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Debris Flow Warning Threshold Based on Antecedent Rainfall：a Case Study in Jiangjia Ravine, Yunnan, China

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Abstract: Debris flows in Jiangjia Ravine in Yunnan province, China are not only triggered by intense storms but also by short-duration and low-intensity rainfalls. This reflects the significance of antecedent rainfall. This paper tries to find the debris flow-triggering threshold by considering antecedent rainfall through a case study in Jiangjia Ravine. From 23 debris flow events, the I-D (Intensity-Duration) threshold was found, which is very close to the line of 95th percentile regression line of rainfall events, representing that 95% of rainfalls can potentially induce debris flows and reflects the limitation of I-D threshold application in this area. Taking into account the effect of antecedent rainfall, the debris flow-triggering threshold for rainfall quantity and intensity is statistically and empirically derived. The relationships can be used in debris flow warning system as key thresholds. Coupling with the rainfall characteristics in this area, new thresholds are proposed as triggering and warning thresholds.

Keywords: I-D threshold; debris flow warning system; antecedent rainfall; Jiangjia Ravine

Introduction

Debris flows generally initiate in response to slope failures and develop by assimilating channel sediments (Innes 1983; Kang et al. 2004), and rainfall is of primary importance both as predisposing element and triggering factor (Wieczorek 1996; Tiranti et al. 2008). Thus, precipitation is usually as one of the most active factors in models that forecast debris flows. Among them, the most discussed approach is the rainfall intensity-duration (I-D) relationship, which is derived from investigations of rainfall intensity and duration, cumulative event rainfall, and antecedent rainfall (Caine 1980; Tan et al. 1994; Shieh et al. 1995; Reichenbach et al. 1998; Corominas and Moya 1999; Crozier 1999; Fraccarollo and Papa 2000; Fan et al. 2003; Brooks et al. 2004; Jan and Lee 2004; Chien-Yuan et al. 2005; Cannon et al. 2008; Crosta and Frattini 2008; Guzzetti et al. 2007, 2008). In general, the thresholds can be grouped in four categories (Guzzetti et al. 2008):

(1) Thresholds that combine precipitation measurements obtained for specific rainfall events (Guzzetti et al. 2008).

(2) Thresholds that include the antecedent conditions (Crozier 1999; Crosta and Frattini 2008).

(3) Other thresholds, including hydrological thresholds (Reichenbach et al. 1998).

(4) Rainfall event-intensity (EI) thresholds (Guzzetti et al. 2007).

In these categories, the rainfall event related to a debris flow is defined by taking the non-rainfall period as more than 24 h (Fan et al. 2003; Guzzetti

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et al. 2007, 2008). Some researches defined 4 mm and 3 h or 6h as the critical rain amount and duration thresholds, to improve the duration and intensity proper in the dispersion rainfalls (Shieh et al. 1995; Jan and Lee 2004). However, the impact of antecedent rainfall in these criterions is still ambiguous.

Impact of antecedent rainfall appears significant in Jiangjia Ravine, where debris flows are triggered not only by intense rainstorms but also by rainfalls with short duration and low intensity. Observation data shows that the triggering rainfall intensity may be as low as several millimeters per hour, which is much lower than the usual cases in other regions. And it also shows that the critical rainfall intensity in June is much higher than that in July and August. This implies the effect of antecedent rainfall which helps decreasing the shear strength of soil (Wang et al. 1999; Zhang and Tang 1999; Li et al. 2001; Cui et al. 2003).

It's difficult to study the influence of antecedent rainfall to debris flow as it mainly relies on the heterogeneity of soils (strength and permeability properties), which makes it hard to measure the moisture. Usually, the frequently used method for calculating antecedent daily rainfall is the weighted sum equation as below (Crozier and Eyles 1980; Glade et al. 2000):

$$P_b = \sum_{1}^{n} P_i \cdot K_i \tag{1}$$

where P_b is the effective antecedent precipitation, P_i is the daily precipitation in the i-th day proceeding to the debris flow event ($1 \le i \le n$) and K_i is a decay coefficient due to evaporation.

Then the rainfall factor influencing debris flows consists of three parts: indirect antecedent precipitation (IAP), triggering precipitation (TP), and direct antecedent precipitation (DAP). Obviously, IAP increases soil moisture and decreases the soil stability, and DAP saturates soils and thus decrease the critical condition of debris flow occurrence. Although TP is believed to initiate debris flows directly, its contribution amounts to only 37% of total water (Cui et al. 2007).

This study conducts a further exploration of the effect of antecedent rainfall based on 23 debris flows and 61 intense rainfall events during 2006 and 2008 in Jiangjia Ravine, and incorporates the antecedent rainfall factor into the I-D relationship. Then we build a new relationship between the antecedent rainfall and critical rainfall and use it for warning of debris flow.

