

# Temporal differentiation of rainfall thresholds for debris flows in Wenchuan earthquake-affected areas

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**Abstract** The Ms 8.0 Wenchuan earthquake greatly altered the threshold for rainfall-triggered debris flows in the affected areas. It is of both scientific and practical significance to determine the rainfall thresholds. This study examines one of the regions most prone to debris flows to analyze the characteristics of rainfall that caused debris flows, and to explore local rainfall thresholds. We applied the relation between rainfall intensity and duration, peak intensity and event amount, and other single factor approaches. Comparison of effectiveness and accuracy indicates that the event rainfall is the most sensitive factor for forecasting. Analysis of the annual rainfall thresholds showed that the rainfall conditions required for debris flows have increased on the continent during the past 6 years. Besides the rainfall fluctuations over the past few years, material changes were the primary reason for threshold variability. Recovery of vegetation plays an important role in reducing potential loose material that supplies volume for debris flows. Natural solidification, decrease of the potential erosion depth, and surface coarsening make it more difficult to initiate a debris flow, and ultimately

increased rainfall conditions required. The change in rainfall thresholds can be predicted and verified for the entire earthquake-affected region.

**Keywords** Debris flows · Rainfall intensity · Event rainfall · Loose material · Wenchuan earthquake area

## Introduction

Debris flows are generally initiated by the failure of a discrete landslide mass on a hillslope or the failure of channel bed material, progressive bulking of runoff with sediment eroded from hill slopes and channels, or occasionally a combination of these factors (Innes 1983). The Ms 8.0 Wenchuan earthquake was responsible for a high frequency of debris flow because of its significant effect in modifying the conditions for the formation of debris flows. The severe damage and significant losses caused by the debris flows have been extensively recorded and are of wide concern (Tang et al. 2009, 2012; Cui et al. 2013; Guo et al. 2015a). It is of both scientific and societal interest to determine the threshold of precipitation required to trigger debris flows in the areas affected by the earthquake for the purpose of hazard mitigation.

Studies have found that less rainfall is now needed to trigger debris flows than before the earthquake occurred (Cui et al. 2011; Tang et al. 2012; Zhou and Tang 2014; Zhang et al. 2014). Several other case studies have examined the rainfall and rainfall intensities that initiated debris flows (e.g., Xie et al. 2009; Tang et al. 2009, 2012; Liu et al. 2010; Xu 2010; You et al. 2010, 2011; Yu et al. 2011; Guo et al. 2012; Su et al. 2012; Zhou et al. 2012; Cui et al. 2013). However, this rainfall information presented the rainfall conditions that triggered the single event, but not

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the rainfall thresholds. The optimum approach should be selected based on statistical data, where the integrity and quality of the dataset significantly affect the accuracy of the results. For the rainfall thresholds related to debris flows, empirical (statistical) approaches have been used to define the minimal rainfall conditions by analyzing the historical event rainfall amount ( $R$ ), rainfall intensity ( $I$ ), and the relationship between other factors (e.g.,  $I-D$ ) (Tang et al. 2012; Zhou and Tang 2014; Guo et al. 2015b).

The effect of the earthquake as an abrupt disruptive force will weaken over the years. It has been predicted that debris flows will be active for a period of 10–30 years (Xie et al. 2009; Tang et al. 2009; Cui et al. 2011) based mainly on knowledge of other earthquakes, such as the Chi-chi earthquake in Taiwan (Lin et al. 2004; Shieh et al. 2009). These studies also indicated that the rainfall thresholds will gradually increase, qualitatively suggesting a time-scale for the disruptive effect of an earthquake. However, these predictions have not been confirmed.

This study aims to determine the rainfall thresholds and trends for the areas affected by the Wenchuan earthquake. We selected a typical debris-flow-prone region as an example. To identify the trends in this region, data for 26 debris flows and the rainfall processes that initiated them were collected to determine the thresholds and annual variation. The annual rainfall information and aerial photographs of a typical gully in this region were analyzed to reveal the causes for the annual variation. We hope that the results of this work can provide guidance of the building of models for debris flow forecasting in this area.

## Study area

The Wenchuan earthquake mainly impacted the mountainous area in the central and northeastern Sichuan Province, China. The elevation of this mountainous area varies from 479 m on the western side of the Sichuan Basin to 6091 m on the ridges of the Hengduan Mountains (Fig. 1). Because of the abundant loose material produced by the severe disruption to this area, debris flows occur quite frequently. More than 800 gullies have been recorded since May 2008 (Cui et al. 2011). The debris flows are distributed along the Longmenshan Fault, the major fault along which the Wenchuan earthquake occurred.

The area selected for this study is located upstream of the Minjiang River, close to the epicenter (Fig. 1). The physiography of this region comprises mountain ranges trending in an approximately north-northeasterly direction, dissected by the Minjiang River and its tributaries. The topography is typical of that formed by tectonic uplift and fluvial erosion with bedrock that are primarily Archean and Proterozoic metamorphic rock, and Mesoproterozoic

granites (Fig. 2). The channel gradients of large gullies distributed in this region range from 25° to 30°, while the average slope gradients of channels range from 35° to 45°.

