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ORIGINAL PAPER

Patterns of rainfall-threshold for debris-flow occurrence in the Wenchuan seismic region, Southwest China

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Abstract

In recent years, debris flows induced by rainstorms have caused severe casualties and property losses in the Wenchuan earthquake region, Southwest China. The different rainfall patterns point to a composite rainfall threshold for the occurrence of debris flows. The rainfall intensity and antecedent rainfall of debris flow events were analyzed after the Wenchuan earthquake. The results show that the rainfall pattern in time can be classified into three types: a short-term rainfall pattern, a medium persistent rainfall pattern, and a long-term intermittent rainfall pattern. The main differences between the three patterns of a single precipitation event are rainfall intensity, duration, and cumulative rainfall, which can result in different infiltration, saturation, and triggering mechanisms of debris flows. The short-term rainfall pattern can be associated with the highest rainfall intensity and the least cumulative rainfall. The medium persistent rainfall pattern is related to intermediate rainfall intensity and the medium cumulative rainfall, and a long-term intermittent rainfall pattern can be related to the lowest rainfall intensity and the longest rainfall duration. At last, this paper sets up the patterns of rainfall-threshold for debris-flow occurrence. According to the critical initiation, conditions of the debris flow in the five watersheds can be predicted by the intensity-duration curve (ID curve) under different rainfall patterns.

Keywords Debris flow · Rainfall patterns · Rainfall intensity · Cumulative rainfall

Introduction

The rainfall-induced debris flows are the most common secondary geological hazards in the Wenchuan earthquake region. According to the research of Zhang and Matsushima (2016), loose solid materials in seismically active areas are easily entrained by runoff following heavy summer rain so that debris flow forms. After the earthquake, rainstorm debris flow activity can last for 5 to 10 years (Tang et al., 2009), even 30 years (Cui et al. 2008). Many researchers have tried to connect rainstorm debris flows to rainfall factors (Cannon and Savage 1988; Prete et al. 1998). Two types of debris flows were detected: runoff-generated and landslide-induced. Combined with the field observations, laboratory experiments, and theoretical analyses, Iverson et al. (1997) indicate that landslides mobilize to form debris flows by three processes: widespread Coulomb failure, liquefaction of the mass by high pore-fluid pressures, and conversion of landslide translational energy to internal vibrational energy. Coe et al. (2008) found that debris flows were initiated by water runoff from colluvium and bedrock that entrained sediment from rills and channels with slopes ranging from about 14° to 45°. The channelized debris flows can grow volumetrically because of bed-material entrainment transporting up to 1×10^5 m^3 of sediments, and causing several victims (Reid et al. 2016; Gregoretti et al. 2018; Chen et al. 2019). Wieczorek et al. (1989) indicate that the requirements of antecedent rainfall and high-intensity rainfall apply to most areas where debris flows have been researched, but specific amounts vary regionally depending widely on soil thickness, the permeability of soil and bedrock, and topography. Besides, the researcher took into account a notion of seasonal threshold preceding a rainy event that triggered debris flow. After the Chi-Chi earthquake in Taiwan, the evaluation of

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factors controlling earthquake-induced landslides and initiation mechanisms of rainfall-induced debris flows were discussed (Shin 2001; Khazai and Sitar 2004). Gregoretti and Dalla Fontana (2007) collected historical rainfall data from twenty-eight debris flow events that occurred in six watersheds in the Dolomites and defined a threshold curve for the triggering of debris flows. Zhang et al. (2013) used rainfall conditions to study the prediction model of debris flows duration and runout volume. Okano et al. (2012) analyzed the debris-flow magnitude and flow characteristics using the fourteen sets of rainstorm and debris flow data from 1980 to 2005 at the Kamikamihorizawa Creek of Mount Yakedake. Combined with the precipitation conditions, Wu et al. (2020) established the sensitivity evaluation model for debris flows in the Longxi River area. The temporal frequency and scale of debris flows are related to the intensity and cumulative value of a single precipitation event (Gregoretti et al. 2016; Bogaard and Greco 2018). Zhuang et al. (2015) modeled the prediction of debris flows by analyzing the duration and intensity of post-earthquake rainfall and the thresholds. Staley et al. (2013) objectively defined the thresholds by maximizing the number of correct predictions of debris flow occurrence while minimizing the rate of errors. Van Asch et al. (2014) used hydro-mechanical numerical models to simulate the initiation, and run-out process, then established critical rainfall thresholds.

For the warning and forecast of a single debris flow, several factors that facilitate the triggering of debris flow are known, which included gully length, gully depth, ravines density, vertical slope, types of geological outcrops, surface runoff, channel erosion, pore water pressure, and instability index (Cui et al. 2009; Chen et al. 2011). Besides, the present research also includes some specific geotechnical index, in particular, the granularity and content of the materials in the potential source areas; available volumes of materials present on the slopes and in the gully likely to be mobilized (Ouyang et al. 2015; Yin et al. 2016). However, it is urgent to provide a quick and convenient early warning measure for mass debris-flow events in a small watershed. After the Wenchuan earthquake, massive debris flows occurred in the Longxi River watershed, Min River watershed, Subao River watershed, Mianyuan River watershed, and the Baishui River watershed. There are differences in the topographic, geological, and geotechnical parameters of these watersheds, even for specific watersheds. It is difficult to obtain detailed and reliable data on loose material distribution, triggering rainfall, and some physical factors that control the debris flow occurrence (Berti et al. 2020). However, we still hope to find a more accurate and applicable rainfall pattern to explore the role of rainfall in triggering debris flows. Thus, this paper carries out a study on the occurrence of debris flow under different rainfall patterns, depending on rainfall duration