1 Study Area

Jiangjia Ravine (Figure 1), with an area of 48.6

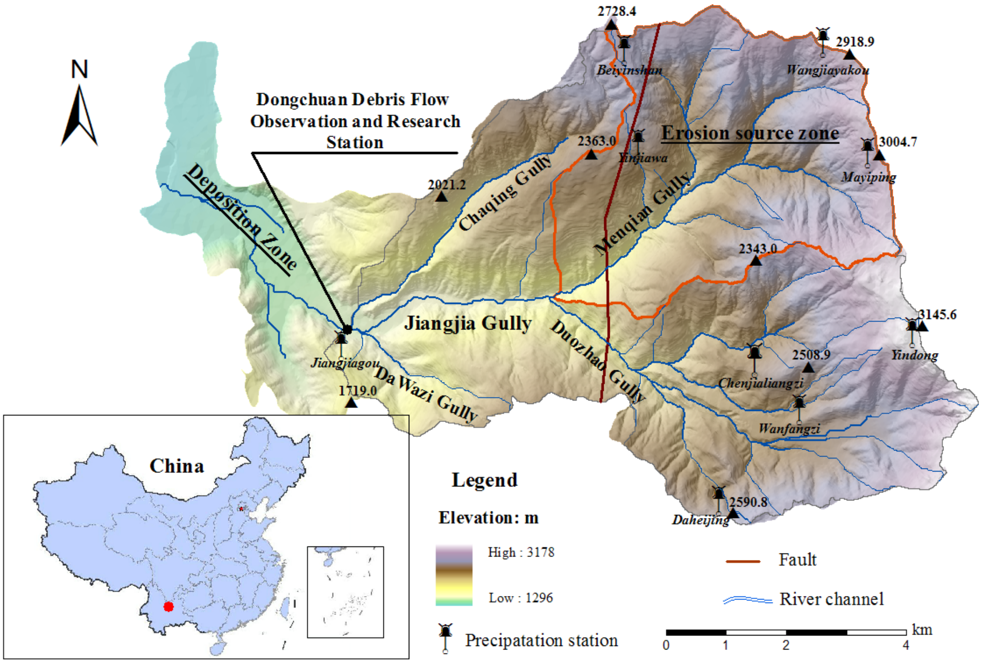

Figure 1 Digital elevation model and the distribution rain gauses in Jiangjia Ravine

km^2, is a tributary of Xiaojiang River and and its mainstream channel extends from the drainage divide at 3,269 m altitude west to the joint with the Xiaojiang at 1,042 m.

Annual rainfall ranges between 400-1,000 mm and varies remarkably with season and elevation. About 85% of the rainfall occurs between May and October and about 40% between altitudes of 2,500 m and 3,000 m, the altitude of debris flow source region.

With Xiaojiang fault intricately distributed, the ravine is deeply cut, steeply sloped and strongly impacted by frequent tectonic activities (Cui et al. 2005). Through the DEM, the ravine's slopes, comprising 55% of the basin area, are steeper than 25°, and the hillslope angle is around 40°, making it prone to shallow landslides and collapses. The main rocks in this ravine are Proterozoic shallow metamorphic rocks and about 80% of the outcrops which are weak and easily weathered. Phyllite, Sandstone and Slate are distributed widely in the source areas of debris flow, resulting large amounts of loose materials, up to 12.3×10^9 m^3 (Cui et al. 2007).

The soil is wide-graded, with grain size between 10^{-6} m and 10^1 m (Cui 1999). The coarse grains form the framework structure and fine grains fill in the framework. The soil on upper layer on the fragmented slope performs high infiltration and evaporation capacity for its high porosity, while the soil of lower layer has good water retention due to the relative impermeable layer generated by the transportation of fine particles. The moisture reserved by the impermeable layer is crucial for subsurface runoff yield and debris flow initiation.

Human-related factors also account for debris flows in this ravine. Many slopes which used to be covered by forests have been developed for human use in the last century, especially for mining industry. The resultant disturbances intensify debris flows by engendering instability of the slopes. The ground cover consists of forest (4.2%), shrub land (8.4%), grassland (26.9%), barren terrain (26.3%), and the other 34.2% includes alluvial surfaces and fans, farmlands and others (Figure 2, Cui et al. 2005).

Since 1965, more than 400 debris flows have occurred, each consisting of many surges, magnitude varies from thousands to millions of cubic meters, exhibiting a variety of flow types and flow regimes. According to Dongchuan debris flow observation and research station, which is located at the intercross of Menqian gully and Duozhao gully, the debris flows can be systemically observed. Due to the prevention constructions in the source area in Duo Zhao gully, the debris flows are mainly from Menqian gully (Figure 1).

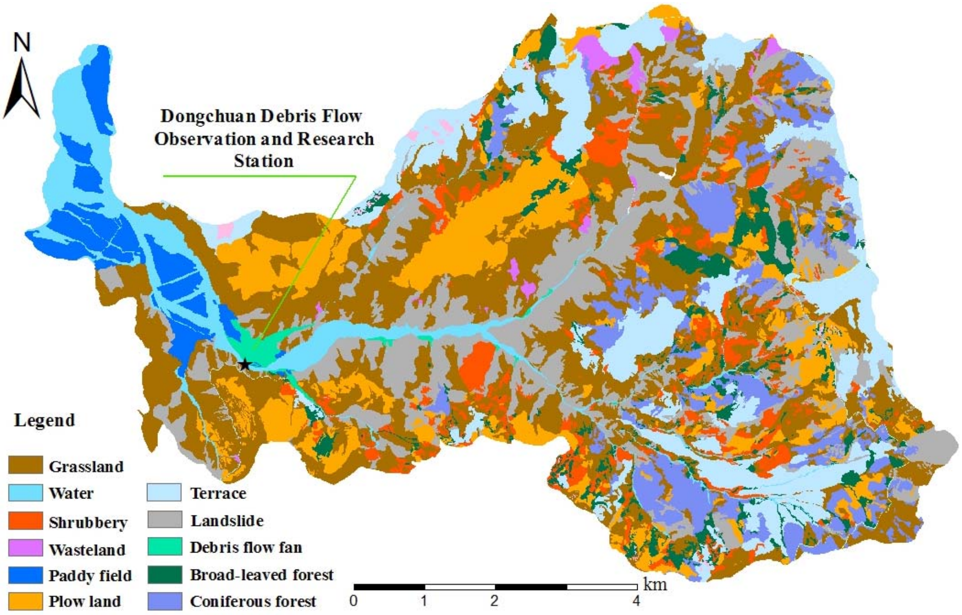

Figure 2 Landuse types in Jiangjia Ravine

2 Data Collection

2.1 Debris flow events

Debris flow is observed at the section about 5 km from the source area, and it takes about 0.5-1.5 h for debris flows to travel from the source area to the observation section.

