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Technical notes: rainfall threshold calculation for debris flow early warning in areas with scarcity of data

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Abstract: Debris flows are one of the natural disasters that frequently occur in mountain areas, usually accompanied by serious loss of lives and properties. One of the most used approaches to mitigate the risk associated to debris flows is the implementation of early warning systems based on well calibrated rainfall thresholds. However, many mountainous areas have little data regarding rainfall and hazards, especially in debris flow forming regions. Therefore, the traditional statistical analysis method that determines the empirical relationship between rainfall and debris flow events cannot be effectively used to calculate reliable rainfall threshold in these areas. To solve this problem, this paper developed a quantitative method to identify rainfall threshold for debris flow early warning in data-poor areas based on the initiation mechanism of hydraulic-driven debris flow. First, we studied the characteristics of the study area, including meteorology, hydrology, topography and physical characteristics of the loose solid materials. Then, the rainfall threshold was calculated by the initiation mechanism of the hydraulic debris flow. The results show that the proposed rainfall threshold curve is a function of the antecedent precipitation index and 1-h rainfall. The function is a line with a negative slope. To test the proposed method, we selected the Guojuanyan gully, a typical debris flow valley that during the 2008-2013 period experienced several debris flow events and

that is located in the meizoseismal areas of Wenchuan earthquake, as a case study. We compared the calculated threshold with observation data, showing that the accuracy of the method is satisfying and thus can be used for debris flow early warning in areas with scaricty of data.

Keywords: Debris flow; rainfall threshold curve; rainfall threshold; areas with scaricty of data

1 Introduction

Debris flow is rapid, gravity-induced mass movement consisting of a mixture of water, sediment, wood and anthropogenic debris that propagate along channels incised on mountain slopes and onto debris fans (Gregoretti et al., 2016). It has been reported in over 70 countries in the world and often causes severe economic losses and human casualties, seriously retarding social and economic development (Tecca and Genevois, 2009; Degetto et al., 2015; Tiranti and Deangeli, 2015; McCoy et al., 2012;Imaizumi et al., 2006; Hu et al., 2016; Cui et al., 2011; Dahal et al., 2009; Liu et al., 2010). On 12 May 2008, the Wenchuan earthquake occurred in the Longmenshan tectonic belt on the eastern edge of the Tibetan plateau, China (Xu et al., 2008; Wang and Meng, 2009). A huge amount of loose deposits remained in the channels and on the slopes of the plateau after the Wenchuan earthquake. These loose deposits have served as source materials for debris flow and shallow landslide in the years since the earthquake (Tang et al. 2009, 2012; Xu et al. 2012; Hu et al. 2014). In the following years since the earthquake, intense rainfall events have triggered massive debris flow that have caused serious casualties and property loss, such as the Zhouqu debris flow and the Wenjia gully debris flow which both occurred in 2010.

As an important and effective means of disaster mitigation, debris flow early warning have received much attention from researchers. The rainfall threshold is the core of the early warning of debris flow, a large number of scientists have made lots of researches yet (Chen and Huang 2010; Cannon et al., 2008; Winter et al., 2013; Segoni et al., 2015; Staley et al., 2013; Baum and Godt, 2010; Rosi et al 2015; Zhou and Tang, 2014). Although the formation mechanism of debris flow has been extensively studied, it is difficult to perform distributed physically based modeling over large areas, mainly because the spatial variability of geotechnical parameters is very difficult to assess (Tofani et al., 2017). Therefore, many researchers (Wilson and Joyko, 1997; Campbell, 1975; Cheng et al., 1998) have had to determine the empirical relationship between rainfall and debris flow events and to determine the rainfall threshold depending on the combinations of rainfall parameters, such as antecedent rainfall, rainfall intensity, cumulative rainfall, etc. Cui (1991), Takahashi (1978) and Iverson (1989) predicted the formation of debris flow based on studies ofslope stability, hydrodynamic action and the influence of pore water pressure on the formation process of debris flow. Caine (1980) first statistically analyzed the empirical relationship between rainfall intensity and the duration of debris flows and shallow landslides and proposed an exponential expression($I = 14.82D^{-0.39}$). Afterwards, other researchers, such as Wieczorek (1987), Jison (1989), Hong et al. (2005), Dahal and Hasegawa (2008), Guzzetti et al. (2008) and Saito et al. (2010), carried out further research on the empirical relationship between rainfall intensity and the duration of debris flows, established the empirical expression of rainfall intensity - duration ($I = D$) and proposed debris flow prediction models. Shiedand Chen (1995) established the critical condition of debris flow based on the relationship between cumulative rainfall and rainfall intensity. Zhang (2014) developed a model for debris flow forecasting based on the water-soil coupling mechanism at the watershed scale. Tang et al. (2012) analyzed the critical rainfall of Beichuan city and found that the cumulative rainfall triggeringdebris flow decreased by 14.8%-22.1% when compared with the pre-earthquake period, and the critical hour rainfall decreased by 25.4%-31.6%. Chen et al. (2013)analyzed the pre- and post-earthquake critical rainfall for debris flow of Xiaogangjian gully and found that the critical rainfall fordebris flow in 2011 was approximately 23% lower than the value during the pre-earthquake period. Other researches, such as Chen et al. (2008) and Shied et al. (2009) has reached similar conclusions that the post-earthquake critical rainfall for debris flow is markedly lower than that of the pre-earthquake period. Zhenlei Wei et al. (2017) investigated a rainfall threshold method for predicting the initiation of channelized debris flows in a small catchment, using field measurements of rainfall and runoff data.

Overall, the studies on the rainfall threshold of debris flow can be summarized as two methods: the demonstration method and the frequency calculated method. The demonstration method employs statistical analysis of rainfall and debris flow data to study the relationship between rainfall and debris flow events and to obtain the rainfall threshold curve

(Bai et al., 2008; Zhuang, et al., 2009; Tian et al., 2008). This method is relatively accurate, but it needs very rich, long-term rainfall sequence data and disaster information; therefore, it can be applied only to areas with a history of long-term observations, such as Jiangjiagou, Yunnan, China, and Yakedake, Japan. The frequency calculated method, based on the assumption that debris flow and torrential rain have the same frequency, and thus, adebris flow rainfall threshold can be calculated based on the rainstorm frequency in the mountain towns that have abundant rainfall data but lack of disaster data (Yao, 1988; Liang and Yao, 2008). Researchers have also analyzed the relationship between debris flow occurrences and precipitation and soil moisture content based on initial debris flow conditions (Hu and Wang, 2003). However, this approach is rarely applied to the determinationof debris flow rainfall thresholds. Pan et al. (2013) calculated the threshold rainfall for debris flowpre-warning by calculating the critical depth of debrisflow initiation combined with the amount and regulating factors of runoff generation.