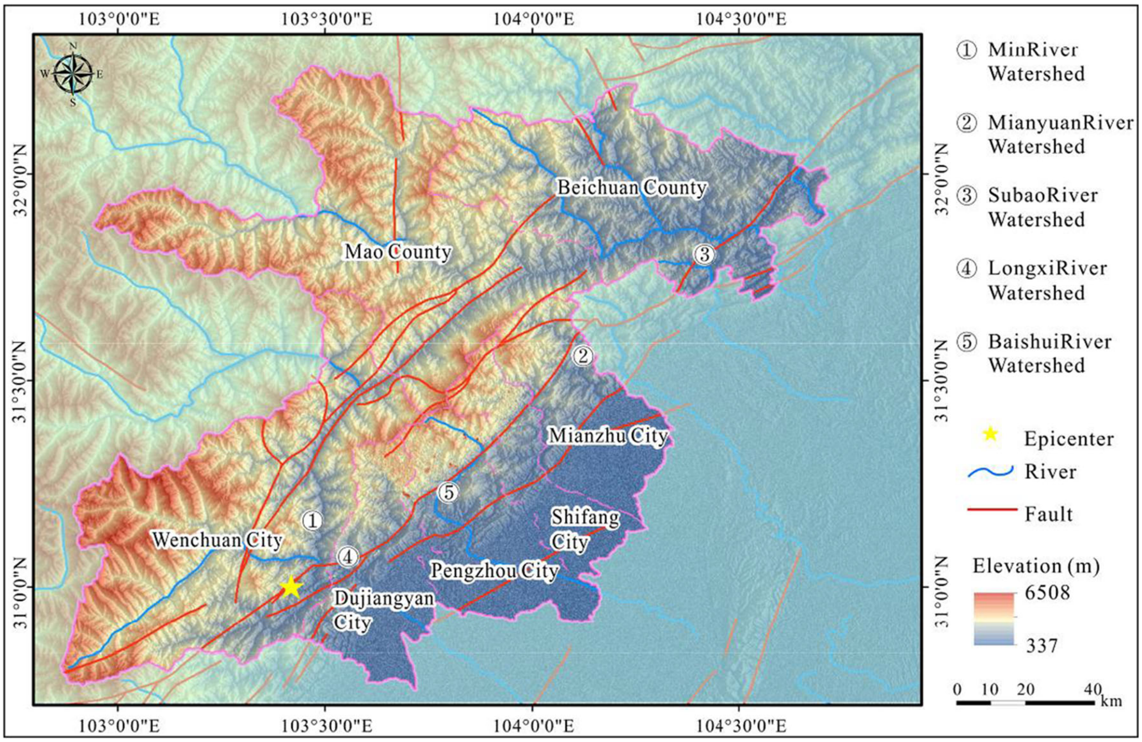


Fig. 1 The study map of the critical rainfall-induced debris flows in the Wenchuan earthquake region

Table 1 Detailed information on the study area

No.	Watershed	Longitude	Latitude	Number of debris flows	Area/km^2
1	Min River	103° 24′ 23″ 103° 32′ 21″ E	31° 3′ 20″ ~ 31° 12′ 6″ N	21	73.49
2	Mianyuan River	104° 4′ 27″ 104° 9′ 32″ E	31° 30′ 8″ ~ 31° 35′ 59″ N	20	34.02
3	Subao River	104° 19′ 50″ ~ 104° 26′ 14″ E	31° 44′ 55″ ~ 31° 49′ 10″ N	14	25.32
4	Longxi River	103° 30′ 57″ 103° 34′ 6″ E	31° 2′ 52″ ~ 31° 5′ 30″ N	12	12.60
5	Baishui River	103° 48′ 20″ ~ 103° 55′ 16″ E	31° 15′ 53″ ~ 31° 22′ 53″ N	12	24.88

and intensity. The results will provide a fast basis for the prediction of debris flows in the Wenchuan earthquake area (Fig. 1).

Study area

The Wenchuan earthquake on May 12th, 2008, Mw 8.3 was one of the most devastating earthquakes in China and induced a large number of post-quake disasters. Many debris flows under different rain patterns occurred in the Wenchuan earthquake-affected area, Southwest China. The number of debris flows, watershed area, and overall longitude and latitude information of the five study areas was included in Table 1. To reflect the distribution of debris flows and rain gauges in each study area, Figs. 2, 3, 4, 5, to 6 show the detailed interpretation results based on remote sensing images. At the same time, we made statistics on the morphological characteristics related to debris flow occurrence in each study area, such as drainage area, channel length, watershed relief, and channel gradient (Tables 2, 3, 4, 5, to 6).

Method and data

For exploring the rainfall patterns triggering debris flows in these river watersheds, the rainfall intensity and the antecedent rainfall are selected as essential analysis parameters. After

Table 2 Geomorphological parameters of the Min River watershed

Gully code	Gully name	Drainage area (km^2)	Channel length (km)	Watershed internal relief (m)	Channel gradient (‰)
MJ-01	Hongchun	5.35	3.55	1260	354
MJ-02	Shaofang	0.71	1.74	1040	649
MJ-03	Xiaojia	0.49	1.64	1070	649
MJ-04	Baijialin	0.60	1.52	980	647
MJ-05	Wangyimiao	0.47	1.39	1000	719
MJ-06	Mozi	5.33	4.23	1600	378
MJ-07	Laohuzui	0.36	1.15	940	821
MJ-08	Douyaping	2.73	2.57	1740	677
MJ-09	Mayangdian	2.02	2.59	1820	703
MJ-10	Maliuwan	0.43	1.30	1120	860
MJ-11	Santaidi	0.19	1.09	750	687
MJ-12	Dagou	1.03	2.02	900	437
MJ-13	Dacaotou	3.99	3.78	1540	406
MJ-14	Zaojiaowan	2.88	2.40	1710	711
MJ-15	Heicaotou	0.34	1.14	1980	857
MJ-16	Xingwenping	1.71	2.44	2020	830
MJ-17	Yiwanshui	7.18	4.82	2480	514
MJ-18	Yeliu	24.42	9.47	2980	315
MJ-19	Supodian	2.81	2.74	1440	525
MJ-20	Maojiawan	0.43	1.30	1120	801
MJ-21	Yingxingping	7.06	4.41	2000	447

Table 3 Geomorphological parameters of the Mianyuan River watershed

Gully code	Gully name	Drainage area (km^2)	Channel length (km)	Watershed internal relief (m)	Channel gradient (‰)
MY-01	Heitanzi	0.93	2.35	780	505
MY-02	Liuquezi	0.45	1.79	300	751
MY-03	Yongjia	2.03	3.14	440	979
MY-04	Zoumaling	4.52	3.39	1000	390
MY-05	Luojia	1.51	2.91	600	532
MY-06	Dongzi	0.09	0.64	420	652
MY-07	Wawa	0.43	1.43	560	610
MY-08	Didong	0.12	0.76	1140	716
MY-09	Wenjia	5.85	4.33	280	471
MY-10	Boqi	0.25	1.25	280	532
MY-11	Caodun	0.22	1.31	620	675
MY-12	Pujia	0.66	1.75	580	662
MY-13	Maliuwan	0.70	2.06	1100	518
MY-14	Linjia	0.88	2.16	540	418
MY-15	Guangqiao	0.77	2.07	500	398
MY-16	Taiyang	0.38	1.13	540	833
MY-17	Caijia	0.38	1.20	500	778
MY-18	Hui	6.05	4.91	580	253
MY-19	Shihui	0.53	1.58	740	296
MY-20	Xiaogangjian	0.93	1.80	860	719

careful study of the existing literature and previous research results, this paper adopted the method by Jan and Lee (2004) to define the event with continuous rainfall. The start of a rainfall event is defined when the intensity reaches 4 mm/h. The end of the rainfall event is defined when the intensity is lower than 4 mm/h during 6 continuous hours (Jan and Lee 2004; Chang et al. 2011). In this paper, the antecedent rainfall is defined as the total amount of rainfall before the debris flow occurs during the accompanying rainfall events. According to Chow et al. (1988), the rainfall depths previously precipitated were named antecedent rainfall. Some rain gauge stations and mud level measurement monitoring devices have been