We collected 23 debris flow events during 2006 and 2008 including the date and arriving time, density and magnitude. Part of the debris flow information is listed in Table 1.

Table 1 Debris flow information in 2007

Date	T_A	T_I	ρ (g/cm^3)	Q_{max} (m^3/s)	R_t (m^3)
2007-7-10	3:12	2:30	1.624	5.6	1948
2007-7-25	21:49	21:16	2.184	2262.5	10,9072
2007-7-30	14:20	13:43	1.831	3.2	2,059
2007-9-17	20:15	19:44	2.014	134.9	5,728

Note: T_A = the debris flow arriving time at the observation section; T_I = the debris flow initiation time; ρ = the debris flow density; Q_{max} = the Maximum surge flux; R_t = the total sediment amount of one debris flow event.

2.2 Rainfall data collection

There are nine siphon rain-gauges in Jiangjia Ravine, four in the major source areas at elevation of 630, 2,728, 2,919 and 3,004 m, respectively (Figure 1). The precision is 0.1 mm, and temporal resolution is 1 min. The data shows little variation because of their close elevation and location within less than 2 km. So we take rainfall data from Mayiping, which is the most continuous and complete rainfall record.

We defined 4 h as the non-rainfall interval between two successive rainfalls, as well as rainfall amount less than 0.5 mm in 6 successive hours as thresholds (Shieh et al. 1999; Jan and Lee 2004). Then we identify 61 rainfall events during 2006 and 2008 (Table 2).

The daily rainfall is between 0-39.6 mm, and the intensity is between 0-20.7 mm/h. Most rainfalls that triggered debris flows have a low intensity and long duration, so if the rainfall events are separated by taking 24 h as the non-rainfall interval threshold, only several rainfall events can be got in one month. So the definition in this paper is more advantaged to keep the data reasonable. For example, as defined, the long-duration rainfall which happened on 24th July 2007 can be divided into 3 separate events, accompanied by 3 debris flows, with total 184 surges (Figure 3).

It is noted that there is a sudden change of rainfall intensity in most events about 0.5-1.5 hours before the debris flow occurred at the observation section, which coincides the travel time. Therefore we take the sudden rainfall change in 1 hour as the inducing rainfall intensity. If there is no sudden

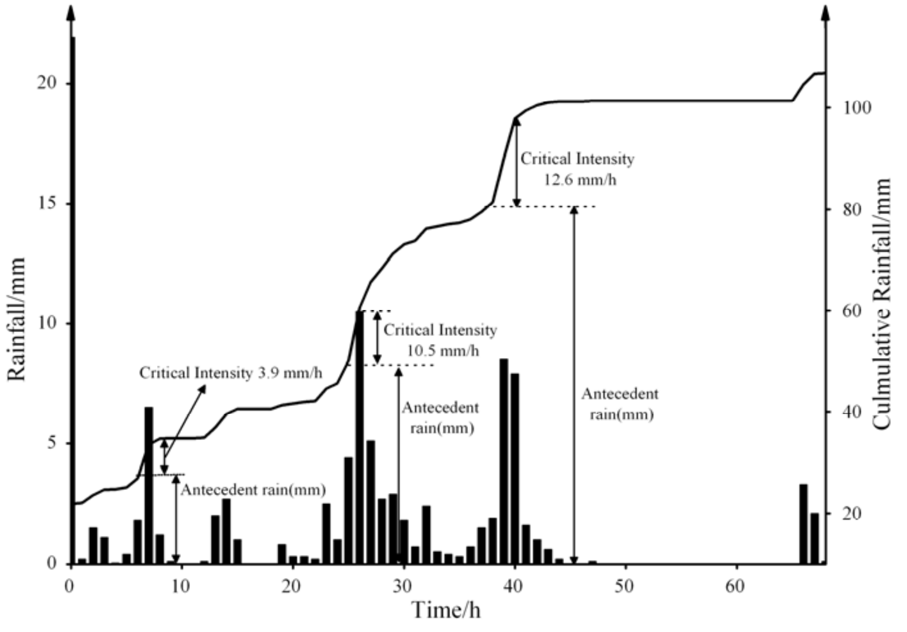

Figure 3 The rainfall process of 24th July 2007 and debris flow events responding to the rainfall: bars correspond to the hourly rainfalls (left Y-axis, mm/h); line indicates the relevant cumulative rainfalls (right Y-axis, mm).

