

Topographical factors in the formation of gully-type debris flows in Longxi River catchment, Sichuan, China

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Abstract There are three groups of factors: topography, geology and hydrology which have influence on the formation of gully-type debris flows. In this paper, a single representative factor (T-factor) for the topography is proposed, which can be used to define threshold values for debris flow formation. This study was carried out in the Longxi River catchment, located in the 2008 Wenchuan earthquake hit area. During a heavy rainfall event on August 13, 2010, 34 gully-type debris flows were triggered. In some catchments, no debris flows were triggered even though these catchments were in the vicinity of gullies with triggered debris flows. The formation mechanism of the triggered debris flows is the runoff-induced mechanism. The influence of the topography on the formation of debris flows in gullies with almost identical hydrological and geological conditions was isolated and analyzed. A new T-factor is proposed in this study as a topographical indicator which is a combination of the form factor, the average gradient of the stream, the catchment size, and the percentage of the catchment area with a slope gradient sensitive to trigger debris flows. Higher T-factor values are generally related to higher probabilities of debris flow formation. The T-factor can be used to predict the

formation of debris flows in the sub-catchments of the Longchi River catchment. The T-factor was successfully validated in debris flow gullies with the same initiation mechanism in the Cida River catchment, Sichuan, China.

Keywords Topography factor · Longxi River · Wenchuan earthquake · Gully-type debris flow

Introduction

Many debris flows were triggered in the Longxi River catchment, Sichuan Province, China by a rainstorm in 2010. Most of these were gully-type debris flows. The gully-type debris flow causes enormous risks in the world. For example, the debris flows in Venezuela in 1999 causing 15,000 deaths (Lopez et al. 2003), and the debris flows in China in 2010 causing 1,744 casualties (Yu et al. 2010) are all gully-type debris flows. Gully-type debris flows differ from the so-called unconfined “hill slope debris flows” (VanDine 1985). They take place in areas with significant gully topography (Liu et al. 2009). The gully-type debris flows in the study area were triggered by flash floods leading to a runoff-induced effect (Kean et al. 2013), which is caused by the entrainment of material due to a concentrated flow of water, as if the material is washed away by a runoff-induced mechanism (Kean et al. 2013). This kind of mechanism leads to erosion of the sediment in the channel. The mechanistic theories are grouped into two categories (Kean et al. 2013): (1) mass failure of the channel sediment by sliding along a discrete failure plane leading to a sudden large impulse of sediment added to and/or entrained within the water flow; this may occur by the failure of the sediment-filled bed of the channel or by failure of the channel banks caused by channel erosion, and (2) grain by grain

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bulking by hydrodynamic forces: a critical discharge of water creating a debris flow surge by eroding the sediment by hydrodynamic forces from the top down rather than by sliding at a failure plane at a depth of several to many grains below the surface. This study will focus on the analysis of gully-type debris flows by the runoff-induced mechanism.

To mitigate and prevent debris flow hazards and related risks, one must understand the formation process of debris flows to make reliable forecasts. Cannon et al. (2010) identified four groups of variables related to the occurrence of debris flows in burned (by wildfire) basins: topography parameters, degree of burning, soil properties, and rainfall variables. They assume that many topography parameters are of influence on the occurrence of debris flows such as the basin gradient, the percentage of basin area with slopes greater than or equal to 30 %, basin ruggedness, additional measures of gradient, and slope aspect (Cannon et al. 2010).

Liu et al. (2009) stated that there are three groups of factors playing a major role in the formation of ordinary gully-type debris flows. They are related to topography, geology and hydrology. The topographical factors of influence include catchment size, channel length, elevation difference, average terrain slope angle, slope curvature, and a form factor (Lin et al. 2002; Lan et al. 2004; Catani et al. 2005; Chang and Chao 2006; Chang 2007; Lu et al. 2007; Lee and Pradhan 2007; Chang and Chien 2007; Tiranti et al. 2008; Tunusluoglu et al. 2008; Ranjan et al. 2004; Akgun et al. 2008). These factors were obtained by statistical correlation analyses between debris flow occurrences and topographic characteristics. Because of the uniqueness of these characteristics in each area, the correlation structure found in one area is generally not valid for other areas, and these studies show many different factors related to debris flow occurrence. Past research revealed more than 47 factors (including topographic, geological and hydrological factors) related to debris flow development (Lee 2006). It is, therefore, difficult to establish a unique universal relationship between debris flow occurrence and topographic, geological and hydrological characteristics. The present authors assume that the formation of debris flows will be much better predictable when topography, geology, and hydrology are each reduced to one single factor.

By focusing on the process mechanisms, the aim of this study was to find significant and more general relationships between debris flow formation and the topographic factors. The flash floods in large and steep channels were analyzed which cause a runoff-induced effect eroding especially the small grain size sediments (Kean et al. 2013), leading to the formation of debris flows. So, the major topographic factors must be characteristic for steep channels, steep slopes,

large catchment areas, and the development of powerful flash floods. One single topographical factor is proposed in this study to define the role of topography in the formation of debris flows triggered by a runoff-induced mechanism.

The debris flow development in the Longxi River catchment, Sichuan on August 13, 2010

Some gully-type debris flows were triggered in two gullies in the Longxi River catchment already before the Wenchuan earthquake occurred. After the Wenchuan earthquake, in the period between May 12, 2008 and August 13, 2010, 15 gully-type debris flows were triggered in 13 gullies in the same catchment (Shen et al. 2008; Zhang et al. 2010).

On August 13, 2010, heavy rainfall event occurred in the Longxi River catchment: the maximum rainfall recorded in 1 h was 55.8 mm, and the cumulative rainfall was 209.8 mm (see Fig. 1). This rainfall event triggered 34 gully-type debris flows and 11 slope debris flows. The total volume of new debris flow deposits was more than $3.3 \times 10^6 \text{ m}^3$. A large amount of sediments was deposited in the downstream part of Longxi River, with an average deposition thickness of 5 m. Mainly, gully-type debris flows damaged 4,240 m of highway, 3,130 m of levees, and 233 buildings. The economic loss amounted to 550 million Chinese Yuan.

The Longxi River is located near Longchi Town, Sichuan Province, China. It is a tributary of the Minjiang River. The Longxi River with a length of 18.2 km is flowing from North to South and flows into the Zipingpu Reservoir. The catchment size of the Longxi River is 96.8 km^2 . The maximum and minimum altitudes in the catchment are 3,290 and 770 m, respectively. There are 47, mostly small sub-catchments with gully-type debris flow within the Longxi River catchment of which 34 sub-catchments

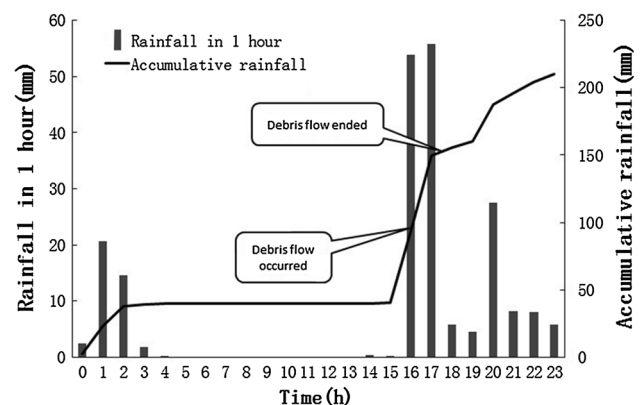


Fig. 1 Hourly and cumulative rainfall in the Longxi River catchment on August 13, 2010

developed a debris flow on August 13, 2010. 33 Sub-catchments have a size of less than 1 km², 10 sub-catchments have a size between 1 and 3 km², 3 sub-catchments have a size between 3 and 4 km², and only 1 sub-catchment has a size larger than 4 km². The sub-catchment with the largest size is 8.55 km². Some of these gullies have tributaries in their upstream part (see Fig. 2; Table 1).