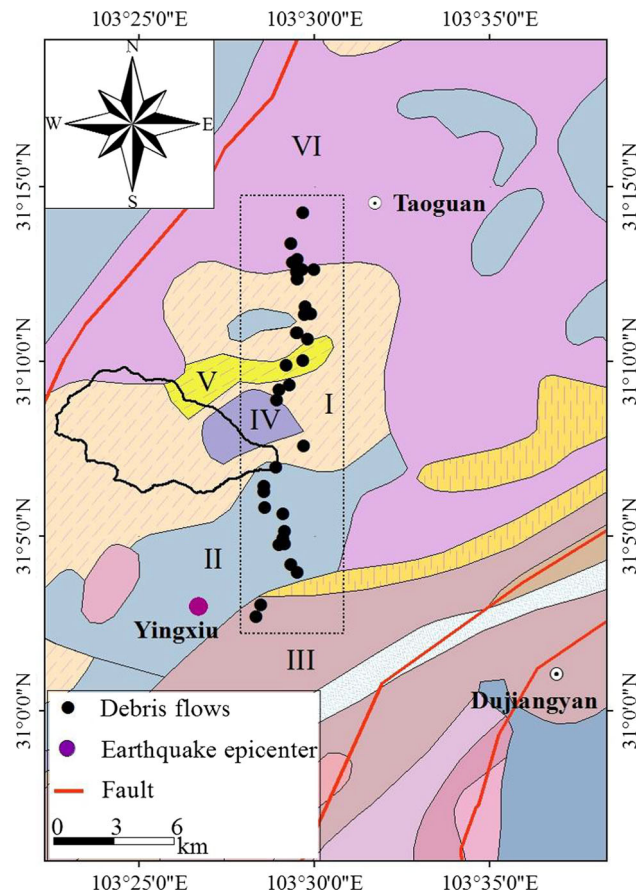
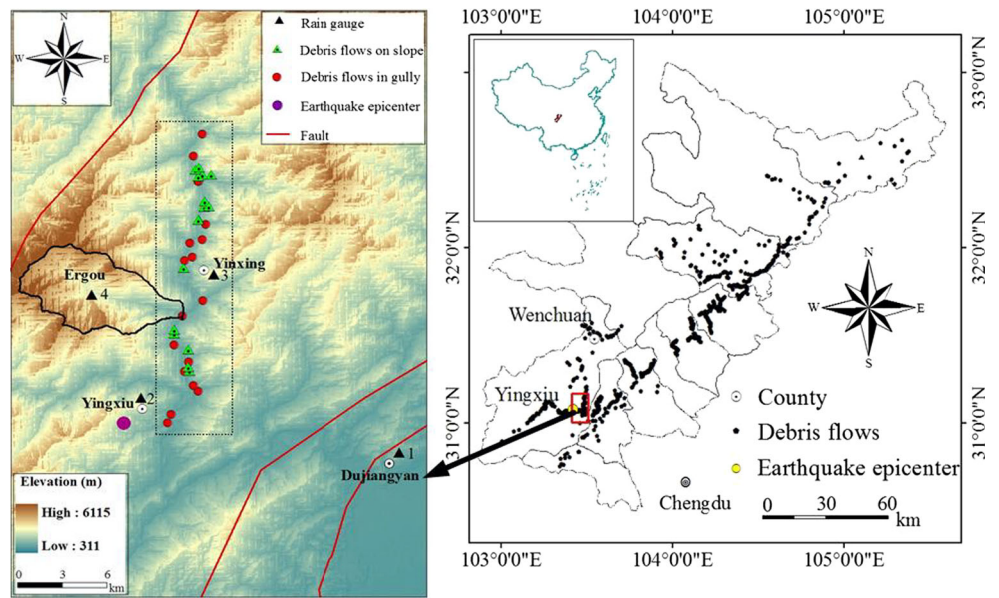
Abundant unconsolidated material loosened by the earthquake has accumulated in the watersheds, increasing the likelihood of geohazards, such as landslides, collapses, rock falls, and debris flows. Because of their high frequency and the resulting damage to local infrastructure, this region is considered to be one of the most vulnerable to geohazards. Debris flows are densely distributed and, as shown in Fig. 1, more than 20 watersheds have debris flows within an area of approximately 20 km in length. Major debris flows were recorded on September 24, 2008; August 13, 2010; July 3, 2011; and July 10, 2013. These events destroyed roads and vehicles, blocked rivers, dammed lakes, and submerged villages, resulting in significant loss of life and property damage (Guo et al. 2012; Tang et al. 2011; Su et al. 2012; Guo et al. 2014, 2015a, 2015b).

The selected area has a wet climate, with an annual average precipitation of approximately 1200 mm. The Sichuan Meteorology Bureau established rainfall stations in various towns in this region before the Wenchuan earthquake. Unfortunately, these stations were destroyed by the earthquake. Therefore, climate data from the Dujiangyan rainfall station, located 16 km from Yingxiu, were used to investigate the rainfall conditions that triggered debris flows (Su et al. 2012). Beginning in 2009, several other rainfall stations were established in gullies, primarily for the purpose of supporting early warning systems for heavy rainstorms and subsequent debris flows.

## Data collection

Since the 2008 earthquake, 26 debris flow events have been recorded. Related information was mainly obtained from field interviews with local witnesses, professional papers, and local media. Debris flows in the area have been studied by numerous researchers, and therefore, nearly every debris flow event that caused damage is well-documented (e.g. Xie et al. 2009; Guo et al. 2012; Tang et al. 2011; Su et al. 2012; Kong et al. 2013; Guo et al. 2014, 2015a). The collected data include the addresses and geographic coordinates (latitude and longitude) of valleys where the debris flows occurred (Fig. 1) and at what time, which is significant for the triggering rainfall identifying. Although there are several gauges in this region established by the administration, we used only one in this analysis to maintain consistency. Therefore, from 2009 to 2013, data from Yingxiu station (No. 2) for 2009–2013 were selected for their completeness, to investigate the rainfall conditions that triggered debris flows. Because all the rainfall stations in this region (No. 2, 3 and 4) were destroyed during the earthquake, the rainfall

**Fig. 1** Debris flow distribution in the Wenchuan earthquake area (right) and the location of the debris flows in the study area (left)



**Fig. 2** Debris flow distribution and the corresponding geological conditions in the study area. The numbers in the circles denote debris flow sites and the Roman alphabet represents the different geological complexes. *I* Archean metamorphic rocks, *II* Proterozoic metamorphic rocks, *III* Jurassic sedimentary rocks, *IV* Early Proterozoic gabbro, *V* Permian sedimentary rocks, *VI* Mesoproterozoic granites

data from the Dujiangyan rainfall station (No. 1 in Fig. 1) were used to for 2008 (as recommended by Su et al. 2012). The debris flow occurrence time and the associated rainfall information are listed in Table 1.