Table 2 Rainfall events in Jiangjia Ravine during 2006 and 2008

No.	Date	D (h)	P (mm)	I (mm/h)	Triggered Debris flow	No.	Date	D (h)	P (mm)	I (mm/h)	Triggered Debris flow
1	2006-5-21	19.6	17.7	0.9	N	32	2007-7-30	9.6	23.1	2.4	Y
2	2006-5-25	12	10.8	0.9	N	33	2007-8-11	22	18.7	0.9	Y
3	2006-5-26	38	40.4	1.1	N	34	2007-8-20	4.6	11	2.4	N
4	2006-5-28	52	20.3	0.4	N	35	2007-8-24	29.6	51.3	1.7	N
5	2006-6-7	1.5	15.4	10.3	N	36	2007-9-14	5.25	18	3.4	Y
6	2006-6-8	24.5	15.5	0.6	N	37	2007-9-17	12	23.6	2	Y
7	2006-6-16	5.5	10.8	2	N	38	2007-10-11	8.5	21	2.5	N
8	2006-6-27	4.5	17	3.8	N	39	2008-6-5	22.7	31.3	1.4	N
9	2006-6-30	11.5	31.9	2.8	N	40	2008-6-9	7.5	20.4	2.7	N
10	2006-7-5	3	25.2	8.4	Y	41	2008-6-11	11.1	50.8	4.6	N
11	2006-7-6	5.5	24.3	4.4	Y	42	2008-6-15	24	48.3	2	N
12	2006-7-17	8.75	38.9	4.4	N	43	2008-7-1	4	13.7	3.4	Y
13	2006-8-15	4.25	30.6	7.2	Y	44	2008-7-3	19.2	20.4	1.1	N
14	2006-8-20	9	20.6	2.3	Y	45	2008-7-5	2	4.7	2.4	Y
15	2006-8-23	9	18.2	2	N	46	2008-7-11	0.5	7.1	14.2	Y
16	2006-9-8	9.2	32.6	3.5	N	47	2008-7-11	0.5	1.1	4.2	Y
17	2006-9-15	14.4	15.2	1.1	N	48	2008-7-18	3.1	32.3	10.4	N
18	2006-9-18	6.4	13.8	2.2	N	49	2008-7-19	1	19.8	19.8	N
19	2006-9-30	7.6	12	1.6	N	50	2008-7-22	4.25	20.9	4.9	Y
20	2006-10-6	2.2	28	12.7	N	51	2008-7-27	17	43.3	2.5	N
21	2007-4-28	7.3	18	2.5	N	52	2008-7-31	0.67	2.6	3.9	Y
22	2007-5-11	17.35	23.8	1.4	N	53	2008-8-3	4	18.8	4.7	Y
23	2007-5-16	26.2	39.1	1.5	N	54	2008-8-3	2	2.2	1.1	Y
24	2007-6-8	16.8	31.9	1.9	N	55	2008-8-4	1	19.8	19.8	Y
25	2007-6-24	2.9	12.3	4.2	N	56	2008-8-5	0.6	1.8	3.6	Y
26	2007-7-7	7.6	20.2	2.7	N	57	2008-8-5	7	7.8	1.1	Y
27	2007-7-10	5	15.9	3.2	Y	58	2008-8-8	25	31.3	1.3	Y
28	2007-7-12	3	47.8	15.9	N	59	2008-8-11	2	7.2	3.6	Y
29	2007-7-19	35.9	51.4	1.4	N	60	2008-8-16	9.2	14.6	1.6	N
30	2007-7-24	7.5	18.2	2.4	Y	61	2008-8-17	5.9	12.8	2.2	N
31	2007-7-25	25.4	60.4	2.4	Y						

Note: D, duration of the rainfall event; P, rainfall amount; I, rainfall intensity.

Table 3 Debris flow and rainfall information during 2006 and 2008 in Jiangjia Ravine

Date	D (h)	I (mm/h)	T	R_T (mm)	R_I (mm)	R_A (mm)	Date	D (h)	I (mm/h)	T	R_T (mm)	R_I (mm)	R_A (mm)
2006-7-5	1.3	19.2	0:15	24	5	18	2008-7-5	2	2.4	15:55	4.7	13.2	38.6
2006-7-6	3.5	5.2	23:42	18.1	5.7	33.3	2008-7-11	0.13	26.9	6:26	3.5	7.3	14.2
2006-8-15	3.3	9.2	17:46	30.3	13.5	19.4	2008-7-11	0.5	9.2	6:48	21.7	19.4	14.2
2006-8-20	1.4	4.3	22:04	6	2.2	23.5	2008-7-22	4.3	4.9	17:46	20.9	9.2	39.7
2007-7-10	1.5	6.7	2:30	10.1	2.4	45.2	2008-7-31	0.7	3.9	5:00	2.6	2.6	31.8
2007-7-24	4.5	1.4	23:42	6.3	1.3	27.8	2008-8-3	0.4	1.2	0:15	0.3	0.3	40
2007-7-25	15.5	1.6	21:16	25.4	5.2	19.5	2008-8-3	2	9.4	4:50	18.4	14.4	40
2007-7-30	3.8	2.8	13:43	10.4	8.4	24.7	2008-8-4	1	19.8	20:10	19.8	0.6	33.1
2007-8-11	1	3.1	1:50	3.1	5.7	23	2008-8-5	0.5	3.6	3:00	1.8	2.2	36.3
2007-9-14	5.2	3.6	1:02	18.4	7.6	22	2008-8-5	5	1.5	13:56	7.5	2.6	44.8
2007-9-17	5.2	1.7	19:44	8.6	2.8	28.2	2008-8-11	2	3.6	2:16	7.2	4	33.1
2008-7-1	4	3.4	3:46	13.7	15.3	25.8							

Note: D, the duration of one rainfall event before debris flow initiated; I, the rainfall intensity of this event before debris flow initiated; T, the debris flow initiation time; R_T, the triggering rainfall amount; R_I, the triggering rainfall intensity; R_A, the calculated antecedent rainfall.

change, we take the biggest 1 h rainfall intensity in 1 hour about 30 min before debris flow as the triggering value.

2.3 Antecedent rainfall calculation

The antecedent rainfall amount is calculated by Equation (1), and the *k* and *n* in Equation (1) are identified as 0.8 and 10 days (Cui et al. 2007). Thus, the duration and intensity of the 1 h triggering rainfall and cumulative rainfall for the 23 debris flows are shown in Table 3.