The Longxi River catchment is located in the Wenchuan earthquake hit area, and it is crossed by the triggering Yingxiu–Beichuan Fault (the north branch) of this earthquake. The northern part of the catchment is located at the hanging wall side of the Yingxiu–Beichuan Fault and the southern part is located at the footwall side. The hanging wall side of the fault shows more landslides, rock falls, and debris flows triggered by the Wenchuan earthquake than the footwall side (see Fig. 3b). The northern part of Longxi River catchment consists of granites. Between the north branch and the south branch of the Yingxiu–Beichuan Fault andesites are exposed. Sandstones and mudstones are exposed between the south branch of Yingxiu–Beichuan Fault and the nappe of outlier. In the southern part of Longxi River catchment, the eastern bank consists of sandstones and shales, and the western bank consists of limestones (see Fig. 2).

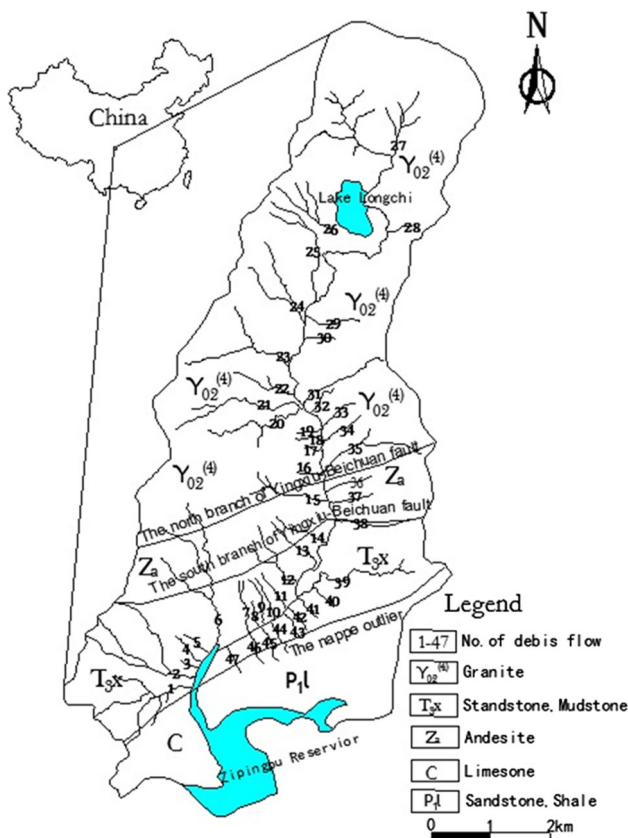


Fig. 2 The catchment of the Longxi River and the distribution of debris flows

Hardly, any landslides and rock falls occurred in the Longxi River catchment before the Wenchuan earthquake in 2008 (see Fig. 3a), which triggered many landslides and rock falls (see Fig. 3b). The images after the debris flows on August 13, 2010 show that there are hardly any new landslides and rock falls triggered by the rainstorms between May 12, 2008 and May 1, 2013 (see Fig. 3c, d). The sediment in the channels produced by landslides and rock falls triggered by the Wenchuan earthquake is the main source of debris flows. So, the sediment in the debris flows was entrained from the channels by flash floods. The mechanism of runoff-induced triggering can explain the occurrence of this kind of debris flows.

Hydrological data are available over a period of 50 years in the Longxi River catchment. The average annual rainfall is 1,134 mm, the maximum daily rainfall is 245 mm, the maximum 1-h rainfall intensity is 83 mm, and the maximum cumulative rainfall is 289 mm in one rainfall event. More than 80 % of the rainfall is concentrated between May and September. Short-duration high-intensity rainfall is the main inducing factor for the development of gully-type debris flows with a runoff-induced mechanism (Chen et al. 2012). The debris flow on August 13, 2010 was triggered on 1600 hours in the afternoon, and ended around 1730 hours. A rainfall station, located in the upstream part of Longxi River catchment showed a cumulative rainfall between 000 and 1500 hours on August 13 of 40.2 mm, while there was almost no rainfall from 300 to 1500 hours. A sudden high-intensity rainfall between 1500 and 1700 hours triggered the debris flows in the Longxi River catchment (see Fig. 1). Huang (2002) suggested the definition that a high-intensity rainfall event ends when: (1) the rainfall intensity is less than 4 mm/h for 6 consecutive hours, or (2) the cumulative rainfall is less than 10 mm in 12 consecutive hours, or (3) the cumulative rainfall is less than 4 mm in 6 consecutive hours. According to all these criteria, the rainfall event triggering the debris flows in Longxi River catchment on August 13, 2010 started at 15:00 pm. That means that the triggering rainfall was a typical short-duration high-intensity rainfall.

The geological and topographical characteristics of 34 sub-catchments with gully-type debris flows, and 13 sub-catchments without debris flows triggered on August 13, 2010 in the Longxi River catchment were obtained from the 1:10,000 topographic map, the 1:200,000 geological map, and field investigations (Table 1).

