Geomorphology 243 (2015) 40–50

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Estimation of debris flow triggering rainfall: Influence of rain gauge density and interpolation methods

E.I. Nikolopoulos [a,*], M. Borga [a], J.D. Creutin [b], F. Marra [c]

[a] Department of Land, Environment, Agriculture and Forestry, University of Padova, Legnaro, Italy
[b] Université de Grenoble/CNRS, Laboratoire d'étude des Transferts en Hydrologie et Environnement, LTHE, UMR 5564, Grenoble F-38041, France
[c] Department of Geography, Hebrew University of Jerusalem, Jerusalem, Israel

ARTICLE INFO

Article history:
Received 14 August 2014
Received in revised form 1 April 2015
Accepted 28 April 2015
Available online 6 May 2015

Keywords:
Debris flows
Landslides
Rainfall estimation
Rainfall threshold
Rain gauge network design
Weather radar

ABSTRACT

The forecast of debris flow occurrence relies mainly on empirical rainfall intensity–duration thresholds, which are based on rain gauge observations. This work focuses on the effect of rainfall estimation uncertainty on the estimation of debris flow triggering rainfall events and on the identification of rainfall thresholds for debris flow occurrence. Specifically, the influence of rain gauge network density and the interpolation method on the estimation of debris flow triggering rainfall is investigated. These questions are examined using high-resolution, carefully corrected radar data to represent space–time patterns of true precipitation at the debris flow initiation points and in the surrounding area. Radar rainfall fields are sampled by simulated rain gauge networks, stochastically generated with varying rain gauge densities. Based on these networks, rainfall is estimated by using three rainfall interpolation methods: nearest neighbor (NN), inverse distance weighting (IDW) and ordinary kriging (OK). Results show that NN provides the estimates with bias smaller than IDW and OK but larger estimation variance. Overall, decrease in gauge density leads to increased underestimation and increased estimation variance of debris flow triggering rainfall. Rainfall estimation error leads to large underestimation of the intensity–duration thresholds. However, comparison of results shows that no particular benefit in intensity–duration threshold estimation is obtained by using approaches that are more complex than the NN method.

1. Introduction

Rainfall-induced landslides and debris flows pose a significant and widespread hazard, resulting in a large number of casualties and enormous economic damages worldwide (Salvati et al., 2010; Petley, 2012; Borga et al., 2014; Dowling and Santi, 2014; Melillo et al., 2014). Considerable research efforts have been made so far to determine the rainfall amount required for rainfall-induced landslides or debris flows (Salvati et al., 2010). Rainfall thresholds are often used to identify the local or regional rainfall conditions that, when reached or exceeded, are likely to result in landslides or debris flows (e.g., Caine, 1980; Wieczorek, 1996; Deganutti et al., 2000; Cannon and Gartner, 2005; Guzzetti et al., 2008; Frattini et al., 2009; Saito et al., 2010; Chen et al., 2011; Jakob et al., 2012). Following the pioneering works of Caine (1980) and Innes (1983), rainfall thresholds for shallow landslides and debris flows (collectively termed 'debris flows' hereinafter) were determined at the local, regional, and global scales. Guzzetti et al. (2008) proposed a review of the literature on rainfall thresholds for the possible initiation of debris flows. The identification of rainfall thresholds is affected by a number of uncertainties that limit the accuracy of debris flow forecasts and warnings (Guzzetti et al., 2008; Kirschbaum et al., 2012; Nikolopoulos et al., 2014). A specific source of uncertainty lies in the estimation of the rainfall amounts that are responsible for debris flows (Guzzetti et al., 2007; Nikolopoulos et al., 2014).

Rain gauge data are the typical source of information for the definition of the rainfall thresholds. This implies that, with the exception of the very rare cases when rain gauge data are available at the debris flow initiation site, rainfall data for debris flow events are estimated based on data from more or less remote neighboring stations. This rainfall estimation is difficult for two main reasons. First, debris flow triggering storms are often characterized by large rainfall gradients, possibly influenced by complex topography (Marra et al., 2014). Second, unknown precipitation must be estimated at points where it exceeds a threshold and it often forms a local peak (Marra et al., submitted for publication). As a result, findings from the literature on rainfall spatial estimation (see Masson and Frei, 2014 and references therein), where the whole rainfall distribution is sought, may not be completely relevant for the case of debris flow triggering storms.

