Geomorphology 257 (2016) 94–107

Contents lists available at ScienceDirect

Geomorphology

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

Probabilistic rainfall thresholds for triggering debris flows in a human-modified landscape

Roberto Giannecchini [a], Yuri Galanti [a,*], Giacomo D'Amato Avanzi [a], Michele Barsanti [b]

[a] Department of Earth Sciences, University of Pisa, Via S. Maria 53, 56126 Pisa, Italy
[b] Department of Civil and Industrial Engineering, University of Pisa, Largo Lucio Lazzarino 2, 56122 Pisa, Italy

ARTICLE INFO

Article history:
Received 24 April 2015
Received in revised form 15 December 2015
Accepted 17 December 2015
Available online 24 December 2015

Keywords:
Probabilistic rainfall threshold
Logistic regression
Debris flow
Human-modified landscape
Tuscany
ROC analysis

ABSTRACT

In the Carrara Marble Basin (CMB; Apuan Alps, Italy) quarrying has accumulated widespread and thick quarry waste, lying on steep slopes and invading valley bottoms. The Apuan Alps are one of the rainiest areas in Italy and rainstorms often cause landslides and debris flows. The stability conditions of quarry waste are difficult to assess, owing to its textural, geotechnical and hydrogeological variability. Therefore, empirical rainfall thresholds may be effective in forecasting the possible occurrence of debris flows in the CMB. Three types of thresholds were defined for three rain gauges of the CMB and for the whole area: rainfall intensity–rainfall duration (*ID*), cumulated event rainfall–rainfall duration (*ED*), and cumulated event rainfall normalized by the mean annual precipitation–rainfall intensity ($E_{MAP}I$).
The rainfall events recorded from 1950 to 2005 was analyzed and compared with the occurrence of debris flows involving the quarry waste. They were classified in events that triggered one or more debris flows and events that did not trigger debris flows. This dataset was fitted using the logistic regression method that allows us to define a set of thresholds, corresponding to different probabilities of failure (from 10% to 90%) and therefore to different warning levels. The performance of the logistic regression in defining probabilistic thresholds was evaluated by means of contingency tables, skill scores and receiver operating characteristic (ROC) analysis. These analyses indicate that the predictive capability of the three types of threshold is acceptable for each rain gauge and for the whole CMB. The best compromise between the number of correct debris flow predictions and the number of wrong predictions is obtained for the 40% probability thresholds. The results obtained can be tested in an experimental debris flows forecasting system based on rainfall thresholds, and could have implications for the debris flow hazard and risk assessment in the CMB.

1. Introduction

The famous marble and a spectacular mountain landscape close to the Versilia coastline make the Apuan Alps (Tuscany, Italy) well-known in the world. Here the marble excavation is intense and quarrying areas and quarry wastes, named *ravaneti*, can dominate the landscape. In the Carrara Marble Basin (CMB; Figs. 1 and 2) the quarry density is among the highest in the world with at least 7 quarries km^{-2}, while the Apuan and the Italian averages are 0.33 and 0.03 quarries km^{-2}, respectively (Cortopassi et al., 2008). Marble quarrying and working are sources of income and tourist attraction and remains of ancient quarries, excavation techniques and buildings are examples of industrial archeology and geosites (D'Amato Avanzi and Verani, 2000). A long-lasting quarrying activity can cause environmental and hydrogeological problems because waste materials are commonly discharged onto the slopes, without stabilization. At present they cover wide areas and often reach and occupy the valley bottoms (Figs. 1 and 2).

The Apuan Alps are among the rainiest areas in Italy and frequently hit by heavy rainstorms, which often induce floods and landslides, sometimes causing damage and casualties (Giannecchini and D'Amato Avanzi, 2012). Mass movements and especially debris flows often involve these waste materials (Cortopassi et al., 2008). In this context, hazard assessment and early warning systems can be helpful in protecting population, workers and factories and reducing the risk. However, a lot of information is needed to model the processes leading to instability and to predict the time of failure.

