

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

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## **SPECIFIC COMMENTS**

*#1 L21 in previous paper version (L23-25 in reviewed paper): a reason for the low threshold should be provided*

We attribute the result primarily to the peculiar geological, morphological, land-use and meteorological conditions that characterize the Entella catchment, with a high MAP and the frequent occurrence of convective thunderstorms, short duration and high to very high intensity rainfall events, whose formation is favored by the local orographic setting. Secondly, as suggest the occurrence of shallow landslides frequently along the road network, we explain the low thresholds with the possible disturbance in triggering landslides due to the presence of man-made structure al the source areas (See Section 6).

*#2 Study area: typical landslides should be characterized (at least typology and size)*

The Entella River basin presents a composite geomorphological setting and features several processes, landforms and deposits due to gravity: the most important types of landslide can be identified with i) shallow landslides, characterized by very short duration and intense rainfalls, and ii) ancient slow deformations, reactivated during prolonged precipitations. The rainfall events analyzed in the present paper trigger mainly shallow landslides and earth flows: they involved moderate volume of material and are featured by a moderate destructive capacity, but they are widely spatial distributed in the catchment area.

*#3 L71 in previous paper version: why inundations are included in a work about landslides?*

We included inundations because the rainfall events used to define the rainfall conditions for the possible initiation of shallow landslides in the Entella catchment, resulted in widespread and severe ground effects both on slopes and along the watercourses, including damaging flash floods in the valley floor of the three main tributaries and in the coastal alluvial plain. In the revised paper, we discuss rightly landslides, without mentioning inundations and flash floods (except in the general introduction).

**#4 L69-81 in previous paper version: two sections cannot have the same title.**

This was our mistake. The title of section 3 was “Landslides and rainfall data”, whereas the correct title of section 4 was “Rainfall events with landslides”. In the reviewed paper, we have reorganized the work and subdivided into new sections.

**#5 L89 in previous paper version: please, avoid generic terms like "most". How many of them?**

For each rainfall event, the number of shallow landslides that really occurred cannot be determined exactly. Information available from various sources is not always accurate and reliable about type and number of the triggered landslides. In many cases, the sources report indefinite or approximate descriptions e.g., “a number of landslides” or “multiple slope failures”, or simply “landslides”. Therefore, we do not know exactly the total amount of slope failures occurred. As shown in Table 1, we classified the abundance of the landslide as “single” or “multiple”. Having said that, using the 16 rainfall events for which spatial and temporal information with sufficient accuracy were known, we identified and georeferenced 94 landslides and we estimated a maximum landslide density of 28 landslides/km<sup>2</sup> in the Lavagna valley (San Colombano Certenoli) during the 24 November 2002 event (see Section 5, L 258).

**#6 L113-177 in previous paper version (Section 4, in reviewed paper): I don't understand the reason of including detailed event reports in a research paper. This part could be consistently shortened or cut.**

In the last decades, the Ligurian Region and the Entella catchment were affected by several rainfall events resulting in widespread and damaging landslides. We include detailed reports about the 24 November 2002, 21–22 October 2013, and 10 November 2014 events because they represent the most recent and severe events, in terms of abundance of landslides and damage, occurred in the in the Entella catchment. Furthermore, we focused on these three occurrences because accurate and copious rainfall and landslide information are readily available for events occurred in the 2000s, due to the increasing attention and visibility reserved by mass media to natural phenomena, such as severe rainfall events and rainfall induced landslides, particularly when they cause extensive damage or fatalities, and the ever-increasing consideration towards natural risks by Authorities and local Administrations.

**#7 L194-198:** *these are just generic statements. They are not supported by in previous paper version data. It would be interesting to see statistics and numbers. E.g. what's the difference between an abandoned and a maintained terrace? From your text it seems that in both cases they increase landslide susceptibility. This is a very strange statement: can terraces be abandoned harmlessly?*

Numbers and statistics about correlation between shallow landslides and land use in the Entella catchment are now illustrated to support out statements in Section 5. We discuss our findings in the next Section 6, and particularly the influence of the land use conditions (urban areas, natural vegetated and agricultural terraces) on the slope stability during intense rainfall events. We observed that shallow landslides involved both abandoned and still-cultivated terraced slopes: terracing control erosion and slope degradation as long as the entire terrace system is well-maintained, but insufficient regulation of water run-off and a bad preservation of the man-made embankments and dry-retaining walls decrease slope stability in response to high-intensity rainfall. In both cases, abandoned and still-cultivated terraced slopes, they increase landslides susceptibility.

For further evidences about agricultural terraced slopes and their response to rainfall events and landslides susceptibility, see also Crosta et al. (2013) and Brandolini et al. (2018).

**#8 L275-281 in previous paper version:** *as I understand, rainfalls have been normalized by the MAP registered by three rain gauges. This is not correct: each rainfall should be normalized by the MAP registered by its own rain gauge.*

Each rainfall record was normalized to the MAP of the same raingauge used to define the D, I threshold (Section 3, L178-183 in reviewed paper). In Section 5, L303-311, we reported the results of the analysis obtained for the three rain gauges of Panesi, Borzone and Pian dei Ratti because they represent the rain gauges nearest to the central portion of the Entella catchment, where the considered rainfall events induced more abundant, widespread and damaging landslides.

**#9 L296 in previous paper version:** *I think in the text you provided different numbers.*

In the 2002-2016 period, we have identified 29 rainfall events with landslides. The events are listed in Table 1. Among these 29 rainfall events, we have information about time and location of landslides with sufficient temporal and geographical accuracy only for a subset of 16 events (not 17, events were wrongly numbered):

- 1) 24/11/2002
- 2) 20/2/2006
- 3) 12/11/2008
- 4) 1/12/2008
- 5) 8/12/2009
- 6) 22-25/12/2009
- 7) 7-9/5/2010
- 8) 2/11/2010
- 9) 21-22/10/2013

- 10)30/10/2013
- 11)26-27/12/2013
- 12)4/1/2014
- 13)16-20/1/2014
- 14)10-11/10/2014
- 15)10-11/11/2014
- 16)14-9-2015

The 34 rainfall intensity-duration conditions listed in Table 3 are related to the landslides induced by the 16 rainfall events mentioned above (see Section 3 in reviewed paper)

## GENERAL COMMENTS

*# The manuscript is about a case study where three main rainfall events are thoroughly described; after, already published and well established methods are applied. Therefore, the only value of the manuscript is presenting the new case study, while no relevant scientific findings are presented.*

Every time a study on rainfall inducing shallow landslides is presented, a new case study is shown: yes, it is true. On the other hand, our paper adds an important piece that was still missing from the great puzzle of knowledge about this phenomenology.

If a journal rejected the "case studies", we would never have had the chance to know the papers of Cancelli & Nova on the Valtellina (1983), by Cannon & Ellen on San Francisco Bay (1985), by Brand et al. on Hong Kong (1984), by Wieczorek on central Santa Cruz (1987), by Reichenbach et al. on Tiber Basin (1998). We think it would have been a big loss, isn't it?

Having said this, we maintain that the manuscript is well within the aims of NHESS. Undoubtedly, several papers on rainfall thresholds and landslides induced by intense rainfall events in the Mediterranean area, including Italy and Liguria region, are published. As it is, we applied an already published and established method: however, we consider that implementation of the method in a region as the Entella River basin, most frequently affected by intense and severe meteorological events, can consolidate and increase the scientific value of the method itself.

*# The introduction is poor. It fails to present the existing state of the art and to introduce the advances presented with this manuscript. Moreover, the introduction is centered only on the case of study. The scientific literature is not properly addressed, thus it is not clear the novelty and the improvements conveyed by the work.*

In the reviewed paper, introduction has been extended: a general first paragraph pointing on the study concerning rainfall thresholds and the existing state of art about investigation of the correlation between rainfalls and landslides occurrence and the major methods adopted to define rainfall curves are now presented. Using an inductive approach, from general to local, the following paragraphs have been entirely rearranged, to point out the novelty and the improvements conveyed by the work. The scientific literature has been extended and revised.

*# References should be completely revised. They are very numerous but they are very biased: almost only Italian authors are present. Some of them with a unnecessary high number of*

*works. Moreover, some of the references are unnecessary or not relevant (e.g. conference proceedings). I suggest to reduce the references and address the recent international literature.*

References have been completely revised: we reduced the unnecessary or not relevant references, and address more recent international literature as suggested.

*# The discussion is not a discussion. It starts with a recap, then it introduces some elaborations (rainfall threshold analysis) that in my opinion should be described in the methodology and in the result section.*

The paper has been entirely revised and reorganized into the new following sections: i) introduction (Section 1); ii) description of the general setting of the Entella catchment (Section 2); iii) description of the sources and criteria used for the compilation of the catalogue of rainfall events that triggered shallow landslides and the method adopted to define the rainfall thresholds (Section 3) ; iv) focus on the three largest and damaging rainfall events (24 November 2002, 21-22 October 2013 and 10 November 2014) that affected the study area (Section 4); v) rainfall thresholds for the possible initiation of shallow landslides in the Entella catchment and results of the rainfall and landslides analysis (Section 5); vi) discussion of our findings, including a comparison with similar, published curves and the correlation with the land-use and human interference (Section 6) and vii) summary of the results of the study and its possible implementation in a landslide warning system and land planning (Section 7).