Methodology

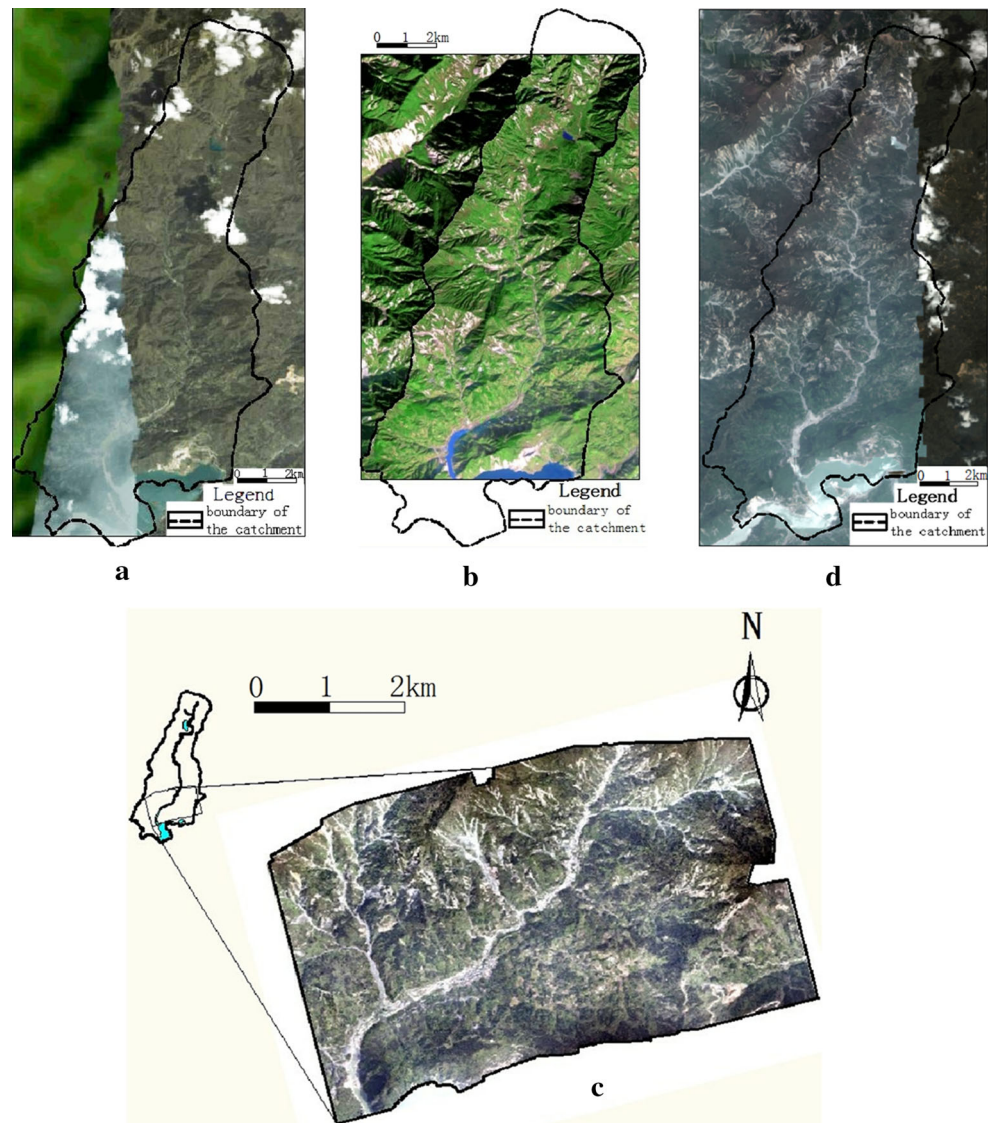
Field investigations in the study area were not possible in the upstream part of some gullies, because many roads were blocked, sometimes even the outlets of the tributaries

Table 1 The geological and topographical characteristics of gullies in the debris flow source areas in the Longxi River catchment

No.	Lithology	Region	A_0 (km ²)	A (km ²)	L (km)	F	J	S	T	D (km)	Debris
1	SM	FW	3.45	0.84	1.47	0.39	0.32	0.76	0.091	3.61	Yes
2	SM	FW	2.76	1.36	2.29	0.26	0.39	0.74	0.08	2.24	Yes
3	SM	FW	0.11	0.07	0.37	0.51	0.51	0.82	0.125	3.07	Yes
4	SM	FW	0.23	0.14	0.49	0.58	0.41	0.8	0.128	2.74	Yes
5	SM	FW	0.08	0.04	0.29	0.47	0.55	0.74	0.1	2.76	Yes
6	Andesite	FW	8.55	5.67	3.72	0.41	0.38	0.79	0.176	0.11	Yes
7	SM	FW	0.3	0.15	0.6	0.42	0.53	0.85	0.13	2.11	Yes
8	SM	FW	0.1	0.05	0.36	0.39	0.56	0.69	0.082	2.27	Yes
9	SM	FW	0.19	0.07	0.45	0.35	0.61	0.7	0.088	2.08	Yes
10	SM	FW	0.25	0.07	0.5	0.28	0.62	0.64	0.066	2.62	No
11	SM	FW	0.14	0.06	0.47	0.27	0.7	0.78	0.084	2.02	Yes
12	Andesite	FW	1.01	0.41	1.28	0.25	0.51	0.79	0.085	0.97	Yes
13	Andesite	FW	0.81	0.36	1.04	0.33	0.63	0.84	0.142	0.73	Yes
14	Andesite	FW	0.39	0.19	0.58	0.56	0.6	0.83	0.202	0.86	Yes
15	Andesite	FW	0.91	0.74	1.41	0.37	0.53	0.85	0.157	0.29	Yes
16	Granite	HW	0.31	0.2	0.7	0.41	0.71	0.84	0.179	0.1	Yes
17	Granite	HW	0.08	0.03	0.36	0.23	0.44	0.61	0.031	0.71	No
18	Granite	HW	0.47	0.38	1.01	0.37	0.6	0.88	0.162	0.53	Yes
19	Granite	HW	0.3	0.25	0.71	0.49	0.43	0.46	0.073	1.09	Yes
20	Granite	HW	2.8	1.5	2.4	0.26	0.48	0.76	0.103	1.37	Yes
21	Granite	HW	2.45	1.27	1.99	0.32	0.47	0.77	0.122	2.45	Yes
22	Granite	HW	0.64	0.42	1.1	0.35	0.67	0.85	0.167	2.5	Yes
23	Granite	HW	2.89	1.29	1.89	0.36	0.47	0.75	0.132	3.45	Yes
24	Granite	HW	2.5	1.21	1.98	0.31	0.53	0.72	0.123	4.63	Yes
25	Granite	HW	1.04	0.28	1.18	0.2	0.63	0.74	0.072	5.88	No
26	Granite	HW	0.99	0.26	1.04	0.24	0.73	0.73	0.098	6.26	Yes
27	Granite	HW	0.76	0.28	1.04	0.26	0.68	0.68	0.093	7.58	Yes
28	Granite	HW	0.17	0.11	0.51	0.42	0.59	0.81	0.129	4.75	Yes
29	Granite	HW	1.34	1.01	1.26	0.64	0.15	0.26	0.026	3.84	No
30	Granite	HW	0.48	0.38	0.83	0.55	0.54	0.7	0.173	2.78	Yes
31	Granite	HW	1.55	1.03	1.72	0.35	0.48	0.66	0.111	2.1	Yes
32	Granite	HW	0.11	0.06	0.37	0.44	0.63	0.77	0.121	1.6	Yes
33	Granite	HW	0.16	0.09	0.53	0.32	0.76	0.72	0.107	1.18	Yes
34	Granite	HW	0.26	0.11	0.52	0.4	0.67	0.68	0.118	0.99	Yes
35	Granite	HW	3.58	1.76	1.98	0.45	0.45	0.82	0.184	0.74	Yes
36	Andesite	FW	0.09	0.04	0.3	0.44	0.67	0.9	0.138	0.47	Yes
37	Andesite	FW	0.4	0.3	0.86	0.41	0.62	0.78	0.154	0.5	Yes
38	Andesite	FW	2.87	0.49	1.24	0.32	0.54	0.73	0.109	0.88	Yes
39	SM	FW	3.68	1.83	2.06	0.43	0.21	0.58	0.06	1.93	No
40	SM	FW	0.28	0.22	0.79	0.35	0.39	0.6	0.061	3.16	No
41	SM	FW	0.42	0.16	0.68	0.35	0.45	0.56	0.061	3.28	No
42	SM	FW	0.29	0.07	0.55	0.23	0.45	0.68	0.042	3.5	No
43	SMS	FW	0.12	0.06	0.45	0.3	0.51	0.63	0.055	3.3	No
44	SMS	FW	0.16	0.1	0.6	0.28	0.5	0.57	0.05	3.51	No
45	SMS	FW	0.28	0.22	0.79	0.35	0.47	0.55	0.066	3.53	No
46	SMS	FW	0.16	0.08	0.53	0.29	0.5	0.51	0.044	3.61	No
47	SMS	FW	0.8	0.34	0.95	0.38	0.43	0.72	0.095	3.81	No

