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Radar rainfall estimation for the identification of debris-flow occurrence thresholds

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SUMMARY

This work aims to evaluate the potential benefits and limitations of radar rainfall estimates for the identification of debris flow occurrence rainfall thresholds. Observations from a C-band weather radar and raingauge data are analyzed for seven convective rainfall events that triggered 117 debris flows in the Upper Adige river basin (Eastern Italian Alps). Four radar rainfall scenarios characterized by incrementally increasing accuracy are used for the estimation of rainfall intensity–duration thresholds. Error sources considered in the radar correction chain include beam blockage, attenuation and vertical profile of reflectivity. The impact of rainfall accuracy on the estimation of the intensity–duration thresholds is analyzed by comparing the thresholds derived from the various radar rainfall scenarios, using the rainfall estimates obtained from the application of the complete correction algorithm as a reference scenario. Results show that the application of the complete correction algorithm improves significantly the accuracy of radar rainfall estimates: Fractional Standard Error is decreased by 20%, Correlation Coefficient is increased by 24% relative to uncorrected data. Correction for atmospheric attenuation is the most important step in the correction chain. The use of uncorrected radar estimates leads to substantially underestimated thresholds with respect to the reference scenario; adjusting radar data for bias is not sufficient to overcome this problem. Radar rainfall estimates which are corrected but not adjusted with raingauge data are able to provide intensity–duration thresholds which are almost indistinguishable from the reference scenario. The derivation of the radar-based threshold is shown to be very sensitive to spatial location errors of rainfall and debris flows. Raingauge-based thresholds are severely underestimated with respect to the reference scenario. This clearly demonstrates the severity of the raingauge-based estimation problem for the derivation of debris flow triggering rainfall and highlights the benefits of using weather radar observations, at least for the case of short duration convective storms.

1. Introduction

In mountain areas, rainfall-triggered landslides and associated debris flows are important geomorphic processes that scour low-order channels and deposit large quantities of sediment in higher-order channels and alluvial fans. These events may pose a significant hazard, resulting in high risks where development has encroached on debris flow source and run-out areas (Iverson et al., 1997). The release of debris flows is in general closely related to triggering meteorological events (e.g. Caine, 1980; Guzzetti et al., 2008). Recent reviews have highlighted the importance of precipitation intensity for the release of debris flows (Chen et al., 2007; Borga et al., 2014). Considerable research efforts have been made so far to determine the rainfall amount required to trigger slope failures and debris flows (Salvati et al., 2010). Susceptibility maps and models are typically used to estimate the spatial variability of the critical rainfall required to trigger landslides and debris flows (Borga et al., 2002; Guzzetti et al., 2005; Baum et al., 2010; Tarolli et al., 2011), while rainfall thresholds are determined to define the local or regional meteorological conditions that, when reached or exceeded, are likely to result in debris flows (e.g., Caine, 1980; Wieczorek, 1996; Cannon and Gartner, 2005; Guzzetti et al., 2008; Chen et al., 2011; Jakob et al., 2012). Rainfall thresholds for the possible initiation of landslides are usually defined as minimum levels above which a landslide may occur. They can be defined using both physical or empirical approaches (Aleotti, 2004; Wieczorek and Glade, 2005; Guzzetti et al., 2007, 2008; Schneuwly-Bollschweiler and Stoffel, 2012; and references

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therein). Often they consist of a relationship that links rainfall duration to the average rainfall intensity (Aleotti, 2004; Guzzetti et al., 2007). A very widely used model is as follows:

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

where I is the mean rainfall intensity over the rainfall duration D and α and β are parameters that adapt the power-law model to the empirical data. Starting with the works by Caine (1980) and Innes (1983), rainfall intensity–duration thresholds (*ID* thresholds, hereinafter) for debris flows occurrence have been identified at the local, regional, and global scales (Guzzetti et al., 2008, and references therein).

Most often, raingauges are used for the estimation of the rainfall characteristics of debris-flow triggering events and for the derivation of the rainfall thresholds. In spite of the large variability exhibited by rainfall fields in mountainous areas, few attention has been dedicated to the problem of rainfall estimation for debris flow triggering storms and researchers largely applied the concept of reference gauges (Jakob and Weatherly, 2003; Aleotti, 2004; Guzzetti et al., 2004; Godt et al., 2006; Brunetti et al., 2010 among many others), which relies on the observation of the nearest (to debris flow location) gauge for the estimation of triggering rainfall characteristics. However, the raingauge-based estimation of debris flow-triggering rainfall is generally characterized by large uncertainties, due to at least two problems. One problem is related to the scarcity of raingauges in the mountainous context where debris flows are more frequent. For example, in Guzzetti et al. (2004) only seven rain gauges were available for a study area of 5418 km^2. The second problem is that raingauges are commonly located at low elevations (e.g., in the valley floors) while debris flows typically originate at high elevations, in the head part of the mountain catchments (Stoffel et al., 2011; Borga et al., 2014). Nikolopoulos et al. (2014) have shown that the rainfall estimation uncertainty results in a systematic underestimation of the rainfall thresholds, leading to a step degradation of the performances of the rainfall threshold for identification of debris flows occurrence under operational conditions.