In Table 1,  $R$  represents the event rainfall amount, mm;  $I_T$  represents the rainfall intensity at the moment of debris flow occurrence, mm/h;  $D$  means duration from the beginning of the rainfall to the debris flow occurrence, h;  $R_e$  represents the inducing rainfall, counting in the period of  $D$ , mm;  $I$  means the average rainfall intensity during the period of “ $D$ ”, mm/h; and  $CAR$  means the cumulative antecedent rainfall, calculated by the method that proposed by Cui et al. (2007), mm.

### Rainfall thresholds for debris flows

#### Rainfall characteristics responsible for debris flows

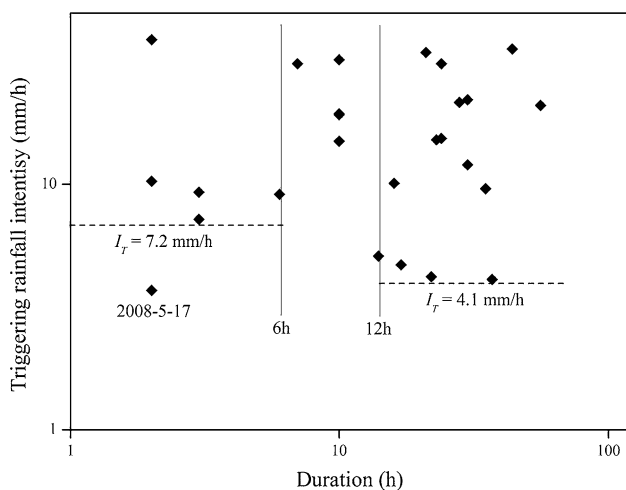
The mean minimum rainfall intensity and rainfall for triggering debris flows were 14.8 and 43.5 mm/h (Table 1), respectively. The minimum rainfall intensity and rainfall for triggering debris flows were as low as 3.7 mm/h and 5.3 mm, respectively, which occurred on May 17, 2008 shortly after the earthquake. The maximum rainfall intensity and rainfall for triggering debris flows were 38.9 mm/h and 140.8 mm, respectively. The mean and minimum rainfall conditions required for debris flows were significantly lower than the 30–50 mm/h intensity and 80–100 mm/d daily rainfall required before the earthquake.

The relationship between triggering rainfall intensity and duration is shown in Fig. 3. Sixty-two percent (16/26) of the debris flows occurred with a rainfall duration longer

**Table 1** Debris flow occurrence time and associated rainfall information

Date	Gauge no.	$R$ (mm)	$I_T$ (mm/h)	$D$ (h)	$R_e$ (mm)	$I$ (mm/h)	CAR (mm)
2008/5/13	1	47.3	9.1	6	19.2	3.2	4.6
2008/5/17	1	5.3	3.7	2	5.4	2.7	24.7
2008/8/6	1	40	15	10	30	3	24
2008/8/11	1	24.7	7.2	3	18.3	6.1	17.9
2008/9/22	1	94.7	31	7	88.9	12.7	2.3
2008/9/24	1	37.2	10.3	2	19.6	9.8	16.5
2009/7/8	2	29.7	9.3	3	13.5	4.5	4.8
2009/7/16	2	21.4	4.2	22	13.2	0.6	21.5
2009/7/17	2	21.4	4.1	37	18.5	0.5	25.1
2009/7/22	2	36.5	9.6	35	28	0.8	26.5
2009/7/25	2	27.9	10.1	16	24	1.5	38.5
2009/8/22	2	25.5	5.1	14	16.8	1.2	17.9
2009/8/26	2	39.6	19.4	10	24	2.4	20
2009/9/14	2	46.6	15.4	24	28.8	1.2	38.8
2010/8/13	2	220	32.2	10	138	13.8	35.4
2010/8/14	2	220	22.1	30	117	3.9	126.1
2010/8/18	2	63.6	12	30	12	0.4	83.7
2010/8/19	2	63.6	21	56	39.2	0.7	81
2010/8/21	2	23.2	4.7	17	10.2	0.6	62
2011/7/1	2	75.6	19.2	10	55	5.5	43.1
2011/7/3	2	144.6	34.5	21	140.7	6.7	159.8
2011/8/20	2	91.4	31	24	91.2	3.8	74.7
2012/8/17	2	158.4	38.9	2	54.4	27.2	68.4
2012/8/18	2	158.4	15.2	23	137.4	6.0	143.6
2013/7/9	2	328.5	21.6	28	69	2.5	75.6
2013/7/10	2	328.5	35.6	44	135.7	3.1	142

In the table,  $R$  represents the event rainfall amount, mm;  $I_T$  represents the rainfall intensity at the moment of debris flow occurrence, mm/h;  $D$  means duration from the beginning of the rainfall to the debris flow occurrence, h;  $R_e$  represents the inducing rainfall, counting in the period of  $D$ , mm;  $I$  means the average rainfall intensity during the period of “ $D$ ”, mm/h; and CAR means the cumulative antecedent rainfall, calculated by the method that proposed by Cui et al. (2007), mm

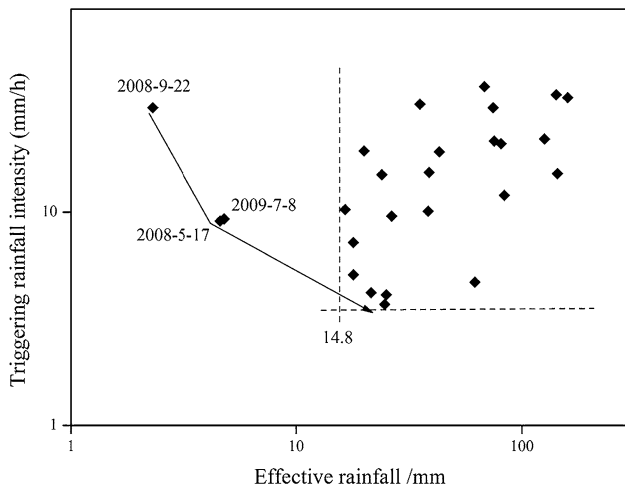


**Fig. 3** Relationship between triggering rainfall intensity and duration

than 12 h. The count for durations shorter than 6 h and between 6 and 12 h was five each. Note that while the historical triggering rainfall intensity is not exact, it is in general higher than the rainfall intensity required for debris flows. We therefore identify the lower limit in Fig. 3, which shows that with rainfall duration shorter than 6 h, the rainfall intensity required is 7.2 mm/h (except for the event on May 17, 2008). Furthermore, the rainfall intensity required is as low as 4.1 mm/h when the rainfall lasts longer than 12 h, indicating that as the rainfall duration increases, the rainfall intensity required for triggering debris flows decreases.

