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An effective antecedent precipitation model derived from the power-law relationship between landslide occurrence and rainfall level

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ABSTRACT

Antecedent rainfall is an important predisposing factor in triggering landslides because it reduces soil suction and increases the pore-water pressure in soils. The existing approaches to quantify the antecedent rainfall were derived from empirical methods used to develop rainfall–runoff models in which the daily decays of rainfall within a given period preceding a given day are considered as independent processes. In this study, a methodology accounting for the effective antecedent rainfall that influences landslide occurrence is developed from a power-law relationship between the frequency of landslide occurrence and the landslide-triggering rainfall level. In this model, the decay rate of the daily rainfall is related to a scaling exponent defined by the power-law relationship, the decay process of daily rainfall within a given period preceding a given day is not independent but is interrelated, and the impact of rainfall in the preceding k days on soil moisture is associated with the precipitation from the preceding $(k-1)$ days.

1. Introduction

Rainfall-induced landslides are well known to have a wide spatial and temporal distribution and a high frequency of occurrence (Campbell, 1975; Lumb, 1975; Nilsen et al., 1976; Crozier, 1986; Wieczorek, 1987; Guzzetti et al., 2007; Keefer and Larsen, 2007; Sassa and Canuti, 2008; Li et al., 2010, 2011). Earlier studies attempted to investigate the relationship between landslides and rainfall using the total daily rainfall only, without considering antecedent conditions (Glade, 1998). The antecedent precipitation affects the rainfall-induced landslides by reducing soil suction and increasing the pore-water pressure in soils (Keefer et al., 1987; Aleotti, 2004). A few studies have been conducted to determine the landslide-triggering rainfall thresholds from empirical rainfall intensity–duration relationships and antecedent precipitation, i.e., the precipitation within a number of days before the landslides occur (e.g., Crozier, 1986; Glade et al., 2000; Aleotti, 2004; Zêzere et al., 2005; Hasnawir and Kubota, 2008).

The impact of a particular rainfall event decreases in time owing to discharge and evapotranspiration processes (Canuti et al., 1985; Crozier, 1986). The actual amount of water infiltrating into hillslopes during rainfall events preceding a landslide occurrence can be defined as an effective antecedent rainfall for the landslide occurrence. However, the effective antecedent rainfall is influenced by a number of physical factors that vary widely over a short distance. Measuring rainfall infiltration or characterizing it accurately over a large area is very difficult (Sassa and Canuti, 2008; Giannecchini et al., 2012). In contrast, rainfall and streamflow data are available at many recording rain gauges and hydrological gauges. Consequently, statistical relationships between precipitation inputs and streamflow outputs in rainfall–runoff models (e.g., Kohler and Linsley, 1951; Fedora, 1987) are often used to quantify the antecedent soil water content in a period preceding the landslide event rainfall or the antecedent precipitation characteristics (e.g., Crozier and Eyles, 1980; Crozier, 1986; Glade et al., 2000; Zêzere et al., 2005; Hasnawir and Kubota, 2008).

Li et al. (2011) established a power-law (fractal) relationship between the frequency of landslide occurrence and the landslide-triggering rainfall level and found that the rainfall–landslide relationship follows two power-law distributions with different scaling exponents for two different ranges of the rainfall level and that the rainfall level corresponding to the inflection point of two fitted correlation lines can be defined as the upper bound for the shallow landslide-triggering cumulative rainfall threshold. In this study, using this power-law relationship, we developed a new methodology for quantifying the effective antecedent rainfall.

2. Previous research

In previous studies, an antecedent precipitation index (API), which was first used by Kohler and Linsley (1951) to predict the runoff from storm rainfall, was employed by Crozier and Eyles (1980) to characterize the effect of antecedent rainfall in rainfall–landslide. The API, which is a

