

# Calibration and validation of rainfall thresholds for shallow landslide forecasting in Sicily, southern Italy

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## ARTICLE INFO

### Article history:

Received 7 June 2014

Received in revised form 26 September 2014

Accepted 13 October 2014

Available online 24 October 2014

### Keywords:

Rainfall threshold

Shallow landslide

Sicily

Contingency table

Skill score

Validation

## ABSTRACT

Empirical rainfall thresholds are tools to forecast the possible occurrence of rainfall-induced shallow landslides. Accurate prediction of landslide occurrence requires reliable thresholds, which need to be properly validated before their use in operational warning systems. We exploited a catalogue of 200 rainfall conditions that have resulted in at least 223 shallow landslides in Sicily, southern Italy, in the 11-year period 2002–2011, to determine regional event duration–cumulated event rainfall (*ED*) thresholds for shallow landslide occurrence. We computed *ED* thresholds for different exceedance probability levels and determined the uncertainty associated to the thresholds using a consolidated bootstrap nonparametric technique. We further determined subregional thresholds, and we studied the role of lithology and seasonal periods in the initiation of shallow landslides in Sicily. Next, we validated the regional rainfall thresholds using 29 rainfall conditions that have resulted in 42 shallow landslides in Sicily in 2012. We based the validation on contingency tables, skill scores, and a receiver operating characteristic (ROC) analysis for thresholds at different exceedance probability levels, from 1% to 50%. Validation of rainfall thresholds is hampered by lack of information on landslide occurrence. Therefore, we considered the effects of variations in the contingencies and the skill scores caused by lack of information. Based on the results obtained, we propose a general methodology for the objective identification of a threshold that provides an optimal balance between maximization of correct predictions and minimization of incorrect predictions, including missed and false alarms. We expect that the methodology will increase the reliability of rainfall thresholds, fostering the operational use of validated rainfall thresholds in operational early warning system for regional shallow landslide forecasting.

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## 1. Introduction

In many regions, rainfall is the primary trigger of shallow landslides that can cause fatalities, widespread damages and economic losses. For this reason, the ability to forecast rainfall-induced shallow landslides is of primary interest to mitigate the related risk. Empirical approaches to forecast the occurrence of rainfall-induced shallow landslides rely upon the definition of rainfall thresholds (e.g., Aleotti, 2004; Guzzetti et al., 2007, 2008). Rainfall thresholds can be implemented in landslide warning systems, where they are compared with rainfall measurements, estimates or forecasts to evaluate the possible occurrence of landslides (e.g., Aleotti, 2004; Guzzetti et al., 2008; Baum and Godt, 2009; Rossi et al., 2012). Accurate prediction of rainfall-induced landslides requires

reliable thresholds, which need to be validated before their use in operational landslide warning systems. Still, proper evaluation of rainfall thresholds is difficult, and only a few validation procedures have been proposed in the literature (Giannecchini et al., 2012; Martelloni et al., 2012; Segoni et al., 2014), all exploiting standard contingency tables and skill scores (Jolliffe and Stephenson, 2003; Staley et al., 2012). None of the proposed validation procedures considers the uncertainty inherent to landslide forecasts, mainly because of the partial or total lack of information on landslide occurrence, hampering the accurate measurement of the performance of empirical rainfall thresholds.

In this work, we use a statistical method (Brunetti et al., 2010; Peruccacci et al., 2012) to define empirical, cumulated rainfall event–rainfall duration (*ED*) thresholds for shallow landslide occurrence in Sicily, southern Italy. Next, we propose a new general procedure for the validation of the thresholds. The validation procedure exploits a standard contingency table and related skill scores (Jolliffe and Stephenson, 2003; Staley et al., 2012), and considers the effects of the

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lack of information on landslide occurrence on the performance of the rainfall thresholds. The paper is organized as follows. In [Section 2](#), we provide background information on the definition and validation of empirical rainfall thresholds for landslide occurrence. This is followed by a description of the study area ([Section 3](#)), of the landslide and rainfall data used for the study ([Section 4](#)), and of the methods adopted to calibrate the thresholds ([Section 5](#)). Next, in [Section 6](#), we present regional and subregional thresholds for possible shallow landslide occurrence in Sicily; and we discuss how sample size, lithology, and seasonality affect the thresholds. In [Section 7](#), we propose a general validation procedure that allows the definition of *optimal* thresholds for early warning purposes, and we discuss the weakness of the validation procedure caused by the inherent lack of information on landslide occurrence in large study areas. We conclude ([Section 8](#)) by summarizing the lessons learnt.