*# The comparison with some literature thresholds is trivial. It is obvious that different sites are represented by different thresholds. I suggest to either cut this descriptive part, or to deeply discuss the reasons of the similarities/differences.*

Comparison with similar threshold curves proposed in the literature for mountain catchments, local areas or single regions, with analogous physiographic, climatic and meteorological features, in Italy comparable with the Entella River basin is required to discuss and interpret the outcomes of the study. In the revised paper, this part has been improved: we deeply discussed the similarities and the differences between our threshold and the curves proposed in the literature in Section 6 **L339-374**.

*# Some of the conclusions are not supported by data and are just speculations: -How can the study be useful for "land planning" and "risk reduction"? You didn't provide a susceptibility map or a hazard assessment. - the "method to define..." is not original work of this manuscript. It is a published and quite well established procedure.*

Conclusions have been revised and improved, as suggested. We consider the study presents relevant scientific findings and useful prospects in land planning and landslide risk mitigation. The Entella catchment is the largest tyrrhenian basin in the middle-eastern sector of the Ligurian region – one of the Mediterranean areas with the highest MAP values (more than 4000 mm in 2014) – and it is affected by the low-pressure system called “Genoa Low”, that result in very heavy, short duration and local storms. After these severe rainfall events, widespread and damaging ground effects are observed, included rainfall induced shallow landslides and flash

floods. A recent study, still in progress, permitted us to identify 20 intense rainfall events resulted in severe ground effects during the period 2001-2017 for each of the catchments of the two tributaries Sturla and Graveglia Stream: 50% of the events affect both the sub-catchments to testify the extremely localized extent of these phenomena.

In order to forecast the possible initiation of rainfall induced shallow landslides and mitigate the landslides susceptibility and risk, a project for a forecasting and early warning system is under construction by the Ligurian Regional Agency for the Environment Protection (ARPAL). We consider results obtained for the Entella catchment will be useful for the implementation of an early warning system, based on precipitation or forecast measurements, not only at regional scale but also at the level of major basins and their single sub-basin. This consideration arises from the punctual surveys carried out by the authors which have detected as in an area, during the same thunderstorm, many shallow landslides were triggered, while no phenomena were activated in the close area. The violent storms, in fact, often have diameters lower than the kilometer.

In terms of mitigation of landslide risk, since instability phenomena involve both natural vegetated and agricultural terraced slopes, still-cultivated and abandoned, and are frequently favoured by human disturbance, we highlight the importance of improving land-planning and providing also a long-term strategy in order to reduce rainfall induced landslides risk, including restoration of abandoned terraces, recovery of the drainage system, maintenance and management of the wooded surfaces, rigorous monitoring of urbanization.

# **Rainfall events with shallow landslides in the Entella catchment, Liguria, Northern Italy**

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Dear Editor,

after the good revisions of the referees, the original paper has been completely revised and enhanced in each part.

We would like to underline that this paper can be considered significant for the scientific community since the Entella basin is the largest Ligurian Tyrrhenian basin and it is located in the central-eastern sector of the Ligurian arch, among the Mediterranean regions, with the highest average annual rainfall (over 4000 mm in 2014).

Then this area:

- 1) is affected by the depression on the Gulf of Genoa, and therefore is characterized by short and intense rainfall and localized in space;
- 2) presents a unique orographic barrier as represented by a chain that rises up to 1800 m above sea level at about 15 km from the coast;
- 3) as a result of short and intense rainfall, it has always ground effects consisting of rainfall-induced landslides and flash floods; a recent 'work in progress' research on the Sturla and Graveglia sub-basins has permitted to gather information on 20 intense rainfall events with significant ground effects for the period 2001-2017 for each sub-basin. Only half of these events occur in both sub-basins, demonstrating the extreme localized extension of the cloudburst;
- 4) for this purpose, the SARF project (regional alert system), i.e. the definition of pluviometric thresholds for the possible triggering of landslides, is under construction by CNR-IRPI and ARPA Liguria (Regional Agency for the Environment)\*. The project aims to define empirical rainfall thresholds for the possible triggering of rainwater-induced landslides in Liguria and the conception and development of a prototypal warning system for the prediction of landslides on a regional scale based on thresholds.

The results of the project can be used to predict the possible occurrence of pluvio-induced landslides and can contribute to the mitigation of hazards and landslide risk.

For these reasons, we think that the paper is worth publishing on NHESS.

Best Regards.

Fabio Luino and his colleagues

- <http://www.irpi.cnr.it/en/project/previsione-di-frane-indotte-da-pioggie-e-zonazione-del-rischio-da-frana-in-italia/>

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**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-earth 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  $\text{mm h}^{-1}$ ), 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 23-24 November 2002, 21-22 October 2013, and 10-11 November 2014. Examining the timing and location of the slope 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. Failures involved mainly forested and natural surfaces, and secondarily cultivated and terraced slopes, with different level of maintenance. Man-made structures characterize frequently the landslide source areas. Adopting a Frequentist approach, we define the event rainfall intensity–event duration ID, threshold for the possible initiation of shallow landslides and hyper-concentrated debris-flows in the Entella River basin. The threshold is lower than most of the thresholds-curves proposed in the literature for similar mountain catchments, local areas and single regions in Italy. The result suggests a high susceptibility to rainfall-induced shallow landslides of the Entella catchment due to its high-relief topography, geological and geomorphological settings, meteorological and rainfall conditions and human interference. 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.

The study concerning the rainfall thresholds able to trigger shallow landslides is certainly one of the most studied aspects in the geomorphological field in the last decades. The idea of being able to predict the triggering of a mass movements as a function of recorded rainfall has greatly fascinated ranks of researchers all over the world. The study can be exhaustive only if the researcher has precise rainfall data and detailed information about the location, altitude and the time of the landslide trigger.

Many papers have been published about the sort of statistical analysis of the relationship between rainfall and the occurrence of mass-movements (Campbell, 1975; Caine, 1980; Govi and Sorzana, 1980; Moser and Hohensim, 1983; Wieczorek and Sarmiento, 1983; Brand et al. 1984; Govi et al., 1985; Cannon and Ellen, 1985; Crozier, 1986; Wieczorek, 1987) since the beginning of the eighties. And they continued with many other studies also in the following decade (Kim et al., 1991; Page et al., 1993; Ceriani et al., 1994; Premchitt et al., 1994; Crozier, 1997; Glade, 1997; Crosta, 1998).

Italy proves to be an excellent experimental field. Every year, in particular during the summer, there are thousands of shallow landslides during due to short but very heavy rainfall: they In the recent decades, a number of rainfall events have caused widespread landslides and inundations in Italy, resulting incaused 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; Trigila et al., 2018).

In the same period Since 1970, the Liguria region, (northern Italy),— one of the Italian areas where landslide and flood risk is highest in Italy (Guzzetti, 2000; Salvati et al., 2010; Salvati et al., 2014), suffered from rainfall events characterized by flash floods, shallow landslides, large scale complex landslides and earth flows along small creeks (Faccini et al 2015c—). Since the early 1990s, the Liguria region seems to be suffering a sort of resurgence of these events, more and more characterized by short duration and intense rainfall that have triggered damaging landslides was affected frequently by short duration, intense rainfall events that have triggered damaging landslides (Guzzetti et al., 2004; Faccini et al., 2005; 2015a; 2015b; 2017; Giannecchini et al., 2010; 2015; Silvestro et al., 2012; 2016; Cevasco et al., 2015; 2017; D'Amato Avanzi et al., 2015) 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). Globally

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, since 1970, the rainfall induced landslide and flood events which have claimed 37–16 lives, and have caused widespread and extensive damage to private and public properties, structures and infrastructures, and business.

The acknowledge of the amount of precipitation needed to trigger shallow landslides and earth flows is essential for the implementation of an operational landslide warning system (Aleotti, 2004; Baum and Godt, 2010; Tiranti and Rabuffetti, 2010; Martelloni et al., 2012; Mathew et al., 2014). Definition of rainfall thresholds is the key issue for the prediction of rainfall-

65 induced landslides. In literature, various methods have been proposed to define the rainfall condition that are likely to trigger slope failures. Physically based approaches depend on the understanding of the complex physical processes that control slope stability (Montgomery and Dietrich, 1994; Wilson and Wieczorek, 1995; Iverson 2000; Crosta and Frattini, 2003; Segoni, 2009); they are elaborate to apply because of the difficulty of defining the exact spatial and temporal variation of the many factors involved, particularly on large regions (e.g., effects of vegetation, rainfall variation, mechanic and hydraulic properties of both bedrock and soils). Empirical approaches rely on the definition of empirical or statistical rainfall thresholds through the analysis of the rainfall conditions that in the past triggered landslides (Caine, 1980; Wieczorek, 1996; Aleotti, 2004; 70 Guzzetti et al., 2008; Brunetti et al., 2010; Saito et al., 2010; Peruccacci et al., 2017); they differ in rainfall data adopted (e.g., intensity and duration of precipitation, cumulative event rainfall, antecedent rainfall, etc.) and geographical extent of their validity (e.g., local, regional, national, global).

