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Estimating return period of landslide triggering by Monte Carlo simulation

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SUMMARY

Assessment of landslide hazard is a crucial step for landslide mitigation planning. Estimation of the return period of slope instability represents a quantitative method to map landslide triggering hazard on a catchment. The most common approach to estimate return periods consists in coupling a triggering threshold equation, derived from an hydrological and slope stability process-based model, with a rainfall intensity–duration–frequency (IDF) curve. Such a traditional approach generally neglects the effect of rainfall intensity variability within events, as well as the variability of initial conditions, which depend on antecedent rainfall. We propose a Monte Carlo approach for estimating the return period of shallow landslide triggering which enables to account for both variabilities. Synthetic hourly rainfall-landslide data generated by Monte Carlo simulations are analysed to compute return periods as the mean interarrival time of a factor of safety less than one. Applications are first conducted to map landslide triggering hazard in the Loco catchment, located in highly landslide-prone area of the Peloritani Mountains, Sicily, Italy. Then a set of additional simulations are performed in order to evaluate the traditional IDF-based method by comparison with the Monte Carlo one. Results show that return period is affected significantly by variability of both rainfall intensity within events and of initial conditions, and that the traditional IDF-based approach may lead to an overestimation of the return period of landslide triggering, or, in other words, a non-conservative assessment of landslide hazard.

1. Introduction

Landslide susceptibility and hazard mapping can be effectively used as an aid for urban and landslide mitigation planning, which often requires a multidisciplinary approach (Carrara, 1983; Carrara et al., 1991; Van Westen et al., 1997; Guzzetti et al., 1999; Lee, 2004; Ayalew and Yamagishi, 2005; Hürlimann et al., 2006; Gorsevski et al., 2006; Conoscenti et al., 2008; Dewitte et al., 2010; Oh and Lee, 2011; Conforti et al., 2012; Pradhan, 2013; Regmi et al., 2013; Bregoli et al., 2015). Several authors map landslide hazard in terms of return period of landslide triggering (Borga et al., 2002; D'Odorico et al., 2005; Rosso et al., 2006; Salciarini et al., 2008; Tarolli et al., 2011; Lanni et al., 2012; Schilirò et al., 2015). To this end, models considering at least both rainfall intensity and duration as control factors in landslide triggering are suitable (Wu and Sidle, 1995; Baum et al., 2002; Iverson, 2000; D'Odorico et al., 2005; Rosso et al., 2006; Simoni et al., 2008; Baum et al., 2008, 2010; Sorbino et al., 2010; Greco et al., 2013; Capparelli and Versace, 2014). In these works the estimation of return period is generally carried out by coupling hydrological rainfall infiltration and geomechanical slope-stability physically-based models with rainfall intensity duration-frequency (IDF) relationships, these providing the link between rainfall events and their long-term frequency of occurrence (see Stedinger et al., 1993; Burlando and Rosso, 1996). Simplistic assumptions commonly made within this approach include representation of rainfall events as uniform (i.e. of constant intensity) hyetographs, and the use of prefixed initial conditions. On the other hand, as shown by D'Odorico et al. (2005) and by Peres and Cancelliere (2014), the shape of the hyetograph or, in other words, the variability of instantaneous rainfall intensity within events, may have a significant effect on the triggering of landslides. Use of only rainfall duration and average intensity to characterise the rainfall events' potential to trigger landslides, though very common in literature (Guzzetti et al., 2007), may not be sufficient. On the other hand, initial conditions are not properly taken into account, since in most of the cited studies on hazard mapping they are fixed with no regard to their probability of occurrence, which generally may affect return period of landslide triggering. For instance, in Rosso et al. (2006) two return-period maps are presented making the assumption of an initial water table height of 0 and of 0.15 m,

