, earth flows, and debris flows, which have resulted in a total of five fatalities and severe damage to public and private structures and the infrastructure.

Analysis of three, particularly severe rainfall events occurred in the Entella catchment in the 15-year investigated period, revealed that the rainfall-induced landslides triggered by the intense or very intense rainfall occurred primarily at the same time, or in a period from one to six hours, from the maximum recorded peak rainfall intensity, at or near the geographical location where the measured rainfall intensity was highest. Using different sources of landslide and rainfall information, we identified 29 rainfall events that have resulted in landslides. We used rainfall and landslides information for 17 rainfall events for which the time and location of landslides were known with sufficient geographical and temporal accuracy to define a new rainfall intensity-duration (ID) threshold for the possible initiation of shallow landslides and debris flows in the Entella catchment. Adopting an accepted statistical approach (Brunetti et al., 2010; Peruccacci et al., 2012), we defined the empirical ID threshold corresponding to the 5% exceeding probability, and the associated uncertainty. Comparison of the new rainfall threshold for the Entella catchment to empirical rainfall thresholds proposed in the literature for mountain catchments, local areas, and single regions in Italy revealed that the new threshold is lower than most of the published thresholds, in the range $4\text{h} < D < 170\text{h}$. We attribute the result to the orographic and meteorological settings of the Entella catchment.

To evaluate the possible role of the antecedent rainfall conditions in the initiation of landslides in Entella catchment, we confronted the antecedent rainfall for different periods, from 3 to 30 days, with the cumulated event rainfall that have and have not resulted in landslides between 2002 and 2016 in the study area. The analysis revealed that significant correlations between the event cumulated rainfall and the antecedent rainfall do not exist. Based on this finding, we conclude that the antecedent rainfall conditions did not play a major role in the initiation of shallow landslides in the Entella catchment.

We expect that the results of this study will be useful for the implementation of landslides early warning system on a catchment scale, and for land-planning aimed at reducing landslides risk in the study area. We further expect that the method to define new threshold curves for possible rainfall-induced landslides tested in this work can be used in other mountain catchments, in Italy and elsewhere.

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Figure 1: (A) Geography and morphology of the Entella River basin and the surrounding areas. White triangles show location of rain gauges. Dots show locations of shallow landslides for the 24 November 2002 (blue), the 21–22 October 2013 (red), and the 10 November 2014 (green) rainfall events. (B) Simplified geological map for the Entella River. 1, quaternary deposit; 2, marly limestone, calcareous or clayey marl; 3, shale, shale with interlayered siltstone and limestone; 4, sandstone; 5, marl and silty marl; 6, ophiolite; 7, chaotic complex. (C) Location map.

Figure 2: Example of shallow landslides triggered by intense rainfall in the Entella catchment in the 15-year period 2002–2016. (a) Leivi; view of a debris flow that destroyed a building, causing two casualties, on 10 November 2014. (b) Ne; view of a shallow landslide occurred on 4 January 2014. (c) Mezzanego; damage to a road and private property caused by a shallow landslide on 22 October 2013. (d) San Colombano Certenoli; view of a debris flow that damaged a building on 24 November 2002. **S**ee Fig. 1 for location of the landslide sites.

Figure 3: Comparison of (a) the total (cumulated) rainfall, and (b) the mean number of rainy days, in the 15-year period 2002–2016 (blue), in 2013 (red) and in 2014 (green), at selected rain gauges in the Entella catchment. Rain gauges: Cc, Chiavari; Gi, Giacopiane Lago; Re, Reppia, Pa, Panesi; Ci, Cichero, Bo, Borzone. See Fig. 1 for the location of the rain gauges.

Figure 4: (a) Seasonal and (b) geographical distribution of rainfall events with landslides in the 15-year period 2002–2016 in the Lavagna, Graveglia and Sturla tributary valleys of the Entella catchment. Landslide sites: BR, Borzonasca; CG, Cicagna; CR, Carasco; FM, Favale di Malvaro; LM, Lumarzo; LR, Lorsica; LV, Leivi; MG, Mezzanego; NE, Ne; OR, Orero; SC, San Colombano Certenoli. See Fig. 1 for location of the landslide sites.

Figure 5: Hourly rainfall (blue bars) and cumulated event rainfall (red line) for the three considered rainfall events in the Entella catchment (Table 1). (A) 24 November 2002 rainfall event measured at the San Martino del Monte rain gauge. (B) 21–22 October 2013 rainfall event measured at the Borzone rain gauge. (C) 9–11 November 2014 rainfall event measured at the Panesi rain gauge. See Fig. 1 for location of the rain gauges.

Figure 6. Spatial distribution of the cumulated event rainfall (mm) for the three considered rainfall events in the Entella catchment (Table 1). White triangles show location of the rain gauges used to prepare the maps, also shown in Fig. 1. Coloured contour lines show event cumulated rainfall. (a) 24 November 2002. (b) 21–22 October 2013. (c) 9–11 November 2014.

Figure 7. (a) Rainfall condition (D,I) (dots) that have resulted in shallow landslides and debris flows in the Entella River basin, in the 15-year period 2002–2016 (Table 1). The black line represents the power law best-fit curve to the empirical rainfall (D,I) conditions. Small dots show single landslides and large dots show multiple landslides. (b) Graphic representation of the threshold corresponding to the 5% exceedance probability for the distribution of the empirical data points (D,I). Black line is the Gaussian model fit of the difference, for the distribution of the empirical data points (D,I). Grey vertical line corresponds to the 50% threshold (mean value). Red vertical line corresponds to the 5% threshold. (c) Red line represents the 5% rainfall threshold for the Entella catchment. Coloured dots show rainfall conditions for the 10 November 2014 rainfall event (green), the 21-22 October 2013 rainfall event (red), and the 24 November 2002 rainfall event (blue). Small dots show single landslides and large dots show multiple landslides. Grey area around shows uncertainty of the threshold.

Figure 8. (A) Comparison between the ID threshold defined for the Entella catchment and threshold curves available in literature for regions, individual catchments, and local areas in Italy (Tab. 6). Plot is in logarithmic coordinates. Dashed black lines show regional thresholds and continuous black lines show local thresholds. Red line (22) shows the rainfall threshold defined in this work for the Entella catchment. Sources: 1, Cancelli and Nova (1985); 2, Ceriani et al. (1994); 3, Paronuzzi et al. (1998); 4-9, Bolley and Olliaro (1999); 10, Calcaterra et al. (2000); 11, Marchi et al. (2002); 12, Aleotti (2004); 13, Floris et al. (2004); 14-15, Giannecchini (2005); 16–18, Gianecchini et al., (2012); 19–21, Peruccacci et al. (2017). (B) Location map shows sites for which the threshold curves were defined: dots are threshold curves for individual catchments and local areas, squares are regional threshold curves.