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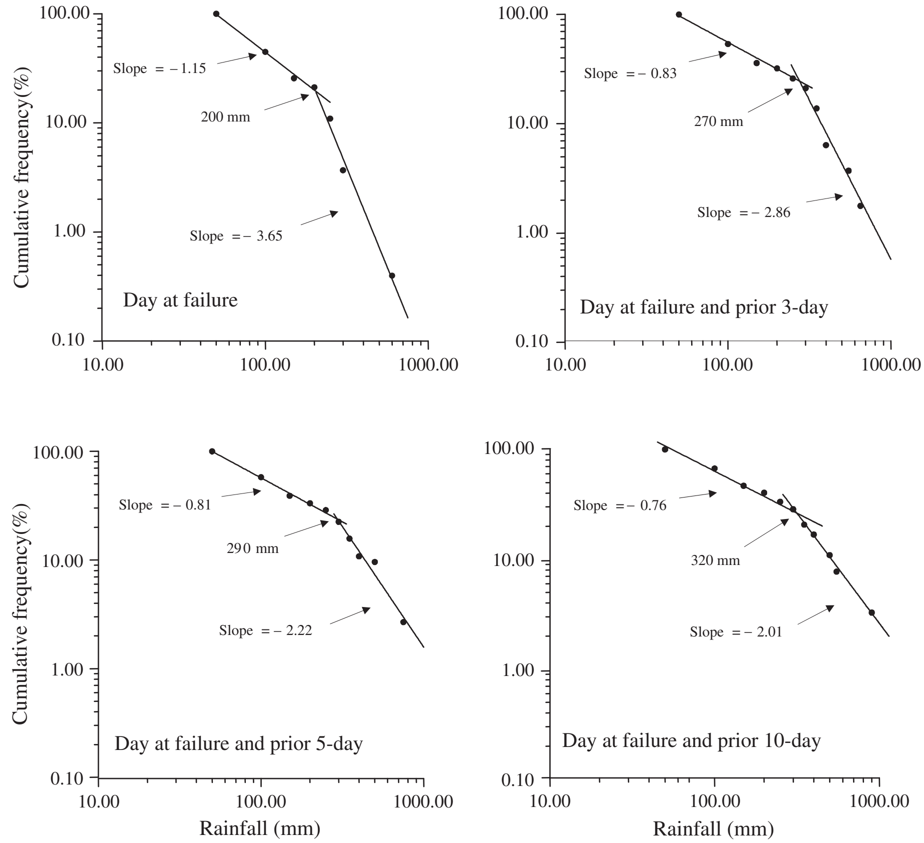

Fig. 1. Relationship between the cumulative frequency of landslides (L_{cf}) and the cumulative rainfall (R) of different time intervals during the period 1990 to 2003, Zhejiang, China (after Li et al., 2011). The distributions are well characterized by $L_{cf}(>R) \propto R^{-\beta}$ within two scale ranges (refer to Table 1).

linear combination of rainfall in a period preceding a landslide event and on the day of the event, can be written as (Crozier and Eyles, 1980; Crozier, 1986)

$$P_{a0} = KP_1 + K^2P_2 + \ldots + K^nP_n \quad (1)$$

where P_{a0} is the antecedent rainfall for day 0, on which the landslide event occurs, P_1 is the daily rainfall for the day before day 0, n is the total number of days considered in the model, P_i is the daily rainfall for the i-th day before day 0, and K is the constant decay factor representing the outflow of the regolith. Crozier and Eyles (1980), following Bruce and Clark (1966), used $K = 0.84$ and $n = 10$ days, which come from Ottawa (United States) streamflow data. The rates of drainage and evaporation processes in this model are assumed to be constant throughout the year.

In an improved approach to API (Glade et al., 2000), the decay coefficient was related to the recession curves of storm hydrographs as

$$y = cn^d \quad (2)$$

where y is discharge at any point in the recession curve, c is the peak of streamflow, n is time in days, and d is the coefficient of the decay curve. The antecedent rainfall index becomes (Glade et al., 2000)

$$P_{a0} = P_1 + 2^dP_2 + 3^dP_3 + \ldots + n^dP_n \quad (3)$$

where d is derived from the hydrograph recession curve coefficient (refer to Eq. (2)), and n is the number of days before day 0. For example, for three regions in New Zealand (Glade et al., 2000), the parameter n was chosen as 10 days, and the decay curve coefficient was taken as $d = -1.19$, -1.99, and -1.52 for Wairarapa, Hawke's Bay, and Wellington, respectively.

Another alternative method to define the antecedent precipitation index (API_t) was proposed by Fedora (1987) to predict storm hydrographs in small forested catchments of the Oregon Coast Range:

$$\text{API}_t = \text{API}_{t-\Delta t}\lambda + P_{\Delta t} \quad (4)$$

Table 1
Power-law distributions for the rainfall/landslide relationship (after Li et al., 2011).

Time interval of precipitation observations (days)	Equation	Range of rainfall level (mm)	L_{cf} [a] (%)	TH_{CR} [a] (mm)
Day at failure (1)	$L_{cf} = 9010.93R^{-1.15}$	$50 < R \le 200$	79.3	200
	$L_{cf} = 5.26\text{E}+9R^{-3.65}$	$200 < R < 600$	20.7	
Day at failure and prior 3-day (4)	$L_{cf} = 2535.81R^{-0.83}$	$50 < R \le 270$	77.4	270
	$L_{cf} = 2.17\text{E}+9R^{-2.86}$	$270 < R < 650$	22.6	
Day at failure and prior 5-day (6)	$L_{cf} = 2374.70R^{-0.81}$	$50 < R \le 290$	78.6	290
	$L_{cf} = 7.21\text{E}+6R^{-2.22}$	$290 < R < 650$	21.4	
Day at failure and prior 10-day (11)	$L_{cf} = 2140.60R^{-0.76}$	$50 < R \le 320$	77.6	320
	$L_{cf} = 2.8\text{E}+6R^{-2.01}$	$320 < R < 700$	22.4	

[a] L_{cf} is cumulative frequency of landslides; TH_{CR} is rainfall level on inflexion (see Fig. 1 and text).