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Identification and characterization of rainfall events responsible for triggering of debris flows and shallow landslides

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SUMMARY

The aim of this study is the development of objective and replicable methodologies for the identification, analysis and characterization of rainfall events responsible for the triggering of shallow landslides and debris flows, in order to define empirical rainfall thresholds. The study area is the province of Trento (6208 km^2), located in the north-eastern Alps, and characterized by complex orography, with 70% of the area at an altitude above 1000 m. A rigorous statistical methodology has been defined for the identification of the beginning of the triggering event, based on the critical duration, i.e. the minimum dry period duration separating two stochastically independent rainy periods. The critical duration has been calculated for each rain gauge of the studied area and its variability during the months of the year has been analyzed. An analysis of the rainfall spatial variability in a neighborhood of the landslide detachment zone has been carried out. The adopted methods are: the examination of the Monte Macaion radar maps during some summer convective events, the comparison of rainfall records of rain gauges located in a 10 km buffer around the landslide, and the calculation of the Pearson's correlation coefficient between pairs of neighboring rain gauges. The following rainfall thresholds have been then calibrated with the frequentist approach and compared: average intensity–event duration (I–D), which represents the rainfall event in its entirety, and intensity–duration associated with the event maximum return period (I_{RP}–D_{RP}), which considers the most critical portion of the event. In the absence of information about the landslide time of activation, the end of the triggering event has been identified using two criteria: the rainfall peak intensity and the last registration of the day. The methodology adopted for the objective identification of the beginning of the triggering event has demonstrated good applicability for rainfall induced landslides. During convective summer events the low representativeness of the rainfall information recorded at the nearest rain gauge with respect to the precipitation over the landslide source area has been evaluated as a critical issue for rainfall threshold definition.

1. Introduction

In recent decades debris flows and shallow landslides have caused the most of damage in Italy both in terms of casualties and economic losses (Trigila and Iadanza, 2012). Debris flows are very rapid to extremely rapid flows of saturated granular material in steep channels (Cruden and Varnes, 1996; Hungr, 2005). Shallow landslides (debris slide, soil slip) are phenomena that affect cover deposits and are generally characterized by small size and thickness from a few decimeters to a few meters (2–3 m). The landslide triggering is related in almost all cases to intense rainfall (Wieczorek and Glade, 2005). For these types of landslides one of the measures for risk mitigation is the adoption of early warning systems based on rainfall thresholds that identify the critical amount of precipitation for landslide triggering.

The rainfall thresholds are divided into physically based and empirical ones. Physically based thresholds combine a hydrological model and a geotechnical stability model based on a infinite slope (Crosta and Frattini, 2003; Frattini et al., 2009; Segoni et al., 2009; Tarolli et al., 2006). The empirical thresholds consist of a statistical relationship between two or more variables that describe the rainfall conditions capable of triggering landslides (Govi et al., 1985). Input data are the landslide location, the type of movement, the date and time of occurrence, the rainfall event and the precipitation of the antecedent days. Being this a statistical approach, the reliability of the results is strongly influenced by the availability

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and quality of input data. The main problem is related to the fact that the dates of activation are available almost exclusively for landslides that caused damage, that the available rain gauges are often located in the valley at altitudes significantly lower than the landslide source area or that provide only daily records. Another critical issue concerns the thresholds calibrated using extreme rainfall events, which may overestimate the minimum rainfall value above which the landslide trigger occurs.

The correct representation of the rainfall triggering event depends on the criteria adopted for the identification of the beginning of the event, on the definition of the end of the event and on the availability of rainfall records near the landslide source area. Procedures adopted in previous works suffer often from a certain degree of subjectivity. In particular, the identification of the beginning of the event is generally based on a subjective definition of the duration in hours of the no-rain interval before the event and just recently a more objective assessment has been addressed in a small number of scientific papers (Berti et al., 2012; Melillo et al., 2014; Segoni et al., 2014a,b; Vessia et al., 2014). With regard to the end of the event, when the time of activation of the landslide is not known, it is identified conventionally in correspondence of the main peak of rainfall intensity (Frattini et al., 2009) or of the last record of the day (Brunetti et al., 2010; Vessia et al., 2014). Such choices significantly influence the identification of the triggering event, especially in case of a sequence of intense bursts alternating with short periods of absent or low intensity rainfall. Moreover regarding the choice of the reference rain gauge, the commonly performed selection of the nearest station to the detachment zone may not be representative of the triggering rainfall in orographically complex environments (Borga et al., 2008, 2014; Marra et al., 2014; Nikolopoulos et al., 2014).