Table 4 Geomorphological parameters of the Subao River watershed

Gully code	Gully name	Drainage area (km^2)	Channel length (km)	Watershed internal relief (m)	Channel gradient (‰)
SB-01	Gaojiakan	1.61	2.31	589	352
SB-02	Gangou	0.60	1.24	586	342
SB-03	Huijiaping	0.64	1.40	671	390
SB-04	Gangouzi	3.97	3.16	1300	333
SB-05	Guanyintang	2.17	2.46	1265	415
SB-06	Guanmenzi	3.06	2.95	1509	306
SB-07	Chayuantou	4.27	3.89	1352	254
SB-08	Huangjiashan 1#	0.21	1.01	722	596
SB-09	Huangjiashan 2#	0.29	0.82	712	694
SB-10	Xiaojiaping	0.87	1.31	885	557
SB-11	Xiaopingshan	2.00	2.22	884	333
SB-12	Huangnidi	3.93	3.57	947	206
SB-13	Jingzhuyuan	1.03	1.47	893	512
SB-14	Zhongliangzi 1#	0.65	1.07	866	617

Table 5 Geomorphological parameters of the Longxi River watershed

Gully code	Gully name	Drainage area (km^2)	Channel length (km)	Watershed internal relief (m)	Channel gradient (‰)
LX-01	Chamagudao	0.25	0.71	460	657
LX-02	Yanziwo	0.10	0.32	300	946
LX-03	Gongjia	0.49	1.31	640	491
LX-04	Bayi	8.50	4.23	1650	389
LX-05	Maliu	0.92	1.76	940	535
LX-06	Shuijingcao	0.15	0.33	360	1084
LX-07	Huangyang	0.61	1.64	950	582
LX-08	Shuida	0.33	1.12	620	550
LX-09	Baiguotang	0.19	0.43	360	833
LX-10	Maliucao	0.89	1.81	910	505
LX-11	Shaziping	0.17	0.59	560	951
LX-12	Liquantai	0.32	0.86	680	789

installed in the field and could provide data in real-time when a debris flow event occurred. With the weather forecasts provided by the weather bureau, the following rainfall data were obtained: ① hourly rainfall intensity, which is the amount of rainfall in mm per hour; ② cumulative rainfall, which is the total amount of one continuous precipitation event; ③ rainfall duration, which is the duration of one precipitation event; ④ the starting time of debris flows, which can be defined from field surveys and the data of mud level measurement monitoring devices.

In some specific seasonal rainfall events, the rainfall threshold may play an important role in the initiation of debris flow, such as influencing the saturation degree of soil or loose rock mass. However, the effect of rainfall may be different under different rainfall events. Through the field investigation and previous study, we obtained rainfall data for the five river watersheds and then studied the occurrence characteristics of debris flows under different rain patterns. The occurrence time, rainfall intensity, antecedent rainfall, rainfall duration, and corresponding rainfall pattern of debris flow in five river watersheds are listed in Table 7.

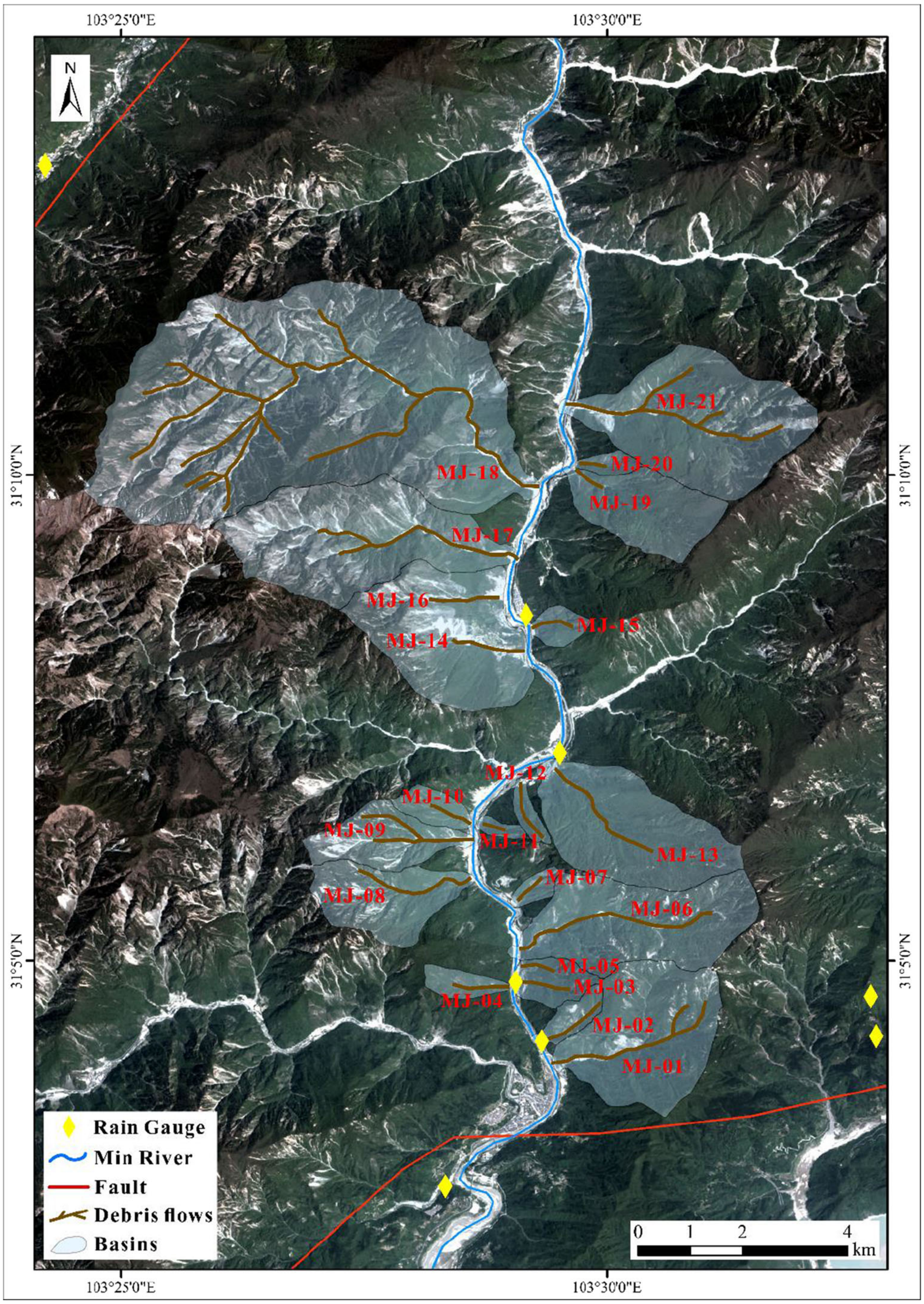
Results

In this paper, the detailed rainfall data and the cumulative value of antecedent rainfall of all debris flow events above are plotted in Figs. 7, 8, to 9. Through comparative analyses of the different rainfall diagrams, this paper distinguishes three types of triggering rainfall patterns: short-term sudden rainfall pattern, medium-term persistent rainfall pattern, and long-term intermittent rainfall pattern.