75 Here we discussed the rainfall events that have triggered shallow landslides in the Entella River basin, in eastern Liguria, in the 15-year period 2002–2016. During this period, the study area was one of the most frequently affected catchments, with a total of 29 damaging rainfall events and 94 known shallow landslides that have caused 2 fatalities. We use rainfall and landslide information of a subset of 17 events, for which location and timing of the failures are exactly known, to define the rainfall thresholds for the possible initiation of shallow landslides in the Entella catchment. In addition, we investigate the correlation between landslides and land cover and the possible role of the antecedent rainfall in slope failures.

80 The paper is organized as follows: i) description of the general setting of the Entella catchment (Section 2); ii) description of the sources and criteria used for the compilation of the catalogue of rainfall events that triggered shallow landslides and the method adopted to define the rainfall thresholds (Section 3) ; iii) focus on the three largest and damaging rainfall events (23-24 November 2002, 21-22 October 2013 and 10-11 November 2014) that affected the study area (Section 4); iv) rainfall thresholds for the possible initiation of shallow landslides in the Entella catchment and results of the rainfall and landslides analysis (Section 5); v) discussion of our findings, including a comparison with similar, published curves and the correlation with the land-use and human interference (Section 6) and vi) summary of the results of the study and its possible implementation in a landslide warning system and land planning (Section 7). 85

~~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.~~

90 ~~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.~~

## 95 2 Study area

The Entella River basin extends for 375 km<sup>2</sup> in the Tyrrhenian sector of the Liguria Apennines, north-western Italy (Fig. 1) and encompasses the Lavagna (160 km<sup>2</sup>), Sturla (130 km<sup>2</sup>), and Graveglia (63 km<sup>2</sup>) 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. Different types of landslides generally characterize the Entella catchment, with different state of activity, from active to dormant and stabilized: i) shallow landslides, slow-moving and rapid to extremely rapid earth flows (Hungar et al., 2001) and rock falls on steep slopes (in particular along the roads), triggered by very short and intense rainfalls, and ii) ancient slow large deep-seated gravitational slope deformations, particularly at the head of the valleys, reactivated during prolonged precipitations. Landslides are widely distributed and involve mainly debris cover from few centimeters to 3-4 meters thick, and portions of the fractured and weathered bedrock (Faccini et al., 2002, 2017; Cevasco et al, 2017). Slope failures affect areas from few square meters to several square kilometers (DSGSD) and involve volumes ranging from few to thousands of cubic meters. 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. 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. The Apennines range, exceeding locally 1700 m in elevation, runs parallel to the coast of the Liguria Sea, and acts as a barrier for the low-pressure systems; ~~that characterized the Gulf of Genoa, primarily in the autumn and winter periods (Anagnostopoulou et al., 2006): these typical Mediterranean cyclones of orographic origin, called “Genoa Low”, facilitating result the formation of in~~ thunderstorms ~~characterized by with~~ intense and very intense rainfall– that cause widespread and damaging ground effects, both on the slopes

~~and along the drainage pattern, in the Ligurian and Northern Toscana regions (Brandolini et al., 2012; Sacchini et al., 2012; Silvestro et al., 2012, 2015). 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.~~

### 130 ~~3~~ **Landslide and rainfall data** Methods

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 one events of them~~ (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) 135 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 140 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.

~~Among the 29 rainfall events, we collected useful information for 16 events. Using this subset of 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 145 the cumulated event rainfall,  $E$  (in mm), the event rainfall duration,  $D$  (in h), the rainfall intensity,  $I$  (in  $\text{mm h}^{-1}$ ) for 1, 3, 6, 12 and 24-hour periods, and the average rainfall intensity for the rainfall event,  $\hat{I}$  ( $\text{mm h}^{-1}$ ) (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 150 to the geographical and morphological settings. For 82% of the landslides, the representative rain gauge was the one closest to the landslide or the cluster of landslides. 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 is known accurately, the end-time coincides with the time of the last rainfall measurement in the hour when the slope failure occurred. 155 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.

160 For each rainfall event, the corresponding event rainfall intensity ( $I$ , in  $\text{mm h}^{-1}$ ) 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.

165 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 earth 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,

170 
$$\log(I) = \log(\alpha) - \beta \log(D) \tag{1}$$

which is entirely equivalent to the power law curve

$$I = \alpha D^{-\beta} \tag{2}$$

175 in linear coordinates commonly adopted to represent ID thresholds in the literature (Guzzetti et al., 2007; 2008), where  $I$  is the rainfall intensity ( $\text{mm hr}^{-1}$ ),  $D$  is the duration of the rainfall event (h),  $\alpha$  is the intercept, and  $\beta$  defines the slope of the power law curve.

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  $\log[I_f(D)]$ ,  $\delta(D) = \log[I(D)] - \text{fit } \log[I_f(D)]$ . Then we estimated the probability density of the distribution of  $\delta$  and model the distribution through least square fitting using the Gaussian function:

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

180 where  $\mu$  is the mean value, and  $\sigma$  is the standard deviation. Lastly, the threshold corresponding to the 5% exceeding probability, is defined, based on the fitted distribution of  $\delta(D)$ .

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  $\bar{\alpha}$  and  $\bar{\beta}$  and the associated uncertainty  $\Delta\alpha$  and  $\Delta\beta$  in terms of standard deviation of the  $\alpha$ ,  $\beta$  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  $\alpha$  and  $\beta$  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  $\alpha$ ,

$\beta$  values calculated. We repeated the procedure for all the  $n=34$  (D,I) conditions, and calculated the standard deviation of the  $\alpha$  and the  $\gamma$  values.

190 We compare the obtained curve to similar ID empirical thresholds proposed in the literature for similar mountain catchments, local areas or single regions in Italy to investigate the influence of the local physiographical (e.g., meteorological, morphological, lithological, hydrological) and land cover setting on the rainfall thresholds.

195 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 normalized cumulated event rainfall  $E_{MAP}$ , to the MAP-normalised normalized 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. Each rainfall record was normalized to the MAP of the same raingauge used to define the D, I rainfall conditions.

#### **4 Rainfall events and shallow landslides**

200 The most severe rainfall events, in terms of abundance of shallow landslides and extent of damage, that affected the Entella catchment in the considered period 2002–2016 are those occurred on 23-24 November 2002, 21-22 October 2013 and 10-11 November 2014. In the next sections, a briefly focus of them is carried out to illustrate the peculiar meteorological conditions that caused intense and damaging precipitations in the Entella catchment, and the rainfall conditions and their ground-effects.

##### **4.1 The 23-24 November 2002 rainfall event**

205 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<sup>2</sup> 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. 3a). 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.

215 Figure 4a 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).

220 The rainfall event triggered numerous shallow landslides and earth 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**

225 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.

230 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. 3b). 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  
235 peak of the rainfall intensity.

Figure 4b 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  
240 (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  
245 24-hour period between 12:00 UTC on 21 October, and 12:00 UTC on 22 October 2013.

#### **4.3 The 10-11 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

250 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. 3c). 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 255 between 17:00 and 23:00 UTC on 10 November, with a maximum intensity peak between 21:00 and 22:00 UTC. Figure 4c 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 260 (Pian dei Ratti, 82.4 mm) and upper (Ognio, 18.4 mm) Lavagna valley. The heavy rainfall produced widespread shallow landslides and earth flows, which caused serious damage to structures and infrastructures, and two casualties (Cevasco et al., 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 265 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.

#### **4.5 Landslide and rainfall data Results**

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). 270 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  $\text{mm h}^{-1}$ ) for 1, 3, 6, 12 and 24 hour periods, and the average rainfall intensity for the rainfall event,  $\bar{I}$  ( $\text{mm h}^{-1}$ ) (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), 275 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 of the 16 events for which spatial and temporal failure information are known with sufficient accuracy, 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

280 affected limited sectors of the Entella catchment, where they triggered ~~numerous~~ 94 known landslides. We note that the five rainfall events with the largest hourly cumulated rainfall exceeding 70 mm (23-24 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-two~~ casualties. With the exception of the 10-11 November 2014 rainfall event, the three events characterized by 24-hr  
285 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. 3-5 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. 4a6a). This is in  
290 agreement with results obtained at the national (Guzzetti, 2000) and regional (Giannecchini, 2006) scales in Italy.

