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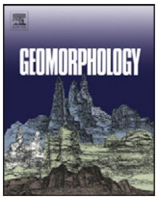

Scaling properties of rainfall induced landslides predicted by a physically based model

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ABSTRACT

Natural landslides exhibit scaling properties revealed by power law relationships. These relationships include the frequency of the size (e.g., area, volume) of the landslides, and the rainfall conditions responsible for slope failures in a region. Reasons for the scaling behavior of landslides are poorly known. We investigate the possibility of using the Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability analysis code (TRIGRS), a consolidated, physically-based, numerical model that describes the stability/instability conditions of natural slopes forced by rainfall, to determine the frequency statistics of the area of the unstable slopes and the rainfall intensity (I)–duration (D) conditions that result in landslides in a region. We apply TRIGRS in a portion of the Upper Tiber River Basin, Central Italy. The spatially distributed model predicts the stability/instability conditions of individual grid cells, given the local terrain and rainfall conditions. We run TRIGRS using multiple, synthetic rainfall histories, and we compare the modeling results with empirical evidences of the area of landslides and of the rainfall conditions that have caused landslides in the study area. Our findings revealed that TRIGRS is capable of reproducing the frequency of the size of the patches of terrain predicted as unstable by the model, which match the frequency size statistics of landslides in the study area, and the mean rainfall D, I conditions that result in unstable slopes in the study area, which match rainfall $I - D$ thresholds for possible landslide occurrence. Our results are a step towards understanding the mechanisms that give rise to landslide scaling properties.

1. Introduction

There is accumulating evidence that natural landslides exhibit scaling properties (Hergarten, 2000; Hergarten, 2002; Turcotte et al., 2002; Chen et al., 2011), including the area and volume of the slope failures (Pelletier et al., 1997; Stark and Hovius, 2001; Guzzetti et al., 2002; Malamud et al., 2004; Van Den Eeckhaut et al., 2007; Brunetti et al., 2009a), and the amount of rainfall required for the initiation of landslides in a region (Caine, 1980; Innes, 1983; Aleotti, 2004; Guzzetti et al., 2007; Guzzetti et al., 2008b). The scaling properties of landslides are revealed by power law dependencies, and are considered evidence of the critical state of landscape systems dominated by slope wasting phenomena (Hergarten, 2002; Turcotte et al., 2002).

It is known that, regardless of the physiographic or the climatic settings, the probability (or frequency) density of event landslides increases with the area of the landslide up to a maximum value, known as the “rollover”, after which the density decays along a power law (Stark and Hovius, 2001; Malamud et al., 2004; Van Den Eeckhaut et al., 2007). The length scale for the rollover, and the rapid decay along a power law, are conditioned by the mechanical and structural properties of the soil and bedrock where the landslides occur (Katz and Aharonov, 2006; Stark and Guzzetti, 2009), and are independent of the landslide trigger (Malamud et al., 2004). The probability (or frequency) density of the landslide volume obeys a negative power-law, with a scaling controlled by the type of the landslides (Brunetti et al., 2009a). The dependence of landslide volume on landslide area was also shown to obey a distinct scaling behavior over more than eight orders of magnitude (Guzzetti et al., 2009; Larsen et al., 2010; Klar et al., 2011).

Rainfall is a recognized trigger of landslides, and early investigators have recognized that empirical rainfall thresholds can be established to determine the amount of rainfall required to initiate landslides in a region (Endo, 1970; Caine, 1980; Govi and Sorzana, 1980; Innes, 1983; Moser and Hohensinn, 1983; Cancelli and Nova, 1985). Different types of empirical thresholds that use combinations of rainfall measurements obtained from the analysis of rainfall events that resulted (or did not result) in landslides were proposed in the literature, including mean intensity–duration ($I - D$) and rainfall cumulated event–duration ($E - D$) thresholds, and their variations (Guzzetti et al., 2007; Guzzetti et al., 2008b). With a few exceptions (Cannon and Ellen, 1985; Wieczorek, 1987; Crosta and Frattini, 2003) all the empirical rainfall thresholds are represented by power law models, indicative of the self-similar behavior of the rainfall characteristics responsible for landslide occurrence.