Most mountainous areas have little data regarding rainfall and hazards, especially in Western China. When a debris flow outbreak occurs, it often causes serious harm to villages, farmland, transport centers and water conservation facilities in the downstream area. Neither the traditional demonstration method nor frequency calculated method can satisfy the debris flow early warning requirements in these areas. Therefore, how to calculate the rainfall threshold in these data-poor areas has become one of the most important challenges for the debris flow early warning systems. To solve this problem, this paper developed a quantitative method of calculating rainfall threshold for debris flow early warning in data-poor areas based on the initiation mechanism of hydraulic-driven debris flows.

2 Materials and methods

This study makes an attempt to analyze the trigger rainfall threshold for debris flow by using the initiation mechanism of debris flow. The characteristics of rainfall in the watershed were analyzed firstly by the field survey. At the same time, the critical runoff depth to initiate debris flow was calculated by the initiation mechanism with the underlying surface condition (materials, longitudinal slope, etc.) of the gully. Then, the corresponding rainfall for the initiation of debris was back-calculated based on the hypothesis that runoff generation under saturated condition. At last, these factors were combined to build the rainfall threshold model. This method can be applied to the early warning system in the areas with scarcity of rainfall data.

The flow chart of the research is shown in Figure 1.

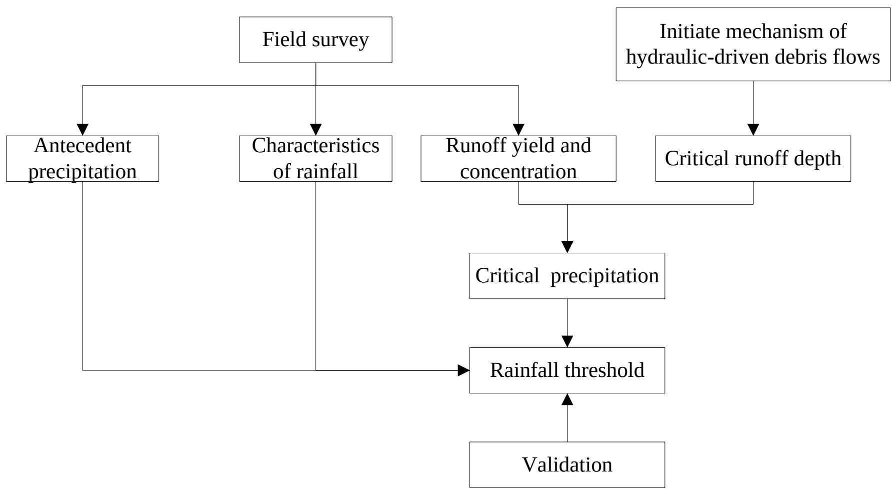

Figure 1 The flow chart of the research

2.1 Rainfall pattern and the spatial-temporal distribution characteristics

Mountain hazards such as debris flows are closely related to rainfall duration, rainfall amount and rainfall pattern (Liu et al., 2009). Rainfall pattern not only affects the formation of surface runoff but also affects the formation and development of debris flows. Different rainfall patterns result in different soil water contents; thus, the internal structure of the soil, stress conditions, corrosion resistance, slip resistance and removable thickness can vary. The initiation of a debris flow is the result of both short-duration heavy rains and the antecedent rainfall. Many previous observational data have shown that the initiation of a debris flow often appears at a certain time that has a high correlation with the rainfall pattern (Guido Rianna, 2014; Mohamad Ayob Mohamadi, 2015).

Based on the rainfall characteristics, rainfall patterns can be roughly divided into two kinds, the flat pattern and the peak pattern, as shown in Figure 2. If the rainfall intensity has little variation, there is no obvious peak in the whole rainfall process; such rainfall

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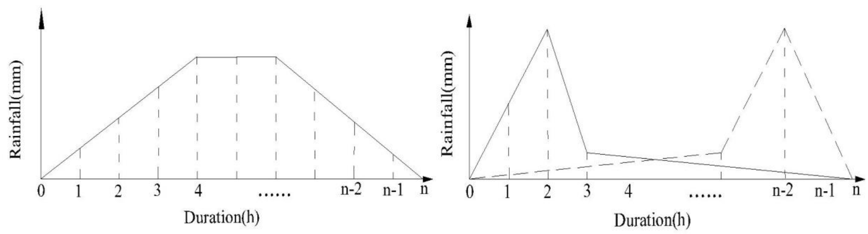
can be described as flat pattern rainfall. And the debris flows, if occur, are mainly caused by the great amount of antecedent precipitation. While if the rainfall intensity increases suddenly during a certain period of time, the rainfall process will have an obvious peak and is termed peak pattern rainfall. And these debris flows are mainly controlled by the short-duration heavy rains. Peak pattern rainfall may have one peak or more than one peak (Pan, et al., 2013).



(a) Flat pattern rainfall (b) Peak pattern rainfall

Figure 2 The diagram of rainfall patterns

Through analyzing the rainfall data of the Guojuanyan gully, the rainfall pattern and the spatial-temporal distribution characteristics can be obtained.

2.2 The rainfall threshold curve of debris flows

2.2.1 The initiation mechanism of hydraulic-driven debris flows

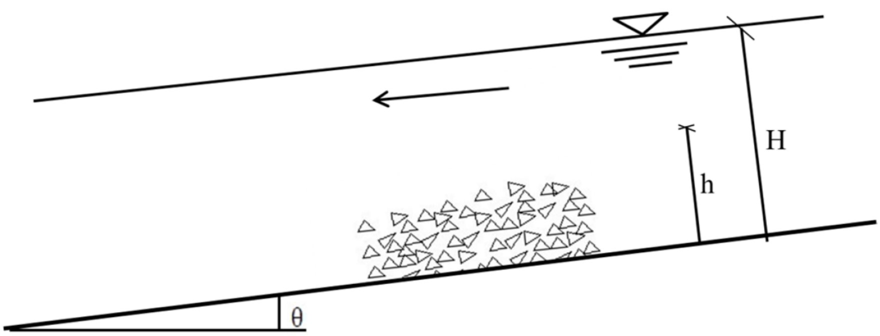


Figure 3 The typical debris flow initiate model

When the watershed hydrodynamics, which include the runoff, soil moisture content and the discharge, reach to a certain level, the loose deposits in the channel bed will initiate movement and the sediment concentration of the flow will increase, leading the sediment laden flow to transform into a debris flow. The formation of this kind of debris flow is a completely hydrodynamic process.