The landslide events ~~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. 4b6b, Table 4). ~~In this central part of the catchment, where~~ the most severe and damaging events occurred on 23-24 November 2002, 21-22 October 2013, and 10-11 November 2014. The ~~three~~ events caused ~~many~~ shallow landslides, primarily soil-slips, ~~(Crosta et al., 2003)~~, slow-moving ~~earth flows~~ and rapid to extremely rapid debris-earth flows, ~~secondarily debris slides and avalanches (Cruden and Varnes, 1996; Hungr et al., 2001, 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, mud, debris, ~~boulders~~ and vegetation were mobilized along the slopes and the thalwegs. Landslides occurred mainly ~~in~~ on steep and very steep slopes, in the range of acclivity from 36% to 50% (26) and from 51% to 75% (44), and were particularly abundant where roads, walking paths, embankments, slope cuts and other human made structures were present (Fig. 2, and in vegetated areas, both natural (62) and cultivated (19). Only 13 landslides involved urban areas; however, roads, trails, embankments, buildings, trenches and other man-made structure are often present in the source area of the failures (Fig. 2). In particular, shallow landslides developed mainly within forests and woodlands (48), followed by olive groves (9), transitional woodland/shrubs vegetation (10) and agricultural lands (10) (Table 5). A number of failures (15) affected terraced slopes, mainly planted with olive groves (11), both still-cultivated and abandoned. ~~→~~  
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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 (Fig. 7) for the possible initiation of shallow landslides (Guzzetti et al., 2007; 2008) in the catchment. The black line in Fig. 7a represents the best-fit line  $T_{50}$ :

$$I = 31.88 D^{-0.60} \quad (4)$$

310 The black line in Fig. 7b represents the Gaussian model of the empirical distribution of the  $\delta$  values around the central value,  $\mu = 0$ , measured by the standard deviation,  $\sigma = 0.26$ . The red curve in Fig. 7c is the 5% ID threshold ( $T_5$ ) for the study area:

$$I = (11.28 \pm 1.04) D^{(-0.60 \pm 0.02)} \quad (5)$$

where  $\Delta\alpha=1.04$  and  $\Delta\gamma=0.02$  are the standard deviation of the  $\alpha$ ,  $\gamma$  values and the grey pattern shows a proxy for the uncertainty associated to the threshold, in the range  $4 \text{ h} < D < 170 \text{ h}$ . The  $T_5$  threshold should Eq. (5) 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 analyzed in this work i.e., the 10-11 November 2014, the 21-22 October 2013, and the 23-24 November 2002 events, all plot above the established ID threshold curve. 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  $\delta^*$  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  $\beta = 0.60$ . 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  $4 \text{ h} < D < 169 \text{ h}$  and in the range of mean intensity  $0.5 \text{ mm h}^{-1} < I < 4.9 \text{ mm h}^{-1}$ .

As regard the possible role of the antecedent rainfall conditions in the initiation of rainfall-induced landslides in the Entella catchment, we highlight the results of the relationship between the MAP-normalized cumulated event rainfall and the MAP-normalized antecedent rainfall for the different periods for the Panesi, Borzone and Pian dei Ratti rain gauges i.e., the rain gauges nearest to the central portion of the Entella catchment where the considered rainfall events that have resulted in more abundant, widespread and damaging 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). 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.

## 5-6 Discussion

Intense and very intense, geographically limited rainfall events generated by local convective thunderstorms, including the 10-11 November 2004/2014, the 21-22 October 2013, and the 23-24 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-earth 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  
345 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.  
350 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-earth~~ flows initiated chiefly from steep and  
355 very steep slopes in the range from 30° to 40°, primarily in ~~forested-forested~~ and ~~uncultivated-natural~~ areas, and  
secondarily on cultivated and terraced slopes with different level of maintenance well-maintained and abandoned terraced  
slopes with olive and chestnuts trees. Natural vegetated surfaces represent the preferential regions where landslides and erosive  
processes induced by rainfall easily occur. Generally, agricultural terraced surfaces contribute to maintain the slope stability  
and the regulation of the rainfall run-off as long as the entire terrace system is well-maintained (Brandolini et al., 2018). We  
360 found that both abandoned and still-cultivated, supposedly well-maintained, terraced slopes are involved by landslides: we  
attribute this fact to insufficient regulation of water run-off and bad preservation of the man-made embankments and dry-  
retaining stone walls that nowadays frequently characterized still-cultivated terraces, causing an increase in landslide  
susceptibility. Roads, trails, embankments, ~~trenches~~ and other man-made structures along the slope cause a general reduction  
of soil permeability and induce negative effects on the natural drainage system and stability, were often present in the source  
365 areas favouring the initiation 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.

$$370 * \exp \left\{ \frac{[\delta - \mu]^2}{2\sigma^2} \right\} \quad (3)$$

where  $\mu$  is the mean value, and  $\sigma$  is the standard deviation. The black line in Fig. 7b represents the Gaussian model of the  
empirical distribution of the  $\delta$  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 ( $T_s$ ), the grey vertical line portrays the mean of the distribution, corresponding to the 50%  
375 threshold ( $T_{50}$ ), and the distance  $\delta^*$  between the red and the grey lines is used to calculate the intercept of the 5% threshold  
curve. The 5% threshold  $T_s$ , is the curve parallel to the best fit line  $T_{50}$ , with intercept  $\alpha_s = \alpha_{50} - \delta^*$  and slope  $\beta = 0.60$ .

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  $4 \text{ h} < D < 169 \text{ h}$  and in the range of mean intensity  $0.5 \text{ mm h}^{-1} < I < 4.9 \text{ mm h}^{-1}$ .

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  $\bar{\alpha}$  and  $\bar{\beta}$  and the associated uncertainty  $\Delta\alpha$  and  $\Delta\beta$  in terms of standard deviation of the  $\alpha$ ,  $\beta$  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  $\alpha$  and  $\beta$  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  $\alpha$ ,  $\beta$  values calculated. We repeated the procedure for all the  $n=34$   $(D, I)$  conditions, and calculated the standard deviation of the  $\alpha$  (1.04) and the  $\beta$  (0.02) values. The red curve in Fig. 7e is the 5% ID threshold ( $T_5$ ) for the study area:

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

and the grey pattern shows a proxy for the uncertainty associated to the threshold, in the range  $4 \text{ h} < D < 170 \text{ h}$ . The  $T_5$  threshold should Eq. (4) leave 5% of the  $(D, I)$  empirical points below the power law curve; in Fig. 7e, 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 obtained for the Entella catchment to similar ID empirical threshold curves (Table 7) proposed in the literature for mountain catchments, local areas, or single regions in Italy (Fig. 9). In the range of validity for the threshold ( $4 \text{ h} < D < 170 \text{ h}$ ), the new threshold for the Entella catchment is lower to significant lower than other thresholds proposed for mountain catchments in Italy. It means that rainfall mean intensity required to trigger shallow landslides in the Entella basin are lower for the same rainfall durations than those expected in other Italian regions on the average. 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

410 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).

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

415 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 firstly to the high

420 landslides susceptibility that characterize the study area due to the complex geological, geomorphological and land-use setting, the high-relief topography and to the peculiar orographic and meteorological conditions that characterize the Entella catchment of the region, with a high MAP and the frequent occurrence of convective thunderstorms, short duration and high to very high intensity rainfall events, whose formation is favored by the local orographic setting. Secondarily, we explain the low

425 curve obtained with the possible disturbance in triggering landslides due to the presence of man-made structures at the source areas. However, comparison with other curves has to take in account the possible uncertainty due to different rainfall and landslide information analyzed, the different methods used to define the thresholds, or the different criteria adopted to identify the rainfall events and the consequent rainfall duration values. For example, some Authors use information from few particularly severe meteorological events that triggered abundant and destructive landslides, as for the Valtellina (Cancelli and

430 Nova, 1985) or the NE Alps (Paronuzzi et al., 1998), with higher mean intensity values; others consider different type of landslides and involved material, as debris flows for the Apuane Alps (Giannellini, 2010), with larger rainfall amounts required to fail; some Authors use different criteria to define the rainfall event, i.e., duration and intensity value, as for the Piedmont region (Aleotti, 2004).

435 As regards the comparison between MAP-normalized cumulated event rainfall and MAP-normalized antecedent rainfall, we conclude that antecedent rainfall conditions do not play a significant role in the initiation of landslides in the Entella catchment.

~~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. 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.

## **6.7 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 ~~and soil slips~~, earth flows, ~~and debris flows~~, which have resulted in a total of ~~five~~ two 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. ~~Among these 29 events, w~~We used rainfall and landslides information for ~~17-16~~ 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-earth~~ 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  $4h < D < 170h$ . We attribute the result mainly to the geological, geomorphological, orographic and meteorological settings of the Entella catchment that highly increase the susceptibility to rainfall-induced shallow landslides, and secondarily to the human disturbance.

To evaluate the possible role of the antecedent rainfall conditions in the initiation of landslides in Entella catchment, we ~~confronted-compared~~ 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 consider the study presents relevant scientific findings and useful prospects in land planning and landslide risk mitigation: the Entella catchment is the largest tyrrhenian basin in the middle-eastern sector of the Ligurian region – one of the Mediterranean areas with the highest MAP values (more than 4000 mm in 2014) – and it is affected by the low-pressure system called “Genoa Low”, that results in very heavy, short duration and local storms. After these severe rainfall events, widespread and damaging ground effects are observed, included rainfall induced shallow landslides and flash floods. A recent study, still in progress, permitted us to identify 20 intense rainfall events resulted in severe ground effects during the period 2001-2017

for each of the catchments of the two tributaries Sturla and Graveglia Stream: 50% of the events affect both the sub-catchments to testify the extremely localized extent of these phenomena.