3 Warning Threshold based on Antecedent Rainfall

3.1 I-D threshold in Jiangjia Ravine

The I-D (Intensity-Duration) diagram is shown in Figure 4, in which the dashed line defines the threshold relationship:

$$I = 2.6724 D^{-0.4298} \tag{2}$$

where I = rainfall intensity calculated in mm/h and D = duration of critical rainfall event expressed in hours.

3.2 Rainfall threshold based on the antecedent rainfall

I-D plots represent only average conditions of the rainfall event, and do not necessarily reflect high rainfall intensity at the time of debris flow occurrence. In addition, it ignores the effect of antecedent rainfall that is significant in the study area.

In Figure 4, the rainfall characteristic is represented as I_2-D_2 plot (real line). Here I_2 (mm/h) is defined as the average rainfall intensity (mm/h) and D_2 the duration of each rainfall event. The rainfall characteristic is shown as the real line, and assumes the power law:

$$I_2 = 5.9466 D_2^{-0.4095} \tag{3}$$

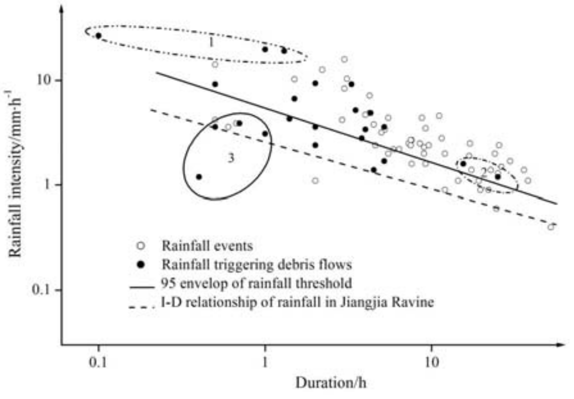

Figure 4 The I–D graphs for debris flows triggering thresholds (dashed line) and for all rainfall events (real line) in Jiangjia Ravine in double logarithmic coordinates.

The line of 95th percentile regression line of rainfall events is very close to the debris flow trigging threshold (dashed line), representing that 95% of rainfalls can potentially induce debris flows which reflects the limitation of I-D threshold in this area.

Figure 5 shows the relationship between the cumulative antecedent rainfall and the triggering rainfall by comparing the two quantities together. Considering the debris flows triggered by small rainfall amount, the 95% envelop line in exponential is

$$R_T = 176.36 \exp(-0.1621 R_A) \quad R^2 = 0.9834 \tag{4}$$

Figure 5 also shows the relationship between the cumulative antecedent rainfall and 1 h triggering rainfall and the 100% envelop line can be identified as critical line for debris flow:

$$R_I = 4.13 \exp(-0.1254 R_A) \quad R^2 = 0.9982 \tag{5}$$

3.3 Application in debris flow warning

In Jiangjia Ravine, it is possible to define the critical rainfall based on the rainfall characteristics. In order to identify a critical duration D_n, we used Equations (2) and (5), Equations (3) and (4) to obtain Equations (6) and (7),

$$\ln D = 6.52 - 0.2914 R_A \tag{6}$$

$$\ln D = 5.74 - 0.2745 R_A \tag{7}$$

When identifying thresholds for debris flow warning, it is important to take into account both the trend of triggering thresholds and the logistical evacuation time to establish effective emergency

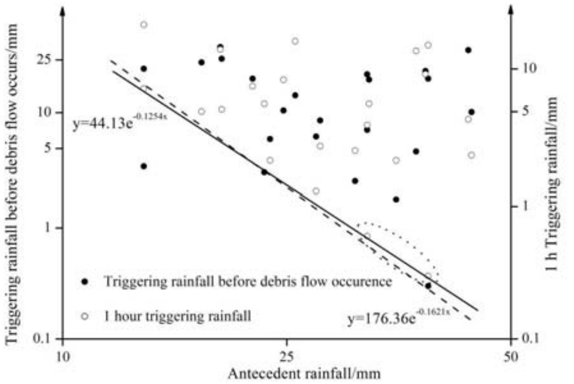

Figure 5 Critical thresholds of triggering rainfall, enveloping 95% of all available debris flow events, and 1 h triggering rainfall (rainfall intensity) enveloping 100% of debris flow events by considering the effect of antecedent rainfall.

procedures. Therefore before the exceeding of triggering line, a warning line should be identified. When the rainfall intensity and duration exceeds the line of Equation (2), and the relationship between its intensity and antecedent rainfall exceeds Equation (5), the debris flow is highly potential, so we define the Equation (6) as the triggering line.

Meanwhile, before that, when the amount of a rainfall event is related with its antecedent rainfall as Equation (4), as the rainfall characteristics expressed by Equation (3), and it will be close to the triggering line, so we define Eq.7 as the warning line (Figure 6).

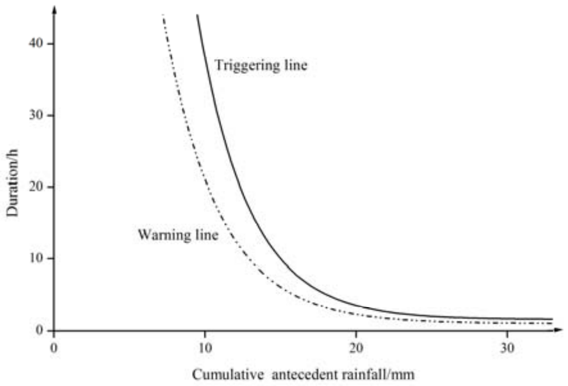

Figure 6 Relationship between duration (D) and cumulative antecedent rainfall (R_A)

Accordingly, a debris flow can be easily triggered by a rainfall with small density if the antecedent rainfall arrives at as high as more than 30mm as shown in Figure 8. This is proved by the events in circle 3 in Figure 3, especially by the event which is with a 40mm antecedent rainfall and only 0.3mm/h intensity. The calculated triggering rainfall and 1h triggering rainfall based on the cumulative antecedent rainfallare listed in Table 4.