The rainfall duration indirectly influences the antecedent effective rainfall amount, which was counted as the sum of CAR and  $R_e$  in Table 1. The relationship between the triggering rainfall intensity and the antecedent effective rainfall amount is plotted in Fig. 4, which shows that the





**Fig. 4** Relationship between the triggering rainfall intensity and effective antecedent rainfall

higher the antecedent effective rainfall amount, the lower the triggering rainfall intensity that is required. For example, the antecedent effective rainfall amount is merely 2.3 mm, and debris flows were triggered with a rainfall intensity of 31.0 mm/h, while when the antecedent effective rainfall amount exceeded 14.8 mm, the triggering rainfall intensity required was only 4–5 mm/h.

**Rainfall thresholds for debris flows**

The relationship between rainfall intensity ( $I$ ) and rainfall duration ( $D$ ) was analyzed following the previous proposed method (Caine 1980; Larsen and Simon 1993; Jibson 1989; Aleotti 2004; Gabet et al. 2004; Hong et al. 2005; Cannon et al. 2008; Dahal and Hasegawa 2008; Guzzetti et al. 2007, 2008; Saito et al. 2010; Guo et al. 2013, 2015b). The threshold curve was assumed to be in the form of a power law;

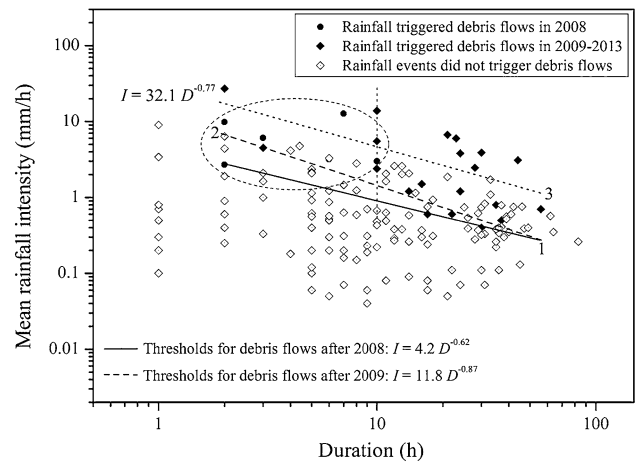
$$I = aD^{-b}, \tag{1}$$

where  $a$  and  $b$  are constants,  $D$  is expressed in hours, and  $I$  is expressed in millimeters per hour.

The  $I$ - $D$  thresholds for the study region are shown in Fig. 5. Because of the extensive disruption by the Wenchuan earthquake that caused widespread landslides, collapses, and vegetation deterioration, the debris flows shortly after the earthquake in 2008 would have been related to the anti-scourability of the soils, instead of the slope stability. Therefore, the  $I$ - $D$  thresholds were also proposed for debris flows in 2009–2013 (Line 2 in Fig. 5). The equations are as follows:

$$I = 4.2D^{-0.62} (2h < D < 56h) \tag{2}$$

$$I = 11.8D^{-0.87} (2h < D < 56h). \tag{3}$$



**Fig. 5** Intensity and duration thresholds for debris flows. Lines 1 and 3 denote the lower and upper limits, respectively, of rainfall events that triggered debris flows. Line 2 is the threshold proposed for debris flows during 2009–2013, excluding the events in 2008

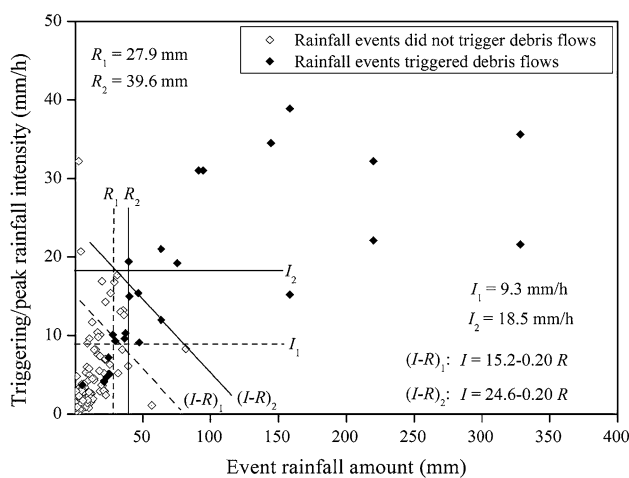
The rainfall duration in 2008 ranged between 2 and 10 h (circle in Fig. 5), indicating that debris flows were triggered rapidly, while after 2009, the rainfall duration range of 2–56 h indicates that the antecedent rainfall conditions required increased. The coefficient in Eq. (3) is much higher than that in Fig. 2, showing that the mean rainfall intensity required is much higher. This result is reasonable, indicating that vegetation restoration, consolidation of the soils, and fine particles in the source material in the channels increased the rainfall conditions required for the initiation of debris flows. The exponential term is also lower, showing that as the rainfall duration increases, the rainfall intensity required decreases. This indicates that while rainfall continues, the soils are easily liquefied and small rainfall intensity can trigger debris flows.

