Slope stability scaling laws within physically based models and their modifications under varying triggering conditions

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ABSTRACT

The appearance of scaling phenomena in rainfall-induced landslides has been observed by several authors, and discussed within variuos theoretical models. A few properties of landslides are known to exhibit a power-law functional dependence, as shown by a number of world-wide datasets, which is often interpreted as a signature of the occurrence of self-organized criticality. We show that the adoption of a complex, physically motivated model for rainfall infiltration and slope stability can reproduce fairly well the observations over a wide range of rainfall durations and intensities, accounting for most of the features exhibited by the datasets in a natural way. Namely, we reproduce within our approach the observed functional dependencies and the slope of the scaling laws of intensity-duration triggering thresholds for shallow landslides, and the observed distribution of landslide sizes. We applied the model over a very large study area partitioned in many sub-basins characterized by different geological, hydrological and morphological conditions. Focusing on the intensity/duration dependence of rainfall thresholds for triggering shallow landslides, we estimate the response of the various sub-basins under different triggering conditions, and analyze the dynamics of the systems under different climatic scenarios, examining the scaling properties of slope responses.

1 - INTRODUCTION & STUDY AREA

Natural landslides exhibit scaling properties, described by power-law dependencies of the area and volume of the slope failures and the amount of rainfall required for the initiation of landslides in a region [Guzzetti et al., 2008b]. Early investigators have recognized that empirical rainfall thresholds can be established to determine the amount of rainfall required to initiate landslides in a region [Caine, 1980, Innes, 1983]. **Despite the abundant empirical evidence, the reasons for the scaling behaviors of landslide phenomena are poorly known**; we show [Alvioli et al., 2014a] that a relatively simple, physically based model that describes the stability conditions of slopes forced by rainfall produces results in agreement with known scaling properties of landslides: **(i)** the rainfall conditions that result in unstable slopes, which match regional empirical Intensity-Duration (I-D) thresholds for possible landslide occurrence **(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 (see, *e.g.* [Malamud et al., 2004]).

We performed our analysis in the Upper Tiber River basin, central Italy - Fig. 1A - selecting the regions in the area where unconsolidated and poorly consolidated continental sediments crop out (*green* area, b, in Fig. 1), where shallow landslides are frequent [Cardinali et al., 2000], and where the TRIGRS model is best suited to describe the stability conditions of slopes forced by rainfall.

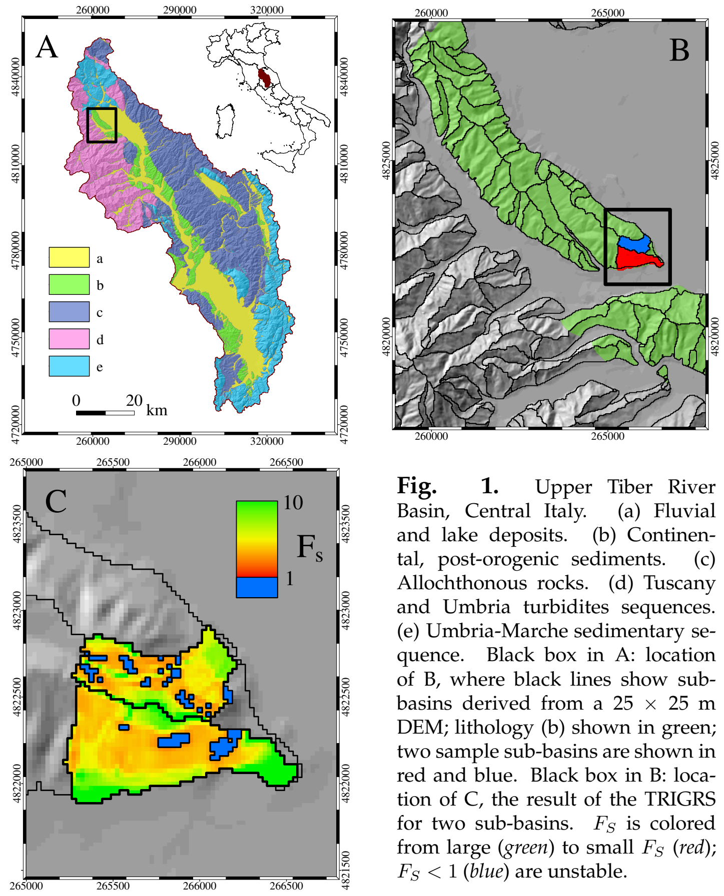

Fig. 1. Upper Tiber River Basin, Central Italy. (a) Fluvial and lake deposits. (b) Continental, post-orogenic sediments. (c) Allochthonous rocks. (d) Tuscany and Umbria turbidites sequences. (e) Umbria-Marche sedimentary sequence. Black box in A: location of B, where black lines show sub-basins derived from a 25 × 25 m DEM; lithology (b) shown in green; two sample sub-basins are shown in red and blue. Black box in B: location of C, the result of the TRIGRS for two sub-basins. F_S is colored from large (*green*) to small F_S (*red*); $F_S < 1$ (*blue*) are unstable.

We adopted TRIGRS version 2.0 [Baum et al., 2008]. The software implements a **grid-based, spatially distributed** slope stability model coupled with an infiltration model capable of **simulating the infiltration of rainfall** in the terrain, modulating the stability conditions of the individual grid cells. The TRIGRS adopts a grid-based representation of a real landscape based on a DEM, and uses **local terrain characteristics** as an input for the solution of a system of equations whose output is the **factor of safety** F_S *i.e.* , a positive number **representing the balance of the driving and the resisting forces** acting in each grid cell. For unstable conditions, where the resisting driving exceed the resisting forces, $F_S < 1.0$.