Table 6 Geomorphological parameters of the Baishui River watershed

Gully code	Gully name	Drainage area (km^2)	Channel length (km)	Watershed internal relief (m)	Channel gradient (‰)
BS-01	Xiaohaizi	3.03	2.12	640	189.91
BS-02	Dahaizi	2.15	1.42	860	330.77
BS-03	Haihuiqiao	1.69	2.37	1400	555.56
BS-04	Bianjie	1.52	2.57	1060	488.48
BS-05	Guanzi	2.43	1.89	820	369.37
BS-06	Zhujuanmen	0.59	1.33	460	377.05
BS-07	Xiangzhangshu	1.58	1.62	560	388.89
BS-08	Yijiawan	1.41	1.42	260	254.90
BS-09	Luoheqiao	3.23	3.61	900	218.45
BS-10	Qinggang	2.29	2.04	1360	445.90
BS-11	Xiejiadianzi	1.46	1.40	560	378.38
BS-12	Xiangshuidong	3.50	3.75	960	326.53

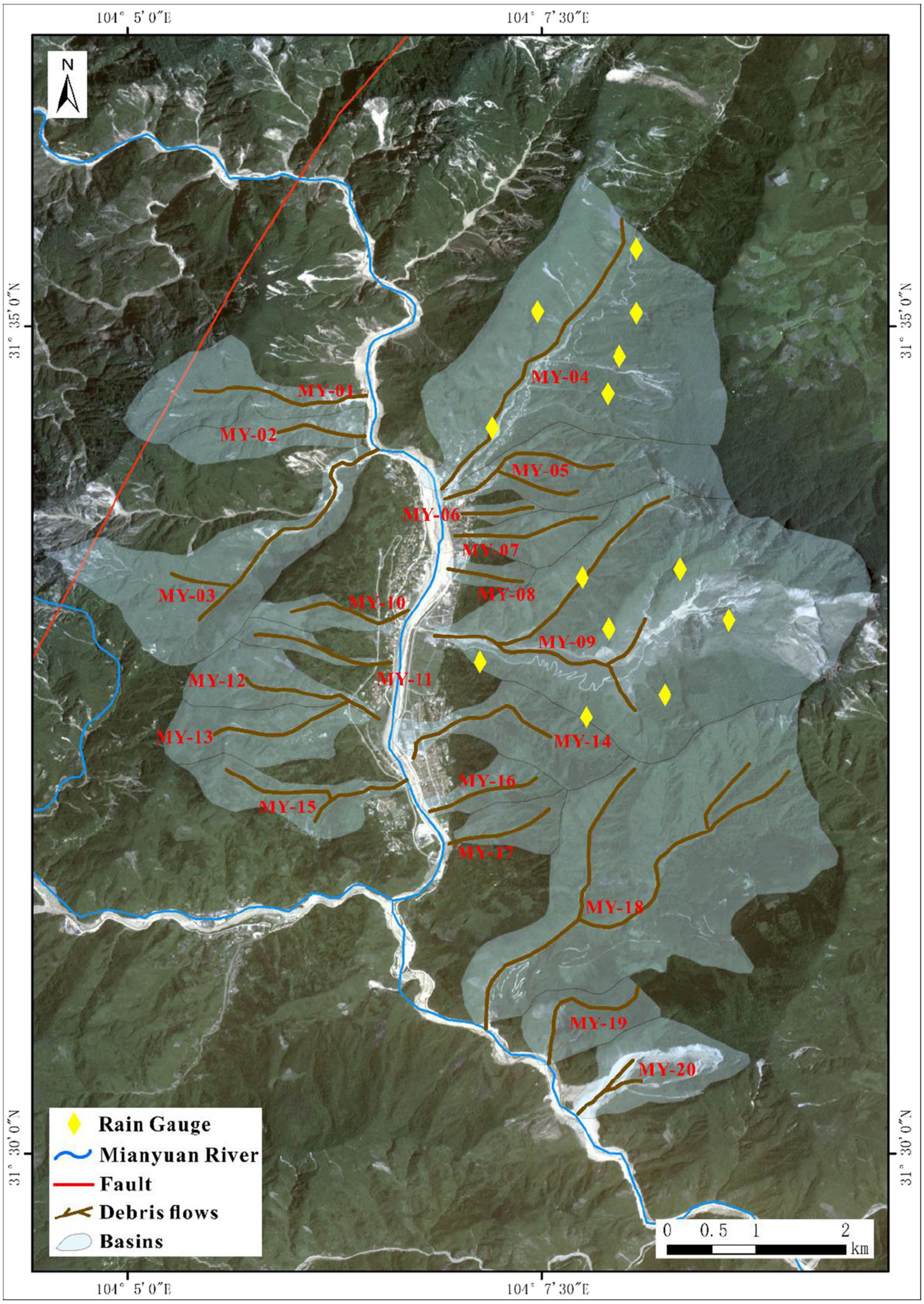
Fig. 2 Distribution map of twenty-one debris flows in the Min River watershed



Short-term sudden rainfall pattern

A "short-term sudden rainfall pattern" is characterized by a rapid increase of rainfall intensity so that debris flows are triggered in a short time interval. One important sign of this pattern is that the antecedent rainfall duration is not exceeding more than 5 h. Depending on the data measured in the field, the duration of antecedent rainfall is short, usually less than 5 h. There could be little rain in the first few hours but with a quick rise of the rainfall intensity, and the debris flow will occurrence immediately. Figure 7 shows the rainfall is relatively small due to the short duration of antecedent rainfall. The yellow stars in Figs. 7, 8, to 9 show the timing of debris-flow occurrence. With high-intensity rainfall conditions, the intensity of rain exceeds the seepage intensity to form slope runoff (Kean et al. 2013; Simoni et al. 2020). The generated