Note that  $I$ - $D$  thresholds consider the rainfall process based on the relation of rainfall intensity and duration. It can therefore represent the lowest required rainfall conditions, but it may not be the most effective method to forecast debris flows. When applying debris flow thresholds for forecasting, the debris flow coverage is significant for safety. However, forecasting accuracy should also be considered as another element for model evaluation. As shown in Fig. 5, Line 3 with  $I = 32.1 D^{-0.77}$  illustrates the upper limit of the rainfall events that do not trigger debris flows and can therefore be regarded as a warning line that once rainfall conditions exceed this threshold, debris flows will certainly occur. However, when this threshold was used, 62 % of the debris flows that occurred failed to raise a warning. Furthermore, if Lines 1 and 2 were used as thresholds, 39 and 26 rainfall events that did not trigger debris flows had an unnecessary warning, indicating 40 and 50 % accuracy, respectively.

The rainfall event–intensity ( $I$ – $R$ ) relationship is another widely used approach for determining thresholds (Guzzetti et al. 2007; Shieh et al. 2009). The threshold curve was assumed to be a linear expression. The relation of the triggering rainfall intensity and the event rainfall amount is plotted in Fig. 6. The lines for  $I_2$ ,  $R_2$ , and  $(I-R)_2$  can be regarded as the upper limit for rainfall events that did not trigger debris flows for 90, 93, and 100 % accuracy, respectively. However, when these thresholds were used, a considerable number of debris flows that occurred failed to raise a warning; 14 (54 %), 10 (38 %), and 12 (46 %) events, respectively. When  $I_1$ ,  $R_1$ , and  $(I-R)_1$  were used as thresholds, 21 (81 %) debris flow events were identified, with 54, 66, and 70 % accuracy, respectively. The rainfall event, which is a direct rainfall parameter, can therefore be applied as the key index. Rainfall exceeding 39.6 mm has a very high potential to induce debris flows. When the rainfall exceeds 27.9 mm, which is more conservative, there is an almost 70 % likelihood that debris flows will be triggered.

### Annual variation for critical rainfall conditions responsible for debris flows

To gain dynamic knowledge of the evolution of the critical rainfall conditions responsible for debris flows, the rainfall events that trigger debris flows each year were analyzed. In this section, we combined events in 2012 and 2013 to compile a database. Based on the above analysis showing that the rainfall event can be regarded as the key index for debris flow formation, we used the cumulative count from the beginning of the rainfall event to the moment when debris flows occurred as the triggering rainfall. Overall, the



**Fig. 6** Relationship between triggering intensity and event rainfall amount for debris flows. The solid lines represent the upper limit of rainfall events that triggered debris flows, and the dotted lines represent the thresholds based on different rainfall parameters; single  $I$  and  $R$ , and compounding  $I$ – $R$

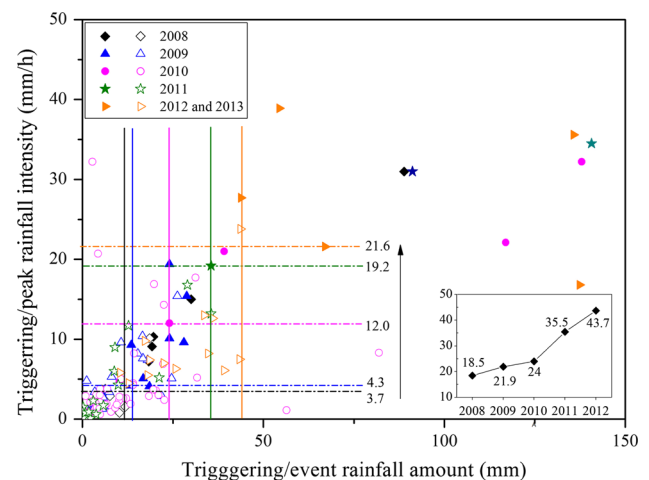
triggering rainfall amount and triggering rainfall intensity required for debris flows increased each year (Fig. 7). The triggering rainfall for each year for 2008–2013 increased from 18.5 to 43.7 mm, and rainfall intensity rose from 3.7 to 21.6 mm/h. Furthermore, the triggering rainfall amount in each year can be regarded as a forecasting index, with a higher effectiveness than peak rainfall intensity. Cases in 2009 and 2010 had 70 and 67 % accuracy, respectively, whereas the accuracy for the other years is as high as 100 %.

### Cause of the annual variation of rainfall thresholds

The recovery tendency of rainfall conditions required for debris flows is shown by the lowest variability of rainfall conditions (Fig. 7). In general, the initiation of debris flows depends on factors, such as precipitation, material source, and topography (Takahashi 1991). For a given watershed, the topography remains almost the same for several years. Ergou Gully, a debris flow-prone watershed (Fig. 1) in this region, was therefore selected as a typical case study to analyze the changes in material supply conditions for debris flows using local rainfall information in the rainy season, and to study the cause of this tendency.

### Variation of source amount for debris flow

Aerial photographs (taken in 2008, 2010, 2011, and 2013) of Ergou Gully were used as comparison of the landslide area, its proportion in the watershed, and the vegetation



**Fig. 7** Relationship of the triggering intensity and event rainfall amount for debris flows. The solid and open symbols are rainfall events that did and did not trigger debris flows, respectively. The transverse and vertical lines represent the triggering rainfall and rainfall intensity as thresholds, respectively. The line chart in the lower right corner shows the annual increases in the event rainfall amount

regeneration area to represent the debris flow sediment supply condition. Field investigations were also carried out to validate the interpretation of the aerial photographs.

This typical gully, located approximately 8 km from the epicenter and with an area of 39.4 km<sup>2</sup>, is selected as an example for its relatively large area. Because of the disruption by the 2008 Wenchuan earthquake, the co-seismic landslide was distributed widely in the fluvial system, leading to frequent debris flows in each of the five tributaries. Aerial photographs taken shortly after the earthquake indicate that the vegetation decreased significantly than that before the earthquake and the area of landslides, covering approximately 24 % of the total gully area (Zhuang et al. 2010). Based on the interpretation of the aerial photographs from 2011 to 2013 (Fig. 8a, b), the landslide area covered approximately 12 and 6 %, respectively. The vegetation recovered from 47 % in 2008, to 62 % in 2011 and 73 % in 2013. The recovered vegetation can protect the soil on the slopes from erosion, and therefore decrease the supply of material for debris flows.