2 - SYNTHETIC RAINFALL THRESHOLDS

We partitioned the study area into sub-basins *i.e.* , a set of hydrological **slope units, homogeneous regions bounded by drainage and divide lines** [Alvioli et al., 2014b]. We applied a uniform rainfall of a given intensity I, for a given period of time D, studying the conditions that have resulted in unstable cells in each sub-basins. We considered only (nearly) mono-lithological sub-basins (at least 50% of the area is covered by lithology b), and considered unstable the sub-basins with at least 10% of the grid-cells with $F_S < 1.0$; a typical output of the code for F_S is shown in Fig.1C.

For each sub-basin, we run TRIGRS with incresing I maintaining D constant, and **we checked if these conditions had resulted in landslides**. The procedure was repeated for different D. For each of the sub-basins we obtained a set of rainfall (D, I) conditions that had resulted in predicted instabilities.

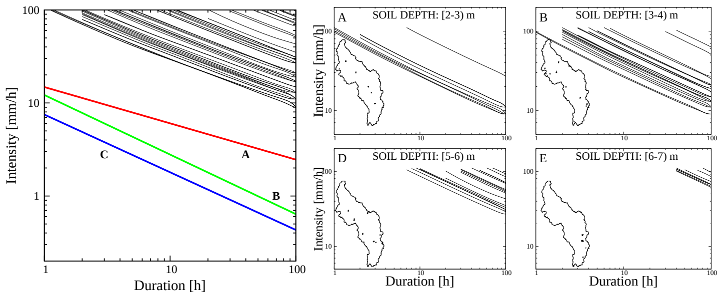

Fig. 2. Synthetic rainfall thresholds. Left box: comparison with A [Caine, 1980], B [Brunetti et al., 2010] and C [Peruccacci et al., 2012]. Right boxes: curves in the left box, grouped according to average soil depth intervals of the corresponding sub-basin (insets).

CONCLUSIONS:

- the log-log D, I plot of the results in Fig. 2 shows that in each sub-basin the rainfall (D, I) **synthetic thresholds** lines are well defined, and **obey distinct power law trends** for a significant range of rainfall durations ($1 \leq D \leq 100$ hours).
- the slope of the curves agrees with the slope of empirical thresholds in Italy, *i.e.* **scaling exponents are almost identical**
- synthetic thresholds, corresponding to a specific, local morpho-lithological setting, correctly **lay above the empirical ones**, defined as lower I-D boundary conditions in an area

3 - SYNTHETIC FREQUENCY-SIZE DISTRIBUTIONS

We determined the probability density of the area of the patches of terrain predicted as unstable by TRIGRS, and we compared the probability density of the patches to the probability density of natural landslides in the UTRB. We defined a patch of unstable terrain a **cluster of contiguous grid cells that individually have $F_S < 1.0$**. To identify the unstable grid cells, we ran TRIGRS with a fixed rainfall duration D = 1 h, increasing the rainfall intensity I from 25 to 100 mm h^{-1} (Fig. 3A). We repeated the calculations with a fixed rainfall intensity I = 100 mm h^{-1}, and we varied D from 1 to 10 h (Fig. 3B).

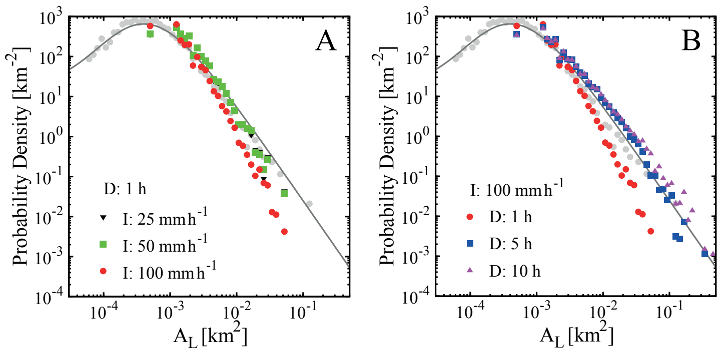

Fig. 3. Synthetic frequency-size distributions obtained with TRIGRS, compared with data (grey dots and grey fitting curve; [Malamud et al., 2004]). Left: varying intensity I at fixed duration, $D = 1$ h. Right: varying duration D at fixed intensity, $I = 100$ mm/h^{-1}.

CONCLUSIONS:

- the synthetic frequency-size ditributions obtained using realistic $(D,\ I)$ conditionsare in **fair agreement with empirical observations** in the area and known models [Marchesini et al., 2012, Rossi et al., 2012]
- we found a dependence of the slope in the power-law region of data, with the **synthetic slope converging to the empirical one** for both increasing I and D
- simulations reveal a ***"rollover"* for smaller areas**, a deviation from the power law trend [Li et al., 2014], observed in data
- we found some **resolution dependence** (not shown in the figure); best results were obtained with DEM resolution of 10 × 10 m

GENERAL CONCLUSIONS: The **scaling behavior emerged from the physical modeling**, reconciling the physically-based and the empirical, statistically-based approaches to the prediction of rainfall induced landslides. The results were obtained **without any attempt to fine-tune the parameters** or to use probabilistic-inspired approaches [Raia et al., 2014], using for the simulations reported here and in [Alvioli et al., 2014a], fictitious rainfall D and I.

Using the flexibility of the TRIGRS code it is possible to **run realistic scenarios**, in which actual climatic conditions and soil properties can by simulated. The fact that rainfall thresholds can actually be observed from simulations makes us confident that actual climatic conditions would reproduce the local thresholds with great detail, and **climate change scenarios** can be effectively described within our approach.

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