Fig. 3 Distribution map of twenty debris flows in the Mianyuan River watershed

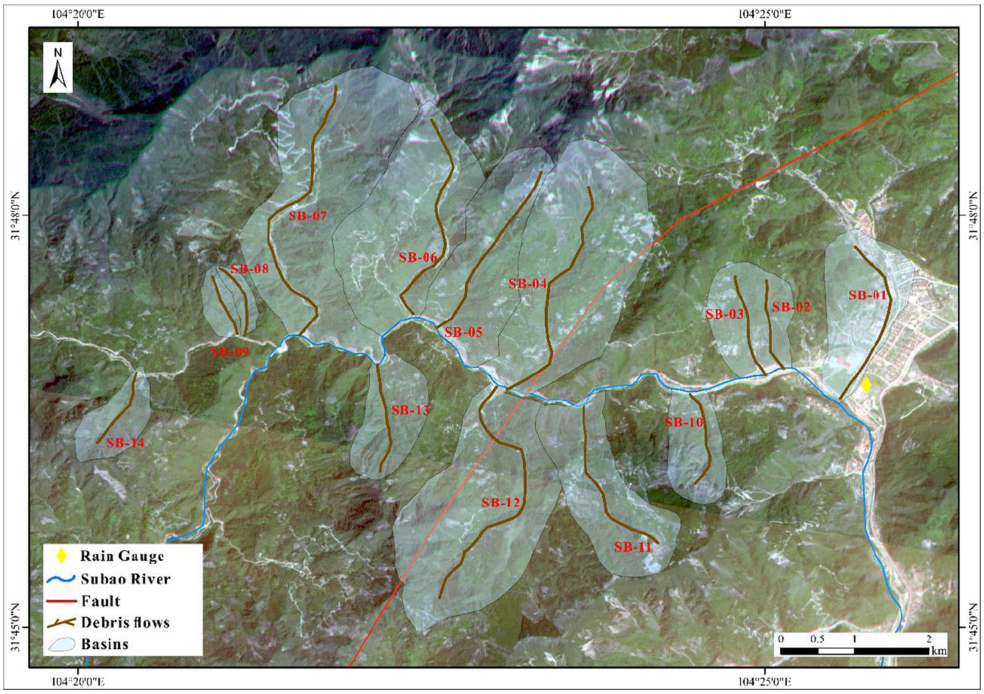


flash floods entrain abundant loose materials in the channel that can quickly convert into debris flows. The representative events with this type of rainfall pattern are as follows: the “8.13” debris flows in the Longxi River watershed, the “7.31” debris flows in the Mianyuan River watershed, the “9.23” debris flows in the Subao River watershed, and the “7.31” debris flows in Baishui River watershed.

Medium-term persistent rainfall pattern

Antecedent rainfall is an important indicator of the classification of the medium-term persistent rainfall pattern. The debris flow is preceded by a period of antecedent rainfall. For medium-term persistent rainfall events, the antecedent sufficient rain duration time is about 7 h, and the total duration will

Fig. 4 Distribution map of fourteen debris flows in the Subao River watershed

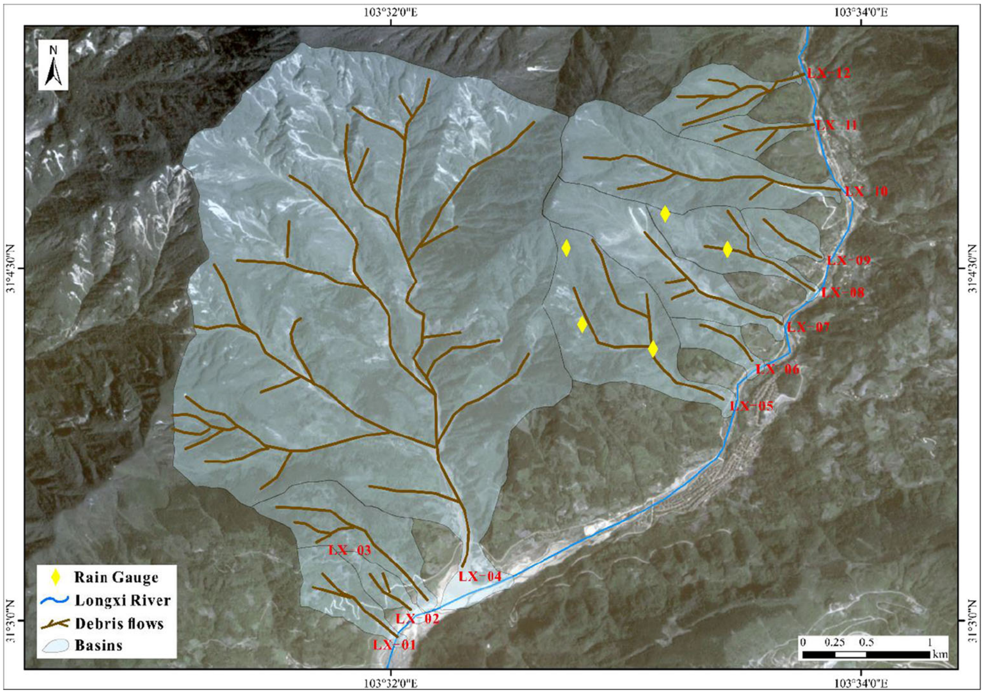


continue more than 10 h but less than 1 day. As shown in Fig. 8, although the rainfall intensity at the time of these debris flow occurrence was relatively small, the antecedent rainfall had resulted in the saturation of loose materials and accelerated surface runoff. The representative events with this type of rainfall pattern are as follows: the "8.18" debris flows in the Longxi River watershed, the "8.13" and "8.19" debris flows in the Mianyuan River watershed, and the "8.21" debris flows in the Min River watershed.

Long-term intermittent rainfall pattern

The long-term intermittent rainfall pattern is mainly characterized by prolonged antecedent rainfall. The