In order to predict the possible occurrence of surface landslides induced by rainfall, a project for a forecasting and early warning system based on regional rainfall thresholds is under construction by the Ligurian Regional Agency for the Environment Protection (ARPA). The authors hope that the approach adopted, and the results obtained in the Entella catchment will be useful for the implementation of an early warning system, based on precipitation or forecast measurements, not only at regional scale, but also at level of both major basin and single sub-basin. This consideration arises from the punctual surveys carried out by the authors which have detected as in an area, during the same thunderstorm, many shallow landslides were triggered, while no phenomena were activated in the close area. The violent storms, in fact, often have diameters lower than the kilometer.

We expect that the results of this study will be useful for the implementation of landslides early warning system on a catchment scale. Using this method, further rainfall thresholds may be defined for different exceedance probability levels, in order to identify the correspondent rainfall conditions needed to initiate slope failures. Since instability phenomena involve both natural vegetated and agricultural terraced slopes, still-cultivated and abandoned, and are frequently favoured by human disturbance, we highlight the importance of improving, and for land-planning, and providing also a long-term strategy in order to reduce rainfall induced landslides risk in the study area, including restoration of abandoned terraces, recovery of the drainage system, maintenance and management of the wooded surfaces, rigorous monitoring of urbanization aimed at reducing landslides risk in the study area.

We further expect that the ~~method~~ approach adopted to define new threshold curves for possible rainfall-induced landslides tested in this work and its implementation in a early warning system, can be used in other mountain catchments, in Italy and elsewhere.

## References

Anagnostopoulou, C., Tolika, K., Flocas, H. and Maheras, P.: Cyclones in the Mediterranean region: present and future climate scenarios derived from a general circulation model (HadAM3P), *Adv. Geosci.*, 7, 9–14, 2006.

Aleotti, P.: A warning system for rainfall-induced shallow failures, *Eng. Geol.*, 73, 247–265, doi.org/10.1016/j.enggeo.2004.01.007, 2004.

Alpert, P., Ben-Gai, T., Baharad, A., Benjamin, Y., Yekutieli, D., Colacino, M., Diodato, L., Ramis, C., Homar, V., Romero, R., Michaelides, S., and Manes, A.: The paradoxical increase of Mediterranean extreme daily rainfall in spite of decrease in total value, *Gephys. Res. Lett.*, 29–1536, doi.org/10.1029/2001gl013554, 2002.

ARPAL-CMIRL – Agenzia Regionale per la Protezione dell’Ambiente Ligure–Centro Funzionale Meteo-idrologico di Protezione Civile della Regione Liguria, 2013.—: Rapporto di Evento Meteoroidrologico del 20–21 ottobre 2013,

- [http://www.arpal.gov.it/contenuti\\_statici//pubblicazioni/rapporti\\_eventi/2013/REM\\_20131021-\\_temporali-Carasco\\_vers20112117.pdf](http://www.arpal.gov.it/contenuti_statici//pubblicazioni/rapporti_eventi/2013/REM_20131021-_temporali-Carasco_vers20112117.pdf) (in Italian, 2013).
- 510 ARPAL-CMIRL – Agenzia Regionale per la Protezione dell’Ambiente Ligure–Centro Funzionale Meteo-idrologico di Protezione Civile della Regione Liguria, 2015–: Rapporto di Evento Meteoidrologico del 9–13 November 2014, [http://www.arpal.gov.it/contenuti\\_statici//pubblicazioni/rapporti\\_eventi/2014/REM\\_20141109-13\\_alluvione\\_Tigullio\\_vers20150123.pdf](http://www.arpal.gov.it/contenuti_statici//pubblicazioni/rapporti_eventi/2014/REM_20141109-13_alluvione_Tigullio_vers20150123.pdf) (in Italian, 2015).
- Bartolini, G., Grifoni, G., Torrigiani Malaspina, T., Vallorani, R., Meneguzzo, F., and Gozzini, B.: Precipitation changes from two long-term hourly dataset in Tuscany (Italy), *Int. J. Climatol.*, doi.org/10.1002/joc.3956, 2014.
- 515 Baum, R.L. and Godt, J.W.: Early warning of rainfall-induced shallow landslides and debris flows in the Usa, *Landslides*, 7(3), 387, doi.org/10.1007/s10346-010-0204-1, 2010.
- Bolley, S., and Olliario, P.: Analisi dei debris flows in alcuni bacini campione dell’Alta Val Susa, *Geingegneria Ambientale e Mineraria*, March, 69–74, in Italian, 1993 (in Italian).
- 520 Brand, E. W., Premchitt, J. and Phillipson, H. B.: Relationship between rainfall and landslides in Hong Kong, *Proc. 4th Int. Symp. Landslides*, Toronto, 377–384, 1984.
- Brandolini, P., Cevasco A., Firpo M., Robbiano A., Sacchini A., Geo-hydrological risk management for civil protection purposes in the urban area of Genoa (Liguria, NW Italy), *Nat. Hazards and Earth Sys. Sci.*, 12, 943–959, doi.org/10.5194/nhess-12-943-2012, 2012.
- 525 Brandolini, P., Pepe, G., Capolongo, D., Cappadonia, C., Cevasco, A., Conoscenti, C., Marsico, A., Vergari, F. and Del Monte, M.: Hillslope degradation in representative Italian areas: just soil erosion risk or opportunity for development?, *Land Deagrad. Dev.*, 1–19, doi.org/10.1002/ldr.2999, 2018.
- 530 Boni A., Braga G., Conti S., Gelati R., Marchetti G., Passeri L.D. Note illustrative della Carta Geologiche d’Italia 1:100.000, Foglio 83 “Rapallo”, Min. Ind. Comm. Artig., Serv. Geolo. It., Roma, 1969 (in Italian).Brunetti, M.T., Peruccaci, S., Rossi, M., Luciani, S., Valigi, D. and Guzzetti, F.: Rainfall thresholds for the possible occurrence of landslides in Italy, *Nat. Hazard Earth Sys. Sci.*, 10, 447–458, doi.org/10.5194/nhess-10-447-2010, 2010.
- 535 Caine, N.: The rainfall intensity duration control of shallow landslides and debris flows, *Geogr. Ann.*, 62(1-2), 23–27, doi.org/10.2307/520449, 1980.
- Calcaterra, D., Parise, M., Mauro, B., and Pelella, L.: The influence of meteoric events in triggering shallow landslides in pyroclastic deposits of Campania, Italy, in: *Proceedings of the 8th International Symposium on Landslides*, edit by Bromhead, E., Dixon, N., and Ibsen, M.L. (Eds.), A.A. Balkema, Cardiff, 1, 209–214, 2000.
- 540 Campbell, R.H.: Soil slip, debris flows, and rainstorms in the Santa Monica Mountains and vicinity. Southern California, U.S. Geological Survey Prof. Paper 851, 51 pp., 1975.

- Cancelli, A., and Nova, R.: Landslide in soil debris cover triggered by rainstorm in Valtellina (Central Alps, Italy), in Proceedings of the IV International Conference and Field Workshop on Landslides, Tokio September 1985, 267–272, 1985.
- 545 ~~Cannon, S.H. and Ellen, S.D.: Rainfall conditions for abundant debris avalanches, San Francisco Bay region, California, California Geology, 38(12), 267-272, 1985.~~
- Ceriani, M., Lauzi, S., and Padovan, N.: Rainfall thresholds triggering debris flows in the alpine area of Lombardia Region, central Alps—Man and Mountain '94 Proceedings, Ponte di Legno, 123–139, 1994.
- 550 ~~Cevasco, A., Diodato, N., Revellino, P., Fiorillo, F., Grelle, G., and Guadagno, F.M.: Storminess and geo-hydrological events affecting small coastal basins in a terraced Mediterranean environment, Sci. Total Environ., 532, 208–219, doi.org/10.1016/j.scitotenv.2015.06.017, 2015a.~~
- ~~Cevasco, A., Pepe, G., Brandolini, P.: The influences of geological and land use settings on shallow landslides triggered by an intense rainfall event in a coastal terraced environment, B. Eng. Geol. Environ., 73, 859–875, doi.org/10.1007/s10064-013-0544-x, 2014.~~
- 555 ~~Cevasco, A., Pepe, G., D'Amato Avanzi, G., Gianecchini, R.: A study on the 10 November 2014 intense rainfall and the related landslides in the lower Lavagna valley (eastern Liguria), Rend. Online Soc. Geol. It., 35, 66–69, doi.org/10.3301/rol.2015.65, 2015b.~~
- Cevasco, A., Pepe, G., D'Amato Avanzi, G., and Gianecchini, R.: Preliminary analysis of the November 10, 2014 rainstorm and related landslides in the lower Lavagna Valley (Eastern Liguria), Italian Journal of Engineering Geology and Environment, Special Issue, 1, 5–15, doi.org/10.4408/IJEGE.2017-01.S-01, 2017.
- CNR IRPI (Istituto di Ricerca per la Protezione Idrogeologica – Consiglio Nazionale delle Ricerche) Provincia di Genova: — Eventi alluvionali del novembre 2014, Area di Chiavari. Rilevamento LiDAR e analisi dei ottenuti—, Pubblicazione del 27 febbraio 2015, <http://gmg.irpi.cnr.it>, (in Italian, 2015).
- 565 ~~Crosta, G.B., Dal Negro, P. and Frattini, P.: Soil slips and debris flows on terraced slopes, Nat. Hazards Earth Sys. Sci., 3, 31–42, doi.org/10.5194/nhess-3-31-2003, 2003.~~
- ~~Crosta, G.B. and Frattini, P.: Distributed modelling of shallow landslides triggered by intense rainfall, Nat. Hazards Earth Syst. Sci., 3, 81–93, 2003.~~
- ~~Crozier, M.J. Landslides: causes, consequences and environment, Croom Helm, London, 252 pp., 1986.~~
- 570 ~~Crozier, M.J.: The climatic–landslide couple: a Southern Hemisphere perspective, In: Rapid mass movement as a source of climatic evidence for the Holocene, edit by: Matthews, J.A., Brunsden, D., Frenzel, B., Glaser, B. and Weiß, M.M., Palaeoclimate Research 19, pp. 333–354, 1997.~~
- ~~Crosta, G., Frattini, P.: Rainfall thresholds for triggering soil slips and debris flows, in: Proceedings 2nd EGS Plinius Conference on Mediterranean Storms (Mugnai A., Guzzetti F., Roth G., Eds). Siena, 463–487, 2003.~~
- 575