A potential solution to the observational limitations posed by raingauges, lies on remote-sensing observations, and more specifically on weather radar rainfall estimates. Compared with the sparse distribution of raingauges, the high spatial and temporal resolutions of radar-observed rainfall fields are highly desirable for debris flows and landslide studies, since they offer the unique advantage of estimating rainfall over the actual debris flow location (David-Novak et al., 2004; Chiang and Chang, 2009). The vast advancements of weather radar technology over the last decades enabled the use of these data sources for debris flow warning procedures. However, several factors, both instrumental and meteorological, affect the accuracy of radar-rainfall estimates in mountainous areas: a review is reported in Germann et al., 2006. A number of correction procedures have been proposed and tested for the main sources of errors, mainly for applications concerning the rainfall estimation for flood and flash flood forecasting (Pellarin et al., 2002; Krajewski et al., 2006; Villarini and Krajewski, 2010; Gourley et al., 2011). Nevertheless, radar-based estimation of debris-flow triggering rainfall may pose different challenges with respect to those characterizing more common hydrological applications. These differences are largely related to the small size of debris flow catchments (sometimes even less than 1 km^2, D'Agostino and Marchi, 2001) relative to those involved in flood-related phenomena, which are usually larger by at least an order of magnitude. Owing to the small size of the basin area, the random component of the error may have a larger impact on the total radar-rainfall estimation error (Cunha et al., 2012). Moreover, considering that debris flows scales are comparable to single radar pixel, it is expected that radar beam pointing errors may have an important effect on estimating the actual triggering rainfall properties. This is further reinforced if we take into account that debris flow triggering events are often characterized by high precipitation gradients (i.e. rainfall spatial variability) (Nikolopoulos et al., 2014).

So far, the number of studies on the use of radar rainfall estimates for derivation of debris flows rainfall thresholds is rather limited and focused on the use of standard radar products (often merged with raingauge data) for the purpose of rainfall threshold estimation (Wieczorek et al., 2000; David-Novak et al., 2004; Chen et al., 2007; Chiang and Chang, 2009; Saito et al., 2010). Given this background, the objective of this study is to assess the use of radar rainfall estimates as opposed to the commonly used raingauge-based estimates for *ID* threshold identification. In the study, four radar rainfall estimation scenarios of incremental complexity are evaluated by using the rain gauge observations as a benchmark for seven debris-flows triggering storms. In order to permit evaluation of situations where raingauge data may be unavailable for radar processing, which is not uncommon given the limited spatial extension of such rainfall events, two scenarios are obtained without using raingauges for radar adjustment. Rainfall estimates from all radar-rainfall scenarios and available raingauges are used to identify *ID* thresholds for the occurrence of debris flows by using the method proposed by Brunetti et al. (2010), and expanded by Peruccacci et al. (2012). Three specific objectives are addressed. The first one relates to the impact of various radar-rainfall correction procedures on the estimation of debris flow occurrence thresholds. The second objective is to assess the performance of the radar rainfall estimates, either adjusted and not by using raingauge data, for *ID* threshold identification. Finally, the third objective is to analyze the impact of spatial co-location accuracy of rainfall and debris-flows in the identification of *ID* threshold relationships.

The study area is represented by the Upper Adige river basin in the Eastern Italian Alps where localized intense storms are able to trigger a large number of debris flows especially during the summer season. Over this area, observations from a C-band weather radar and raingauge data are analyzed for seven rainfall events that triggered 117 debris flows.

The presentation of the paper will adopt the following outline. Section 2 describes the study area and the data made available for the investigation. The radar rainfall estimation procedures and the method used for the identification of the *ID* thresholds are illustrated in Section 3. Results are reported in Section 4. Finally, the implications for use of weather radar rainfall information in debris flows occurrence forecasts are discussed in Section 5, together with the conclusions from the study.

2. Study area and data

The study area is represented by the Upper Adige River basin closed at Trento, a mountainous region covering approximately 9700 km^2 in Northern Italy (Fig. 1). The region is characterized by a complex topography, with elevation ranging between 200 and 3990 m a.s.l. and a mean elevation of about 1800 m a.s.l. Two main geological formations can be identified in the area: metamorphic rocks such as gneiss, phyllites, micaschists and, to a lesser extent, calc-schists, prasinites and serpentinites, which are prevailing in the north-western part of the region, whereas dolomites and limestones are prevailing in the south-eastern part of the region (Norbiato et al., 2009).

The dominant climate in the area is continental. The rainfall monthly distribution is influenced by western Atlantic airflows and southern circulation patterns (Frei and Schär, 1998). It shows two maxima in summer (August) and fall season (October), with