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Space–time organization of debris flows-triggering rainfall and its effect on the identification of the rainfall threshold relationship

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SUMMARY

Debris flow occurrence is generally forecasted by means of empirical rainfall depth–duration thresholds based on raingauge observations. Rainfall estimation errors related to the sparse nature of raingauge data are enhanced in case of convective rainfall events characterized by limited spatial extent. Such errors have been shown to cause underestimation of the rainfall thresholds and, thus, less efficient forecasts of debris flows occurrence. This work examines the spatial organization of debris flows-triggering rainfall around the debris flow initiation points using high-resolution, carefully corrected radar data for a set of short duration (<30 h) storm events occurred in the eastern Italian Alps.

On average, triggering rainfall presents a local peak corresponding to the debris flow initiation point, with rain depth at 5 km (10 km) distance being on average around 70% (40%) of rain depth observed at the debris flow initiation points. The peak is consistently enhanced for events characterized by short durations and causes a systematic underestimation of the rainfall depth–duration thresholds when rainfall is measured away from the debris flow initiation points.

We develop an analytical framework that exploits the general characteristics of the spatial rainfall organization to predict the systematic underestimation of the depth–duration thresholds when rainfall is sampled away from the initiation points. Predictions obtained based on this analytical framework are assessed using a Monte Carlo sampling technique.

1. Introduction

Intense rainfall is a primary climatic factor controlling the triggering of shallow landslides and debris flows (termed DF hereinafter). The role of high-intensity rainfall in the triggering of these events was first noticed by Campbell (1975) in southern California. Starkel (1979) conceived a critical rainfall threshold as a combination of rainfall intensity and duration. Forecasting the occurrence of DF is fundamental for issuing hazard warnings and, following the methods developed for landslides, is largely based on rainfall as a triggering agent. Forecasters rely very often on the identification of combinations of depth and duration (or, equivalently, intensity and duration) of rainfall that have triggered widespread events (e.g., Caine, 1980; Wieczorek, 1996; Deganutti et al., 2000; Guzzetti et al., 2008; Frattini et al., 2009; Chen et al., 2011; Borga et al., 2014). A widely used rainfall threshold relationship consists of a power law model that links rainfall depth E to the rainfall duration D (Reichenbach et al., 1998; Aleotti, 2004; Guzzetti et al., 2007):

$$E = \alpha_T D^{\beta} \quad (1)$$

where the α_T and β parameters are derived empirically. Such a relationship is termed *ED* threshold hereinafter. Brunetti et al. (2010) and Peruccacci et al. (2012) proposed the frequentist as an objective method to empirically identify the parameters of the model starting from E, D pairs of rainfall that led to DF in the past. With this procedure, the β exponent is identified from the linear regression of the log transformation of the E, D pairs, while the multiplicative parameter α_T is set to represent a desired probability of exceedance.

The identification of the *ED* thresholds is usually based on raingauge rainfall data and on observations of debris flows occurrence (Guzzetti et al., 2008) and, as such, it is affected by a number of uncertainties (Nikolopoulos et al., 2014). As shown by Marra et al. (2014), the operation of sampling rainfall away from the DF

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initiation point may lead to uncertainties in the extrapolated values as well as in the *ED* threshold parameters, in particular in case of highly variable rainfall fields. Inspection of the literature shows that the quantitative analysis of this problem has been so far rarely approached (Nikolopoulos et al., 2014). This seems to be due mainly to the lack of reliable observations of rainfall spatial organization in the DF initiation region. Whereas rainfall data are available for DF occurred in instrumented catchments (Comiti et al., 2014), the spatial and temporal organization of triggering rainfall has been rarely analyzed. The recent availability of accurate radar rainfall estimates for DF triggering storms offers unprecedented access to high spatial and temporal resolution rainfall measurements in the initiation region and opens new perspectives in the examination of the effect of raingauge sampling for such events (Marra et al., 2014). Among the few studies on this topic, Nikolopoulos et al. (2015a) reported, for a number of DF in the eastern Italian Alps, that the rainfall depth estimated at the initiation point is generally underestimated, despite the interpolation method used, and that the observed bias increases with the distance between raingauge location and debris flows.

Errors associated to the sampling of rainfall away from the DF initiation points (termed estimation errors hereinafter) are in principle composed by both a random and a systematic component, i.e. estimation errors having zero and non-zero mean respectively. Fig. 1a shows a graphical example (hypothetical data) where rainfall is measured at the DF initiation points and the *ED* threshold relationship is obtained by means of the frequentist method. Fig. 1b shows the same case where the rainfall may be approximated by a stationary random field and is sampled away from the DF initiation points. In this case the estimation error is affected only by a random component with zero mean. Nevertheless, uncertainty in rainfall estimation (Borga and Vizzaccaro, 1997; Berne et al., 2004; Peleg et al., 2013) inflates the dispersion in the *E*, *D* pairs causing an underestimation of the identified *ED* threshold (Fig. 1b). Fig. 1c shows the same situation where a systematic estimation error (underestimation, in this case) is superimposed to the rainfall estimates. The systematic estimation error leads to a further underestimation of the identified *ED* threshold.