Despite the abundant empirical evidence, the reasons for the scaling behaviors of landslide phenomena are poorly known, and only a few attempts were made to interpret the empirical evidences with

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deterministic or physically based models (Katz and Aharonov, 2006; Stark and Guzzetti, 2009). In this paper, we show that a relatively simple, physically based model that describes the stability/instability conditions of slopes forced by rainfall, when applied to a sufficiently large geographical area produces results that are in agreement with two known scaling properties of landslides, namely: (i) the rainfall conditions that result in unstable slopes, which match regional empirical $I - D$ thresholds for possible landslide occurrence (Guzzetti et al., 2007; Guzzetti et al., 2008b), and (ii) the frequency distribution of the area of the patches of terrain predicted as unstable by the model, which matches the statistics of landslide area for event landslides (Pelletier et al., 1997; Stark and Hovius, 2001; Malamud et al., 2004; Van Den Eeckhaut et al., 2007).

The paper is organized as follows. In Section 2, we describe the geographical area in Central Italy where we have conducted our experiments (Fig. 1), and in Section 3 we provide general information on the Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability analysis code (TRIGRS, version 2.0; Baum et al., 2008) that we adopted for the experiments. Next, in Section 4, we compare the $I - D$ conditions capable of producing slope instability in the study area predicted by TRIGRS, with empirical rainfall $I - D$ thresholds for possible landslide occurrence in Central Italy. This is followed by a comparison of the probability density of the area of the patches of terrain predicted as unstable by TRIGRS in the study area with the probability density of natural landslides in the same general area, and by a discussion about the possible relations of this work to other existing approaches for the description of landslide scaling phenomena. We conclude, in Section 7, summarizing the lessons learnt.

2. Study area and data

The Upper Tiber River Basin (UTRB) extends for 4098 km^2 in Central Italy, with elevation in the range from 163 m at the basin outlet to 1571 m along the divide between the Adriatic Sea and the Tyrrhenian Sea (Fig. 1). In the area the landscape is hilly or mountainous, with open valleys and intra-mountain basins. In the mountains and the hills, the morphology is conditioned by lithology and the attitude of the bedding planes. Climate is Mediterranean, with most of the precipitation falling from October to December and from February to April (Cardinali et al., 2001; Guzzetti et al., 2008a).

For the UTRB two digital representations of the terrain elevation (DEM) were available to us. A coarser DEM, with a ground resolution of 25 × 25 m, was obtained through the linear interpolation of elevation data along contour lines shown on 1:25,000 topographic base maps (Cardinali et al., 2001). A finer DEM, with a ground resolution of 10 × 10 m, was prepared by the Italian National Institute for Geophysics and Volcanology through the interpolation of multiple sources of elevation data (Tarquini et al., 2007; Tarquini et al., 2012).

Five lithological complexes, or groups of rock units, crop out in the UTRB (Cardinali et al., 2001; Guzzetti et al., 2008a), including, from younger to older: (a) recent fluvial and lake deposits, which crop out mostly along the valley bottoms, (b) unconsolidated and poorly consolidated sediments pertaining to a continental, post-orogenic sequence, Pliocene to Pleistocene in age, (c) allochthonous rocks, lower to middle Miocene in age, (d) sediments pertaining to the Tuscany turbidite sequence, Eocene to Miocene in age, and to the Umbria turbidite sequence, Miocene in age, and (e) sediments pertaining to the Umbria-Marche stratigraphic sequence, Lias to lower Miocene in age. Soils reflect the lithological types, and range in thickness from less than 20 cm to more than 1.5 m. Landslides are abundant in the area, and cover 523 km^2 (12.8% of the catchment), for a total estimated landslide volume of 5.9×10^9 m^3 (Guzzetti et al., 2008a).