Figure 3 shows a simple hydraulic-driven debris flow initiate model, where h is the probable erosion depth (m), H is the whole depth from gully surface to the bottom (m), and θ is the longitudinal slope of gully (°).Takahashi (1977) established a model for the initiation of hydraulic-driven debris flow, which can be expressed as follows:

$$S_v = \frac{\gamma \tan\theta}{(\gamma_s - \gamma)(\tan\alpha - \tan\theta)} \tag{1}$$

$$\tan\theta \geq \frac{S'_{vm}(\gamma_s - \gamma)\tan\phi}{S'_{vm}(\gamma_s - \gamma) + \gamma(H/h)} \tag{2}$$

In these formulas, S_v is the volume concentration of sediment, S'_{vm} is the average volume concentration of stratification flow, γ is the density of water (g/cm3), γ_s is the density of solids (g/cm3), and $\tan\phi$ is the macroscopic friction coefficient among the particles, θ is the longitudinal slope of gully (°).

The Takahashi's model became one of the most common for the initiation of debris flow. Several related studies were published based on Takahashi's model later. Some discussed the laws of debris flow according to the geomorphology and the water content while others examined the critical conditions of debris flow with mechanical stability analysis.

This study aims to the initiation of loose solid materials in the gully; therefore, it can be regarded as the initiation problem of debris flow under hydrodynamic force. According to Takahashi's model, the critical depth for hydraulic-driven debris flows is:

$$h_0 = \left[\frac{C_*(\sigma - \rho)\tan\phi}{\rho\tan\theta} - \frac{C_*(\sigma - \rho)}{\rho} - 1 \right] d_m \tag{3}$$

where C_* is the volume concentration obtained by experiments(0.812); σ is the density of loose deposits (usually is 2.65 t/m3); ρ is the water density,1.0 t/m3, θ is the channel bed slope, (°); ϕ is the internal friction angle (°) and can be measured by shear tests ;

and d_m is the average grain diameter (mm), which can be expressed as:

$$d_m = \frac{d_{16} + d_{50} + d_{84}}{3} \tag{4}$$

where d_{16}, d_{50} and d_{84} are characteristic particle sizes of the loose deposits (mm).

2.2.2 Calculation of watershed runoff yield and concentration

The Guojuanyan gully is located in Du Jiangyan city, which is in a humid area. Therefore, stored-full runoff is the main pattern runoff yield in this gully, and this runoff yield pattern is used to calculate the watershed runoff. That is, it is supposed that the water storage can reach the maximum storage capacity of the watershed after each heavy rain. Therefore, the rainfall loss in each time I is the difference between the maximum water storage capacity I_m and the soil moisture content before the rain P_a. Hence, the water balance equation of stored-full runoff is expressed as follows (Ye, et al., 1992):

$$R = P - I = P - (I_m - P_a) \tag{5}$$

where R is the runoff depth (mm); P is the precipitation of one rainfall (mm); I is the rainfall loss (mm); I_m is the watershed maximum storage capacity (mm) for a certain watershed, it is a constant for a certain watershed that can be calculated by the infiltration curve or infiltration experiment data. In this study, I_m has been picked up from Handbook of rainstorm and flood in Sichuan (Sichuan Water and Power Department 1984); and P_a is the antecedent precipitation index, referring to the total rainfall prior to the 1 hour peak rainfall leading to debris flow initiation.

Eq. 5 can be expressed as follows:

$$P + P_a = R + I_m \tag{6}$$

In this study, P and P_a are replaced by I_{60} (1 hour rainfall) and API (the antecedent precipitation index), respectively; thus, Eq. 6 is expressed as:

$$I_{60} + API = R + I_m \tag{7}$$

In the hydrological study, the runoff depth R is:

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$$R=\frac{W}{1000F}=\frac{3.6\sum Q\cdot\Delta t}{F}=\frac{3.6Q}{F} \tag{8}$$

where R is the runoff depth (m); W is the total volume of runoff (m³); F is the watershed area (km²); Δt is the computational time step; and Q is the average flow of the watershed (m³/s), which can be expressed as follows:

$$Q = BVh_0 \tag{9}$$

where B is the width of the channel (m), V is the average velocity (m/s) and h_0 is the critical depth (m).

Eq. 7 is the expression of the rainfall threshold curve for a watershed, which can be used for debris flow early warning. This proposed rainfall threshold curve is a function of the antecedent precipitation index (API) and 1 hour rainfall (I_{60}), which is a line and a negative slope.

3 Case study

3.1 Location and gully characteristics of the study area

The Guojuanyan gully in Du Jiangyan city, located in the meizoseismal areas of the Wenchuan earthquake, China, was selected as the study area (Figure 4). It is located at the Baisha River, which is the first tributary of the Minjiang River. The seismic intensity of the study area was XI, which was the maximum seismic intensity of the Wenchuan earthquake. The Shenxi Gully Earthquake Site Park is at the right side of this gully. The area extends from 31°05′27″ N to 31°05′46″ N latitude and 103°36′58″ E to 103°37′09″ E longitude, covering an area of 0.15 km² with a population of 20 inhabitants. The elevation range is from 943 m to 1222 m, the average gradient of the main channel is 270‰, and the length of the main channel is approximately 580m.