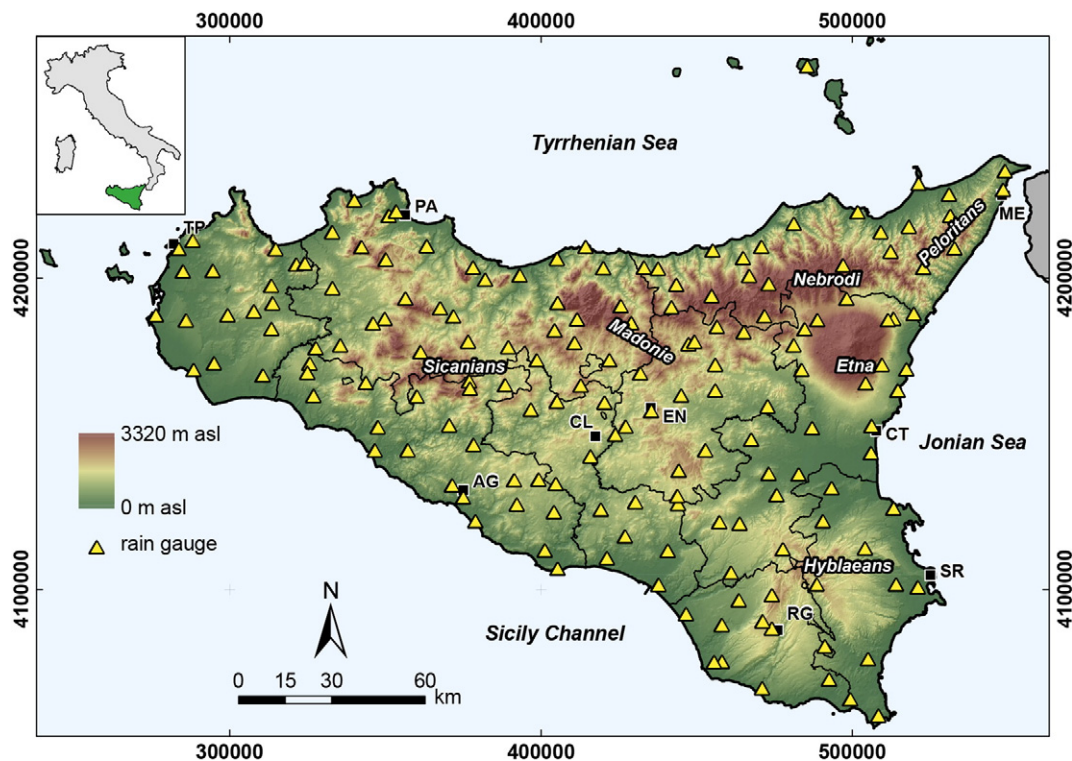
## 2. Background

Most commonly, prediction of rainfall-induced landslides relies on empirical rainfall thresholds obtained from the analysis of past rainfall events that have resulted in slope failures ([Reichenbach et al., 1998](#); [Guzzetti et al., 2007, 2008](#); [Berti et al., 2012](#)). Empirical rainfall thresholds are relationships linking rainfall events to the occurrence (or lack of occurrence) of landslides. Most of the empirical rainfall thresholds for possible landslide occurrence available in the literature link the duration of the rainfall events ( $D$ ) to the mean rainfall intensity ( $I$ ) (e.g., [Caine, 1980](#); [Crosta, 1998](#); [Aleotti, 2004](#); [Guzzetti et al., 2007](#); [Cannon et al., 2008](#); [Guzzetti et al., 2008](#)) or to the cumulated event rainfall ( $E$ ) (e.g., [Innes, 1983](#); [Cannon and Ellen, 1985](#); [Wieczorek, 1987](#); [Crosta, 1998](#); [Kanji et al., 2003](#)) of past rainfall events that have resulted in landslides. Where information on rainfall events that did not result in slope failures is available, rainfall thresholds attempt to separate the rainfall conditions that have and have not resulted in landslides (e.g., [Jibson, 1989](#); [Crozier, 1997](#); [Corominas and Moya, 1999](#); [Marchi et al., 2002](#); [Pedrozzì, 2004](#); [Giannecchini, 2005](#); [Berti et al.,](#)

[2012](#)). Regardless of the method used to determine the thresholds, the empirical rainfall thresholds are represented by curves in the  $D,I$  or  $D,E$  planes that separate rainfall conditions that are expected to trigger landslides (above the threshold lines) from rainfall conditions that are not expected to cause slope instability (below the thresholds).

Inspection of the literature ([Guzzetti et al., 2007, 2008](#)) revealed that most of the empirical rainfall thresholds available in the literature were – and most commonly still are – defined using non objective and poorly reproducible methods. As a result, existing and new thresholds are difficult – or impossible – to compare and to evaluate quantitatively ([Guzzetti et al., 2007](#); [Brunetti et al., 2010](#)). This hampers the use of thresholds in operational landslide warning systems. To overcome the problem, investigators have proposed new methods and procedures for the objective and reproducible definition of empirical rainfall thresholds for possible landslide occurrence. [Guzzetti et al. \(2007\)](#) exploited a Bayesian approach to obtain reproducible rainfall thresholds from a catalogue of  $(D,I)$  rainfall conditions that have resulted in landslides in southern Europe. [Brunetti et al. \(2010\)](#) proposed a method based on a frequentist statistical analysis of  $(D,I)$  rainfall conditions that have resulted in landslides in Italy. [Peruccacci et al. \(2012\)](#) have extended the method to (i) consider  $(D,E)$  rainfall conditions, (ii) determine the uncertainty associated to the empirical thresholds, and (iii) evaluate the minimum number of empirical points required to determine reliable thresholds. [Berti et al. \(2012\)](#) applied a Bayesian statistical approach to a catalogue of  $(D,I)$  rainfall conditions in the Emilia-Romagna region, central Italy, that have and have not resulted in landslides to determine mean rainfall intensity – rainfall duration ( $ID$ ) regional thresholds. [Staley et al. \(2012\)](#), working in two small areas in southern California, proposed a method for the objective definition of  $ID$  rainfall thresholds for the initiation of post-fire debris flows. Considering rainfall conditions that have and have not resulted in debris flows, they obtained thresholds considering the number of correct and incorrect predictions.

Despite the clear relevance of validation for the sound evaluation of rainfall thresholds for possible landslide occurrence, inspection of the



**Fig. 1.** Map of Sicily showing terrain elevation (shades of green to brown) and location of rain gauges used in this study (yellow triangles). Names of major mountain ranges (in white) and location of capital cities of the nine Provinces (black squares; AG, Agrigento; CL, Caltanissetta; CT, Catania; EN, Enna; ME, Messina; PA, Palermo; SR, Siracusa; RG, Ragusa; TP, Trapani) are also shown.

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