Fig. 5 Distribution map of twelve debris flows in Longxi River watershed



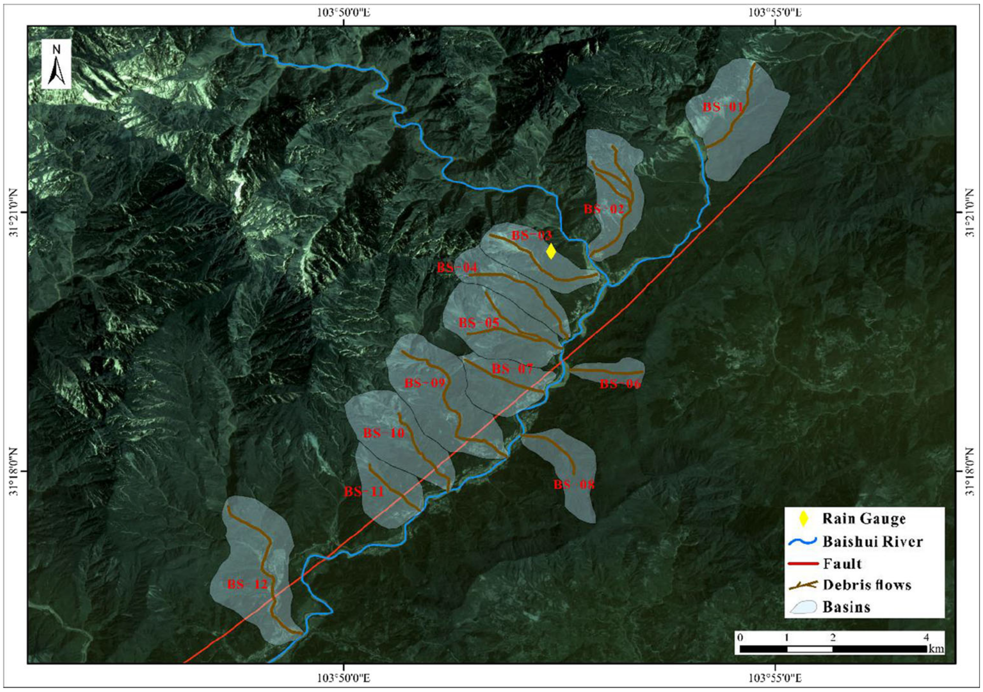


Fig. 6 Distribution map of twelve debris flows in the Baishui River watershed

rainfall may continue 2 or 3 days, with one or sometimes more short breaks. Generally speaking, the first rainfall period has a clear maximum, while the second rainfall period does not exceed 10 h. The long antecedent rainfall period can increase the overland flow and moisture of the soil. The increasing high discharge can saturate loose materials and transport them to the channel. Figure 9 shows during the antecedent period, a repetition of separate rain events with moderate rain intensities. These rain events have a long antecedent duration that leads to the high moisture content in materials. Massive erosion occurs in the channel by entrainment of material from both sides of the channel. With the passing of the peak rainfall, the water level drops, and erosion in the channel gradually stops. As the rain continues and the flow increases, the immature

Table 7 Rainfall data of typical debris flow events in the Wenchuan seismic region (*S*, short-term sudden rainfall patterns; *M*, medium-term persistent rainfall patterns; *L*, long-term intermittent rainfall patterns)

Id	Location	Time	Rainfall duration (h)	Rainfall intensity (mm/h)	Antecedent cumulative rainfall (mm)	Rainfall pattern	Reference
1	Min River watershed	2010.8.14	14	16.6	111.2	L	Tang et al. 2011
		2011.8.21	7	56.5	125.8	M	Zhou and Tang 2014
		2013.7.11	76	6.4	111.4	L	Jing et al. 2015
2	Mianyuan River watershed	2010.7.31	2	50.4	89.5	S	Zhou et al. 2013
		2010.8.13	6	37.4	82.6	M	Zhou et al. 2013
		2010.8.19	10	31.9	121.6	M	–
		2013.7.10	45	4.3	120.6	L	–
3	Subao River watershed	2008.9.23	3	33.5	82.7	S	Cui et al. 2012
		2008.9.24	10	41.8	163.1	L	Chen et al. 2012
4	Longxi River watershed	2010.8.13	3	75	97	S	Wu et al. 2020
		2010.8.18	9	69	183.8	M	Wu et al. 2020
5	Baishui River watershed	2012.8.18	3	72	112	S	Huang and Tang 2014

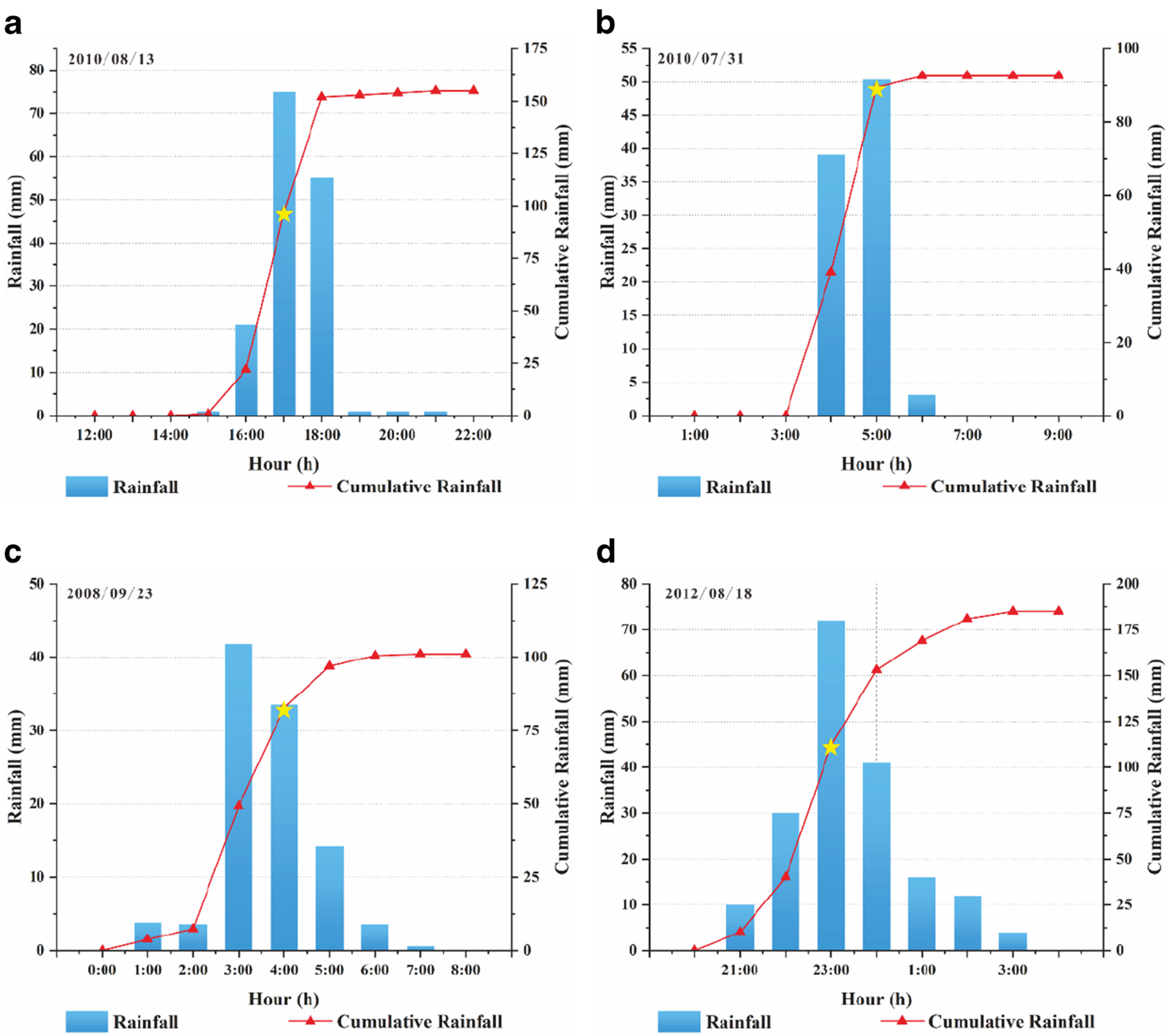


Fig. 7 Short-term sudden rainfall patterns at the origin of the triggering of debris flow in the Wenchuan earthquake area (yellow star: the occurrence time of debris flow)

flow will move downstream with increasing sediment concentration and volume until it becomes a fully formed debris flow (Berti et al. 2020). On the whole, compared with the conditions of debris flow induced by short-term sudden rainfall pattern and medium-term persistent rainfall pattern, the time stage of the generation and triggering of long-term intermittent rainfall pattern-induced debris flow is relatively later and the peak rainfall required is also lower. The representative events with this type of rainfall pattern are as follows: the "8.14" and "7.11" debris flows in the Min River watershed, the "9.24" debris flows in the Subao River watershed, and the "7.10" debris flows in the Mianyuan River watershed.