A_0 Area of the whole gully, *SM* sandstone and mudstone, *SMS* sandstone, mudstone, and shale, *FW* footwall, *HW* hanging wall, D distance between formation area and the triggering fault of Wenchuan earthquake

Fig. 3 Landslides and rock falls in the Longxi River catchment. Vegetation shows a *green color* in the image, bare land, landslides, rock falls, debris flows show a *white color*. **a** Before the Wenchuan earthquake on Sep. 19, 2007, Google earth image; **b** just after the Wenchuan earthquake on May 30, 2008, aerial photograph; **c** after the debris flows on April 26, 2011, aerial photograph; **d** after the debris flows on May 1, 2013, Google earth image



could not be reached. So, the presence of debris flows was concluded on the basis of presence of debris flow material at the outlet of those gullies close to the Longxi River. As this study focuses on the role of topography in the formation of debris flows, a series of debris flow events was selected which occurred under more or less identical hydrological (rainfall) and geological conditions. Debris flow catchments situated close to each other may have more or less identical geological characteristics. However, it is difficult to find debris flow gullies which have identical rainfall characteristics during an event, even though they are situated close to each other. The intensely varying relief and the heterogeneous rainfall distribution in mountainous areas result in extreme variation of rainfall intensities over short distances.

Heavy rainfall occurred in the Longxi River catchment on August 13, 2010. The hydrological conditions in the different sub-catchments within short distance were almost

identical during the large rainfall event. Neighboring catchments with similar geological conditions were available and could be selected. Therefore, the only decisive factors for debris flow formation which differ in these sub-catchments must be related to topography.

The debris flows were concentrated along the triggering fault of the earthquake. Table 2 shows the number of gullies with and without debris flows at different distance intervals from the fault. The catchment was divided into six regions according to the distance from the fault in: Hanging wall: less than 1, 1–4, and 4–8 km; Footwall: less than 1, 1–4, and 4–8 km. Due to the relative small size of each region, the rainfall conditions are assumed to be very similar for the sub-catchments. The lithologies are identical, and the distances to the triggering earthquake fault are comparable within each region. Therefore, the rainfall factor and the geological factor have no decisive effect on the triggering or no-triggering of debris flows in each

Table 2 The number of gullies with and without debris flows at different distances from the triggering fault in the six sub-areas

	Distance (km)		
	<1	1–4	4–8
Hanging wall			
Debris flow	8	5	4
No debris flow	1	1	1
Lithology	Granites	Granites	Granites
Footwall			
Debris flow	6	11	–
No debris flow	–	6	4
Lithology	Andesites	SM	SS
Total			
Debris flow	14	16	4
No debris flow	1	7	5

SM sandstone and mudstone, SS sandstone and shale

region can be assumed, so the topography is the dominant factor for the triggering of debris flows in each region.

Generally, the sub-catchment of a debris flow is subdivided into a formation or source area, a transport or passing area, and a deposition area. The topographical factors influence in a different way the processes in these three sections of the catchment. In this study, we focused on the role of topographic factors in the formation (source) area of debris flows. When there are two or more branches in the formation area, only the branch which was assumed to be most sensitive for debris flow triggering was selected.

The major topographic factors which play a role are steep channels, steep slopes, large size of catchment, and the development of large flash floods with the runoff-induced mechanism. Some parameters were selected to quantify these factors, such as: watershed area, channel length, elevation difference, average gradient of stream, form factor, and percentage of the basin area with a slope angle sensitive for the triggering of debris flows. It was concluded that there are four important topography factors related to the development of debris flows with runoff-induced mechanism.

Form factor

The form factor F can be defined as:

$$F = A/L^2 \quad (1)$$

In which A is catchment size (km^2) and L is length of stream (km) in the catchment in the formation (source) area of debris flows.

The form factor is strongly related to the characteristics of the hydrograph: a large form factor produces a larger discharge and flow velocity than a small form factor.

Therefore, under the same conditions, a watershed with a large form factor has a higher likelihood to generate debris flows (Chang 2007).

Average gradient of a stream

The average gradient of a stream is calculated as the elevation difference between the upslope origin of the stream and the outlet of the catchment, divided by the stream length. The stream length is determined by accumulating the length of a series of straight line segments along its flow direction. For more precise calculation of the gradient, the stream can be divided into a number of sections, for each of which the average gradient of the stream is calculated (see Eq. 2). The average gradient J of a stream in the formation (source) area of debris flow can be defined as:

$$J = \frac{\sum (H_{i-1} + H_i)l_i - 2H_0L}{1000L^2} \quad (2)$$

In which H_0 is the elevation of the outlet of the catchment (m); H_i is the elevation at section i (m); l_i is the stream length of the section i (km). The gradient also influences the surface flow discharge and the flow velocity and thus the resulting down slope transport of sediments.

Catchment size

The catchment size is a measure for the amount of debris source material: a large catchment area means that more sediment may be provided by landslides and rock falls. The size of the formation area of the gully also controls the collection of water: a larger catchment area produces a larger discharge and flow velocity than a smaller catchment area.

Percentage of catchment area with steep terrain gradient

The gradient of a slope also plays a very important role in the formation of gully-type debris flows with a runoff-induced mechanism: (1) there are many landslides triggered on slopes of 20° – 40° , which provide abundant sediment as source material for debris flows. If the slope gradient is more than 40° , rock fall will be triggered as source material. Generally, landslides provide more sediment than rock falls, and thus are more sensitively related to debris flow occurrence. (2) More runoff is caused by rainfall on high gradient slopes than on gentle slopes.

The relationship between these four important topography factors, related to the development of debris flows with runoff-induced mechanism, can be studied by comparing the occurrence of debris flows in all sub-catchments.

Therefore, the topographical factor can be studied following the scheme outlined in Fig. 4.

The topographical factors in the study area and the formation of debris flows

Gradient intervals of 20°–40°, 20°–45°, 20°–50°, 25°–40°, 25°–45°, 25°–50°, etc., were selected to compare the sensitivity of the gradients of the slopes in Longxi River catchment. Figure 5 shows the relationship between the size *A* of the source area and the percentage of the source area with slopes of: (a) 20°–40°, (b) 20°–45°, (c) 20°–50°, (d) 25°–40°, (e) 25°–45°, (f) 25°–50°. The gradient range of 25°–50° proves to be the most sensitive for the triggering of debris flows in Fig. 5. The catchments in which no debris flows occurred (with the black triangles and squares) generally have a smaller area percentage (*S*) of slopes between 25° and 50° than the catchments in which debris flows occurred (with open squares and triangles) in Fig. 5f.

