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Rainfall threshold for initiation of channelized debris flows in a small catchment based on in-site measurement

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ABSTRACT

The peak runoff discharge plays an important role in triggering channelized debris flows, especially for small catchments, due to the features of a small area and short channels. In small catchments, intense rainfall can trigger a flood within a short period of time. But currently, there are few rainfall threshold models that address the runoff from short-duration (<2 h) rainfall. In this context, 37 short–duration rainfall events were analyzed, and field measurements were made for a partially-modified landscape in order to compare the variation in the amount of runoff. The grey relational analysis allowed us to rank the influence of the various factors that affected variations in the runoff. The results indicated that the intensity of rainfall was the most important factor, having a greater effect than other factors, such as the depth of the rainfall and its duration. Then, we trained a runoff prediction model based on these factors and verified its accuracy using the moving least squares (MLS) method, the genetic back-propagation neural network (GABP) method and the genetic support vector machine (GASVM) method. This analysis indicated that the MLS method had the best predictive capability. The assessment of the debris-flow hazard based on the predicted runoff and intensity-duration-frequency (IDF) curves is discussed in the study area. It was indicated that even a rainfall event of a two-year return period was dangerous for this specific case.

1. Introduction

Debris flows are commonly triggered by a combination of three essential factors, i.e., sufficient loose solid materials, water runoff, and a steep terrain. The water runoff is the only variable environmental factor in a comparatively short time, and the stability of the loose deposits is related closely to the flow of surface water especially for channelized debris flows (Gregoretti and Fontana, 2008). The initiation is typically attributed to runoff during rain storms, which at a critical discharge threshold, mobilizes loose sediment into a channelized debris flow (Kean et al., 2013). Since debris flows usually occur in remote mountainous areas, it is difficult for researchers to observe their occurrence because they occur suddenly and don't last very long. Artificial rainfall has been utilized extensively in flume experiments on the initiation of debris flows (Hu et al., 2016; Ni, 2015; Chen et al., 2006a). Nevertheless, the processes that initiate real debris flows are far more complicated, so the physical simulation experiments should be improved by further enhancing the similarity between experimental and actual conditions. Some researchers have focused on the development of hydrological numerical models that enable us to investigate the relationship between rainfall and runoff in debris flow areas (Berti and Simoni, 2005; Coe et al., 2008). Recently, rainfall characteristics that trigger debris flows have been studied extensively to derive the so-called "rainfall threshold" that separates the zone in which debris flow occurs from those in which it does not occur. The simplest form of rainfall thresholds is the lower-bound rainfall condition, also known as "minimum rainfall threshold," which, according to a database of a single and multiple rainfall events, has generated abundant debris flows. Accordingly, several rainfall thresholds for the initiation of debris flow have been suggested, such as the intensity and duration (I-D) precipitation model (Cannon and Ellen, 1985; Cannon et al., 2008, 2011; Aleotti, 2004; Dai and Lee, 2001), antecedent rainfall-cumulative rainfall (AR-R) model (Wieczorek and Guzzetti, 1999), antecedent effective rainfall-cumulative rainfall (AER-R) model (Baum and Godt, 2010), and the maximum hourly rainfall intensity-cumulative rainfall (I_{MAX}-R) model (Guzzetti et al., 2007; Guzzetti et al., 2008). The precipitation parameters that are most often used in determining thresholds for debris flow are antecedent rainfall, antecedent effective rainfall, precipitation duration, precipitation intensity, cumulative rainfall, and maximum hourly rainfall intensity (Guzzetti et al., 2008). These proposed thresholds have been applied in different regions, including the studies conducted near San Francisco, CA, USA (Baum and Godt, 2010; Godt et al., 2006), the Alps in Europe (Guzzetti et al., 2007), and Taiwan (Chen et

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al., 2006b, 2014; Huang, 2013). Most of the aforementioned critical thresholds were empirical thresholds that were based solely on the statistical relationship between rainfall and the occurrences of debris flows. In addition to rainfall, channelized debris flows are also influenced by many other factors, including the availability of loose solid material and its average grain size, the slope gradient, the geometrical and morphological characteristics of a site, and, above all, runoff discharge (Gregoretti and Fontana, 2008). The value of runoff discharge has been proven to be a decisive factor that is responsible for triggering debris flow (Genevois et al., 2000).

The topographic, geological, and hydraulic conditions of a catchment usually do not vary over a comparatively short period of time, so the characteristics of the rainfall could have the principal influence on the amount of runoff in channels. Wei et al. (2010) discussed the relationship between rainfall and runoff based on field observations in small catchments over a long period of time. Penna et al. (2015) used a tracer-based method to investigate the seasonal variability of the processes that generate runoff from a small, forested catchment. Small catchments generally have quick hydrological response due to the tiny areas and the short lengths of the channels. In the case of extensive rainfall with high intensity, the concentrated flow will cause debris flows (Yu, 2011). Berti et al. (1999) witnessed the initiation of a debris flow shortly after an intense rainstorm (25 mm in 30 min). The concentration time defined as the travel time for a parcel of water moving from the most remote point in the watershed to the outlet (Yu et al., 2000) was very short (9–14 min) due to the small area and steep terrain of the catchment. Yu (2011) also suggested that the occurrence of debris flows was correlated strongly with the 10-mm rainfall intensity, and they used this intensity to calculate the runoff and the unit discharge. Cannon et al. (2008) analyzed debris flows that were produced from 25 recently-burned basins in Colorado in response to 13 short-duration, high-intensity, convective storms. They indicated that debris flows were triggered after as little as 6 to 10 min of storm rainfall. As the runoff in small catchments is sensitive to short-duration rainfall, 30-min or 10-min intensity should be used to evaluate the threshold. For those rainfall events shorter than 1 h, if the hourly intensity is used, the obtained average intensity will be smaller than the actual intensity, which may probably cause inappropriate assessment of rainfall threshold. It is difficult to just use hourly intensity to develop correlations between short-duration rainfall and runoff. But the current literature indicates that only a few rainfall threshold models have addressed the correlation between rainfall and runoff for short-duration (<2 h) precipitation (Li et al., 2011; Zhuang et al., 2015).