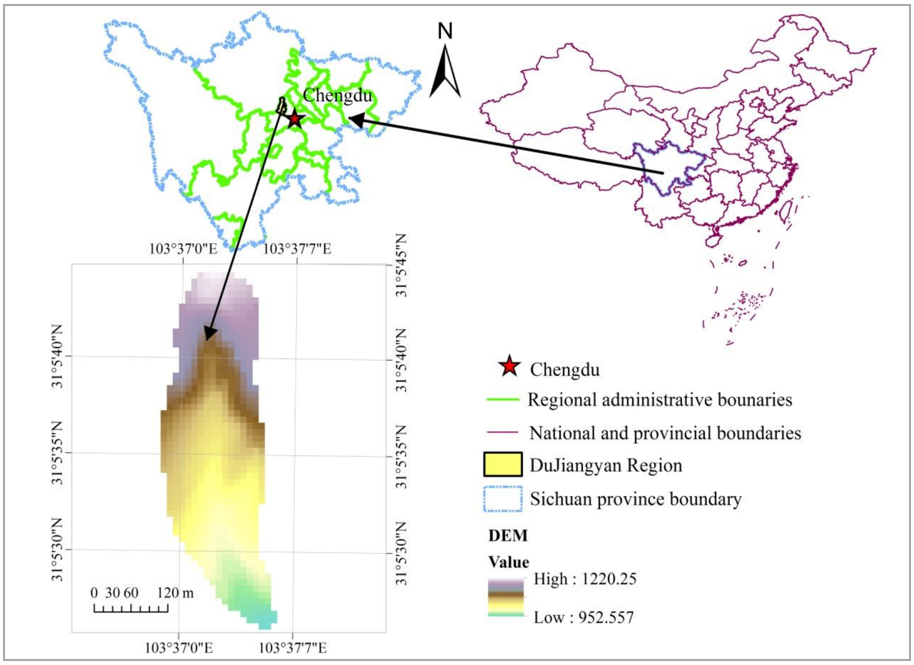

Figure 4 The location of the Guojuanyan gully

Geologically, the Guojuanyan gully is composed of bedrock and Quaternary strata. The bedrock is upper Triassic Xujiahe petrofabric (T_3x) whose lithology is mainly sandstone; mudstone; carbonaceous shale belonging to layered, massive structures; and semi solid-solid petrofabric. The Quaternary strata are alluvium (Q_4^{el+pl}), alluvial materials (Q_4^{pl+dl}), landslide accumulations and debris flow deposits ($Q_4^{sef+del}$). The thickness of the Quaternary strata ranges from 1 m to 20 m and varies greatly. The strata profile of the Guojuanyan gully is shown in Figure 5.

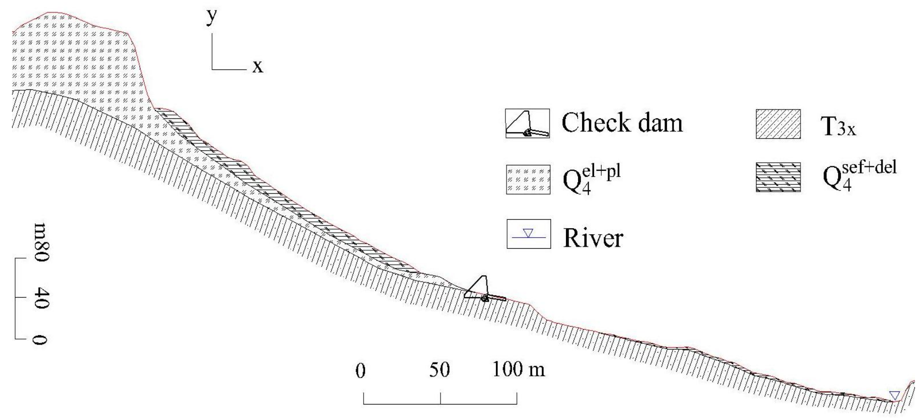

Figure 5 The strata profile of the Guojuanyan gully (Jun Wang et al, 2017)

Geomorphologically, the study area belongs to the Longmenshan Mountains. The famous Longmenshan tectonic belt has a significant effect on this region, especially the Hongkou- Yinxiu fault. The study area has strong tectonic movement and strong erosion, and the main channel is "V"-shaped. The area is characterized by a rugged topography, and the main slope gradient interval of the gully is 20° to 40°, accounting for 52.38% of the entire study area.

Climatically, this area has a subtropical and humid climate, with an average annual temperature of 15.2°C and an average annual rainfall of 1200 mm (Wang et al., 2014).

3.2 Materials and debris flow characteristics of the study area

The Wenchuan earthquake generated a landslide in the Guojuanyan gully, leading to an abundance of loose deposits that have served as the source materials for debris flows. A comparison of the Guojuanyan gully before and after the Wenchuan earthquake is shown in Figure 6. The field investigations show that the volume of materials is more than 20×10^4 m^3. Therefore, the trigger rainfall for debris flow has decreased greatly. The Guojuanyan gully had no debris flows before the earthquake; however, it became a debris flow gully after the earthquake, and debris flows occurred in the following years (Table 1). The field investigations and experiments determined that the density of the debris flow was between 1.8 and 2.1 g/cm³.

(a) 14 September, 2006 (b) 28 June, 2008

Figure 6 The Guojuanyan gully before (a) and after the Wenchuan earthquake (b) (from Google Earth)

Table 1 The frequency table of debris flow pre- and post-Wenchuan earthquake in the study area

Before the earthquake	After the earthquake								
Before 2008	2008	2009	2010		2011	2012	2013		2014
No record	24 September	17 July	13 August	17 August	1 July	17 August	9 July	26 July	18 July

3.3 Debris flow monitoring and streambed survey of the study area

After the Wenchuan earthquake, continuous field surveillance was undertaken in the study area. A debris flow monitoring system was also established in the study area. To identify the debris flow events, this monitoring system recorded stream water depth, precipitation and real-time video of the gully (Figure 7). The water depth was measured using an ultrasonic level meter, and precipitation was recorded by a self-registering rain gauge. The real-time video was recorded onto a data logger and transmitted to the monitoring center, located in the Institute of Mountain Hazards and Environment, Chinese Academy of Sciences. When an abnormal rainfall or a debris flow event occurs, the real-time data, including rainfall data, video record, and water depth data, can be observed and queried directly in the remote client computer in the monitroring center. Figure 8 shows images taken from the recorded video. These data can be used to analyze the rainfall or other characteristics, such as the 10-min, 1- and 24-h critical rainfall. The recorded video is usually used to analyse the whole inundated process of debris flow events and to identify debris flow events as well as the data from rainfall, flow depth, and field investigation.

(a)Real-time camera and rain gauge (b) Ultrasonic level meters

Figure 7 Debris flow monitoring system in the study area

Figure 8 Real-time images from video taken during the debris flow movement

3.4 Data collection and the characteristics of rainfall

The Wenchuan earthquake occurred in the Longmenshan tectonic belt, located on the eastern edge of the Tibetan plateau, China, which is one of three rainstorm areas of Sichuan Province (Longmen mountain rainstorm area, Qingyi river rainstorm area and Daba mountain rainstorm area).Heavy rainstorms and extreme rainfall events occur frequently. The spatial-temporal variability of rainfall has the following characteristics:

(1) Abundant precipitation: The average annual precipitation was 1177.3 mm from 1971 to 2000, and the average monthly precipitation is shown in Figure 10. From 1971 to 2000, the minimum annual precipitation of 713.5 mm occurred in 1974, and the maximum annual precipitation of 1605.4 mm occurred in 1978.