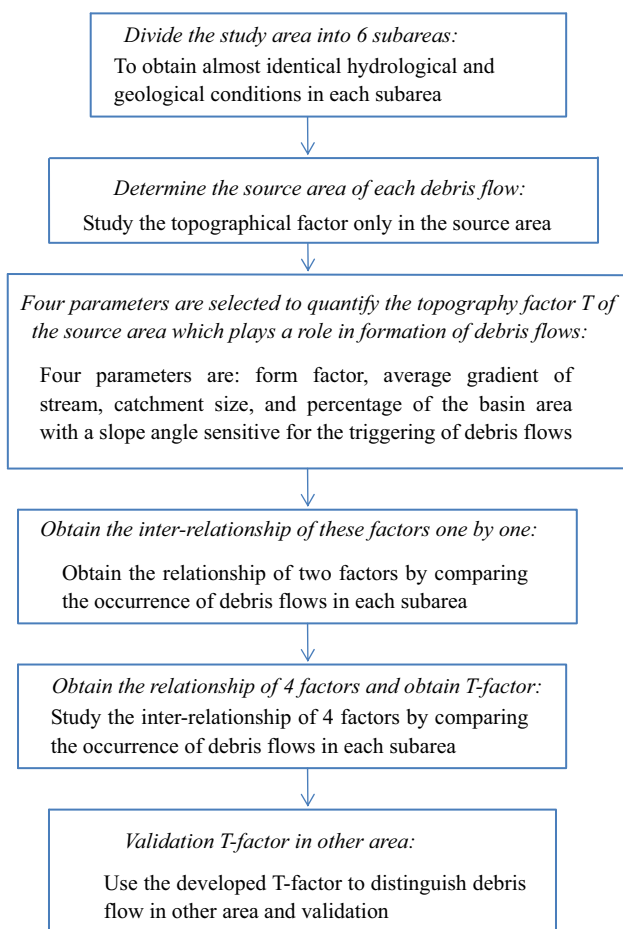


Fig. 4 The flow diagram of study on the topographical factor

Figure 6 shows the relationship of the average stream gradient *J* and the form factor *F* in the source area of the debris flows. The size of the catchments with debris flows is divided into two types: <1 km² for small catchments, and ≥1 km² for large catchments. The steeper the average slope in the source area, the larger is the energy of the flood loaded with sediments. The larger the form factor *F* in the source area, the larger is the discharge of the flood. Figure 6 shows that the factor *FJ* can distinguish between areas with debris flows and areas without debris flows in large catchments (*A* ≥ 1 km²). In the small catchments (*A* < 1 km²), only one point is on the wrong side of the border line between sub-catchments with and without debris flows.

Because the catchment size factor was introduced in Fig. 6, it is necessary to combine the catchment size factor with the form factor and the average slope factor. Figure 7a–d shows the relationships between the catchment size factors and the form factors, and the average slope factor in the source area of the debris flows. Figure 7 is more conclusive than Fig. 6. The larger the catchment area in the source area, the larger is the availability of sediment and the larger is the discharge of the flood. In Fig. 7, the factor $FJ(A/a)^{0.2}$ (*a* is the unit area = 1 km²) separates areas with debris flows from areas without debris flows except for one catchment with debris flow, and two catchments without debris flows (in Fig. 7d). The factor $FJ(A/a)^{0.2}$ is suitable for the separation between catchments with debris flows and catchments without debris flows in these diagrams.

Figure 8a–d shows the relationship between the percentage (expressed as ratio *S*) of the catchment area with slope between 25° and 50° *S* and the factor $FJ(A/a)^{0.2}$. The larger the factor *S*, the larger is the amount of available source sediments, and the larger is the discharge of the flood. So, a new topographical factor *T* can be obtained:

$$T = FJS \left(\frac{A}{a} \right)^{0.2} \tag{3}$$

Figure 8 shows that the factor *T* can distinguish between catchments with debris flows and areas without debris flows except for one catchment. The probability of debris flow formation increases with increasing *T* values.

Validation in other catchments

Also in other parts of Sichuan Province, China many debris flows are triggered every year with a runoff-induced mechanism. Some of them cause enormous damage and many casualties (Yu et al. 2010). On August 24, 2004, heavy rainfall occurred in the Cida River catchment: the maximum 1-h rainfall was around 60 mm, and the