- Cruden D.M., Varnes D.J.: Landslide types and processes, in: Turner A.K. & Shuster R.L. (Eds.), *Landslides: Investigation and Mitigation. Transportation Research Board Special Report 247*, National Academy Press, WA, 36–75, 1996.
- 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. Geol.*, 73(3–4), 215–228, doi.org/10.1016/j.enggeo.2004.01.005, 2004.
- ~~D'Amato Avanzi G., Galanti Y., Giannecchini R., Puccinelli A.: Fragility of territory and infrastructures resulting from rainstorms in Northern Tuscany (Italy), in: *Proceedings of the 2nd World Landslide Forum, Roma, 3–9 October 2011, Springer Verlag, doi.org/10.1007/978-3-642-31319-6\_33, 2012.*~~
- D'Amato Avanzi, G., Galanti, Y., Giannecchini, R. and Bartelletti, C.: Shallow landslides triggered by the 25 October 2011 extreme rainfall in Eastern Liguria (Italy), in: *Engineering Geology for Society and Territory, Vol. 2*, edit by: Lollino, G., Giordan, D., Crosta, G.B., Corominas, J., Azzam, R., Wasowski, J. & Sciarra, N. (Eds.), *Engineering Geology for Society and Territory, Vol. 2*. Springer International Publishing, 515–519, Switzerland, doi.org/10.1007/978-3-319-09057-3\_85, 2015.
- Del Ventisette, C., Garfagnoli, F., Ciampalini, A., Battistini, A., Gigli, G., Moretti, S., and Casagli, N.: An integrated approach to the study of catastrophic debris-flows: geological hazard and human influence, *Nat. Hazard Earth Sys.*, 12, 2907–2922, doi.org/10.5194/nhess-12-2907-2012, 2012.
- Faccini, F., Giostrella, P., Lazzeri, R., Melillo, M., Raso, M., and Roccati, A.: The 10th November 2014 flash-flood event in Chiavari City (Eastern Liguria, Italy), *Rend. Online Soc. Geol. It.*, 35, 124–127, doi.org/10.3301/rol.2015.80, 2015a.
- ~~Faccini F., Luino F., Paliaga G., Sacchini A., Turconi L.: Yet another disaster flood of the Bisagno stream in Genoa (Liguria, Italy), *Rend. Online Soc. Geol. It.*, 35, 128–131, doi.org/10.3301/rol.2015.81, 2015b.~~
- Faccini, F., Luino, F., Sacchini, A., and Turconi, L.: The 4th October 2010 flash flood event in Genoa Sestri Ponente (Liguria, Italy), *Disaster Advanced*, 8 (8), 1–14, ~~2015e~~2015b.
- ~~Faccini, F., Luino, F., Sacchini, A., Turconi, L. and De Graff, J.: *Geo-hydrological hazard and urban development in the Mediterranean area: an example from Genoa city (Italy)*, *Nat. Hazards Earth Syst. Sci.*, 15, 2631–2652, doi.org/10.5194/nhess-15-2631-2015, 2015c.~~
- Faccini, F., Brandolini, P., Robbiano, A., Perasso, L., and Sola, A.: Fenomeni di dissesto e precipitazioni in rapporto alla pianificazione territoriale: l'evento alluvionale del novembre 2002 nella bassa Val Lavagna (Liguria Orientale), *Geogr. Fis. Dinam. Quat.*, suppl. VII, 145–153, *in Italian*, 2005-(~~in Italian~~).
- Faccini, F., Piana, P., Sacchini, A., Lazzeri, R., Paliaga, G., and Luino, F.: Assessment of heavy rainfall triggered flash floods and landslides in the Sturla stream basin (Ligurian Apennines, northwestern Italy), *Jokull*, 67(2), 44, 2017.
- ~~Faccini F., Robbiano A., Sacchini A.: *Geomorphic hazard and intense rainfall: the case study of the Recco Stream Catchment (Eastern Liguria, Italy)*, *Nat. Hazard Earth Sys.*, 12, 893–903, doi.org/10.5194/nhess-12-893-2012, 2012.~~

- 610 Floris<sub>2</sub> M., Mari<sub>2</sub> M., Romeo<sub>2</sub> R.W., ~~and~~ Gori<sub>2</sub> U.: Modelling of landslides-triggering factors - A case study in the Northern Apennines, Italy, in: Notes in Earth Sciences 104, Engineering Geology for Infrastructure Planning in Europa, edit by: Hack<sub>2</sub> R., Azzam<sub>2</sub> R., ~~and~~ Chalier R., (Eds.), Springer-Verlag Berlin Heidelberg, 745–753, 2004.
- Geological Service of Italy (Servizio Geologico d'Italia): Carta Geologica d'Italia in scala 1:100.000 - Foglio 83 "Rapallo", II ed. Serv. Geol. It., Roma, in Italian, 1968 (in Italian).
- Giannecchini<sub>2</sub> R.: Rainfall triggering soil slips in the southern Apuane Alps (Tuscany, Italy), Adv. Geosci., 2, 21–24, doi.org/10.5194/adgeo-2-21-2005, 2005.
- 615 Giannecchini<sub>2</sub> R.: Relationship between rainfall and shallow landslides in the southern Apuan Alps (Italy), Nat. Hazard Earth Sys., 6, 357–364, doi:10.5194/nhess-6-357-2006, 2006.
- Giannecchini<sub>2</sub> R., Damilano<sub>2</sub> D., and Puccinelli<sub>2</sub> A.: Critical rainfall thresholds for triggering rapid shallow landslides in the Eastern Ligurian Riviera (Italy), in: Proceedings of 85th Italian Geological Society National Congress, Pisa, Italy, 6–8 September 2010, 2, 596–597, 2010.
- 620 Giannecchini<sub>2</sub> R., Galanti<sub>2</sub> Y., and D'Amato Avanzi<sub>2</sub> G.: Critical rainfall thresholds for triggering shallow landslides in the Serchio River Valley (Tuscany, Italy), Nat. Hazard Earth Sys., 12, 829–842, doi:10.5194/nhess-12-829-2012, 2012.
- Giannecchini<sub>2</sub> R., Galanti<sub>2</sub> Y., ~~and~~ Barsanti<sub>2</sub> M.: Rainfall intensity-duration thresholds for triggering shallow landslides in the Eastern Ligurian Riviera (Italy), in: Engineering Geology for Society and Territory, Vol. 2, edit by: Lollino<sub>2</sub> G., Giordan<sub>2</sub> D., Crosta<sub>2</sub> G.B., Corominas<sub>2</sub> J., Azzam<sub>2</sub> R., Wasowski<sub>2</sub> J., ~~and~~ Sciarra<sub>2</sub> N. (Eds.), Engineering Geology for Society and
- 625 Territory, Vol. 2. Springer International Publishing, 1581–1584, Switzerland, doi.org/10.1007/978-3-319-09057-3\_281, 2015.
- Glade, T.: The Temporal and Spatial Occurrence of Rainstorm-triggered Landslide Events in New Zealand. PhD Thesis. Wellington, School of Earth Science, 380 pp., 1997.
- 630 Govi, M. and Sorzana, P.F.: Landslide susceptibility as a function of critical rainfall amount in Piedmont basin (Northwestern Italy), Studia Geomorph. Carpatho-Balcanica, 14, 43–61, Krakow, 1980.
- Govi, M., Mortara, G. and Sorzana, P.F.: Eventi idrologici e frane, Geologia Applicata & Ingegneria, Bari, Italy, 20(2), 359–375, 1985.
- Guzzetti F.: Landslide fatalities and the evaluation of landslide risk in Italy, Eng. Geol., 58, 89–107, doi.org/10.1016/s0013-7952(00)00047-8, 2000.
- 635 Guzzetti<sub>2</sub> F., Peruccacci<sub>2</sub> S., Rossi<sub>2</sub> M., ~~and~~ Stark<sub>2</sub> C.P.: Rainfall thresholds for the initiation of landslides in central and southern Europe, Meteorol. Atmos. Phys., 98(3–4), 239–267, doi.org/10.1007/s00703-007-0262-7, 2007.
- Guzzetti<sub>2</sub> F., Peruccacci<sub>2</sub> S., Rossi<sub>2</sub> M., ~~and~~ Stark<sub>2</sub> C.P.: Rainfall intensity-duration control of landslides and debris flows: an update, Landslides, 5, 3–17, doi.org/10.1007/s10346-007-0112-1, 2008.
- 640 Guzzetti F., Stark C.P., Salvati P.: Evaluation of flood and landslide risk to the population of Italy, Environ. Manage., 36, 15–36, doi.org/10.1007/s00267-003-0257-1, 2005.