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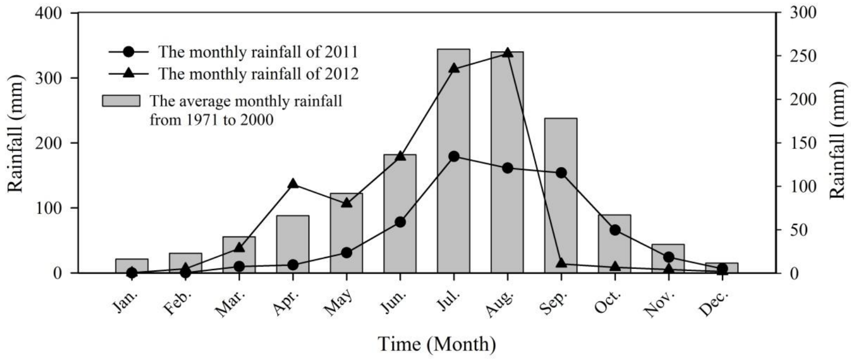

Figure 9 The average monthly precipitation of the Guojuanyan gully from 1971 to 2000 and the monthly rainfall of 2011 and 2012

(2) Severely inhomogeneous distribution of precipitation in time: from Figure 9 we can observe that rainfall is seasonal, with approximately 80% of the total rainfall occurring during the monsoon season (from June to September) and the other 20% in other seasons. For instance, in 2012, the total annual rainfall in this area was approximately 1148 mm, and rainfall in the monsoon season from June to September was 961 mm, accounting for 83.7% of the annual total.

(3) Due to the impact of the atmospheric environment, the regional and annual distribution of rainfall is seriously inhomogeneous; moreover, the rainfall intensity has great differences. From 1957 to 2008, the maximum monthly rainfall was 592.9 mm, the daily maximum rainfall was 233.8 mm, the hourly maximum rainfall was 83.9 mm, the 10 minute maximum rainfall was 28.3 mm, and the longest continuous rainfall time was 28 days.

Debris flow field monitoring data and on-site investigation data were used to identify the debris flow events and to analyze the characteristics of the rainfall pattern and the critical rainfall characteristics. From several typical rainfall process curves (Figure 10), the rainfall pattern of the Guo Juanyan gully is the peak pattern, displaying the single peak and multipeak, a characteristic of short-duration rainstorms. Through the statistical analysis of the 10-min, 1-, and 24-h critical rainfall of debris flow events after the earthquake, their characteristics can be obtained, as shown in Figure 11.

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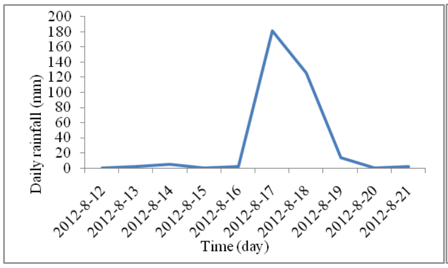
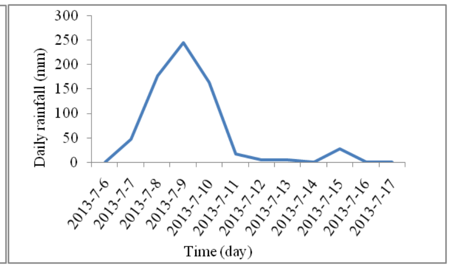
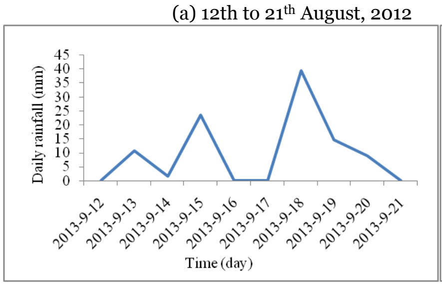
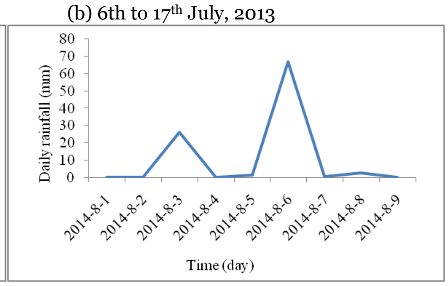




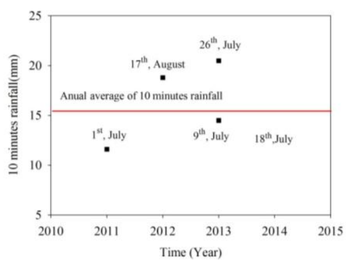
(a) 12th to 21th August, 2012 (b) 6th to 17th July, 2013

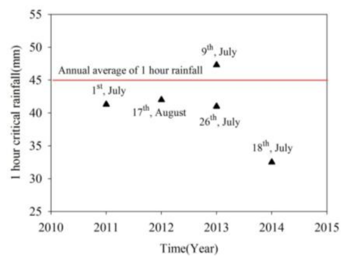




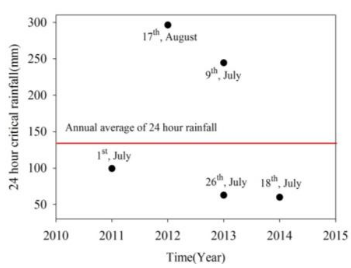
(c) 12th to 21th September, 2013 (d)1st to 9th August, 2014

Figure 10 The typical rainfall process curves of the Guojuanyan gully





(a) The 10-min critical rainfall (b) The 1-h critical rainfall



(c) The 24-h critical rainfall

Figure 11 The critical rainfall of debris flows in the Guojuanyan gully

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Figure 11a shows that the observed 10-min critical rainfall is between 11.1 mm and 21.5 mm. According to the Sichuan Hydrology Record Handbook (Sichuan Water and Power Department 1984), the annual average 10-min rainfall of the study area is approximately 15.1 mm. According to the obsevation, 60% of debris flow events occurred below the annual average 10-min rainfall. In addtion, the 1-h critical rainfall varied between 34.5 mm and 47.3 mm in the study area (Figure 11b). And the annual average 1-h rainfall is 45.0 mm based on the Sichuan Hydrology Record Handbook (Sichuan Water and Power Department 1984). Figure 11b shows that 80% debris flow events occurred below the annual average 1-h rainfall, except for the debris flow event occurred on July 9, 2013. At last, the minimum value of 24-h critical rainfall is 60.4 mm and the maxmum value is 296.4 mm in the study area. According to the Sichuan Hydrology Record Handbook (Sichuan Water and Power Department 1984), the annual average 24-h rainfall is 132 mm. From Figure 11c, we can see that 24-h critical rainfall for different debris flow events vary widely and 60% debris flow events occurred below the annual average 24-h rainfall.