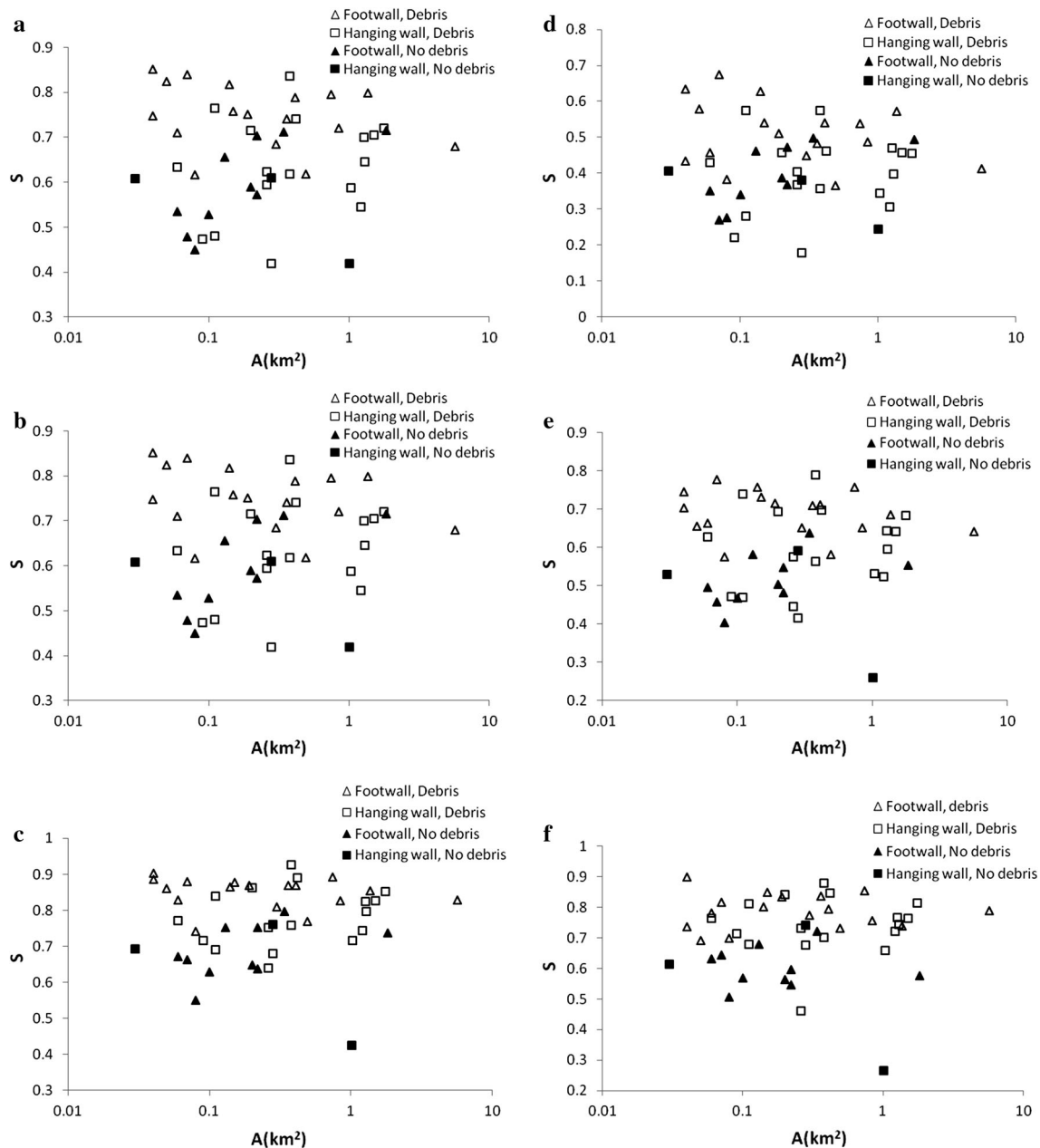


Fig. 5 The relationship between the catchment size and the area percentage (expressed as ratio S) of slopes in six different gradient intervals. **a** 20° – 40° ; **b** 20° – 45° ; **c** 20° – 50° ; **d** 25° – 40° ; **e** 25° – 45° ; **f** 25° – 50°

cumulative rainfall was 173.8 mm. This rainfall triggered 10 gully-type debris flows (Su et al. 2010). The hydrological conditions in these different catchments within short distance of each other were almost identical during the rainfall event.

Figure 9 shows the location of 17 debris flow gullies, 10 of them with presence of debris flows, and 7 of them with absence of debris flows. The triggering mechanism of the debris flows is runoff-induced. The geological and topographical characteristics of the ten catchments with gully-type debris flows, and the seven catchments without debris

flows were obtained from the 1:50,000 topographic map, the 1:200,000 geological map, and field investigations (Table 3).

Figure 10 shows the validation of the T-factor for the debris flow formation in Cida River. There are three thresholds of the T-factor for formation of debris flows, corresponding to the three regions in the Cida River catchment with different geology: 0.059, in the region with dolomite, 0.045 in the region with phyllite, and 0.042 in the region with extremely strong weathered granite. There is no debris flow triggered in the area with siliceous siltstone

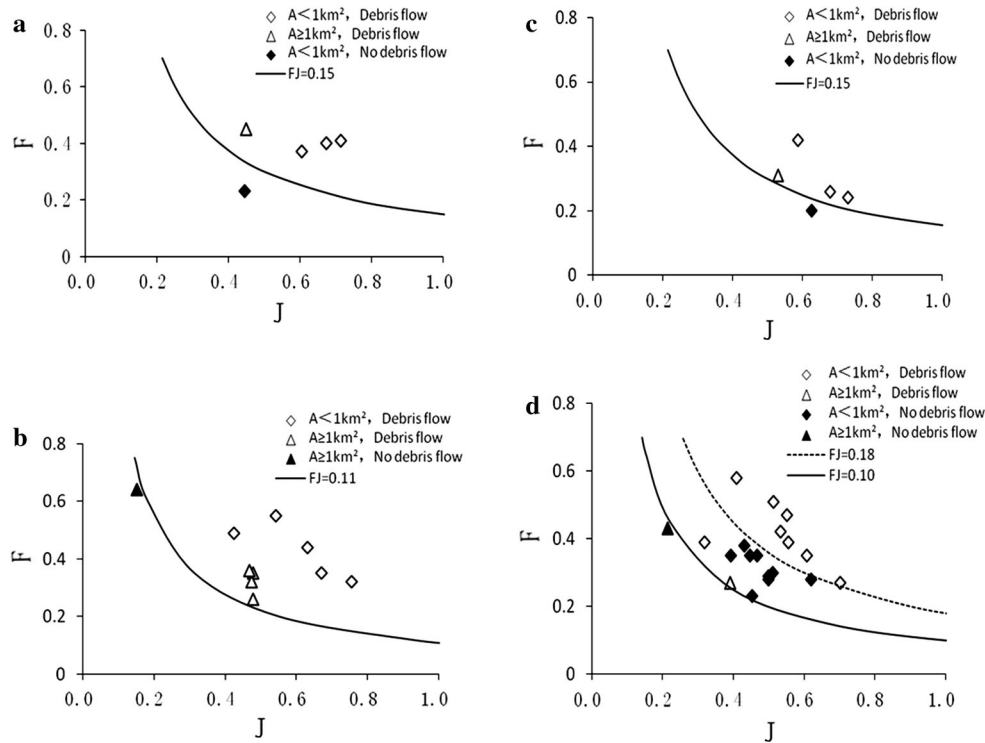


Fig. 6 The relationship between the average slope (J) of stream and the form factor (F) in the source area of the debris flows for four different sub-areas. **a** Hanging wall; granites; $D < 1$ km; **b** hanging

wall; granites; $D = 1-4$ km; **c** hanging wall; granites; $D = 4-8$ km; **d** footwall; sandstones, mudstones, and shales; $D = 1-4$ km

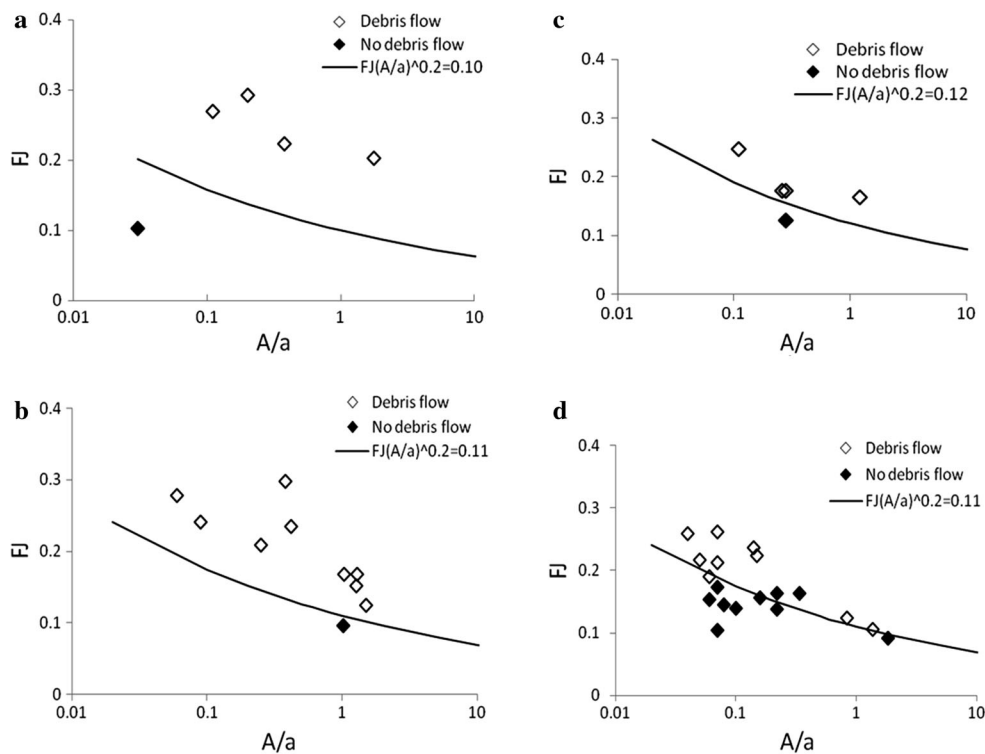


Fig. 7 The relationship between the catchment size A , the form factor F and the average stream gradient J in the source area of debris flows, (a is the unit of area: 1 km^2) in four sub-areas. **a** Hanging wall;

granites; $D < 1$ km; **b** hanging wall; granites; $D = 1-4$ km; **c** hanging wall; granites; $D = 4-8$ km; **d** footwall; sandstones, mudstones, and shales; $D = 1-4$ km