- Guzzetti, F., Cardinali, M., Reichenbach, P., Cipolla, F., Sebastiani, C., Galli, M., ~~and~~ Salvati, P.: Landslides triggered by the 23 November 2002 rainfall event in the Imperia Province, Western Liguria, Italy, *Eng. Geol.*, 73, 229–245, doi.org/10.1016/j.enggeo.2004.01.006, 2004.
- 645 [Hungri, O., Evans, S.G., Bovis, M.J. and Hutchinson, J.N.: A review of the classification of landslides of the flow type. \*Environmental and Engineering Geoscience\*, 7\(3\), 221–238, doi.org/10.2113/gsegeosci.7.3.221, 2001.](#)
- Hungr, O., Leroueil, S., ~~and~~ Picarelli, L.: The Varnes classification of landslides types, an update, *Landslides*, 11(2), 167–194, doi.org/10.1007/s10346-013-0436-y, 2014.
- [Inverson, R.M.: Landslide triggering by rain infiltration. \*Water Resour. Res.\*, 36\(7\), 1897–1910, 2000.](#)
- [Kim, S.K.: Prediction of rainfall triggered landslides in Korea. \*Landslides\*, 2, 989–994, 1991.](#)
- 650 ~~Regione Liguria Liguria Region: Carta uso e copertura del suolo (COR.IN.E) scala 1:100.000, in Italian, 2000 (in Italian).~~  
~~Regione Liguria Liguria Region: Carta geologica regionale (CGR) scala 1:25.000 – tav. 231.1, 231.4 – Chiavari-Recco, in Italian, 2005 (in Italian).~~
- ~~Regione Liguria: Carta uso e copertura del suolo (COR.IN.E) scala 1:100.000, 2000 (in Italian).~~  
~~Regione Liguria: Carta geologica regionale (CGR) scala 1:25.000 – tav. 231.1, 231.4 – Chiavari Recco, 2005 (in Italian).~~
- 655 Luino, F.: Sequence of instability processes triggered by heavy rainfall in the northern Italy, *Geomorphology*, 66, 13–39, doi.org/10.1016/j.geomorph.2004.09.010, 2005.
- Marchi, L., Arattano, M., ~~and~~ Deganutti, A.M.: Ten years of debris flow monitoring in the Moscardo Torrent (Italian Alps), *Geomorphology*, 46, 1–17, doi.org/10.1016/s0169-555x(01)00162-3, 2002.
- Marini, M.: L’Unità del M. Gottero fra la Val Trebbia e Sestri Levante (Appennino ligure): nuovi dati di analisi di bacino e ipotesi di evoluzione sedimentaria, *Boll. Soc. Geol. It., Roma*, 3–23, [in Italian](#), 1992 ~~(in Italian)~~.
- [Martelloni, G., Segoni, S., Fanti, R. and Catani, F.: Rainfall thresholds for the forecasting of landslide occurrence at regional scale. \*Landslides\*, 9\(4\), 485–495, doi.org/10.1007/s10346-011-0308-2, 2012.](#)
- [Mathew, J., Babu, D.G., Kundu, S., Vinod Kuma, K. and Pant, C.C.: Integrating intensity-duration-based rainfall threshold and antecedent rainfall-based probability estimate towards generating early warning system for rainfall-induced landslides in parts of the Garhwal Himalaya, India. \*Landslides\*, 11\(4\), 575–588, doi.org/10.1007/s10346-013-0408-2, 2014.](#)
- 665 [Montgomery D.R. and Dietrich W.E., A physically based model for the topographic control of shallow landsliding. \*Water Resour. Res.\*, 30\(4\), 1153–1171, 1994.](#)
- ~~Marini M.: Litologia, stratimetria e sedimentologia delle Ardesie del Monte Verzi (Unità del M. Gottero AUCT., Appennino ligure), *Boll. Soc. Geol. It., Roma*, 333–352, 1993 (in Italian).~~
- 670 ~~Marini M.: Le Arenarie del M. Gottero nella sezione del M. Ramaceto (Unità del M. Gottero, Appennino ligure), *Boll. Soc. Geol. It., Roma*, 283–302, 1994 (in Italian).~~
- Moser, M., ~~and~~ Hohensinn, F.: Geotechnical aspects of soil slips in Alpine regions, *Eng. Geol.*, 19, 185–211, doi.org/10.1016/0013-7952(83)90003-0, 1983.

- 675 Paronuzzi, P., Coccolo, A., and Garlatti, G.: Eventi meteorici critici e debris flows nei bacini montani del Friuli-L'Acqua, Sez. I/Mem., 39–50, [in Italian](#), 1998 (~~in Italian~~).
- Peruccacci, S., Brunetti, M.T., Luciani, S., Vennari, C., and Guzzetti, F.: Lithological and seasonal control on rainfall thresholds for the possible initiation of landslides in central Italy, *Geomorphology*, 139-140, 79–90, doi.org/10.1016/j.geomorph.2011.10.005, 2012.
- 680 Peruccacci, S., Brunetti, M.T., Gariano, S. L., Melillo, M., Rossi, M., and Guzzetti, F.: Rainfall thresholds for possible landslide occurrence in Italy, *Geomorphology*, 290, 39–57, doi.org/10.1016/j.geomorph.2017.03.031, 2017.
- [Premchitt, J., Brand, E.W. and Chen, P.Y.M.: Rain induced landslides in Hong Kong, 1972-1992, \*Asia Engineer\*, 43-51, 1994.](#)
- [Sacchini, A., Ferraris, F., Faccini, F. and Firpo, M.: Environmental climatic maps of Liguria, \*Journal of Maps\*, 8\(3\), 199–207, doi.org/10.1080/17445647.2012.703901, 2012.](#)
- 685 Salvati, P., Bianchi, C., Rossi, M., and Guzzetti, F.: Societal landslide and flood risk in Italy, *Nat. Hazard Earth Sys.*, 10, 465–483, doi.org/10.5194/nhess-10-465-2010, 2010.
- [Segoni, S., Leoni, L., Benedetti, A.I., Catani, F., Righini, G., Falorni, G., Gabellani, S., Rudari, R., Silvestro, F. and Rebor, N.: Towards a definition of a real-time forecasting network for rainfall induced shallow landslide, \*Nat. Hazard Earth Sys. Sci.\*, 9, 2119–2133, doi.org/10.5194/nhess-9-2119-2009, 2009.](#)
- [Saito, H., Nakayama, D. and Matsuyama, H.: Relationship between the initiation of a shallow landslide and rainfall intensity-duration thresholds in Japan, \*Geomorphology\*, 118\(1-2\), 167–175, doi.org/10.1016/j.geomorph.2009.12.016, 2010.](#)
- 690 [Salvati P., Bianchi C., Fiorucci F., Giostrella P., Marchesini I., Guzzetti F.: Perception of flood and landslides risk in Italy: a preliminary analysis, \*Nat. Hazard Earth Sys.\*, 14, 2589–2603, doi.org/10.5194/nhessd-2-3465-2014, 2014.](#)
- Silvestro, F., Gabellani, S., Giannoni, F., Parodi, A., Rebor, N., Rudari, R., and Siccardi, F.: A hydrological analysis of the 4 November 2011 event in Genoa, *Nat. Hazard Earth Sys.*, 12 (9), 2743–2752, doi.org/10.5194/nhess-12-2743-2012, 695 2012.
- Silvestro, F., Rebor, N., Giannoni, F., Cavallo, A., and Ferraris, L.: The flash flood of the Bisagno Creek on 9th October 2014: an “unfortunate” combination of spatial and temporal scales, *Journal of Hydrology*, 541, 50–62, doi.org/10.1016/j.jhydrol.2015.08.004, 2016.
- [Tiranti, D. ad Rabuffetti, D.: Estimation of rainfall thresholds triggering shallow landslides for an operational warning system implementation, \*Landslides\*, 7\(4\), 471–481, doi.org/10.1007/s10346-010-0198-8, 2010.](#)
- [Trigila, A., Iadanza, C., Bussetini, M. and Lastoria, B.: Dissesto idrogeologico in Italia: pericolosità e indicatori di rischio. Rapporto 2018. Istituto Superiore per la Protezione e la Ricerca Ambientale – ISPRA, Rapporti 287/2018, 159 pp., ISBN 978-88-448-0901-0, in Italian, 2018.](#)
- 705 Wasowski, J.: Understanding rainfall-landslide relationship in man-modified environment: a case history from Caramanico Terme (Italy), *Environ. Geol.*, 35, 197–209, doi.org/10.1007/s002540050306, 1998.