Figure 9. Relationship between the MAP-normalized cumulated event rainfall E_{MAP}, and the MAP-normalized antecedent rainfall $A_{(d)MAP}$, for 3-day, 5-day, 15-day and 30-day antecedent periods, for the Panesi, Borzone and Pian dei Ratti rain gauges. See Fig. 1 for location of the rain gauges. Red triangles show rainfall events with shallow landslides, soil slips or debris (Table 1), and black squares show rainfall events that did not trigger landslides or for which the occurrence of landslides is unknown.

Table 1. Rainfall events that have triggered – mostly shallow – landslides in the Entella River catchment in the 15-year period 2002–2016. In bold, the three events discussed in the paper. Sites: BR, Borzonasca; CG, Cicagna; CR, Carasco; CV, Chiavari; FM, Favale di Malvaro; LM, Lumarzo; LR, Lorsica; LV, Leivi; MG, Mezzanego; NE, Ne; OR, Orero; SC, San Colombano Certenoli. See Fig. 1 for location of the sites. Type of geo-hydrological event: L, landslide; I, inundation. Abundance of landslides: S, single landslide; M, multiple landslides. Damaged element: B, building; I, infrastructure; R, road; S, structure; C, casualty.

ID	Date	Site	Type	Abundance	Damage
1	**24/11/2002**	**BR, CV, NE, SC**	**L, I**	**M**	**C, S, I**
2	31/10-1/11/2003	BR, NE, SC	L, I	M	S, I
3	19-20/2/2006	BR	L	S	S, I
4	21-23/11/2007	MG	L	S	I
5	11-12/11/2008	BR, CR, NE	L	M	S, I
6	1/12/2008	CR	L	S	S, I
7	19-20/1/2009	NE	L	M	S, I
8	29-30/11/2009	NE	L	M	S, I
9	8/12/2009	CR	L	S	S, I
10	22-25/12/2009	BR, CR, MG, NE, OR	L, I	M	S, I
11	7-9/5/2010	NE, FM	L	M	S, I
12	31/10-2/11/2010	BR, MG, NE	L	M	S, I
13	23-24/12/2010	MG	L	M	S, I
14	8/6/2011	NE	L	M	S, I
15	4-5/9/2011	NE	L	M	S, I
16	25/10/2011	NE	L	M	S, I
17	5/11/2012	NE	L	S	S, I
18	8/3/2013	MG	L	M	S, I
19	**21-22/10/2013**	**BR, CR, LV, MG, NE, SC**	**L, I**	**M**	**C, S, I**
20	30/10/2013	CG, FM	L	M	S, I
21	8-9/11/2013	SC	L	S	S, I
22	26-27/12/2013	BR, LM, MG, NE	L, I	M	S, I
23	4/1/2014	BR, MG, NE, SC	L, I	M	S, I
24	16-20/1/2014	BR, CR, LM, MG, NE	L, I	M	S, I
25	10-11/10/2014	CG, LR, MG	L, I	M	S, I
26	3-6/11/2014	NE	L	M	S, I
27	**10-11/11/2014**	**BR, CR, LV, MG, NE, SC**	**L, I**	**M**	**C, S, I**
28	14/9/2015	BR, CR, FM, MG	L	M	S, I
29	9/2/2016	NE	L	M	S, I

Table 2. Rain gauges in the Entella River catchment used to analyze the rainfall conditions that have resulted in landslides in the catchment, in the 15-year period 2002–2016 (Fig. 1). Rainfall records are locally incomplete, and measurements are not available for all rain gauges in the period 1999–2001.

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Rain gauge	Elevation	Period	Tributary
Chiavari Caperana	6	2002–2015	Entella
Panesi	25	1933–2015	Entella
Pian dei Ratti	70	2012–2015	Lavagna
Pian di Soglio	75	1936–2010	Lavagna
San Michele di Borzonasca	170	1924–2007	Sturla
Tigliolo	293	1924–2010	Sturla
San Martino del Monte	309	1919–2004	Lavagna
Borzone	386	2006–2015	Sturla
Ognio	490	2012–2015	Lavagna
Reppia	530	1972–2015	Graveglia
Statale	570	1934–2015	Graveglia
Sella Giassina	593	2012–2015	Lavagna
Cichero	615	2007–2015	Sturla
Croce di Orero	640	2012–2015	Lavagna
Giacopiane Lago	1030	1924–2015	Sturla

Table 3. Rainfall conditions used to define the rainfall threshold for the possible initiation of shallow landslides in the Entella catchment. Rain gauges (R): Bo, Borzone; Ci, Cichero; Cc, Chiavari Caperana; Cr, Croce di Orero; Gi, Giacopiane Lago; Md, Monte Domenico; Og, Ognio; Pa, Panesi; Ps, Piana di Soglio; Pr, Pian dei Ratti; Re, Reppia; Se, Sella Giassina; Sa, San Michele; Sm, San Martino del Monte; St, Statale; Ti, Tigliolo. See Fig. 1 for location of the rain gauges. E_{*h}, maximum cumulated rainfall recorded in the catchment, for different periods (mm). Rainfall measures that have resulted in landslides: E, event cumulated rainfall (mm); D, event rainfall duration (hr); I, event rainfall intensity (mm hr^{-1}). Abundance of landslides (AL): S, single landslide; M, multiple landslides.