Zhejiang Province, which is in the southeast coastal region of China, often has subtropical monsoons and frequently has severe typhoon rainstorms from July to October every year. The hilly and mountainous terrain with elevations above 300 m accounts for >70% of its total area (Li et al., 2011). Owing to its geologic, geomorphologic, and climatic features, the region is prone to rainfall-induced debris flows, and many upstream catchments of these debris flows are small as the area of these catchments are usually <50 km^2 (Zhejiang Investigation and Design Institute of Water Conservancy and Hydropower, 1984).

In this context, our aim was to find an approach to quantitatively assess the probability of channelized debris flows triggered by high-intensity, short-duration rainfall in a partially-modified landscape. We chose a small catchment in Zhejiang Province as the study area, and we collected real-time rainfall and runoff data in channels. First, the data were analyzed using grey relational analysis to confirm the main characteristics of the rainfall that influenced the runoff; then, the moving least squares (MLS) method, the genetic back-propagation neural network (GABP) method, and the genetic support vector machine (GASVM) method were used to predict the runoff of the catchment when it was subjected to different types of rainfall with different return periods; based on the predicted runoff, the probability of the occurrence of a debris was evaluated in order to prevent or mitigate possible disastrous consequences.

2. Study area and data collection

2.1. Description of the catchment

The catchment was located in Fenghua City, Zhejiang Province, as shown Figs. 1 and 2. The basin had a trumpet shape (Fig. 2) that was prone to concentrate surface flows into channels. The morphological characteristics of the catchment in Table 1 were calculated with ArcMap using the ASTER GDEM Data (ASTER Global Digital Elevation Model). The resolution of the DEMs (Digital Elevation Models) is 30 m × 30 m. In addition, we also verified the slope angle by using a laser ranger. The only road that connects Lingjiao Village (about 50 citizens) to the outside world is located downstream of the catchment, and it is very vulnerable to the occurrence of debris flows (Fig. 1).

The average annual rainfall of the study area was approximately 1500 mm (Dynamic water and rainfall system in Zhejiang Province) (Fig. 3), and the amount of rainfall from May to October typically accounts for more than two-thirds of the annual rainfall because of the impact of the monsoon troughs and tropical cyclones. In addition, the amount of rainfall from a single storm can vary greatly over a short distance in the mountainous area because of the strong topographic influence. Loose solid materials are distributed extensively in various channels due to the construction of provincial road No. 33. During the last few decades of extensive development in China, waste materials commonly are disposed in channels without stabilization, as shown in Fig. 4. At present, the gullies are often filled with the waste materials and very prone to debris flows when heavy rainfall occurs. Obviously, this situation highlights the necessity of establishing rainfall thresholds for debris flows in order to prevent and control the hazard.

2.2. Field survey and deposit sampling

In the triggering area, the presence of loose waste materials and the channelized morphology allow the formation of both debris and overland flows. Table 2 shows the characteristics of a typical channel section (Fig. 5), such as the bottom width, the slopes of the right and left banks, and the longitudinal bottom slope angle, θ_{trig} which were obtained in the same way as Table 1.

The grain-size characteristics of the loose materials in the triggering area were analyzed using the sieving method. The sample was taken from a 2 × 1 m rectangular window at the location shown in Fig. 5. Fig. 6 and Table 3 show the distribution of the grain sizes of the materials.

2.3. Collection of precipitation data

The rain gauge was fixed on the roof of a house that was located in Lingjiao Village, 200 m away from the catchment. The rain gauge was a HOBO RGM-3 automatic rainfall tipping-bucket recorder from Onset Company, USA. The rain gauge sampled the amount of rainfall with a minimum value of 0.2 mm. It was able to indicate the intensity and duration of the rainfall in the measurement process.

2.4. Measurement of runoff

Two triangular weirs were installed at the outlets of the two channels. Each weir consisted of a V-shaped, notched flume that was braced and leveled during installation and adjusted to correct any minor settlement. Before casting the concrete of the weir, a sheet metal mold was nailed to the bedrock surface and sealed with quick-set concrete. An automated water-level recorder was installed in a stilling well (Fig. 7) in each weir. The recorder sampled the water level at 10-min intervals with a resolution of 0.8 mm and a range between 0 and 0.5 m. According to the recorded in-situ data, the peak discharges in the study area usually lasted for an hour with no obvious changes, so the 10-min interval was short enough to accurately characterize flow stages in such small

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