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

710

Wieczorek, G.F.: Effects of rainfall intensity and duration on debris flows in central Santa Cruz Mountains, California, in: Debris flows/avalanches: process, recognition and mitigation, edit by: Costa, J.E. and Wieczorek, G.F., Reviews in Engineering Geology, Geological Society of America, Boulder, CO, 7: 93-104, 1987.

Wieczorek, G.F.: Landslide triggering mechanism, in: Landslides investigation and mitigation, special report, edit by: Turner, A.K. and Schuster, R.L., Transportation Research Board, National Academy Press, Washington, 247(4), 76–89, 1996.

715

Wieczorek, G.F. and Sarmiento, J.: Significance of storm intensity-duration for triggering debris flows near La Honda, California (Abstracts with Programs No. 15, pp. 5, 289), Geological Society of America, Boulder, CO, 1983.

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725 **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 23-24 November 2002 (blue), the 21-22 October 2013 (red), and the 10-11 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.

730 **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-earth 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-earth flow that damaged a building on 24 November 2002. See Fig. 1 for location of the landslide sites.

735 **Figure 3** Hourly rainfall (blue bars) and cumulated event rainfall (red line) for the three considered rainfall events in the Entella catchment (Table 1). (A) 23-24 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.

740 **Figure 4.** 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) 23-24 November 2002. (b) 21–22 October 2013. (c) 9–11 November 2014.

745 **Figure 35:** 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.

750 **Figure 46:** (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.

755 **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.

760 **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.

765 **Figure 7.** (a) Rainfall condition (D,I) (dots) that have resulted in shallow landslides and debris-earth 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 10-11 November 2014 rainfall event (green), the 21-22 October 2013 rainfall event (red), and the 23-24 November 2002 rainfall event (blue). Small dots show single landslides and large dots show multiple landslides. Grey area around shows uncertainty of the threshold.

770 **Figure 8.** 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 or earth flow (Table 1), and black squares show rainfall events that did not trigger landslides or for which the occurrence of landslides is unknown.

775 **Figure 89.** (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

780 catchment. Sources: 1, Cancelli and Nova (1985); 2, Ceriani et al. (1994); 3, Paronuzzi et al. (1998); 4-9, Bolley and Oliaro (1999); 10, Calcaterra et al. (2000); 11, Marchi et al. (2002); 12, Aleotti (2004); 13, Floris et al. (2004); 14-15, Gianecchini (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.

785 ~~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                          | Abundance <sup>[AR1]</sup> | Damage         |
|-----------|----------------------|-------------------------------|----------------------------|----------------|
| <b>1</b>  | <b>23-24/11/2002</b> | <b>BR, CV, NE, SC</b>         | <b>M</b>                   | <b>C, S, I</b> |
| 2         | 31/10-1/11/2003      | BR, NE, SC                    | M                          | S, I           |
| 3         | 19-20/2/2006         | BR                            | S                          | S, I           |
| 4         | 21-23/11/2007        | MG                            | S                          | I              |
| 5         | 11-12/11/2008        | BR, CR, NE                    | M                          | S, I           |
| 6         | 1/12/2008            | CR                            | S                          | S, I           |
| 7         | 19-20/1/2009         | NE                            | M                          | S, I           |
| 8         | 29-30/11/2009        | NE                            | M                          | S, I           |
| 9         | 8/12/2009            | CR                            | S                          | S, I           |
| 10        | 22-25/12/2009        | BR, CR, MG, NE, OR            | M                          | S, I           |
| 11        | 7-9/5/2010           | NE, FM                        | M                          | S, I           |
| 12        | 31/10-2/11/2010      | BR, MG, NE                    | M                          | S, I           |
| 13        | 23-24/12/2010        | MG                            | M                          | S, I           |
| 14        | 8/6/2011             | NE                            | M                          | S, I           |
| 15        | 4-5/9/2011           | NE                            | M                          | S, I           |
| 16        | 25/10/2011           | NE                            | M                          | S, I           |
| 17        | 5/11/2012            | NE                            | S                          | S, I           |
| 18        | 8/3/2013             | MG                            | M                          | S, I           |
| <b>19</b> | <b>21-22/10/2013</b> | <b>BR, CR, LV, MG, NE, SC</b> | <b>M</b>                   | <b>C, S, I</b> |
| 20        | 30/10/2013           | CG, FM                        | M                          | S, I           |
| 21        | 8-9/11/2013          | SC                            | S                          | S, I           |
| 22        | 26-27/12/2013        | BR, LM, MG, NE                | M                          | S, I           |
| 23        | 4/1/2014             | BR, MG, NE, SC                | M                          | S, I           |
| 24        | 16-20/1/2014         | BR, CR, LM, MG, NE            | M                          | S, I           |
| 25        | 10-11/10/2014        | CG, LR, MG                    | M                          | S, I           |
| 26        | 3-6/11/2014          | NE                            | M                          | S, I           |
| <b>27</b> | <b>10-11/11/2014</b> | <b>BR, CR, LV, MG, NE, SC</b> | <b>M</b>                   | <b>C, S, I</b> |
| 28        | 14/9/2015            | BR, CR, FM, MG                | M                          | S, I           |
| 29        | 9/2/2016             | NE                            | 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.

| 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.  $E_{nh}$ , 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<sup>-1</sup>). Abundance of landslides (AL): S, single landslide; M, multiple landslides.

| <u>ID</u> | Date       | Maximum event cumulated rainfall |          |          |           |           | Event rainfall |     |      |    | AL |
|-----------|------------|----------------------------------|----------|----------|-----------|-----------|----------------|-----|------|----|----|
|           |            | $E_{1h}$                         | $E_{3h}$ | $E_{6h}$ | $E_{12h}$ | $E_{24h}$ | E              | D   | I    | R  |    |
| <u>1</u>  | 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  |
| <u>2</u>  | 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  |
| <u>3</u>  | 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  |
| <u>4</u>  | 1/12/2008  | 20 Bo                            | 49 Bo    | 77.8 Bo  | 97.4 Bo   | 81.8 Cr   | 63.5           | 95  | 0.7  | Pa | S  |
| <u>5</u>  | 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  |
| <u>6</u>  | 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  |
| <u>7</u>  | 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  |
| <u>8</u>  | 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  |
| <u>9</u>  | 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  |
| <u>10</u> | 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  |
| <u>11</u> | 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  |
| <u>12</u> | 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  |
| <u>13</u> | 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  |
| <u>14</u> | 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  |
| <u>15</u> | 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  |
| <u>16</u> | 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  |
| <u>17</u> | 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  |
| <u>18</u> | 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  |
| <u>19</u> | 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  |
| <u>20</u> | 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  |
| <u>21</u> | 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  |
| <u>22</u> | 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  |
| <u>23</u> | 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  |
| <u>24</u> | 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  |
| <u>25</u> | 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  |
| <u>26</u> | 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  |
| <u>27</u> | 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  |
| <u>28</u> | 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  |
| <u>29</u> | 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  |
| <u>30</u> | 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  |
| <u>31</u> | 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  |
| <u>32</u> | 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  |
| <u>33</u> | 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  |
| <u>34</u> | 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.

| Date                      | Sites where event rainfall induced landslides were most abundant |
|---------------------------|--|
| <del>23</del> -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.** Comparison between spatial distribution of the landslides use to define the rainfall threshold and the land-use setting in the Entella River catchment.

| <u>Land-use category</u>                         | <u>Number of landslides</u> |
|--|-----------------------------|
| <u>Urban fabric</u>                              | <u>13</u>                   |
| <u>Complex cropland</u>                          | <u>4</u>                    |
| <u>Olive groves</u>                              | <u>7</u>                    |
| <u>Abandoned olive groves</u>                    | <u>2</u>                    |
| <u>Vineyard</u>                                  | <u>0</u>                    |
| <u>Agricultural land with natural vegetation</u> | <u>6</u>                    |
| <u>Forested areas</u>                            | <u>48</u>                   |
| <u>Natural grassland and/or high pastures</u>    | <u>4</u>                    |
| <u>Transitional woodland/shrub</u>               | <u>10</u>                   |

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**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.

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

**Table 57.** Intensity-Duration (ID) thresholds for the initiation of landslides in Italy. Rainfall intensity,  $I$  ( $\text{mm hr}^{-1}$ ); 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   |