Inspection of the literature shows that little attention has been dedicated to the problem of rainfall estimation for debris flow triggering storms (Chiang and Chang, 2009; Melillo et al., 2014). While the spatial variability of rainfall fields is often identified as a potential problem,

* Corresponding author. Tel.: +39 498272681; fax: +39 498272750.
E-mail address: efthymios.nikolopoulos@unipd.it (E.I. Nikolopoulos).

http://dx.doi.org/10.1016/j.geomorph.2015.04.028
0169-555X/

researchers often overlook it in debris flow threshold modeling primarily because of the scarcity of rain gauges, especially in mountainous areas (Jakob and Weatherly, 2003; Guzzetti et al., 2004). Debris flow triggering rainfall is often estimated based on the concept of the reference gauges (e.g., Jakob and Weatherly, 2003; Aleotti, 2004; Godt et al., 2006; Brunetti et al., 2010; Berti et al., 2012; Schneuwly-Bollschweiler, and Stoffel, 2012), which relies on the observation at the gauge nearest to the debris flow location. Nikolopoulos et al. (2014) have shown that inferring rainfall properties at initiation points from the closest rain gauge is associated with significant uncertainty. Furthermore, they showed that application of the closest gauge estimates leads to significantly underestimated thresholds of debris flow occurrence with a subsequent degradation of the efficiency of the warning procedures based on these thresholds. However, the work of Nikolopoulos et al. (2014) is based on a simulation exercise; hence, results may be claimed dependent on the realism of the simulation experiment itself.

The work presented in this paper has two main objectives. Firstly, we aim to quantify the dependence of the accuracy of debris flow-triggering rainfall estimation on rain gauge density and the use of various rainfall estimation procedures. Secondly, we evaluate the impact of the rainfall estimation errors on the identification of the intensity–duration (*ID*, hereinafter) thresholds used for predicting landslide and debris flow occurrence. These questions are examined by using high-resolution, carefully corrected radar rainfall data to represent space–time patterns of true precipitation at the debris flow initiation points and in the surrounding area. These rainfall fields are sampled by simulated rain gauge networks, stochastically generated with varying gauge densities. This approach is ideally suited to assess the properties of rainfall estimation errors in areas with strong gradients, where alternative methods are lacking. As such, this approach has been used in a number of studies for the assessment of the influence of rainfall sampling on areal rainfall estimation and rainfall–runoff modeling (Seed and Austin, 1990; Duncan et al., 1993; Fabry et al., 1994; Bradley et al., 2002; Volkmann et al., 2010). The present work is based on the availability of accurate radar-based estimates of rainfall fields for 10 storms, which triggered 82 debris flows in a mountainous region in the Eastern Italian Alps (the Upper Adige River basin).

Based on such simulated networks, four gauge densities are considered and three interpolation techniques are used to derive rainfall estimates at the debris flow initiation points. The rainfall estimation procedures considered here are: i) the nearest neighbor technique; ii) the inverse distance method; and iii) ordinary kriging. These estimates are then used to identify the *ID* thresholds for debris flows occurrence. Results are compared against the reference threshold obtained by using the actual rainfall data at debris flow initiation locations. In order to isolate the properties of the interpolation algorithms and to assess the effects of varying rain gauge density, we do not apply here further criteria for the reconstruction of rainfall events, i.e. application of minimum rainfall depth thresholds (Melillo et al., 2014; Nikolopoulos et al., 2014).