For the numerical experiments we selected the area in the UTRB where unconsolidated and poorly consolidated continental sediments crop out (green area in Fig. 1). This is the lithological complex where

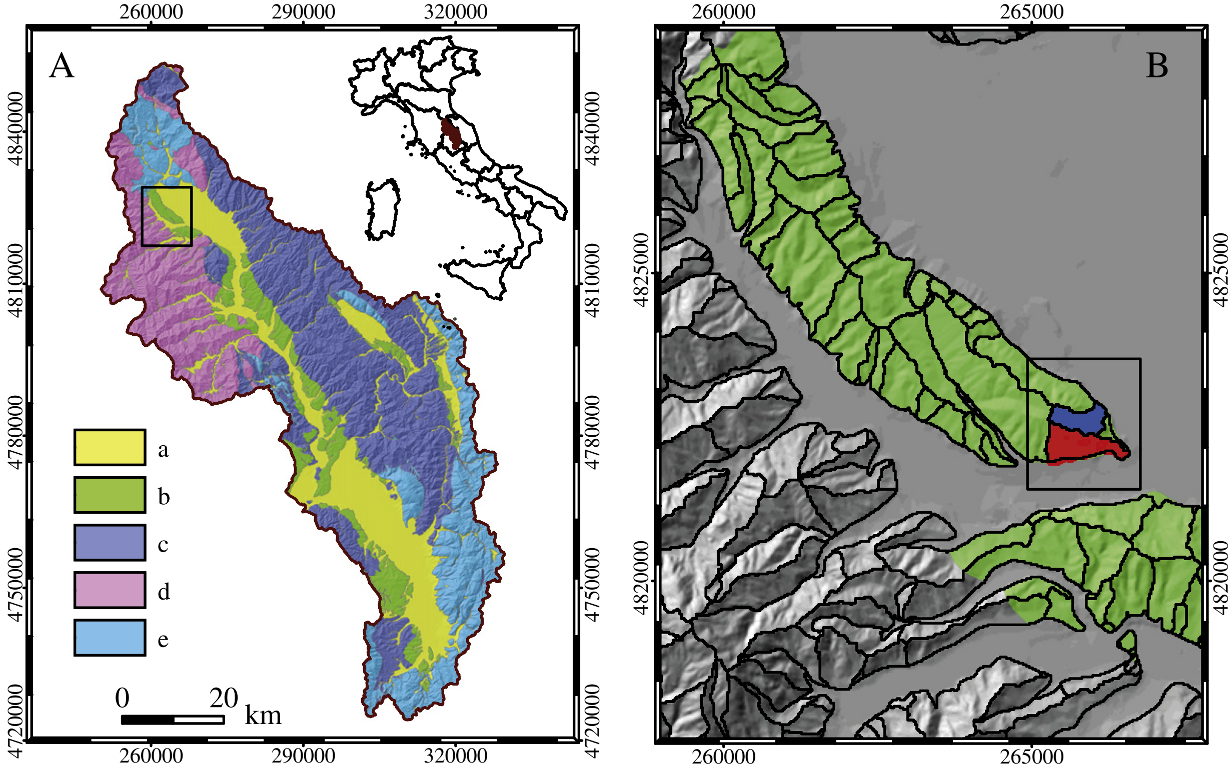

Fig. 1. The Upper Tiber River Basin (UTRB), in Central Italy. Colors in (A) show five lithological complexes (Cardinali et al., 2001; Guzzetti et al., 2008a): (a) Fluvial and lake deposits, recent in age. (b) Continental, post-orogenic sediments, Pliocene to Pleistocene. (c) Allochthonous rocks, lower to middle Miocene. (d) Tuscany and Umbria turbidite sequences, Eocene to Miocene. (e) Umbria-Marche sedimentary sequence, Lias to lower Miocene. Black box in (A) shows location of enlargement portrayed in (B) where black lines show hydrological sub-basins derived automatically from a 25 × 25 m DEM; the only lithological area shown in color in (B) is b of (A), and in (B) two sample sub-basins are shown in red and blue. Black box in (B) shows location of Fig. 2.