Table 4 The triggering rainfall for debris flows responding to the cumulative antecedent rainfalls

R_A (mm)	R_T Needed (mm)	R_I Needed (mm/h)
10	34.9	12.6
15	15.5	6.7
20	6.9	3.6
25	3.1	1.9
30	1.4	1

Comparing with rainfall threshold as 18.4mm (Hu et al. 2010), these warning and triggering thresholds are further constructed statistically and empirically, incorporating antecedent rainfall. For debris flow warning on a watershed scale, thresholds are important elements, as well as the rainfall forecasts, real-time rainfall monitoring, and the evacuation measures following (Aleotti 2004). According to the different roles of the rainfall parameters, the thresholds should be provided in detail, including the antecedent rainfall, the rainfall types of the event rainfall, and so on, as well as the total quantity of rainfall. Based on antecedent rainfall, Figure 7 gives a sketch map of debris flow warning approach by rain paths which represents the rainfall intensity and amount, types, also describes an operating procedure which is presently being verified in the study area. In the figure, the gray region is the cumulative antecedent rainfall before each debris flow event in 2007. Red and blue poles are the daily rainfall and 1 h triggering rainfall, respectively.

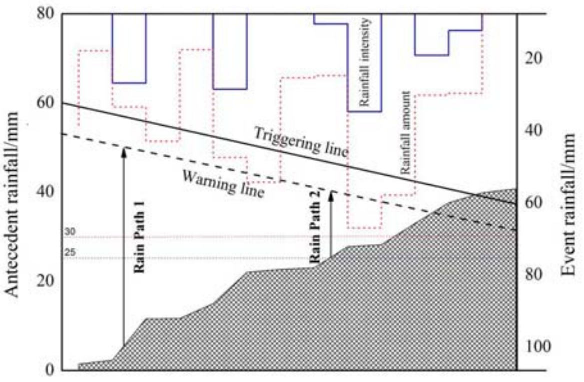

Figure 7 Graph of warning by rain path based on antecedent rainfall

4 Discussion

4.1 Comparison

The I-D threshold proposed in this study is comparable with other results all over the world (Table 5, Figure 8). In this study, I and D were defined as the average rainfall intensity (mm/h) and the duration (h) from the beginning of a rainfall event, which was delimited by a non-rainfall period of more than 4 h, or rainfall amount less than 0.5 mm in successive 6 h. And most of other thresholds were also determined as the lower boundary of rainfall conditions, permitting a direct

Table 5 I-D threshold equations for Jiangjia Ravine and other regions in the world

Reference	Area	Equation	Range(h)	Number in Figure 4
Caine (1980)	World	$I=14.82D^{-0.39}$	$0.167<D<240$	W-1
Jibson (1989)	World	$I=30.53D^{-0.57}$	$0.5<D<12$	W-2
Guzzetti et al. (2008)	World	$I=2.2D^{-0.44}$	$0.1<D<1000$	W-3
Cannon et al (2008)	Southern California	$I=14.0D^{-0.5}$	$0.167<D<12$	R-1
Larsen and Simon (1993)	Puerto Rico	$I=91.46D^{-0.82}$	$2<D<312$	R-2
Chien-Yuan et al (2005)	Taiwan	$I=115.47D^{-0.8}$	$1<D<400$	R-3
Guzzetti et al. (2007)	Cfa	$I=10.30D-0.35$	$0.1<D<48$	R-4
	Cfa	$I=6.9D-0.58$	$0.1<D<1000$	R-5
Dahal and Hasegawa (2008)	Nepal Himalaya	$I=73.9D^{-0.79}$	$5<D<720$	R-6
Jibson (1989)	Japan	$I=39.71D^{-0.62}$	$1<D<12$	R-7
Hitoshi (2010)	Japan	$I=2.18D^{-0.26}$	$3<D<537$	R-8
This study	Jiangjia Ravine	$I=2.67D^{-0.4298}$	$0.13<D<25$	R-9

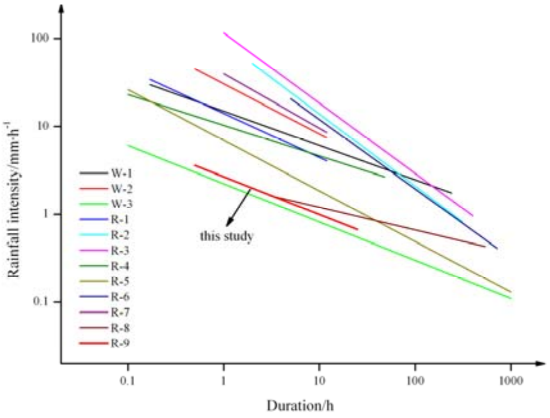

Figure 8 I-D thresholds determined by this study (red one) and those of various studies presented in Table 3 (in double logarithmic coordinates).