Date	Maximum event cumulated rainfall					Event rainfall				AL
	E_{1h}	E_{3h}	E_{6h}	E_{12}h	E_{24h}	E	D	I	R	
24/11/2002	79.4 Sa	97.2 Ps	104.6 Ps	106.8 Ps	178.8 Ti	157.0	20	7 9	Sa	M
20/2/2006	19.0 Sa	37.6 Ci	47.0 Sa	85.6 Sa	92.8 Sa	128.4	58	2.2	Gi	S
12/11/2008	21.6 Ci	31.6 Re	53.0 Re	62.6 Bo	107.0 Bo	74.4	50	1 5	Pa	S
1/12/2008	20 Bo	49 Bo	77.8 Bo	97.4 Bo	81.8 Cr	63.5	95	0.7	Pa	S
8/12/2009	14.6 Re	33.0 Re	64.8 Re	94.2 Re	138.8 Bo	66.6	18	3.7	Pa	S
22/12/2009	13.8 Cr	34.6 Cr	61.8 Cr	76.6 Cr	105.4 Cr	50.8	28	1.8	Pa	S
22/12/2009	13.8 Cr	34.6 Cr	61.8 Cr	76.6 Cr	105.4 Cr	203.0	51	4.0	Cr	S
23/12/2009	25.2 Ci	49.2 Ci	78.0 Ci	101.0 Ci	120.2 Ci	157.0	47	3.3	Bo	M
9/5/2010	7.8 Ci	16.6 Cc	22.0 Cc	24.4 Cc	29.6 Cc	15.2	6	2.5	Cr	S
2/11/2010	40.8 Bo	54.0 Bo	84.0 Bo	132.2 Bo	180.0 Bo	228.2	64	3.6	Bo	S
22/10/2013	86.0 Bo	173.2 Bo	186.2 Bo	187.4 Bo	188.0 Bo	188.0	20	99.4	Bo	M
22/10/2013	86.0 Bo	173.2 Bo	186.2 Bo	187.4 Bo	188.0 Bo	55.6	20	2.8	Pr	S
30/10/2013	51.4 Pr	70.4 Pr	71.0 Pr	71.0 Pr	89.6 Cr	71.0	5	14.2	Pr	S
30/10/2013	51.4 Pr	70.4 Pr	71.0 Pr	71.0 Pr	89.6 Cr	27.4	4	6.9	Cr	S
26/12/2013	27.4 St	53.4 St	100.4 Ci	166.6 Ci	228.2 Og	188.0	28	6.7	Re	M
26/12/2013	27.4 St	53.4 St	100.4 Ci	166.6 Ci	228.2 Og	312.0	169	1.9	Og	M
26/12/2013	27.4 St	53.4 St	100.4 Ci	166.6 Ci	228.2 Og	172.2	24	7.2	Pr	S
2/1/2014	5.4 Cr	12.6 Cr	20.8 Cr	40.6 Cr	50.2 Cr	38.6	34	0.1	Gi	S
4/1/2014	15.6 Ci	36.4 Ci	64.4 Ci	110.2 Ci	117.2 Ci	152.6	74	2.1	Re	S
4/1/2014	15.6 Ci	36.4 Ci	64.4 Ci	110.2 Ci	117.2 Ci	127.6	72	1.8	Bo	M
17/1/2014	20.8 Ci	43.2 Cr	77.0 Pr	169.6 Ci	190.6 Ci	46.2	15	3.1	Pa	S
17/1/2014	20.8 Ci	43.2 Cr	77.0 Pr	169.6 Ci	190.6 Ci	117.8	21	5.6	Bo	S
17/1/2014	20.8 Ci	43.2 Cr	77.0 Pr	169.6 Ci	190.6 Ci	165.8	24	6.9	Og	M
10/10/2014	72.2 Se	161.8 Se	187.8 Se	215.4 Se	271.6 Se	157.8	21	7.5	Gi	M
11/10/2014	72.2 Se	161.8 Se	187.8 Se	215.4 Se	271.6 Se	90.8	5	18.2	Pr	M
11/10/2014	72.2 Se	161.8 Se	187.8 Se	215.4 Se	271.6 Se	109.6	4	27.4	Cr	M
10/11/2014	70.4 Pa	129.2 Pa	147.8 Pa	152.4 Pa	181.8 Pa	185.4	26	7.1	Pa	M
11/11/2014	70.4 Pa	130.6 Pa	169.4 Pa	202.4 Pa	213.8 Pa	238.0	37	6.4	Bo	M
11/11/2014	70.4 Pa	130.6 Pa	169.4 Pa	202.4 Pa	213.8 Pa	239.4	31	7.7	Pa	M
13/11/2014	70.4 Pa	130.6 Pa	169.4 Pa	202.4 Pa	215.6 Pa	280.0	81	3.5	Pa	M
13/9/2015	36.2 Pr	58.0 Og	58.2 Og	76.8 St	78.6 St	61.2	13	4.7	Pa	S
14/9/2015	109.8 Cr	159.2 Cr	169.2 Cr	188.2 Cr	236.6 Cr	180.4	21	8.6	Gi	S
14/9/2015	109.8 Cr	159.2 Cr	169.2 Cr	188.2 Cr	236.6 Cr	182.6	16	11.4	Pr	S
14/9/2015	109.8 Cr	159.2 Cr	169.2 Cr	188.2 Cr	236.6 Cr	236.6	21	11.3	Cr	S

Table 4. Rainfall events that have triggered – mostly shallow – landslides in the central sector of the Entella catchment, from November 2002 to September 2015.

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Date	Sites where event rainfall induced landslides were most abundant
24/11/2002	Borzonasca, San Colombano Certenoli
31/10 - 1/11/2003	Borzonasca, San Colombano Certenoli
19-20/2/2006	Borzonasca
21-23/11/2007	Mezzanego
11-12/11/2008	Borzonasca
1/12/2008	Carasco
22-25/12/2009	Borzonasca, Carasco and Mezzanego
31/10 – 2/11/2010	Borzonasca, Mezzanego
23-24/12/2010	Mezzanego
8/3/2013	Mezzanego
21-22/10/2013	Borzonasca, Carasco, Leivi, Mezzanego, San Colombano Certenoli
26-27/12/2013	Borzonasca, Mezzanego
4/1/ 2014	Borzonasca, Mezzanego, San Colombano Certenoli
16-20/1/2014	Borzonasca, Carasco, Mezzanego
10-11/10/2014	Mezzanego
10-11/11/2014	Borzonasca, Carasco, Leivi, Mezzanego, San Colombano Certenoli
14/9/2015	Borzonasca, Carasco

Table 5. Intensity-Duration (ID) thresholds for the initiation of landslides in Italy. Rainfall intensity, I (mm hr^{-1}); rainfall duration, D (hr). Geographical extent: R, regional; L, local; C, catchment. Area: area where the threshold was defined. Landslides type: A, all types; D, debris flow; S, soil slip; Sh, shallow landslides. Source: 1, Cancelli and Nova (1985); 2, Ceriani et al. (1994); 3, Paronuzzi et al. (1998); 4-9, Bolley and Olliaro (1999); 10, Calcaterra et al. (2000); 11, Marchi et al. (2002); 12, Aleotti (2004); 13, Floris et al. (2004); 14-15, Giannecchini (2005); 16-18, Giannecchini et al. (2012); 19-21, Peruccacci et al. (2017).

#	Extent	Area	Landslide type	Threshold curve	Duration range (hr)
1	L	Valtellina, Lombardy	S	$I = 44.668D^{-0.78}$	1÷1000
2	R	Lombardy	A	$I = 20.1D^{-0.55}$	1÷1000
3	R	NE Alps	D	$I = 47.742D^{-0.507}$	0.1÷24
4	C	Rho Basin, Susa Valley, Piedmont	D	$I = 9.521D^{-0.4955}$	1÷24
5	C	Rho Basin, Susa Valley, Piedmont	D	$I = 11.698D^{-0.4783}$	1÷24
6	C	Perilleux Basin, Piedmont	D	$I = 11.00D^{-0.4459}$	1÷24
7	C	Perilleux Basin, Piedmont	D	$I = 10.67D^{-0.5043}$	1÷24
8	C	Champeyron Basin, Piedmont	D	$I = 12.649D^{-0.5324}$	1÷24
9	C	Champeyron Basin, Piedmont	D	$I = 18.675D^{-0.565}$	1÷24
10	R	Campania	A	$I = 28.10D^{-0.74}$	1÷600
11	C	Moscardo Torrent	A	$I = 15D^{-0.70}$	1÷30
12	R	Piedmont	Sh	$I = 19D^{-0.50}$	4÷150
13	C	Valzangona, Apennines	A	$I = 18.83D^{-0.59}$	24÷3360
14	C	Apuane Alps, Tuscany	Sh	$I = 26.871D^{-0.638}$	0.1÷35
15	C	Apuane Alps, Tuscany	Sh	$I = 38.363D^{-0.743}$	0.1÷12
16	C	Middle Serchio Basin, Tuscany	Sh	$I = 43.48\ D^{-0.74}$	2÷70
17	C	Middle Serchio Basin, Tuscany	Sh	$I = 43.25\ D^{-0.78}$	1.5÷80
18	C	Middle Serchio Basin, Tuscany	Sh	$I = 41.39\ D^{-0.76}$	1÷80
19	R	High MAP regions	A	$I = 8.9\ D^{-0.57}$	1÷544
20	R	Apennine mountain system	A	$I = 8.6\ D^{-0.64}$	1÷918
21	R	Csa climate regions	A	$I = 8.6\ D^{-0.65}$	1÷1176