For a single debris flow source site, the potential volume supplying the debris flow decreased and the initiation of a debris flow was more difficult. To illustrate the detailed changes in the potential erosion sources for a single site, a small-scale slope in the watershed with an area of 2.0 km<sup>2</sup> was chosen for analysis. This slope was formed by the 2008 Wenchuan earthquake, as a landslide and its deposit. The materials were accumulated as loose, coarse-grained colluviums covering on slopes, as a potential source supplying for debris flows. The changes to the landslide area in 2008, 2010, 2011, and 2013 are shown in Fig. 9. The co-seismic landslide occurred in May 2008 and accounted for approximately 55.2 % of the total area of this small region. The sediments were deposited in the sloping channels leading to their partial blockage and providing a large amount of loose material for debris flows. Furthermore, debris flows can also be supplied in the form of rill erosion on the slope and landslide deposit failure. There was a slight change between 2008 and 2010 because of the sparse recovery of the vegetation, with vegetation covering only 35.4 and 36.2 % of the area. However, after the rainy season in 2010, the vegetation recovered rapidly to 64.6 %, mainly as shrubs, and segmented the landslide area into several small isolated regions, and therefore greatly decreased the potential material supply for debris flows. The landslide area accounted for approximately 25.6 % in 2011. After that, the vegetation recovered and the landslide area decreased further over the following years, reaching approximately 72.3 and 18.9 %, respectively, in 2013.

As the landslide area decreased, the potential erosion depth on the slopes also decreased because of the natural solidification and all previous erosions. The landslide had

caused the partial blockage of the channel. The degeneration of the slope toe and slope surface was measured, as shown in Fig. 9, indicating that the potential erosion depth decreased each year, and therefore decreasing the total volume that could potentially be supplied for debris flows.

### Variation of material generation

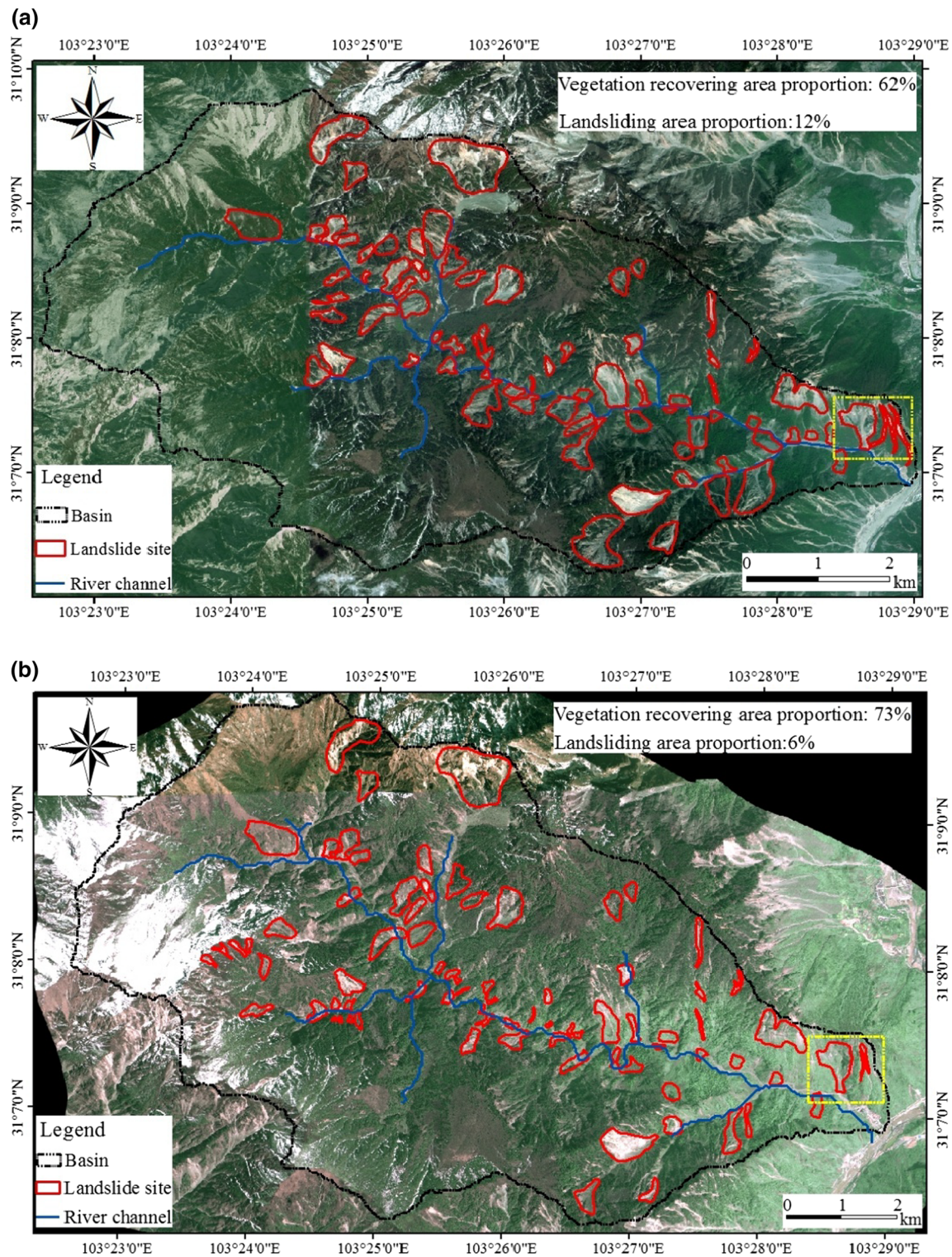
The fine particles loose in the soil on the slope surface and/or in the channel beds have also influenced the conditions required for debris flows initiation. Modeling experiments have revealed the variations of runoff thresholds required to trigger debris flows under similar slope circumstances, but with different clay content (Takahashi 1978; Cui 1992; Gregoretti 2000; Gregoretti and Fontana 2008). The fine particles can move downwards and form a relatively impermeable layer, which can lead to the generation of subsurface runoff and the easier saturation of the slope toe. This will change the soil structure and decrease soil strength, leading to shallow failures and the initiation of debris flows.