From the above study, we can find that the 10-min and the 1-h critical rainfalls of different debris flow events have minor differences; however, the 24-h critical rainfalls vary widely. The reason is that debris flow is usually triggered by short-duration rainstorms. Therefore, the short-durations of 10-min and 1-h rainfall have higher correlation with debris flow occurrence and have the minor differences. Further analyzing the 10-min and 1-h critical rainfalls, we can find that they vary with the antecedent precipitation index (API). They are variable rather than constant. In this paper, the antecedent precipitation index (API) and the 1-h rainfall (I_{60}) were used to calculate the rainfall threshold curve of debris flows in the Guojuanyan gully.

The 10-min, 1-h and 24-h rainfalls changed little pre- and post-Wenchuan earthquake, but the debris flow activity differ considerably. The Guo Juanyan gully has no debris flows under the annual average rainfall before 2008, but it became a debris flow gully after the earthquake under the same conditions, even the rainfall was smaller than the annual average rainfall. This indicates that earthquakes have a big influence on debris

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flow occurrence. The Wenchuan earthquake triggered a landslide in the Guo Juanyan gully and a huge volume of loose deposits was present on the channels and slopes. These loose deposits provide abundant loose source materials for debris flow activity. Therefore, the rainfall threshold of debris flow post-earthquake is an important and urgent issue to study for debris flow early warning and mitigation.

4 Results

4.1 The rainfall threshold curve of debris flow

4.1.1 The critical depth of the Guojuanyan gully

The grain grading graph (Figure 12) is obtained by laboratory grain size analysis experiments for the loose deposits of the Guojuanyan gully. Figure 13 shows that the characteristic particle sizes d_{16}, d_{50}, d_{84} and d_m are 0.18 mm, 1.9 mm, and 10.2 mm, 4.1 mm, respectively. According to Eq. (1), the critical depth (h_0) of the Guojuanyan gully is 7.04 mm.

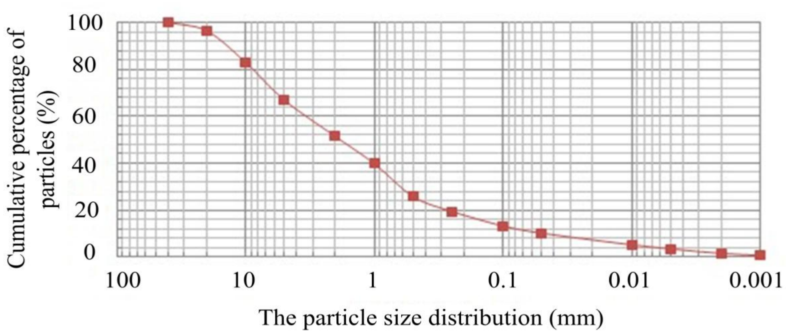

Figure 12 The grain grading graph of the Guojuanyan gully

Table 2 Critical water depth of debris flow triggering in Guojuanyan gully

C_*	σ (g/cm³)	ρ (g/cm³)	$\tan\theta$	d_{16} (mm)	d_{50} (mm)	d_{84} (mm)	d_m (mm)	ϕ (°)	$\tan\phi$	h_0 (mm)
0.812	2.67	1.0	0.333	0.18	1.9	10.2	4.1	21.21	0.388	7.04

4.1.2 The rainfall threshold curve of debris flow

Taking the cross-section at the outlet of the debris flow formation region as the computation object, based on the field investigations and measurements, the width of the cross-section is 20 m, and the average velocity of debris flows is 1.5m/s. Based on the Handbook of rainstorm and flood in Sichuan (Sichuan Water and Power Department 1984), the watershed maximum storage capacity (I_m) of the Guojuanyan gully is 100mm. The calculated rainfall threshold curve of debris flow in the Guojuanyan gully is shown in Table 3.

Table 3 The calculated process of the rainfall threshold

Watershed	h_0 (mm)	B (m)	V (m/s)	Q (m³/s)	Δt (h)	F (km²)	R (mm)	I_m (mm)	$R+I_m$ (mm)
Guojuanyan	7.04	20.0	1.5	0.197	1	0.11	6.9	100	106.9

From the calculated results, we can conclude the rainfall threshold of the debris flow is $I_{60}+API=R+I_m=106.9\approx107$ mm; that is, when the sum of the antecedent precipitation index (API) and the 1 hour rainfall (I_{60}) reaches 107 mm (early warning area), the gully may trigger debris flow.

4.2 Validation of the results

4.2.1 The calculation of the antecedent precipitation index (API)

The 1 hour rainfall (I_{60}) is obtained from the observed data of the Guojuanyan gully. The antecedent precipitation index (API) is calculated as the following expression (Guo, 2013; Zhuang, 2015; Zhao, 2011):

$$API=P_{a0}+R_t \tag{10}$$

where P_{a0} is the antecedent effective rainfall (mm) and R_t is the stimulating rainfall (mm), which can be expressed as:

$$R_t=\sum_{t_0}^{t_n} r \tag{11}$$

where t_0 is the start time (days) for the rainfall on a given day, t_n is the time prior to the 1 hour rainfall peak and r is the precipitation (mm).

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The antecedent effective rainfall P_{a0} is:

$$P_{a0} = KP_1 + K^2P_2 + K^3P_3 + \ldots + K^nP_n \quad (12)$$

where P_n (n =1, 2, 3…, n) is the daily rainfall prior to debris flow events (mm), and K is the decreasing coefficient (K =0.8-0.9), which is determined by weather conditions, such as sunny or cloudy conditions.

Eq.12 can be used to estimate the amount of solid material and the moisture content prior to the debris flow. The effect of a rainfall event usually diminishes within 20days and decreases with lower daily K values. Different patterns of storm debris flow gullies require different numbers of previous indirect rainfall days, which can be determined by the relationship between the stimulating rainfall and the antecedent rainfall of a debris flow (Pan, et al., 2013). Generally, a typical rainstorm debris flow gully requires 20 days of antecedent rainfall.

In this paper, n =20 and K =0.8. The complete rainfall processes of debris flow events obtained from the observed data can be used to calculate P_{a0} , R_t , and API .