Table 6. Results of the Pearson test for the correlation between MAP-normalised cumulated rainfall and the MAP-normalised antecedent rainfall, for periods of 3, 5, 15 and 30 days before the rainfall events that have resulted (L) and have not resulted (R) in landslides, for the Borzone (A), Panesi (B) and Pian dei Ratti (C) rain gauges. **See** Fig. 1 for location of the rain gauges.

		Test value, r			
		3-day	5-day	15-day	30-day
A	Rainfall events resulted in landslides	0.34	0.05	-0.15	-0.19
	Rainfall events	0.03	0.03	0.06	0.02
B	Rainfall events resulted in landslides	0.22	0.07	0.05	-0.03
	Rainfall events	0.05	0.09	0.21	0.12
C	Rainfall events resulted in landslides	-0.36	-0.33	-0.29	0.01
	Rainfall events	0.26	0.31	0.28	0.32

FIGURES

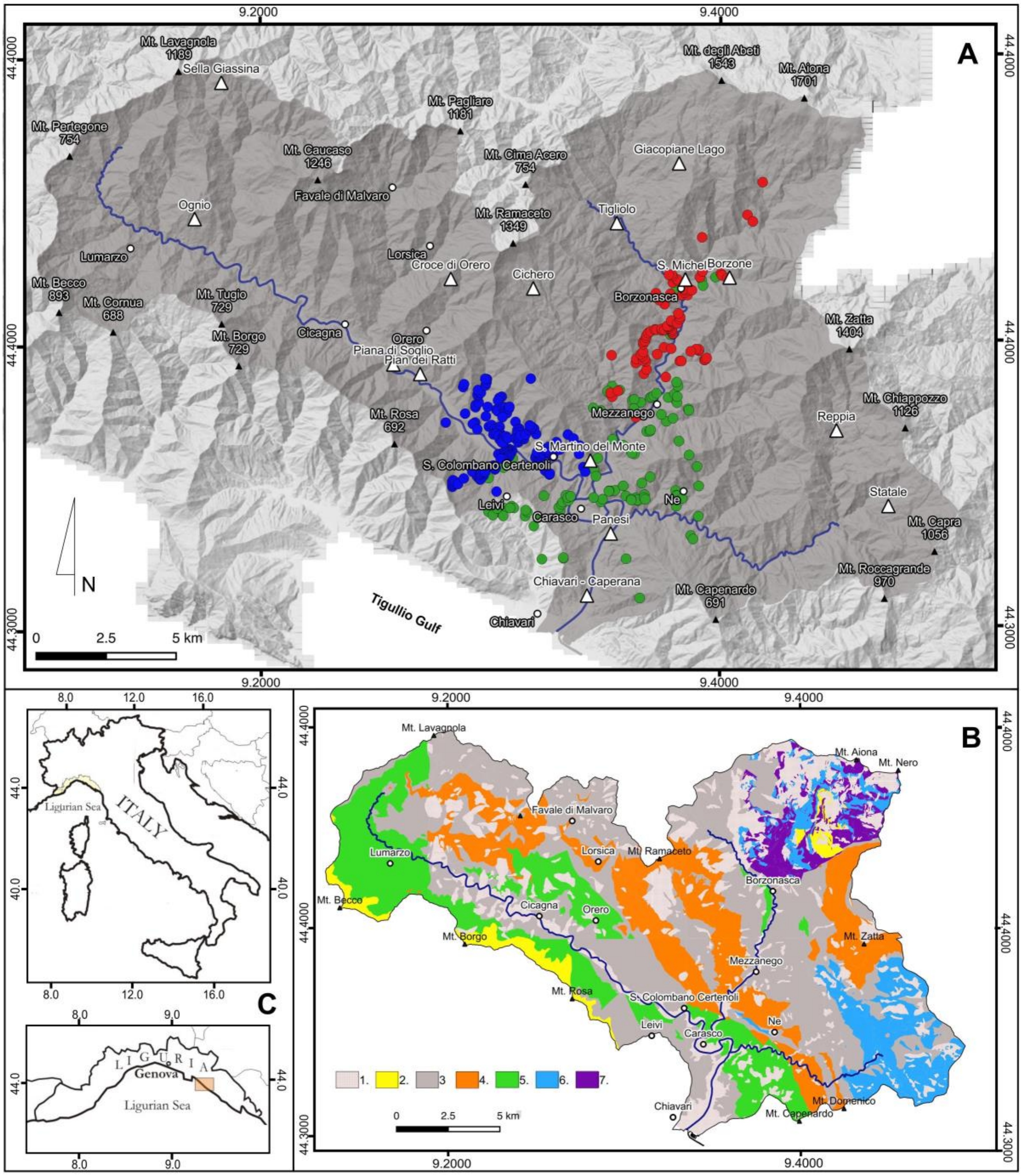
A
9.2000
9.4000
44.4000
44.3000
Mt. Lavagnola 1189
Sella Giassina
Mt. Pertegone 754
Mt. Caucaso 1246
Favale di Malvaro
Mt. Pagliaro 1181
Mt. Cima Acero 754
Mt. degli Abeti 1543
Mt. Aiona 1701
Giacopiane Lago
Ognio
Mt. Ramaceto 1349
Tigliolo
Lumarzo
Lorsica
Croce di Orero
Cichero
S. Michele
Borzone
Borzonasca
Mt. Becco 893
Mt. Cornua 688
Mt. Tugio 729
Mt. Borgo 729
Cicagna
Orero
Piana di Soglio
Pian dei Ratti
Mt. Zatta 1404
Mt. Chiappozzo 1126
Reppia
Mezzanego
Mt. Rosa 692
S. Martino del Monte
S. Colombano Certenoli
Leivi
Carasco
Panesi
Ne
Statale
Mt. Capra 1056
Mt. Roccagrande 970
Chiavari - Caperana
Mt. Capenardo 691
Tigullio Gulf
Chiavari
N
0
2.5
5 km
C
8.0
12.0
16.0
44.0
40.0
Ligurian Sea
ITALY
9.0
LIGURIA
Genova
B
Mt. Lavagnola
Mt. Aiona
Mt. Nero
Favale di Malvaro
Lorsica
Mt. Ramaceto
Lumarzo
Borzonasca
Mt. Becco
Cicagna
Orero
Mt. Borgo
Mt. Zatta
Mezzanego
Mt. Rosa
S. Colombano Certenoli
Leivi
Ne
Carasco
1.
2.
3
4.
5.
6.
7.
Chiavari
Mt. Domenico
Mt. Capenardo