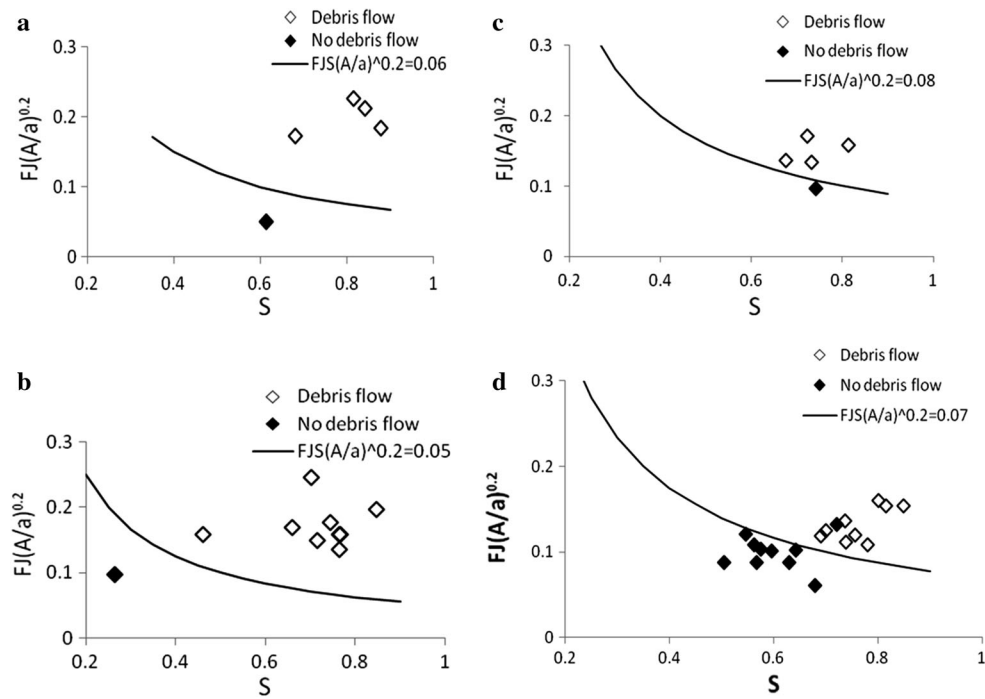


Fig. 8 The relationship between the slope gradient S the form factor F , the average stream gradient, and the size of the catchment area in the source area of debris flows for four sub-areas. **a** Hanging wall;

granites; $D < 1$ km; **b** hanging wall; granites; $D = 1\text{--}4$ km; **c** hanging wall; granites; $D = 4\text{--}8$ km; **d** footwall; sandstones, mudstones, and shales; $D = 1\text{--}4$ km

Fig. 9 The catchment of the Cida River and the location of debris flows

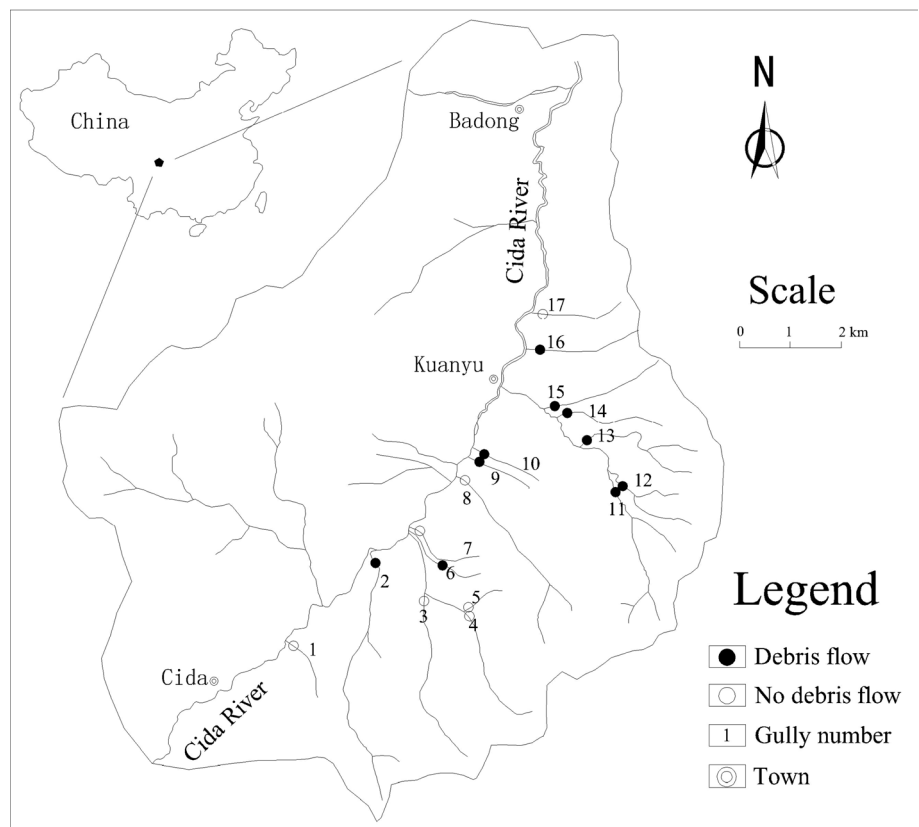


Table 3 The geological and topographical characteristics of gullies in the debris flow source areas in the Cida River catchment

No.	Lithology	A (km ²)	F	J	S	T	Debris flow
1	Dolomite	0.59	0.356	0.403	0.4	0.052	No
2	Dolomite	5.11	0.452	0.241	0.397	0.06	Yes
3	Dolomite	4.68	0.417	0.182	0.409	0.042	No
4	Dolomite	3.25	0.462	0.232	0.434	0.059	No
5	Phyllite	0.38	0.521	0.402	0.394	0.068	No
6	Phyllite	0.26	0.464	0.537	0.593	0.113	Yes
7	SS	0.24	0.53	0.476	0.485	0.092	No
8	Dolomite	2.38	0.317	0.36	0.383	0.052	No
9	Phyllite	0.33	0.344	0.445	0.375	0.046	Yes
10	Phyllite	0.58	0.428	0.382	0.449	0.066	Yes
11	EG	5.01	0.412	0.242	0.401	0.055	Yes
12	EG	1.44	0.387	0.242	0.426	0.043	Yes
13	EG	1.39	0.399	0.261	0.479	0.053	Yes
14	EG	1.33	0.425	0.282	0.474	0.06	Yes
15	EG	0.77	0.501	0.287	0.459	0.063	Yes
16	EG	1.31	0.65	0.26	0.428	0.076	Yes
17	EG	0.41	0.435	0.322	0.359	0.042	No