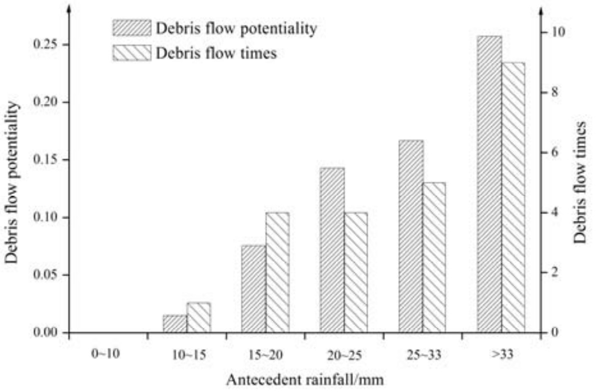

Figure 9 The times of debris flow events and potentialities under different antecedent rainfall ranges from 2006 to 2008.

comparison of these thresholds.

Figure 8 shows that the I-D threshold for Jiangjia Ravine is lower than reports in other regions, except for one global threshold, indicating that the critical rainfall intensity is the lowest in Jiangjia Ravine.

The notably low I-D threshold in Jiangjia Ravine is not only because of the high-relief topography, geologic conditions and human disturbances, but also of the climate condition. The ravine is located in dry-hot gullies and characterized by its rich light and heat resources, hot and dry climate. The precipitation varies in seasons and is mainly concentrated in summer. The daily precipitation is relatively low, and also the minimum daily rainfall necessary to trigger debris flows is notablely lower (Tan et al. 1994; Wang 1994; Gao and Cheng 1994; Cui et al. 2005; Cui et al. 2011). The long-duration and low intensity antecedent rainfall saturated loose materials in the source, facilitate the initiation of debris flow.

4.2 Significant role of antecedent rainfall to debris flows

As shown in Figure 4, the debris flow events can be triggered by rainfalls with high-intensity and short-duration (in circle 1), by rainfalls with low-intensity but long-duration (in circle 2), and by rainfalls with low-intensity and short-duration (in circle 3), while the last indicates the significance of antecedent rainfall.

In Figure 9, during June and September in 2006 and 2008, there were 208 days with antecedent rainfall more than 10mm, approximately 57% days of the rain season. Among them, there were 66 days with antecedent rainfall between 10-15mm, and 1 debris flow event happened; 53 days between 15-20 mm and 4 debris flow events happened; 28 days between 20-25 mm and 4 debris flow events happened; 30 days between 25-33 mm and 5 debris flow happened; and 35 days more than 33mm and 9 debris flow events happened. So this group of data can specifically illustrate the importance of the antecedent rainfall to the debris flow events.

4.3 Further studies about the debris flow warning thresholds

Well-documented episodes of rainfall-triggered debris flows and systematical rainfall monitoring data in Jiangjia Ravine are helpful for debris flow warning researches. An informative threshold should contain not only the total quantity of rainfall, but also other factors. Our study indicates that the rainfall can be conceptually divided into several types according to the intensity changing during the rainfall event, and each type influences debris flow in different manners and probabilities.

We have highlighted the significance and interconnect of antecedent rainfall, critical rainfall, 1 h triggering rainfall, as well as their accurate determination before the hour of debris flow triggering. However, it should be noticed that the rainfall is only the triggering factor of debris flows. A comprehensive warning system must contain more environmental factors, such as the geologic and geomorphologic factors, the distribution of source areas. In particular, real-time monitoring of factors related to slope processes is crucially important.

5 Conclusion

The empirical I-D threshold for initiating debris flows in Jiangjia Ravine is lower than previously proposed in other regions. The threshold is very close to 95th percentile regression line of rainfall events in this area which represents its limitation. This study proposes an exponential relationship between the cumulative antecedent rainfall (R_A) and direct triggering rainfall (R_T) or 1h triggering rainfall (R_I): $R_T = 176.36\exp(-0.1621R_A)$ and $R_I = 4.13\exp(-0.1254R_A)$, respectively. Then it is possible to define the quantity and intensity of critical rainfall for debris flows based on antecedent rainfall. Critical rainfall duration for debris flow triggering and warning can be determined by the antecedent rainfall as $\ln D = 6.52-0.2914R_A$ and $\ln D = 5.74-0.2745\ R_A$.

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References

Aleotti P (2004). A warning system for rainfall-induced shallow failures. Engineering Geology 73: 247-265.

Brooks SM, Crozier MJ, Glade TW (2004) Towards establishing climatic thresholds for slope instability: use of a physically-based combined soil hydrology-slope stability model. Pure and Applied Geophysics 161(4):881-905.

Caine N (1980) The rainfall intensity–duration control of shallow landslides and debris flows. Geografiska Annaler. Series A. Physical Geography 62: 23-27.

Cannon S, Gartner J, Wilson R, et al. (2008) Storm rainfall conditions for floods and debris flows from recently burned areas in southwestern Colorado and southern California. Geomorphology 96: 250-269.

Chien-Yuan C, Tien-Chien C, Fan-Chieh Y, et al. (2005) Rainfall duration and debris-flow initiated studies for real-time monitoring. Environmental Geology 47: 715-724.

Corominas J, Moya J (1999) Reconstructing recent landslide activity in relation to rainfall in the lLobregat River basin, Eastern Pyrenees, Spain. Geomorphology 30(1): 79-93.

Crosta G, Frattini P (2008) Rainfall-induced landslides and debris flows. Hydrological Processes 22: 473-477.

Crozier MJ (1999) Prediction of rainfall-triggered landslides: a test of the antecedent water status model. Earth Surface Processes and Landforms 24: 825-833.

Crozier MJ, Eyles RJ (1980) Assessing the probability of rapid mass movement. In: New Zealand Institution of Engineers-Proceedings of Technical Groups (ed.), Proc. Third Australia-New Zealand Conference on Geomechanics, Wellington. pp 247-251.