2. Study area and data

The area of study is part of the Upper Adige River basin in Northern Italy (Fig. 1), a mountainous region with more than 64% of the area located above 1500 m a.s.l., whereas only 4% of the area is located below 500 m a.s.l. The south-eastern sector of the region belongs to the Dolomites, the north-eastern part to the Noric Alps and the western sector to the eastern Rhaetian Alps, including the highest peak of Mt. Ortles (3902 m) (Norbiato et al., 2009a; Piacentini et al., 2012). The climate pattern in the area is predominantly continental and the precipitation regime is influenced by western Atlantic airflows and southern circulation patterns (Frei and Schär, 1998). The monthly distribution of precipitation in the area is characterized by two maxima, in August and October. During the cold season (October–April) precipitation is dominated by snow and widespread rainfall, while during the warm season (May–September) precipitation is brought by mesoscale

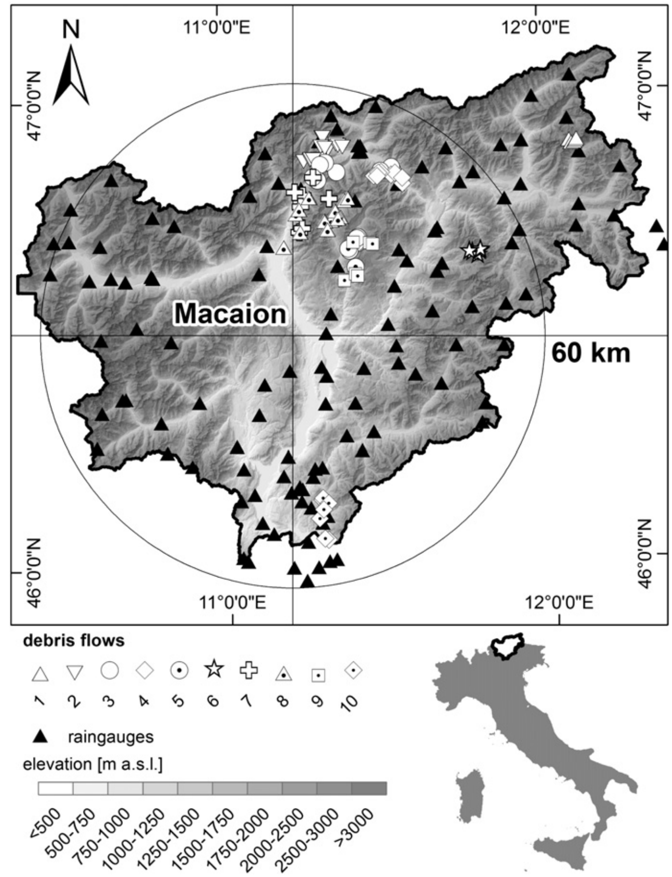

Fig. 1. Map showing the Upper Adige river basin in Trento. Shades of color show terrain elevations. Black triangles show locations of available rain gauges in the region and the other symbols correspond to the locations of the 82 debris flows analyzed. The number corresponding to the symbols refers to the event number in Table 1. Location of the Macaion weather radar with the range circle at 60 km is also shown.

convective systems and localized thunderstorms (Norbiato et al., 2009a; Mei et al., 2014). Mean annual precipitation ranges from 400 to 700 mm at the Western part of the area and rises to 1300–1800 mm at the Northern and Southern parts. Reduced precipitation at the Western part results from the sheltering of Alpine range to southerly and northerly winds and it is typical for the dry internal alpine region (Isotta et al., 2014). The dry-to-moderate rainfall regime is reflected also in the climatology of the rainfall extremes. Rainfall quantiles corresponding to a 100-year return period rarely exceed 50 mm at 1-h duration, and 150 mm at 24-h duration (Norbiato et al., 2009b).

2.1. Debris flow and radar rainfall data

A database reporting the location and the date of debris flow occurrence in the study area is available for more than 400 debris flows during 2000–2012. Location of the initiation point of the individual debris flows is geo-referenced with accuracy better than ± 50 m while the date of occurrence is considered certain for the vast majority of the record except few cases that are flagged with uncertainty of 1 day. This is an unprecedented detail for catalogues of historical landslide events (Guzzetti et al., 1994; Guzzetti and Tonelli, 2004; Pavlova et al., 2014).

The region is monitored by a network of 120 rain gauges with an average spatial density of about 1/80 km^{-2}, and by a C-band, Doppler weather radar located at 1860 m a.s.l. on the top of Mt. Macaion, a central position in the study area (Fig. 1). Quantitative precipitation estimates, derived from the radar reflectivity observations, are available at high spatial (1 km) and temporal (5 min) resolution (Marra et al., 2014).