Various authors assert that the empirical rainfall thresholds can be used in a landslide early warning system to forecast the possible occurrence of rainfall-induced landslides (e.g., Chleborad et al., 2008; Baum and Godt, 2010; Rossi et al., 2012; Vennari et al., 2014; Calvello et al., 2015; Gariano et al., 2015; Rosi et al., 2015; Segoni et al., 2015). Hence, a black box approach can help us to overcome some difficulties in determining the rainfall thresholds to be applied in warning and civil protection activities against quarry waste instability. Historical data on debris flows and related damage can allow us to define the

* Corresponding author.
E-mail address: galanti@dst.unipi.it (Y. Galanti).

http://dx.doi.org/10.1016/j.geomorph.2015.12.012
0169-555X/

Fig. 1. The Apuan Alps close to Carrara. Quarries and quarry waste stand out as white areas.

rainfall thresholds for the CMB, in terms of duration, cumulated event rainfall, intensity, and mean annual precipitation.

2. Study area

This paper focuses on the well-known CMB, where Michelangelo Buonarroti chose the marble for his masterpieces and a lot of quarries are working. The CMB is among the most famous and precious quarrying sites in the world. It is subdivided into the four Colonnata, Miseglia, Torano and Pescina–Boccanaglia sub-basins (Fig. 2).

The Carrara marble consists of Hettangian limestone, metamorphosed to greenschist facies during Upper Oligocene–Upper Miocene. It is part of the Apuan Alps Metamorphic Complex (Paleozoic-Upper Oligocene), the main tectonic structure of the Apuan Alps (Conti et al., 2004). The Carrara marble is a high quality, white or blue-grey ornamental stone, mostly used in sculpture and building decoration. Its beauty and many famous masterpieces make this marble very appreciated and renowned in the world. The marble exploitation has been documented since Roman times, with evidence of pre-Roman activity (Bruschi et al., 2004). In time, quarrying has more and more developed,

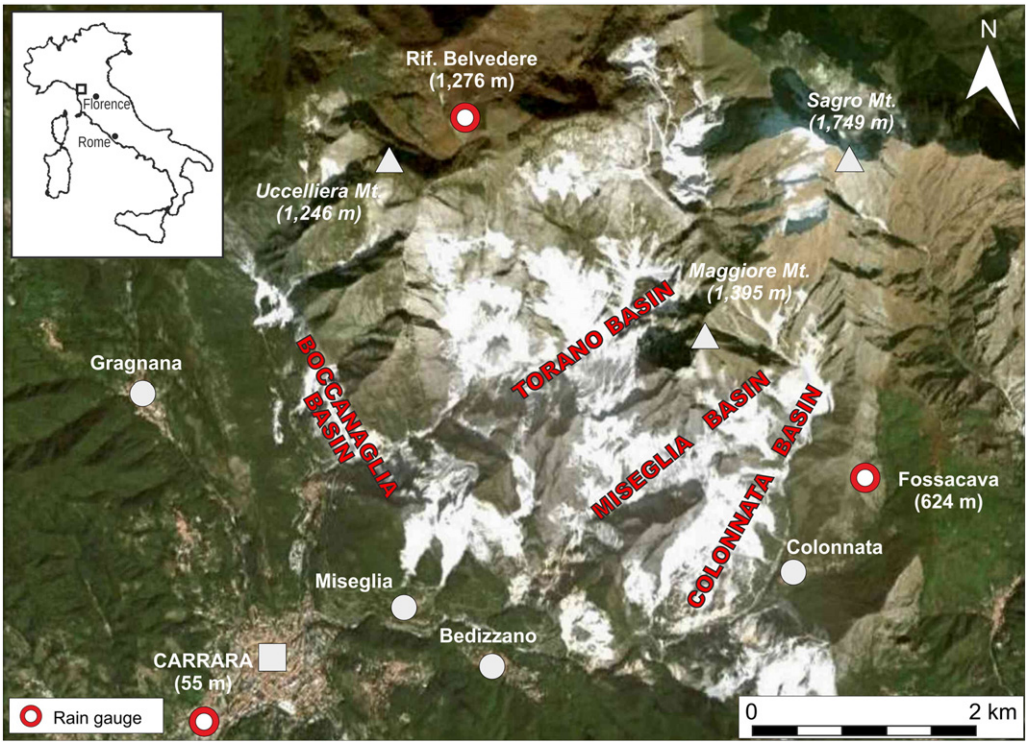

Fig. 2. The Carrara Marble Basin: white areas evidence quarries and quarry waste (base map by Google Earth, captured in 2014).