Cui P (1999) Impact of debris flow on river channel in the upper reaches of the Yangtze River. International Journal of Sediment Research 14(2): 201-203.

Cui P, Chen XQ, Wang YY, et al. (2005) Jiangia Ravine debris flows in south-western China. In: Jakob M, Hungr O (eds.), Debris-flow hazards and related Phenomena. Springer, Heidelberg. pp. 565-594.

Cui P, Chen XQ, Zhu YY, et al. (2011) The Wenchuan Earthquake (May 12, 2008), Sichuan Province, China, and resulting geohazards. Nat Hazards 56:19-36

Cui P, Yang K, Chen J (2003) Relationships between occurrence debris flows and antecedent rainfall: taking Jiangjia Gully as an example. Science of Soil and Water Conservation 1(1): 11-15. (In Chinese)

Cui P, Zhu YY, Chen J, et al. (2007) Relationships between antecedent rainfall and debris flows in Jiangjia Ravine, China. In: Chen C L and Major J J (eds.), Debris-flow hazard mitigation-Mechanics, Prediction, and Assessment. Millpress, Rotterdam. pp 1-10.

Dahal R, Hasegawa S, Nonomura A, et al. (2009) Failure characteristics of rainfall-induced shallow landslides in granitic terrains of Shikoku Island of Japan. Environmental Geology 56: 1295-1310.

Fan JC, Liu CH, Wu MF, et al (2003) Determination of critical thresholds for debris flow occurrence in central Taiwan and their revision after the 1999 ChiChi great earthquake, In: Debris Flow Hazard Mitigation: Mechanics, Prediction, and Assessment, (Eds) Rickenmann D and Chen CL, Millpress, Rotterdam. pp 103-114.

Fraccarollo F, Papa M (2000) Numerical simulation of real debris flow events. Physics and Chemistry of the Earth. B25(9): 757-763.

Gao MX, Cheng Y (1994) the characteristics of storms and its relationship with debris flows in Dandong regions. In: Preceeding of 4th Debris Flow Seminar. Gansu culture Press, Lanzhou. pp 204-213.

Glade T, Crozier M, Smith P (2000) Applying probability determination to refine landslide-triggering rainfall thresholds using an empirical “antecedent daily rainfall model”. Pure and Applied Geophysics 157: 1059-1079.

Guzzetti F, Peruccacci S, Rossi M, et al. (2007) Rainfall thresholds for the initiation of landslides in central and southern Europe. Meteorology and Atmospheric Physics 98: 239-267.

Guzzetti F, Peruccacci S, Rossi M, et al. (2008) The rainfall intensity-duration control of shallow landslides and debris flows: An update. Landslides 5: 3-17.

Hitoshi S, Daichi N, Hiroshi Matsuyama (2010). Relationship between the initiation of a shallow landslide and rainfall intensity-duration thresholds in Japan. Geomorphology 118: 167-175.

Hu KH, Cui P, Wang CC (2010) Characteristic Rainfall for Warning of Debris Flows. Journal of Mountain Sciences 7: 207-214.

Innes L (1983) Debris flows. Progress in Physical Geography 7: 469-501.

Jan CD, Lee MH (2004) A debris flow rainfall-based warning model. Journal of Soil and Water Conservation 35 (3): 275-285. (In Chinese)

Jibson RW (1989) Debris flow in southern Puerto Rico. Geological Society of America 236 (Special Paper): pp 29-55. Doi: 10.1130/SPE236-p29

Kang ZC, Lee CF, Ma AN (2004) Debris flow study in China. Beijing: Science Press.

Larsen M, Simon A (1993) A rainfall intensity-duration threshold for landslides in a humid-tropical environment, Puerto Rico. Geografiska Annaler 75A: 13-23.

Li CZ, Liu XN, Cao SY (2001) Contrast research on sediment yield relationship of minor watershed between prestrom and different sediment source conditions. Journal of Soil and Water Conservation 15(6):36-39 (In Chinese)

Reichenbach P, Cardinali M, De Vita P, et al. (1998) Regional hydrological thresholds for landslides and floods in the Tiber River Basin (Central Italy). Environmental Geology 35(2-3):146-159

Shieh ZL, Lu YZ, You BS, et al. (1995) Study on critical rainfall line for debris flow occurrence. Journal of Chinese Soil and Water Conservation 26 (3): 167-172. (In Chinese)

Tan WP, Wang CH, Yao LK (1994) Regional prediction on rainfall debris flow and landslide. Chengdu: Sichuan Science and Technology Press. (In Chinese)

Tiranti D, Bonetto S and Mandrone G (2008) Quantitative basin characterization to refine debris-flow triggering criteria and processes: an example from the Italian Western Alps. Landslides 5:45-57.

Wang D (1994) The features of shallow debris landslides and preliminary study of its relationship with rainfall. Hydrogeology and Engineering Geology 1:20-23.

Wang YY, Zhou RY, Li CZ (1999) Research on the relationship between the erosion of debris flow and triggering rainfall. Journal of Soil and Water Conservation 5(6):34-38 (In Chinese)

Wieczorek GF (1996) Landslide triggering mechanisms. In: Turner, Shuster (Eds.), Landslides: Investigation and Mitigation. Transportation Research Board-National Research Council, Special Report 247: 76-90.

Zhang LP, Tang KL (1999) Artificial rain simulation the startup of formative regional loosening soil body and erosion experiment. Journal of Mountain Science 17(1): 45-53. (In Chinese)