Fig.1

Fig. 2

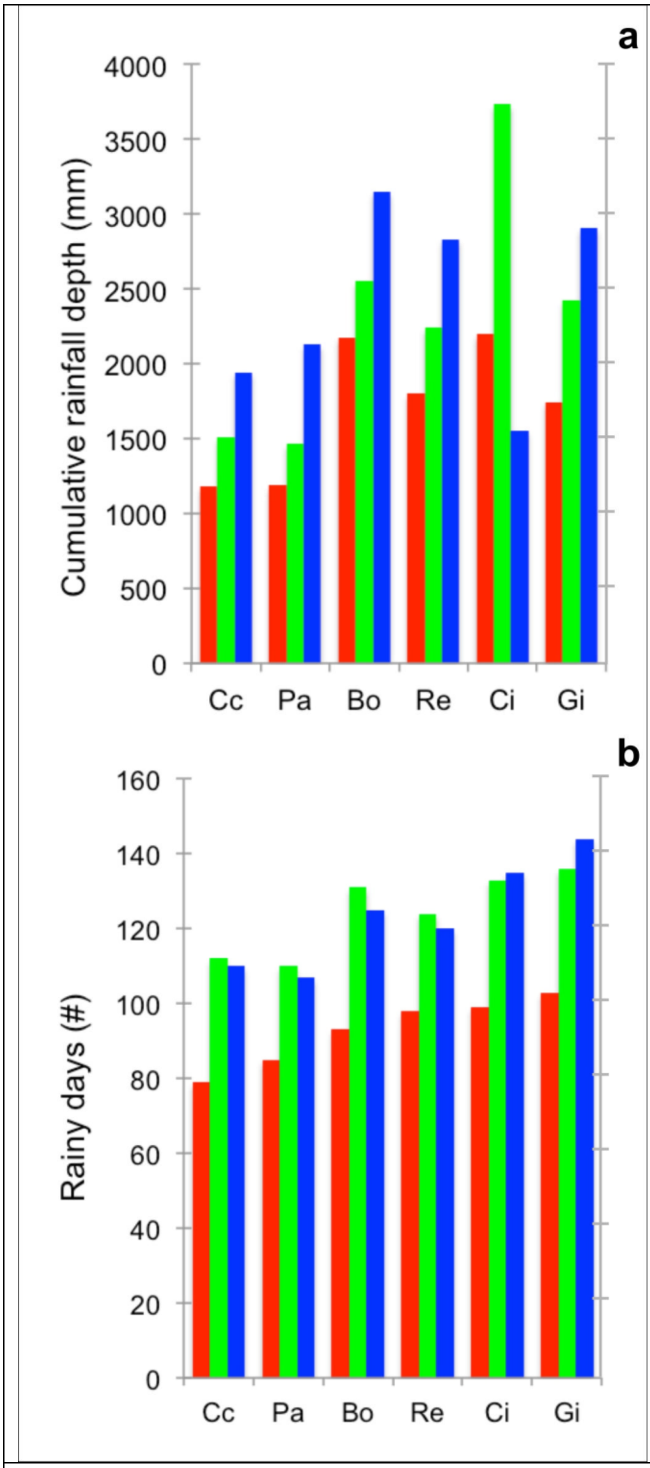
a
Cumulative rainfall depth (mm)
4000
3500
3000
2500
2000
1500
1000
500
0
Cc
Pa
Bo
Re
Ci
Gi
b
Rainy days (#)
160
140
120
100
80
60
40
20
0
Cc
Pa
Bo
Re
Ci
Gi

Fig. 3

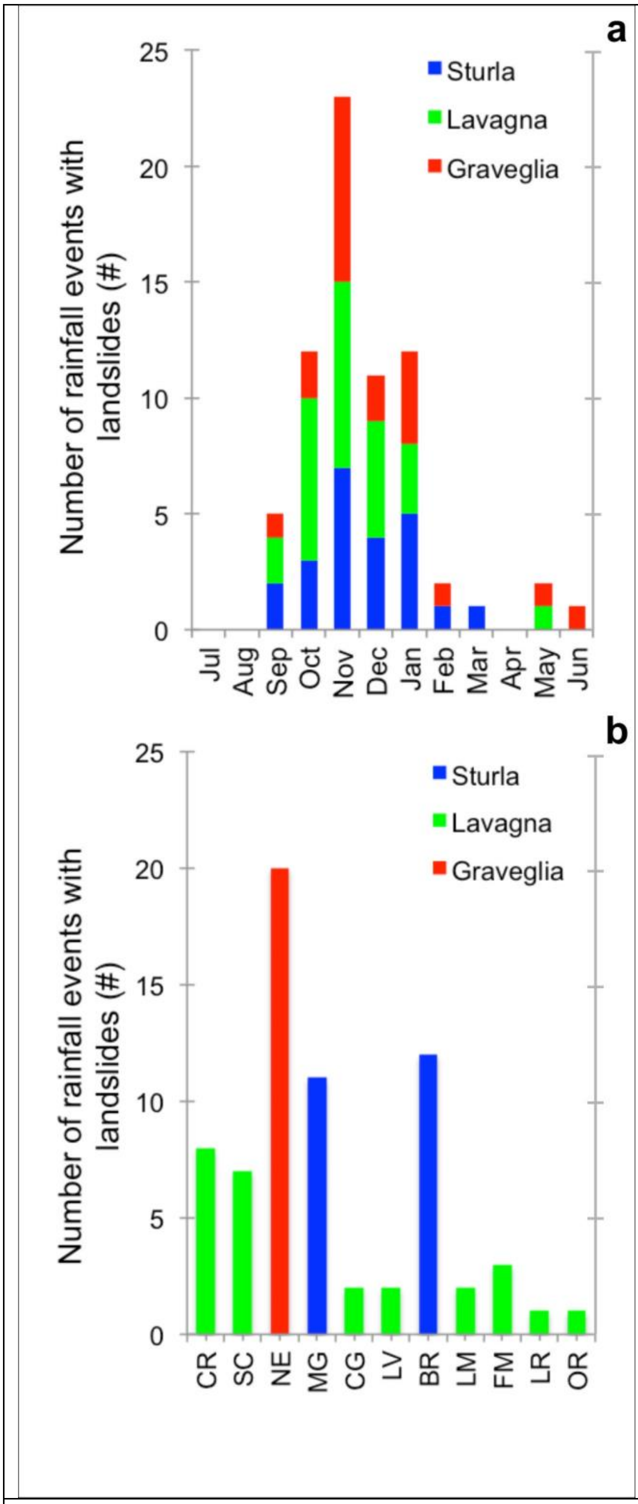
a
Number of rainfall events with landslides (#)
0
5
10
15
20
25
Sturla
Lavagna
Graveglia
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
b
Number of rainfall events with landslides (#)
0
5
10
15
20
25
Sturla
Lavagna
Graveglia
CR
SC
NE
MG
CG
LV
BR
LM
FM
LR
OR