4.2.2 The rainstorm and debris flow events in the Guojuanyan gully during 2010-2014

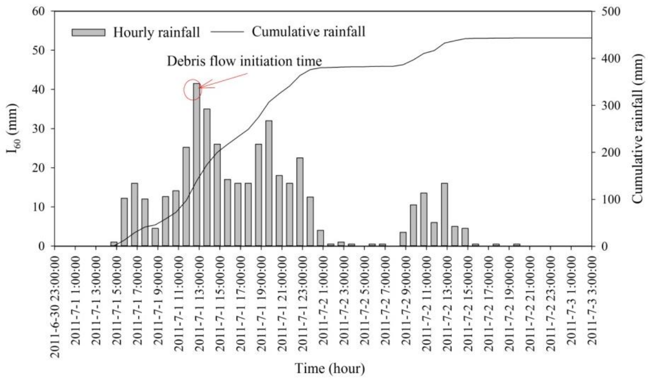
Table 1 shows that debris flows occurred almost every year after the earthquake. The conditions of the debris flow events were collected through field investigations and interviews. The specific conditions of these debris flows are listed in Table 3. Unfortunately, there were no rainfall data before 2011, when we started field surveys in the Guojuanyan gully.

Table 4 The specific conditions of debris flow events in the Guojuanyan gully after the earthquake

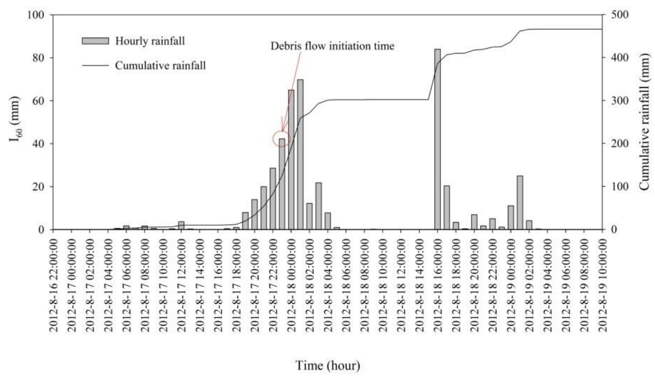
Time	Volume (10^4 m^3)	Surges	Rainfall data record
24 September, 2008	0.6	1	No
17 July, 2009	0.8	1	No
13 August, 2010	4.0	3	No
17 August, 2010	0.4	1	No
1 July, 2011	0.8	1	Yes
17 August, 2012	0.7	1	Yes
9 July, 2013	0.4	1	Yes
26 July, 2013	2.0	2	Yes

18 July, 2014	1.5	1	Yes

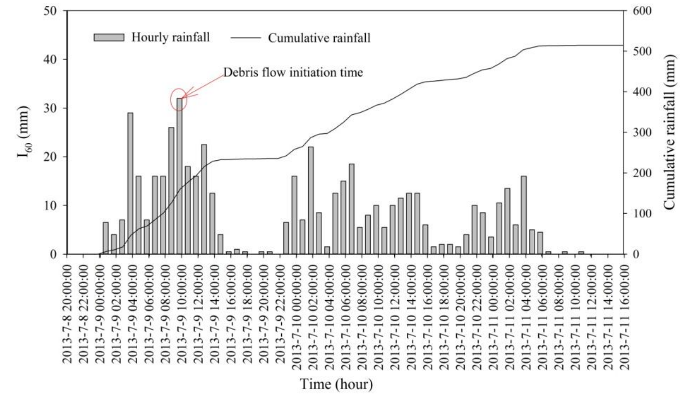
This study analyzed the rainfall process of the 5 debris flows (Figure 13) and calculated the corresponding antecedent effective rainfall (P_{a0}), stimulating rainfall (R_t), and 1 hour rainfall (I_{60}) (Table 5).



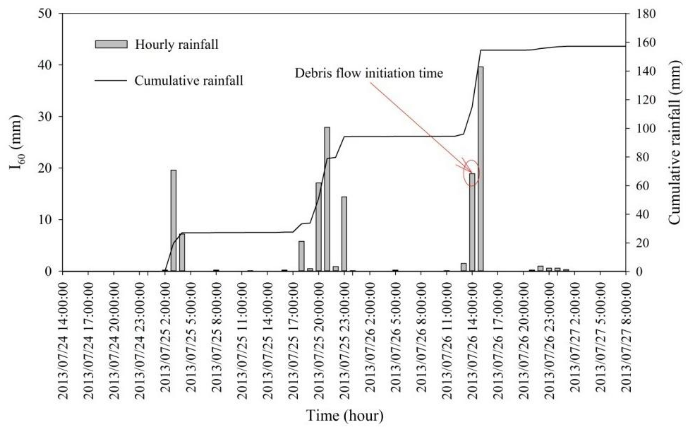
(a)



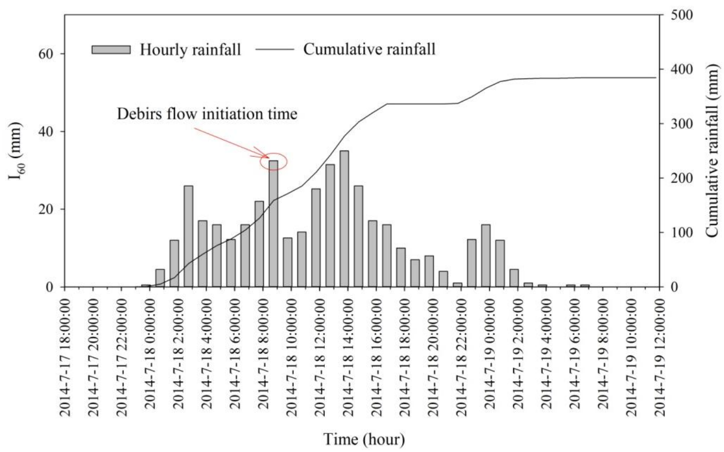
(b)


Hourly rainfall
Cumulative rainfall
Debris flow initiation time
I_{60} (mm)
Cumulative rainfall (mm)
Time (hour)

(c)


Hourly rainfall
Cumulative rainfall
Debris flow initiation time
I_{60} (mm)
Cumulative rainfall (mm)
Time (hour)

(d)


Hourly rainfall
Cumulative rainfall
Debris flow initiation time
I_{60} (mm)
Cumulative rainfall (mm)
Time (hour)

(e)

Figure 13 The rainfall process of debris flowe vents in the Guojuanyan gully from 2011 to 2014 (a, July 1, 2011; b, August 17, 2012; c, July 9, 2013; d, July 26, 2013; e, July 18, 2014)

Furthermore, some typical rainfall whose daily rainfall was greater than 50 mm but did not trigger a debris flow were also calculated; the greatest 1-h rainfall is considered as I_{60} (Table 5).