The most common empirical thresholds are intensity–duration curves

$$I = \alpha \cdot D^{\beta}, \qquad (1)$$

where I is the average rainfall intensity and D the event duration. The exponent β assumes a negative value (-2 to -0.19), indicating that in a bi-logarithmic graph the rainfall intensity able to trigger landslides decreases linearly with increasing duration (Caine, 1980; Ceriani et al., 1994; Crosta and Frattini, 2001; Bacchini and Zannoni, 2003; Aleotti, 2004; Giannecchini, 2006; Guzzetti et al., 2007, 2008; Brunetti et al., 2010). Some thresholds also consider the antecedent precipitation as an indicator of the state of saturation of the soil (Crozier, 1999; Glade, 2000; Glade et al., 2000; Godt et al., 2006; Baum and Godt, 2010; Terlien 1996; Zezere et al., 2005, 2008; Mercogliano et al., 2011). A list of pluviometric variables, in addition to intensity and duration, used for the definition of empirical thresholds is contained in Guzzetti et al. (2007).

Often intensity–duration curves have been manually drawn or have been determined using least squares fit to the data and then shifted down to represent the lower limit (Rappelli et al., 2008). The thresholds obtained with rigorous statistical criteria, such as the Bayesian approach and the frequentist analysis, providing a quantitative assessment of the probability of landslide occurrence, are objective and reproducible (Berti et al., 2012; Guzzetti et al., 2007, 2008; Brunetti et al., 2010, 2014; Peruccacci et al., 2012). The Bayesian method returns a value of probability of landslide triggering, between 0 and 1, for each combination of the selected hydrological variables. With the frequentist analysis, thresholds corresponding to different exceedance probabilities can be defined. In previous works, multivariate statistical techniques such as discriminant analysis, logistic regression or classification trees, have also been used to identify the most significant variables to separate rainfall events that resulted in landslides from events without landslides (Jakob and Weatherly, 2003; Jakob et al., 2006; Chang et al., 2008; Mercogliano et al., 2011). Instead the thresholds used in early warning systems have been calibrated, on the basis of a sample of observed events, to maximize the number of correct predictions of landslide occurrence and minimize model errors both in terms of false positives (FP) or false alarms and of false negatives (FN) or missed alarms (Barberio et al., 2004; Segoni et al., 2014b; Staley et al., 2014).

In the most recent works, data of meteorological radar have been used to calibrate rainfall thresholds. The main problem concerns the use of automatic algorithms to correct the various potential sources of error of the radar data (Crosta and Frattini, 2003; Chen et al., 2007; Chang et al., 2008; Marra et al., 2014).

The aim of this study is the development of objective and replicable methodologies for the identification, analysis and characterization of rainfall events responsible for the triggering of shallow landslides and debris flows, for the definition of empirical rainfall thresholds. The main innovative aspects include: the definition of a rigorous statistical methodology to separate stochastically independent rainfall events and identify the beginning of the triggering event; the analysis of the rainfall spatial variability in a neighborhood of the landslide detachment zone to evaluate the representativeness of the recordings of the reference rain gauge; the influence of definition of the end of the event on rainfall threshold calibration; the comparison of intensity–duration (I–D) threshold and intensity–duration associated with the event maximum return period (I_{RP}–D_{RP}).

2. Materials and methods

2.1. Study area

The studied area is the province of Trento located in the north-eastern of Italian Alps. It is 6208 km^2 large, mainly mountainous with 70% of the territory at an altitude higher than 1000 m above sea level (Fig. 1a) and 44% with slope angle greater than 30° (Fig. 1c).

The climate is mostly continental, with hot, humid summers and cold, dry winters (Bisci et al., 2004). Average annual rainfall varies between 800 and 1600 mm (Provincia Autonoma di Trento, 2006), with the wettest areas in the south and south-west. The Adige Valley has a pre-Alpine rainfall regime with two maximum of precipitation in spring and autumn; areas at higher altitudes have an alpine regime with maximum of precipitation in summer. The contribution of summer and autumn rainfall is almost equal (i.e., ratio of summer/autumn rainfall close to 1) and each accounts for about 30% of annual rainfall (Nikolopoulos et al., 2015a). During the summer period intense convective events are frequent, extremely localized and of short duration (a few hours). During spring and autumn stratiform rainfall events of more days are frequent, affecting a large area with fairly uniform precipitation. The maximum frequency of the short duration (1–3 h) maximum annual rainfall occurs in the months of July and August, while the maximum annual rainfall of 24 h in the months of October and November (Villi and Bacchi, 2001). The snow is modest in the Adige valley but remarkable at high altitude.

Regarding geology, *Australpino* unit emerges in the north-west and is composed mainly of phyllites, mica schists and paragneiss and secondarily of orthogneiss, marbles, amphibolites and peridotites. *Sudalpino* unit, outcropping in the remaining territory, includes mainly sedimentary calcareous-dolomitic and marl-sandstone rocks and secondarily volcanic formations (ignimbrites and acid lavas), metamorphic rocks and intrusive rocks (granite, granodiorite and tonalite). Quaternary soil covering the bedrock are mainly composed of glacial deposits and detritus talus at high altitude and of alluvial deposits in the valley (Provincia Autonoma