Fig. 4

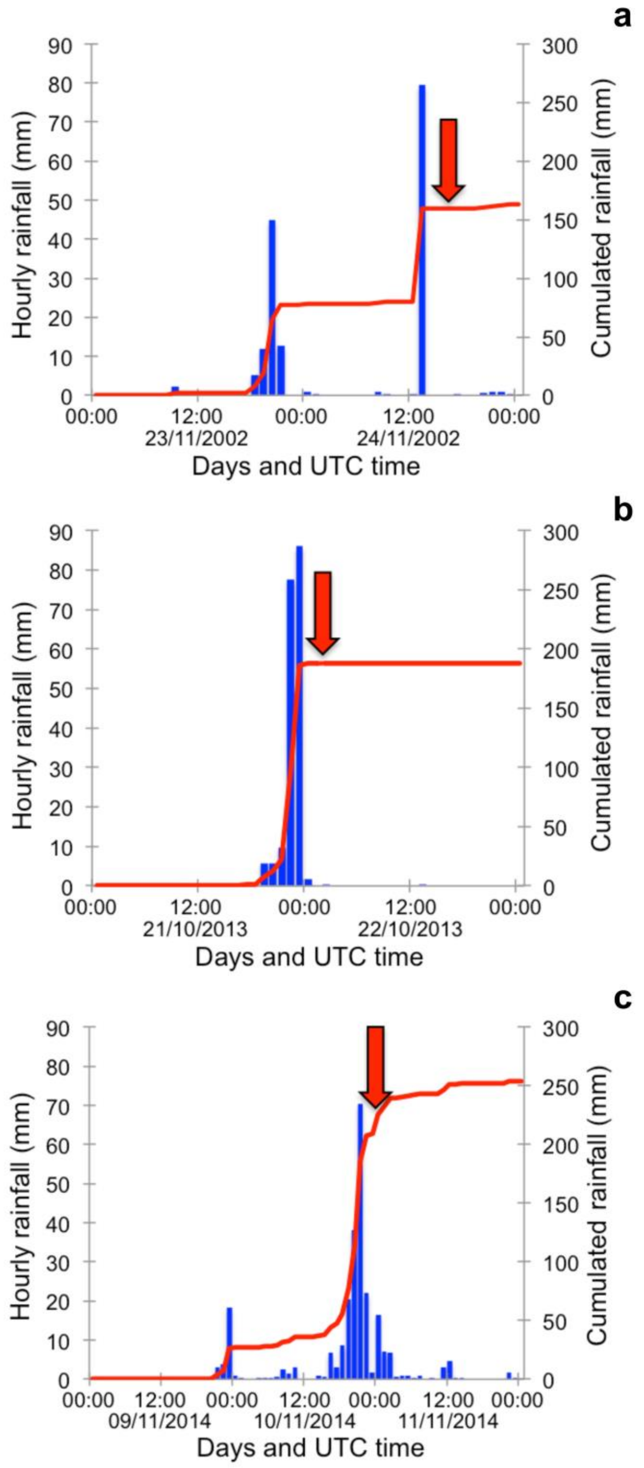
a
Hourly rainfall (mm)
Cumulated rainfall (mm)
0
10
20
30
40
50
60
70
80
90
0
50
100
150
200
250
300
00:00
12:00
00:00
12:00
00:00
23/11/2002
24/11/2002
Days and UTC time
b
Hourly rainfall (mm)
Cumulated rainfall (mm)
00:00
12:00
00:00
12:00
00:00
21/10/2013
22/10/2013
Days and UTC time
c
Hourly rainfall (mm)
Cumulated rainfall (mm)
00:00
12:00
00:00
12:00
00:00
12:00
00:00
09/11/2014
10/11/2014
11/11/2014
Days and UTC time

Fig. 5

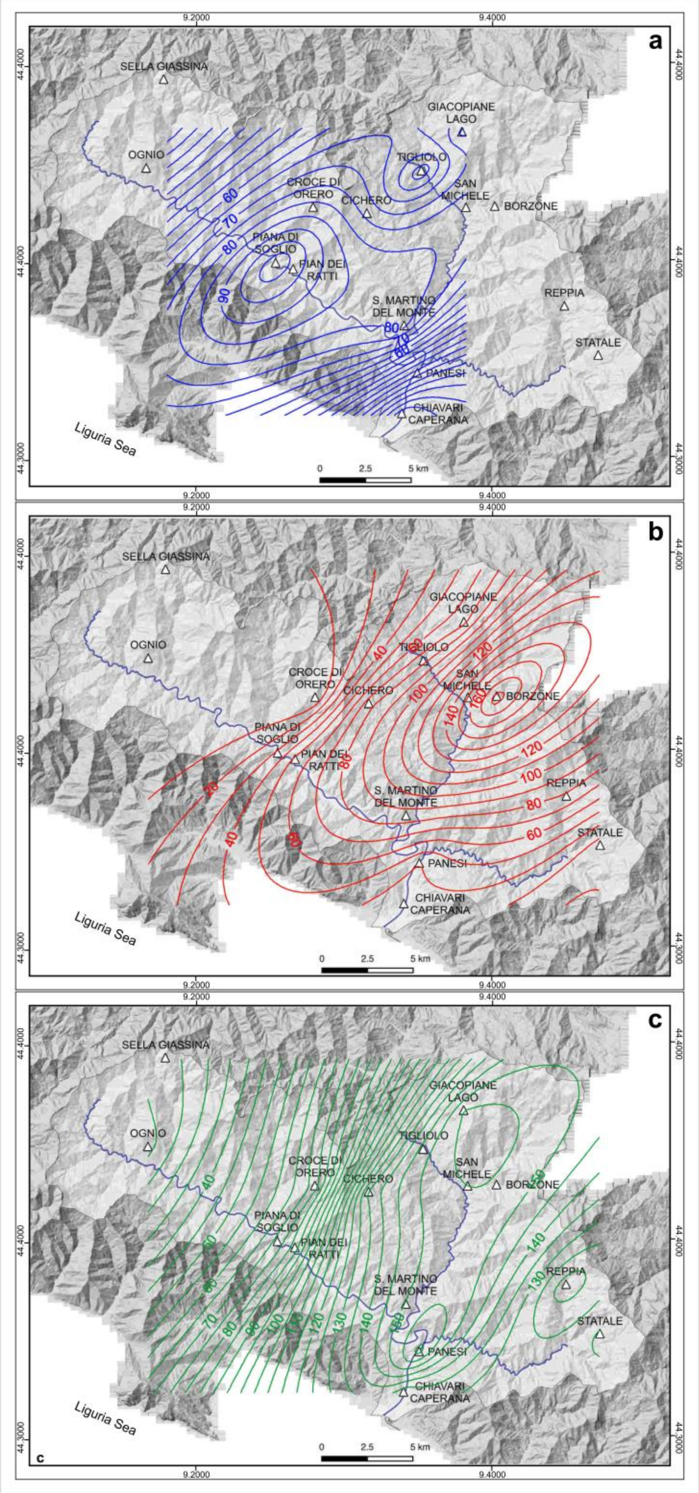
a
b
c
9.2000
9.4000
44.4000
44.3000
SELLA GIASSINA
GIACOPIANE LAGO
OGNIO
TIGLIOLO
CROCE DI ORERO
CICHERO
SAN MICHELE
BORZONE
PIANA DI SOGLIO
PIAN DEI RATTI
REPPIA
S. MARTINO DEL MONTE
STATALE
PANESI
CHIAVARI CAPERANA
Liguria Sea
0
2.5
5 km
60
70
80
90
40
100
120
140
160
130