ID rainfall threshold analysis

According to the above rainfall database of the five river watersheds, the intensity-duration curve (ID curve) of three rainfall patterns was constructed to describe the critical rainfall conditions for debris flow initiation. The intensity-duration rainfall threshold of the most common type has the form of $I = \alpha D^{-\beta}$ (Guzzetti et al. 2007, 2008; Saito et al. 2010; Zhou et al. 2014). To plot the ID curve, all the rainfall intensity I and duration D data of debris flow events were noted in a graph of a rectangular coordinate system (D on the x axis, I on the y axis). Based on the rainfall data, the ID curve for the debris flow events in the Wenchuan

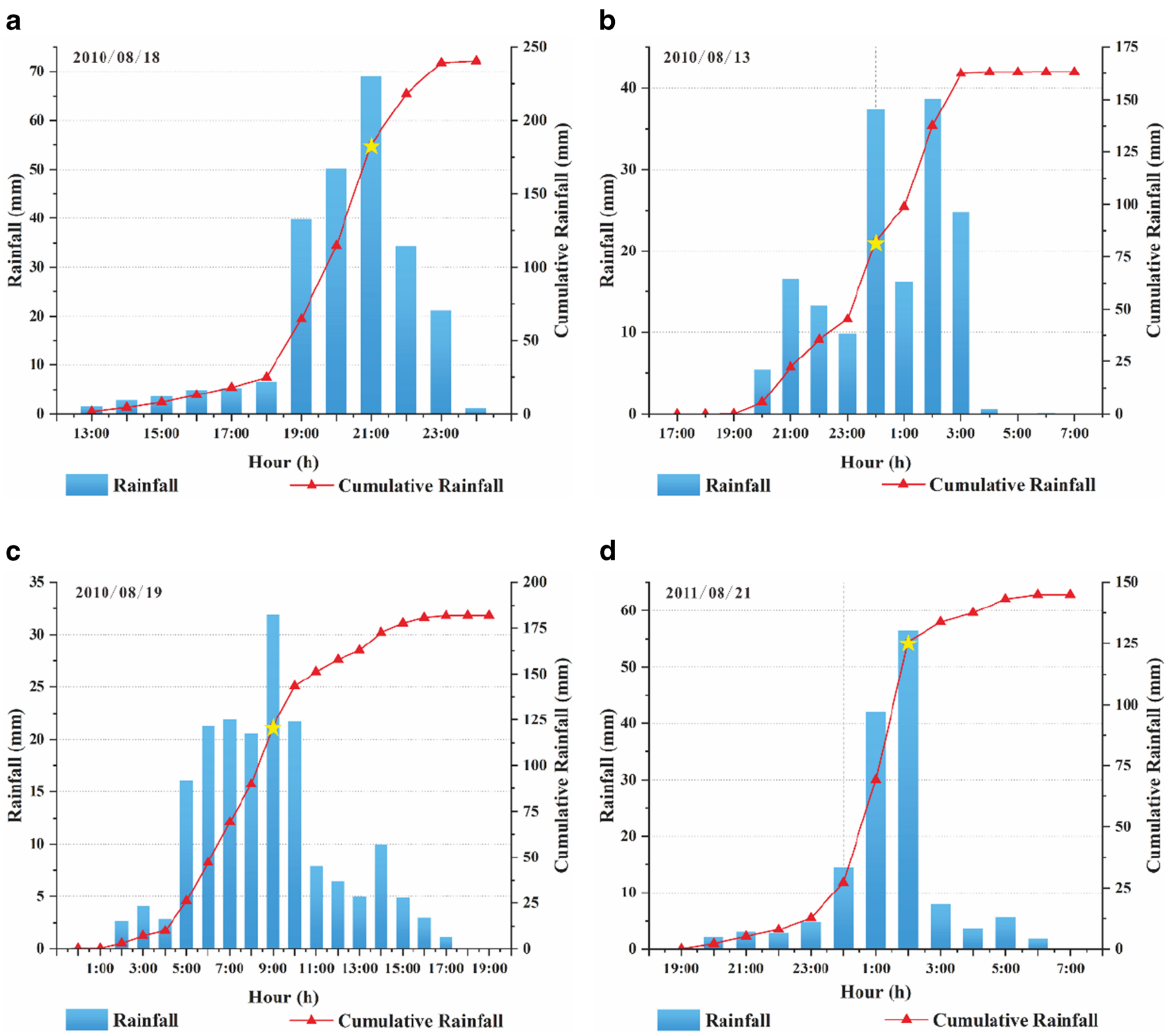


Fig. 8 Medium-term persistent rainfall patterns at the origin of the triggering of debris flow in the Wenchuan earthquake area (yellow star: the occurrence time of debris flow)

earthquake region was drawn by the Origin software. The threshold curve and the formula in different rainfall patterns are shown in Fig. 10.

On August 19th, 2019, a heavy rainstorm occurred at about 0:00 in the Min River watershed. More than eight debris flows occurred after 26 h. According to the characteristics of rainfall, these debris flow events belong to the long-term intermittent rainfall pattern. The triggering rainfall intensity and antecedent rainfall were 24.2 mm/h and 121.1 mm, respectively (Fig. 10a). Using the intensity-duration model to carry out verification, the results show that it can predict this debris flow event (Fig. 10b).

Conclusion and discussion

Debris flows were frequently induced by rainfall after the Wenchuan earthquake, causing substantial economic losses and heavy casualties. Correctly classifying rainfall patterns and precisely setting up a prediction rainfall threshold of post-seismic debris flows based on rainfall data can help to enhance disaster prevention and mitigation. Although there are differences in the topographic, geological, and geotechnical parameters of these watersheds, we still want to get a more accurate intensity-duration threshold curve for different rainfall patterns. In this paper, the relationship between the