This work focuses on the rainfall space–time organization around DF as a cause of systematic estimation error of the DF triggering rainfall. We also analyze how this systematic estimation error propagates as a bias in the identification of the *ED* threshold. This objective is achieved by using accurate radar-based rainfall estimates for ten storms, which triggered 82 DF in a mountainous region in the Eastern Italian Alps. The radar-based rainfall fields are assumed to represent space–time patterns of true precipitation at the DF initiation points and in the surrounding area. We analyze the spatial organization of rainfall depths in a spatial window centered on the DF initiation point itself using this point as coordinate origin.

2. Study area and data

2.1. Study area

The study is focused on the Upper Adige River basin in Northern Italy (Fig. 2), closed at Trento (9700 km^2). This is a mountainous region with more than 64% of the area located above 1500 m a.s.l. The climate is continental and the precipitation regime is mainly influenced by western Atlantic airflows and southern circulation patterns (Frei and Schär, 1998; Norbiato et al., 2009a; Piacentini et al., 2012). The mean annual precipitation ranges from 400 to 700 mm/yr in the Western part to 1300–1800 mm/yr in the North-eastern and Southern part of the area. This difference depends on the sheltering of the Western part to southerly and northerly winds due to the alpine range and it is typical for the dry internal alpine region (Isotta et al., 2014). Rainfall extremes over the area reflects the dry-to-moderate rainfall regime, with 50-yr return period rainfall being around 35 mm at 1-h duration, and 50 mm at 3-h duration (Norbiato et al., 2009b). The temporal pattern of precipitation is characterized by a seasonal peak, in summer or in fall season, depending on the location, as highlighted by Nikolopoulos et al. (2015b). During the cold season (October–April), precipitation is dominated by snow and widespread storms, while during warm season (May–September) precipitation is brought by mesoscale convective systems and localized thunderstorms (Norbiato et al., 2009a; Mei et al., 2014).

Rainfall over the region is monitored by a network of 120 raingauges, that corresponds to an average spatial density of about 1/80 km^{-2}. A C-band, Doppler weather radar, located at 1860 m a.s.l. on the top of Mt. Macaion in a central position on the region (Fig. 2), provides quantitative rainfall estimates every 5 min, at a spatial resolution of 1 km. Detailed information about the instrument are reported in Marra et al. (2014).

A database reporting location and date of occurrence of DF is available for the area and includes more than 400 events during the period 2000–2012. These data have been obtained by systematic post-event surveys. The DF initiation point is geo-referenced with accuracy of 50 m while the date of occurrence is known for the majority of the record with the exception of few cases that are flagged with uncertainty of 1 day. The accuracy of this database represents an unprecedented detail for such a catalogue of historical landslide events (Guzzetti et al., 1994; Guzzetti and Tonelli, 2004; Pavlova et al., 2011).

2.2. Debris flows and radar rainfall data

We examine ten DF triggering rainfall events that occurred in the study area between 2005 and 2010 (Fig. 2). This period is selected based on the availability of high resolution, quality controlled radar rainfall estimates. The ten selected events are among

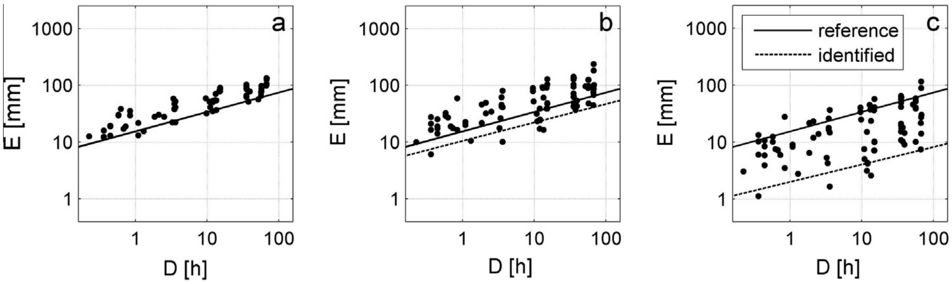

Fig. 1. Conceptual description of the effect of rainfall estimation uncertainty on the identified *ED* threshold relationship. (a) Ideal condition in which rainfall is measured at the DF initiation points; (b) case in which rainfall is measured away from the DF initiation points and rainfall estimation error is affected by a random component; (c) case in which rainfall is measured away from the DF initiation points and rainfall estimation error is affected by both a random and a systematic component.