Fig. 6

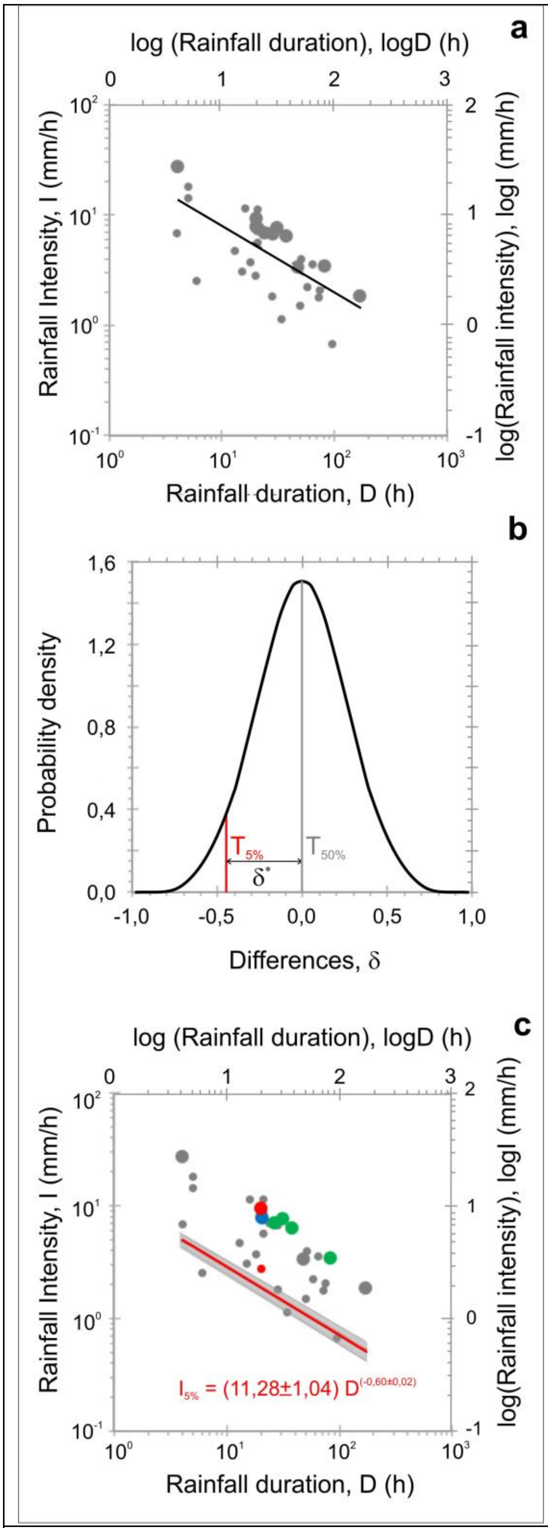
a
log (Rainfall duration), logD (h)
0
1
2
3
Rainfall Intensity, I (mm/h)
10^2
10^1
10^0
10^{-1}
log(Rainfall intensity), logI (mm/h)
2
1
0
-1
10^0
10^1
10^2
10^3
Rainfall duration, D (h)
b
Probability density
1,6
1,2
0,8
0,4
0,0
$T_{5\%}$
$T_{50\%}$
δ^*
-1,0
-0,5
0,0
0,5
1,0
Differences, δ
c
log (Rainfall duration), logD (h)
0
1
2
3
Rainfall Intensity, I (mm/h)
10^2
10^1
10^0
10^{-1}
log(Rainfall intensity), logI (mm/h)
2
1
0
-1
$I_{5\%} = (11,28\pm1,04)\ D^{(-0,60\pm0,02)}$
10^0
10^1
10^2
10^3
Rainfall duration, D (h)