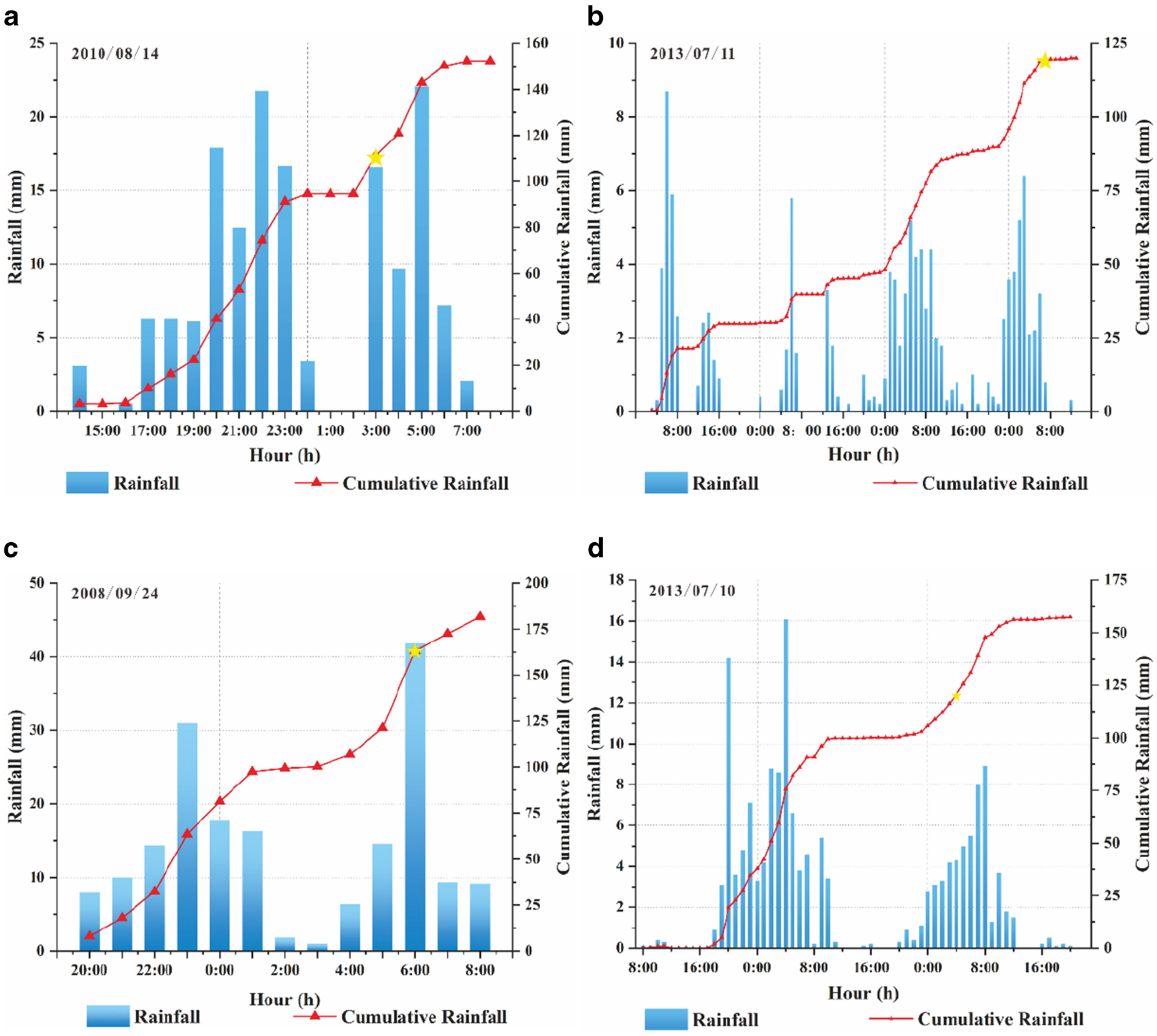


Fig. 9 Long-term intermittent rainfall patterns at the origin of the triggering of debris flow in the Wenchuan earthquake area (yellow star: the occurrence time of debris flow)

characters of rainfall patterns and the debris flow occurrence was analyzed. Five river watersheds in the Wenchuan earthquake region were selected because according to the field investigation, all the debris flows of this region were triggered by rainfall. The pattern of rainfall triggering debris flows in the Wenchuan earthquake region can be divided into three types: short-term sudden rainfall pattern, medium-term persistent rainfall pattern, and long-term intermittent rainfall pattern. In the short-term sudden rainfall pattern, heavy rainfall can lead to the enhancement of surface runoff, and thus bring a large amount of loose sediment into the debris flow in a short period. In the case of medium-term persistent rainfall patterns, both the flow runoff erosion and slope failure mechanisms can play a vital role in initiating debris flows. The long-term intermittent rainfall pattern with the lowest intensities and long duration are favorable for the initiation and reactivation of landslides, which can transform into debris flows, especially when failure at the end is accompanied by a lot of rain. According to the three rainfall patterns, the ID curve for the debris flow events in the Wenchuan earthquake region was established and verified.

As the introduction explains, the excitation condition of debris flow in seismic zones is influenced by many factors, such as geologic structure, geomorphology, rock kind, vegetation, and precipitation. For example, the lithology of outcrops or rock type distributions directly influence the quantity

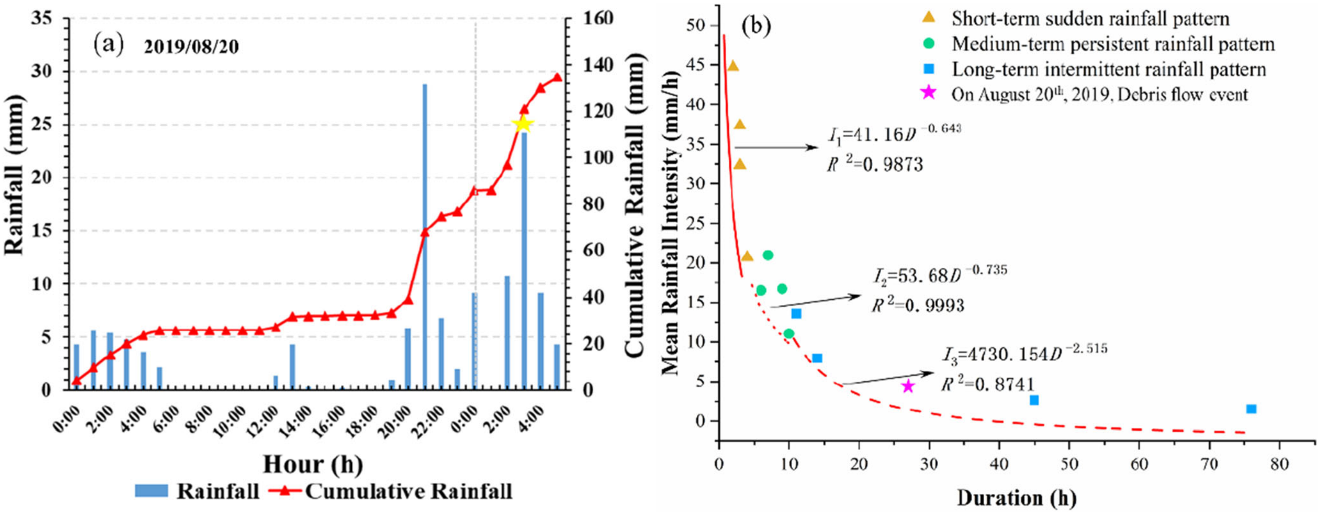


Fig. 10 *ID* thresholds for the debris flow events under three rainfall patterns (**a** example of rainfall data; **b** ID threshold curve)

and quality of available loose materials for the generation of rainstorm debris flows. However, due to the lack of lithological data, this paper only considers the prediction of threshold under one variable of rainfall. In the future, we will further collect relevant data and carry out the study on the rainfall threshold of debris flow using a multivariate approach.

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