Table 5 The data of typical rainfall in the Guojuanyan gully after the earthquake

Time	Daily rainfall (mm)	Pa_0 (mm)	R_t (mm)	*API* (mm)	I_{60} (mm)	*API*+I_{60} (mm)	Location to the threshold line	Trigger debris flow
1 July, 2011		9.7	97.6	107.3	41.5	148.8	Above	Yes
17 August , 2012		12.1	81.9	94.0	42.3	136.3	Above	Yes
9 July , 2013		5.7	127.5	133.2	32	165.2	Above	Yes
26 July , 2013		22.4	96.0	118.4	18.9	137.3	Above	Yes
18 July, 2014		10.7	116.2	126.9	32.5	159.4	Above	Yes
20 August , 2011	82.8	8.5	19.0	27.5	26.8	54.3	Below	No
5 September , 2011	52.1	48.7	1.2	49.9	16.2	66.1	Below	No
16 June , 2012	55.8	5.6	6.6	12.2	27.0	39.2	Below	No
3 August , 2012	148.3	7.5	84.3	91.8	26.7	118.5	Above	No
18 August , 2012	125.7	54.3	0	54.3	65.0	119.3	Above	No
18 June , 2013	50.6	6.2	3.8	10.0	40.0	50.0	Below	No
28 July , 2013	59.4	13.4	30.0	43.4	29.4	72.8	Below	No
6 August , 2013	56.1	12.4	34.0	46.4	17.1	63.5	Below	No

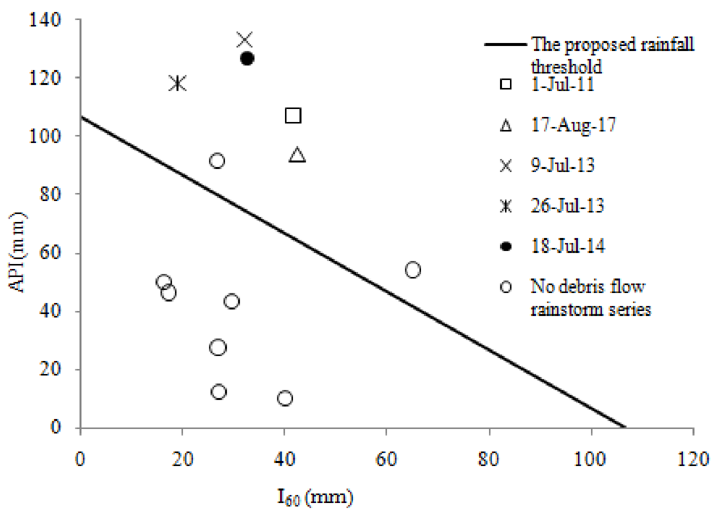


Figure 14 The proposed rainfall threshold curve of debris flow in the Guojuanyan gully

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The proposed rainfall threshold curve is a function of the antecedent precipitation index (API) and 1-h rainfall (I_{60}), which is a line and a negative slope. Figure 14 shows that the calculated values $I_{60}+API$ of debris flow events in the Guojuanyan gully are all above the rainfall threshold curve, while most of the rainstorms that did not trigger debris flow were below the curve. That is, the proposed rainfall threshold curve is reasonable through the validation by rainfall and hazards data of the Guojuanyan gully.

5 Discussions

The proposed rainfall threshold curve is a function of the antecedent precipitation index (API) and the 1-h rainfall (I_{60}), which has been validated by rainfall and hazards data and can be applied to debris flow early warning and mitigation. However, the special prone environment of debris flow after earthquake caused the rainfall threshold is much more complex and uncertain. The rainfall threshold of debris flows varies with the antecedent precipitation index (API), rainfall characteristics, amount of loose deposits, channel and slope characteristics, and so on. In Figure 14, there are two points above the curve that did not trigger debris flow at all; therefore, we should further study the characteristics of the movable solid materials and other factors.

In addition, restricted by the limited rainfall data, this study was validated by only 5 debris flow events. The value of the curve should be further validated and continuously corrected with more rainfall and disaster data in later years.

The proposed approach in this study is based on the physical process of debris flow initiation. As the initiation depth in distrinct watershed is different from each other because of the different topography and loose solid materials, hence the rainfall threshold is independent for each watershed. While most of debris flow gullies in Wenchuan earthquake affected areas with scarcity of rainfall data and disaster data, therefore, the approach presented in this study hasn't been validated by other gullies except the Guojuanyan gully so far.

6 Conclusions

(1) In the Wenchuan earthquake-stricken areas, loose deposits are widely distributed, causing dramatic changes on the environmental development for the occurrence of debris flow; thus, the debris flow occurrence increased dramatically in the subsequent years. The characteristics of the 10-min, 1-h and 24-h critical rainfalls were represented based on a comprehensive analysis of limited rainfall and hazards data. The statistical results show that the 10-min and 1-h critical rainfalls of different debris flow events have minor differences; however, the 24 hour critical rainfalls vary widely. The 10-min and 1-h critical rainfalls have a notably higher correlation with debris flow occurrences than to the 24-h critical rainfalls.

(2) The rainfall pattern of the Guojuanyan gully is the peak pattern, both single peak and multi-peak. The antecedent precipitation index (API) was fully explored by the antecedent effective rainfall and stimulating rainfall.

(3) As an important and effective means of debris flow early warning and mitigation, the rainfall threshold of debris flow was determined in this paper, and a new method to calculate the rainfall threshold is put forward. Firstly, the rainfall characteristics, hydrological characteristics, and some other topography conditions were analysed. Then, the critical water depth for the initiation of debris flows is calculated according to the topography conditions and physical characteristics of the loose solid materials. Finally, according to the initiation mechanism of hydraulic-driven debris flow, combined with the runoff yield and concentration laws of the watershed, this study promoted a new method to calculate the debris flow rainfall threshold. At last, the hydrological condition for the initiation of a debris flow is the result of both short-duration heavy rains (I_{60}) and the antecedent precipitation index (API). The proposed approach resolves the problem of debris flow early warning in areas with scarcity data, can be used to establish warning systems of debris flows for similar catchments in areas with scaricty data. This study provides a new thinking for the debris flow early warning in the mountain areas.

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