Fig. 7

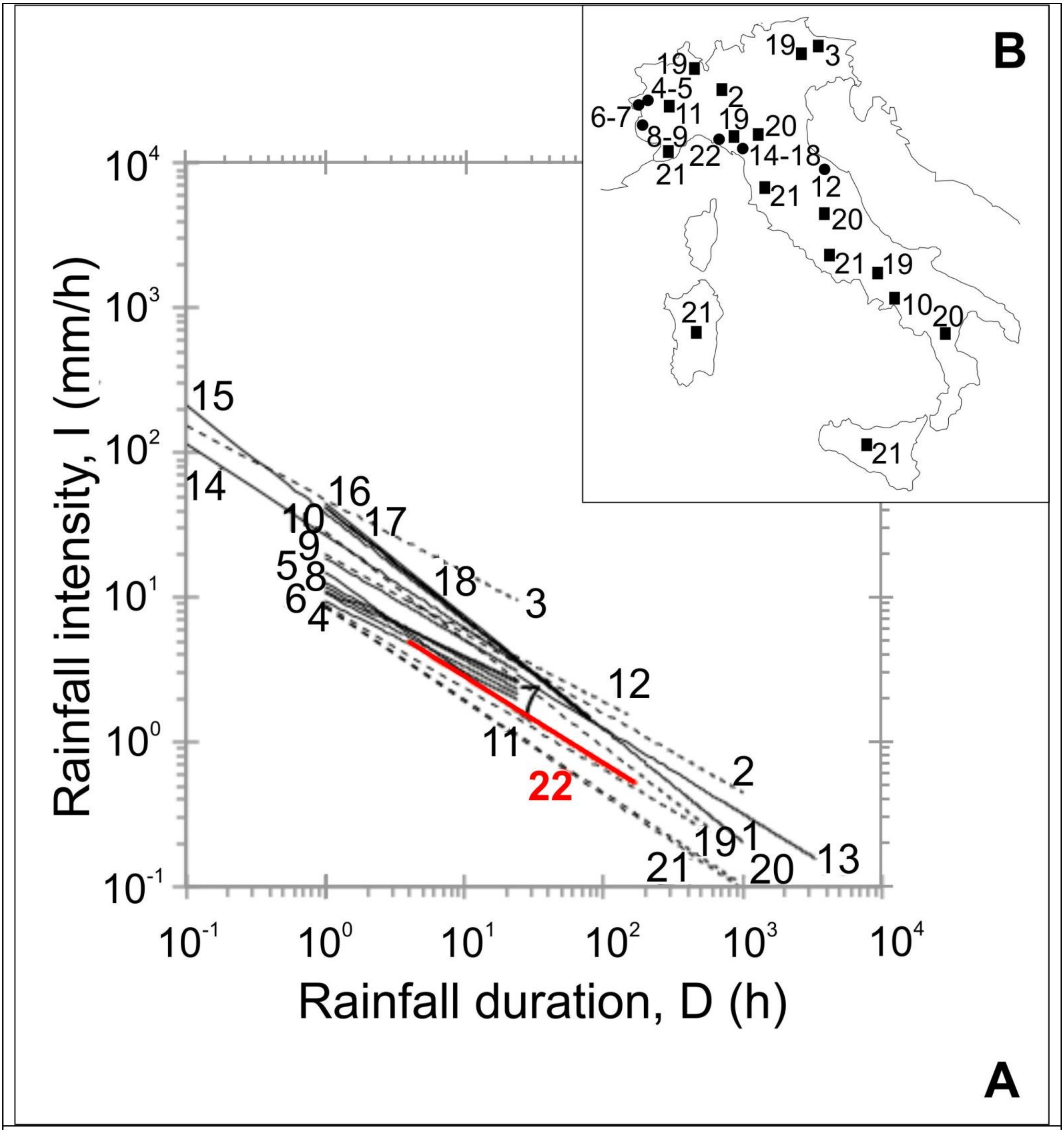
B
19
3
19
4-5
2
6-7
11
19
20
8-9
22
14-18
21
12
21
20
21
19
10
20
21
21
Rainfall intensity, I (mm/h)
10^4
10^3
10^2
10^1
10^0
10^{-1}
15
14
16
17
10
9
5
8
18
3
6
4
12
11
22
2
19
1
21
20
13
10^{-1}
10^0
10^1
10^2
10^3
10^4
Rainfall duration, D (h)
A

Fig. 8

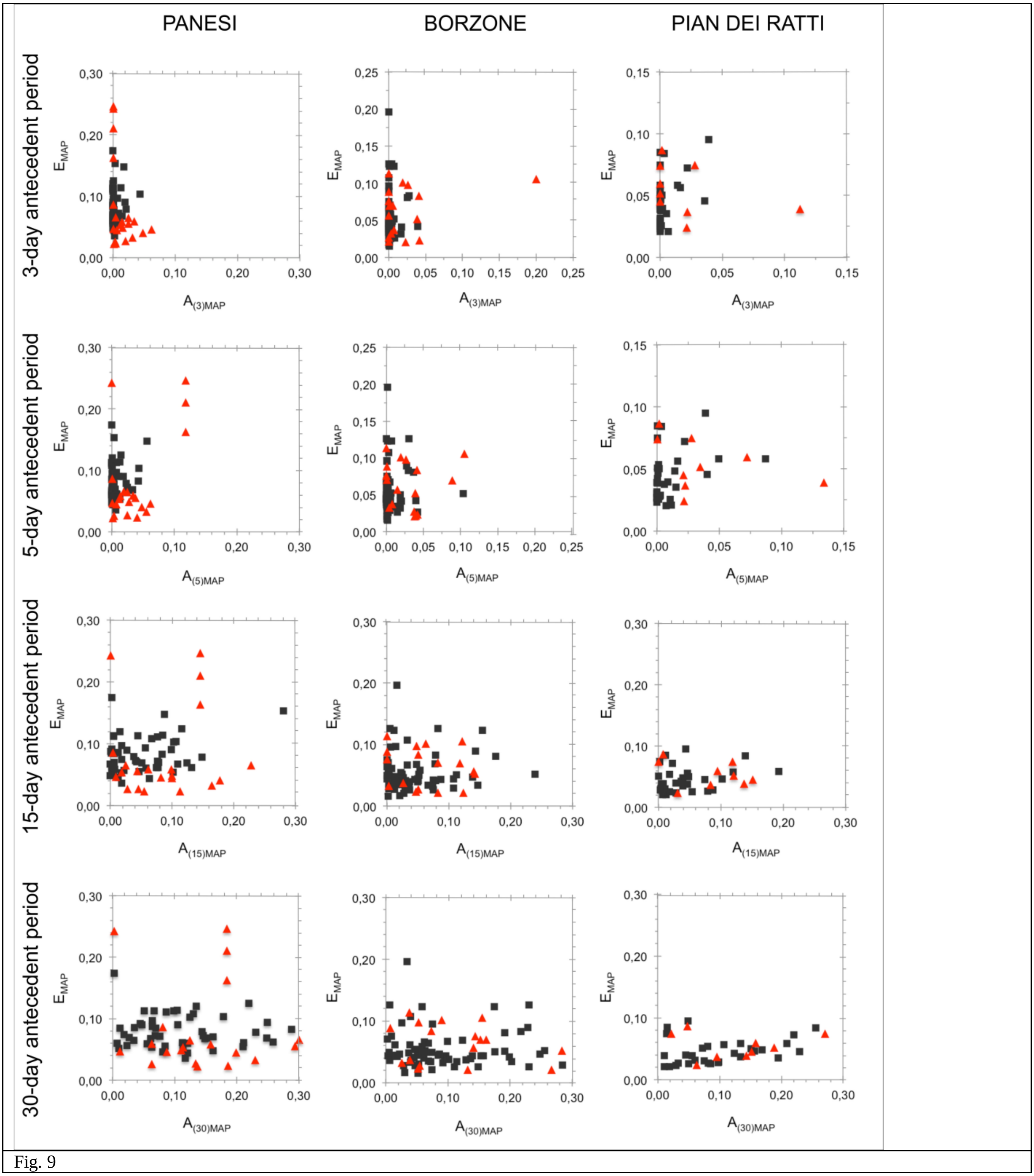
PANESI
BORZONE
PIAN DEI RATTI
3-day antecedent period
5-day antecedent period
15-day antecedent period
30-day antecedent period
E_{MAP}
$A_{(3)MAP}$
$A_{(5)MAP}$
$A_{(15)MAP}$
$A_{(30)MAP}$
0,00
0,05
0,10
0,15
0,20
0,25
0,30

Fig. 9