The debris flow deposit partly reflects the characteristics of the material sources (Coe et al. 2008; Li et al. 2013). Debris flow samples from the same gullies were collected in field investigations in 2008 and 2013, and their compositions were analyzed as shown in Fig. 10. The accumulated material released by the co-seismic landslide was fresh bodies of fine and coarse particles. This therefore easily initiated and formed debris flows shortly after the earthquake. As a consequence, viscous debris flows with high density occurred as the most common type (Cui et al. 2011). However, as shown in Fig. 11, as the clay particles lost over the years following the earthquake, the coarser materials become the main types in the channel and on the slope. The inset table in Fig. 10 shows that the clay content of the samples in 2013 was visually lower than those in 2008, indicating that the fine particles were lost from the material sources. The D50 was also clearly higher than that in 2008, indicating that as the loose materials in the fluvial system became coarser each year, the hydraulic conditions required for debris flow initiation increased, based on the runoff thresholds for debris flows (Takahashi 1991; Cui 1992), and the debris flows became mainly transitional or semi-viscous.

### Variation of annual rainfall conditions

Compared with the changes to the materials in the watersheds, the variation in the annual rainfall conditions contributed less to the change in rainfall thresholds. The annual rainfall volume varied from a minimum of 574 mm in 2009 to a maximum of 919 mm in 2013 (Fig. 12). The





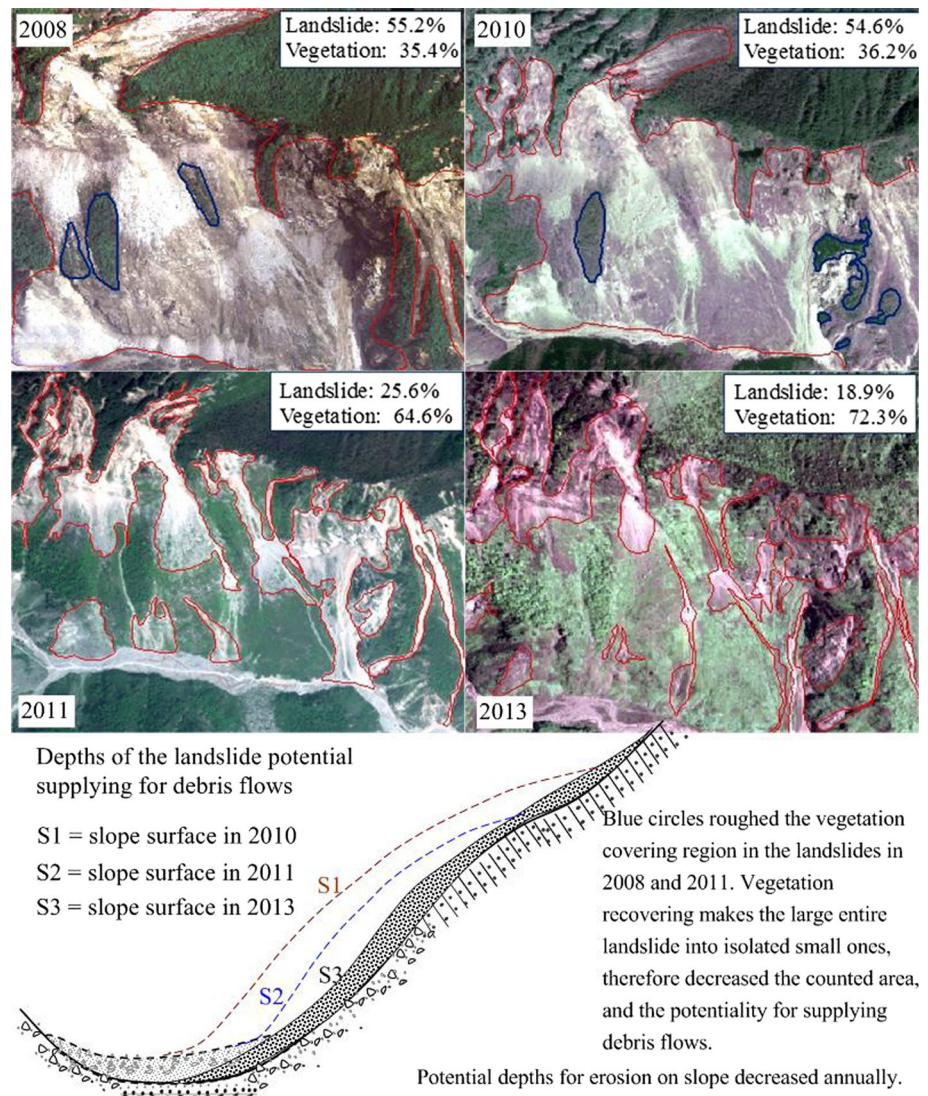
**Fig. 8** a Vegetation cover and landslide area in 2011. b Vegetation cover and landslide area in 2013

number of rainfall events where the volume exceeds 15 mm varied from five times in 2009 and 2013, to nine times in 2010, 2011, and 2012. Corresponding to the

annual increasing trend of rainfall thresholds, this result indicates the negligible effect of the variation in annual rainfall to the rainfall thresholds.