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Nomenclature

A	upslope drainage area
A/B	upslope specific contributing area
B	contour (stream tube) length
D_0	soil saturated hydraulic diffusivity
I_T	rainfall mean intensity of return period T
$K(\psi)$	hydraulic conductivity
K_S	soil saturated hydraulic conductivity
N_{RE}	number of generated synthetic rainfall events
T_R	return period of landslide triggering estimated via the Monte Carlo approach
T_{R0}	return period of landslide triggering as computed by the traditional (IDF) approach
T_{R2}	minimum back-analysis IDF-based return period of landslide triggering
W_{CR}, I_{CR}, D_{CR}	critical (corresponding to slope failure) rainfall event cumulative depth, intensity and duration
Z	vertical depth measured from ground surface
$\overline{P}(1)$	mean annual maxima rainfall depth on a hourly duration
c'	soil cohesion for effective stress
c_d	leakage ratio
d_{LZ}	soil depth
h_i	water table height at the beginning of rainfall event i
n	rainfall scaling exponent, relative to the rainfall IDF curve
p_T	dimensionless rainfall depth quantile of return period T
$t_i^{(in)}$	time instant at which i-th rainfall event begins
$t_{end,i}$	ending instant of i-th synthetic rainfall event
$t_{max,i}$	time instant at which the maximum transient pressure head occurs for i-th rainfall event
α	soil water retention curve (SWRC) parameter
δ	terrain slope respect to an horizontal reference
γ_S	unit weight of soil
γ_w	unit weight of water
$\lambda, \nu, \beta, \eta, \xi, b$	parameters of the Neyman–Scott rectangular pulses (NSRP) stochastic rainfall model
μ_0, σ_0, ξ_0	Generalized Extreme Value (GEV) distribution parameters
ϕ'	soil friction angle for effective stress
ψ	pressure head
ψ_0	initial (at the beginning of rainfall events) part of pressure head
ψ_1	transient part of pressure head
ψ_{CR}	critical pressure head, corresponding to slope incipient unstability
τ_M	water table recession model time constant
θ_r	soil residual water content
θ_s	soil saturated water content
ζ_{CR}	critical soil wetness

without taking into account the different probability associated to these two different initial conditions, whilst in the work by D'Odorico et al. (2005) the initial conditions are derived by the model of Montgomery and Dietrich (1994), but no probability is assigned to the steady-state rainfall required by such a model.

In this paper we use the Monte Carlo simulation procedure presented in Peres and Cancelliere (2014) to show quantitatively how the two above-mentioned hydrological factors may affect the estimation of the return period of shallow landslide triggering. The Monte Carlo simulation approach essentially consists in combining a stochastic rainfall model able to generate fine-resolution (hourly) rainfall data with a physically-based hillslope hydrological model. This latter model is suited to compute initial conditions based on antecedent hillslope response, the built of transient pressure head due to rainfall events, and finally geomechanical slope stability. Specifically, the following models are used in our framework: a seasonal Neyman–Scott rectangular pulses rainfall stochastic model (Neyman and Scott, 1958; Rodriguez-Iturbe et al., 1987a,b; Cowpertwait, 1991; Cowpertwait et al., 1996) and the TRIGRS v.2 unsaturated model (Baum et al., 2008, 2010), combined with a water table recession model based on the linear reservoir hypothesis to compute initial conditions implicitly linked to antecedent rainfall. Finally, return period of shallow landsliding is estimated based on the analysis of the generated synthetic pressure head data. Results obtained by the Monte Carlo method are compared to those obtained by the "traditional" IDF-based approach, in order to demonstrate and quantify how the two above-mentioned simplistic assumptions may affect return period estimation.

An application is carried out to map shallow landslide triggering hazard in the Loco catchment, located in the Peloritani Mountains, Sicily, Italy. Then, sensitivity analyses are conducted in order to verify the generality of considerations about the reliability of the traditional IDF-based method.

2. Methods

2.1. The Monte Carlo method and return period estimation

Generally speaking, the Monte Carlo method consists in the use of a stochastic model for generating the input to a mathematical model which represents the behaviour of the physical system under study, and then to analyse statistically the output (Salas, 1993).

The Monte Carlo simulation technique for synthetic rainfall-landslide data generation is illustrated briefly in Fig. 1 – for a more detailed description see Peres and Cancelliere (2014), where the method has been used with the aim of deriving landslide-triggering thresholds suitable for early warning. First, N_{RE} individual rainfall events are generated from a 1000-year long hourly synthetic rainfall time series, obtained as a Neyman–Scott rectangular pulses process (see Appendix A). For isolating the events from the whole series the following criterion is adopted: when two wet spells are separated by a dry time interval less than Δt_{min} = 24 h, these are considered to belong to the same rainfall event; otherwise they are considered as separate. 24 h is the minimum time interval necessary to avoid overlapping of the response produced by subsequent rainfall events for the analysed hydraulic properties (Peres and Cancelliere, 2014) (see Tables 1 and 4) – a similar approach is adopted by Balistrocchi et al. (2009) and Balistrocchi and Bacchi (2011). Then the hillslope response to the sequence of generated events $i = 1, 2, \ldots, N_{RE}$ is computed by the following steps:

1. The TRIGRS unsaturated model is used during each event to compute the transient pressure head ψ_1 (Baum et al., 2008, 2010) (see Appendix B, Eq. (B.1)). Since pressure head may continue rising after the end of rainfall, the computation of transient pressure head is prolonged for $\Delta t_a = \Delta t_{min} - 1$ h after the ending instant $t_{end,i}$ of any given rainfall event.