**Fig. 9** Variation of the landslide and vegetation area, and the potential erosion depth on a single slope

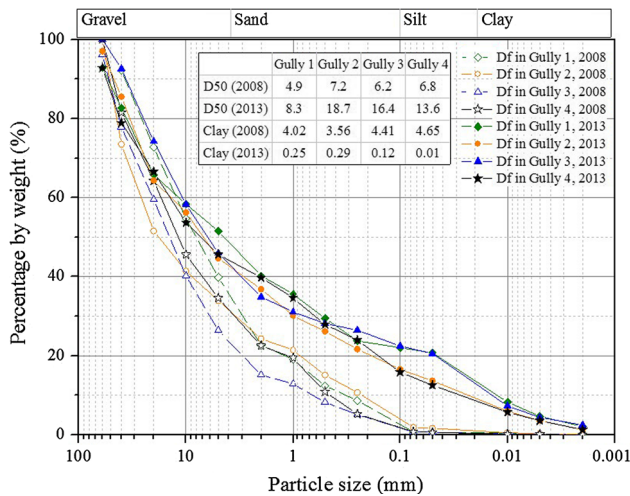


### Discussion

As a sudden and tremendous disturbance, the Wenchuan earthquake greatly altered the rainfall conditions required for triggering debris flows. The results of this study show that the rainfall thresholds, either the direct thresholds as event rainfall or peak rainfall intensity or the compounding thresholds as *I-D* and *I-R* models for debris flows, were significantly lower than those before the earthquake, which were approximated as 80–100 mm/d and/or 30–50 mm/h (Tan and Han 1992). The effectiveness of the rainfall indexes used for forecasting was compared, and the most effective warning model was selected. Note that although the suitable models may differ for different regions, the evolution tendency of rainfall thresholds can be predicted and verified. Besides the rainfall fluctuations over the past few years, the materials variation consisting of the loose

material amount decreases and the grain composition changes were the primary reasons for threshold variability.

A limitation of the definition of rainfall thresholds based on the statistical analysis of empirical data is that the inferred thresholds depend entirely on the dataset used (Brunetti et al. 2010; Peruccacci et al. 2012). Better results are obtained when the frequentist method is applied to a larger dataset. With regard to data collection, the limitations of monitoring debris flows and their triggering rainfall conditions are an impediment to the development of an adequate warning system in the mountainous areas of Western China. In particular, rainfall gauges are generally located at the outlet of gullies, and the rainfall information measured were generally lower than those in debris flow source regions. Overall, to develop a more effective debris flow warning system and to identify the rainfall thresholds that trigger these events, further efforts should focus on



**Fig. 10** Particle composition of debris flow samples collected in 2008 and 2013. The two groups of deposits were collected shortly after the debris flow events. The inset table lists the clay content (%) and D50 (mm), indicating that the clay content of debris flows decreased visibly, whereas the D50 clearly increased

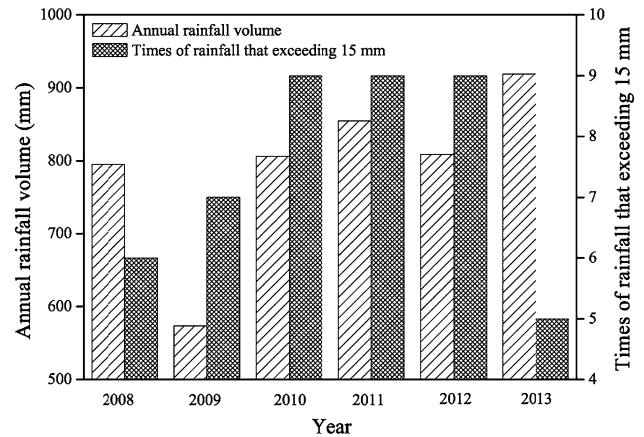


**Fig. 11** Coarser material in the channel and on the slope. Circled area A represents recovering vegetation on the landslide; B and C represent the coarser, loose material on the slope and in the channel bed

building monitoring nets and comparing rainfall information between gauges located within and outside gullies.

**Conclusions**

The catastrophic Ms 8.0 Wenchuan earthquake significantly reduced the amount of rainfall required to trigger a debris flow, inducing the unprecedented high frequency of debris flows compared with other regions in China. We selected a typical region as a case study to illustrate the rainfall thresholds and their annual variation for these post-earthquake debris flows. The conclusions are as follows.



**Fig. 12** Annual rainfall volume and times of rainfall that exceeded 15 mm between 2008 and 2013

Rainfall intensity is the most direct triggering rainfall index, and the more abundant the antecedent effective rainfall, the lower the rainfall intensity that was required. The  $I-D$  threshold for this region was proposed as  $I = 4.2 D^{-0.62}$  ( $2 \text{ h} < D < 56 \text{ h}$ ) for all post-earthquake debris flow events, and as  $I = 11.8 D^{-0.87}$  ( $2 \text{ h} < D < 56 \text{ h}$ ) for debris flows during the period of 2009–2013, which is higher and derived by eliminating the abrupt disturbance in a very short time. The  $I-D$  threshold can represent the rainfall conditions that are required for debris flow initiation, but it is not the most effective warning approach based on comparisons of accuracy and effectiveness with other approaches. The thresholds proposed related to  $I-R$  and/or direct event rainfall are more suitable for debris flow warning based on the debris flow behavior over the past years. The upper limit of rainfall that did not trigger debris flows defined by the event rainfall was 39.6 mm, indicating that debris flows would certainly occur during rainfall exceeding 39.6 mm. The threshold defined by the lower limit of rainfall that triggered debris flows as 27.9 mm indicates that when the rainfall amount exceeds this limit, which is more conservative, there is an almost 70 % likelihood that debris flows will be triggered.

The annual thresholds for debris flows have increased each year over the past 6 years. Besides the rainfall fluctuations over the past several years, the variation in the source materials was the primary reason for the threshold variation. The recovery of the vegetation plays an important role in decreasing the volume of loose material that has the potential to supply debris flows. For a single site, the natural solidification, the decrease in the potential erosion depth and surface coarsening also increase the difficulty to initiate a debris flow, ultimately increasing the rainfall conditions required. Although the suitable models may differ between regions based on the local climate and other conditions, the tendency of rainfall thresholds to change



can be predicted and verified in the entire earthquake-affected area.

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