SS siliceous siltstone, EG extremely strong weathered granite

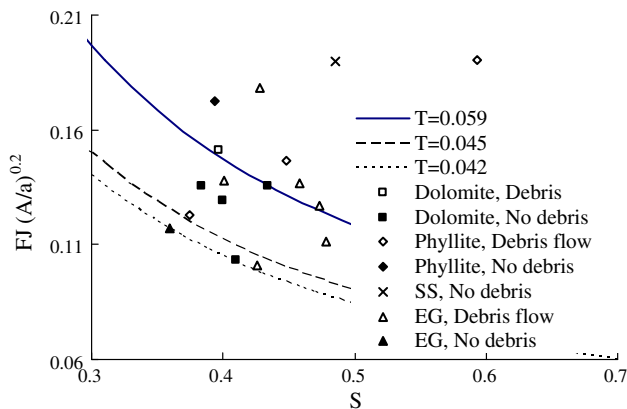


Fig. 10 The relationship between the slope gradient *S* and the form factor *F*, the average stream gradient *J*, and the catchment area size *A* in the source area of debris flows in Cida River catchment, SS siliceous siltstone, EG extremely strong weathered granite

lithology. The thresholds of the T-factor can distinguish the areas with and without debris flows in dolomite, and in extremely strong weathered granite regions. The thresholds of the T-factor can distinguish the areas with and without debris flows except for one catchment in the phyllite region. So, the T-factor can be applied for debris flow prediction both in the Longchi River catchment and in the Cida River catchment which is situated in another region. It may also be a suitable factor in other areas.

Discussion

Landslides, channel bed erosion, and destruction of natural dams are three common causes that trigger debris flows (Takahashi 2000). The debris flows triggered by longer duration and lower peak intensity rainfall may cause landslides first, followed by debris flows. In this study area, only the runoff-induced mechanism (channel bed erosion) is considered as the triggering mechanism of debris flows in the study area. The factor T is not suitable for the other mechanisms of debris flow initiation.

After the Wenchuan earthquake, many gully-type debris flows were triggered in the Longxi River catchment, more than before the Wenchuan earthquake. This is because the Wenchuan earthquake caused many landslides and rock-falls, providing abundant source material for the triggering of debris flows. Furthermore, the Wenchuan earthquake may have loosened the slope materials making them more unstable.

The significance of the T-factor in the formation of debris flows was investigated in the Longxi River catchment by determining the topographical factors in 34 sub-catchments in which debris flows were triggered and 13 sub-catchments without debris flows. Most of the sub-catchments with debris flows are small (<1 km²); the largest catchment is less than 10 km². The position of the sub-catchment with respect to the fault (hanging wall or footwall), and the distance to the triggering fault of the earthquake proved to be influencing factors. Also, the lithology appeared to have some influence, so more research should be done in the future to determine the role of lithology.

There are six sub-areas in the research area. All sub-catchments in the sub-area of Footwall, less than 1 km from the triggering fault show debris flows. No debris flows are present in the sub-area of Footwall in the distance range of 4–8 km from the triggering fault. These two sub-catchments were not used to define the factor T. In the sub-areas at the hanging wall side, there is only one absence of debris flow in each sub-catchment. The results of Figs. 6, 7, 8a–c for the hanging wall area are almost identical: in each sub-area there is only one sub-catchment without debris flows to define *FJ*, or $FJ(A/a)^{0.2}$, and $FJS(A/a)^{0.2}$. These data may be not enough convincing to distinguish debris flows occurrence or not-occurrence with the T-factor. In the sub-area of Footwall, in the distance range of 1–4 km from the triggering fault, there are many data of absence and presence of debris flows. Figure 6d shows a very good difference of absence and presence of debris flow except one data. But these data were from two size classes: (<1 km²) and (>1 km²). This makes it difficult to distinguish debris flow when the area of sub-catchment is approximately 1 km². Figure 7d shows a reasonable good

differentiation of absence and presence of debris flow except for three sub-catchment data (one of presence of debris flow, and two of absence of debris flow). It shows that the combination of form factor F , the average gradient of a stream J and the catchment area A in the formation area gives a better result in Fig. 7, but this is not yet good enough. Figure 8d shows a very good differentiation of absence and presence of debris flow except for one sub-catchment. It shows that the combination (Eq. 3) of form factor F , the average gradient of a stream J , the percentage of catchment area with steep terrain gradient S , and the catchment area A in the source area gives the best result for the distinction between absence and presence of debris flows. F , J , and S are independent factors. The factor F has a sub-factor A (see Eq. 1). This may cause multi-collinearity in Eq. 3. Because the power value of A in Eq. 3 is only 0.2, while the others have a power value of 1, the multi-collinearity is probably not large enough to affect the correctness of Eq. 3.

The rainfall data presented in this paper are from only one rain gauge, so they do not permit to evaluate the spatial distribution of rainfall over the studied sub-catchments. Unfortunately, there were no rainfall data derived from weather radar in the study area. Such data would have permitted to test the assumption that rainfall variations do not influence debris flow triggering in the study area. The rainfall in the study region may be characterized by strong spatial gradients, which result in dramatic differences in rainfall rate, but because most of the catchments are small ($<1 \text{ km}^2$), and the study area was divided into six rather small sub-areas, the differences of rainfall are expected not to have been large enough to affect the assumption that rainfall variations do not influence the likelihood of debris flow triggering between the sub-catchments. A certain error of the T-factor may have been caused by differences of rainfall, which could lead to a limitation of applicability of the T-factor, which would need more validation in the future.

Because the rainfall characteristics were assumed to be almost identical, the occurrence of debris flows was controlled by geological and topographical factors. One can distinguish three parts of the Longxi River catchment showing different distribution patterns of debris flows (see Fig. 2): (1) in the northern part, north of the south branch of the Yingxiu–Beichuan Fault, the number of debris flows along the two banks of the river was almost identical: 12 on the left bank and 10 on the right bank, respectively. (2) in the middle part, between the south branch of the Yingxiu–Beichuan Fault and the nappe outlier, all 12 debris flows were located on the right bank of the river (3) South of the nappe outlier, no debris flow were triggered. The reason for this distribution is: (1) in the northern part, granitic and andesitic rocks are exposed, the area is close to the

triggering fault, and the average slope gradient in these sub-catchments is high; (2) in the middle part, sandstones, mudstones and shales are exposed, the area is close to the triggering fault but in this part of the catchment the average slope gradient is high on the right bank of the river but gentle on the left bank, which explains the high debris flow activity on the right bank and low activity on the left bank. (3) in the southern part of the catchment, sandstones and shales are exposed at the left bank, and limestones at the right bank. The area is situated at a larger distance from the triggering fault and the average slope gradient is higher at the right bank than at the left bank. Because the limestones are not sensitive for triggering debris flows (Zhong et al. 2004), the activity of debris flow development is weak on both sides.

Figure 8 shows that the critical T value generally increases with the distance from the triggering fault. A higher T-factor value is needed in the footwall area than in the hanging wall area to initiate debris flows. The T-factor can be used to predict the triggering of debris flows under uniform geological and rainfall conditions. To compare the occurrence of debris flows between catchments with different geological and rainfall conditions, much more work should be done to find the relationship of the here discussed T-factor and the other predominant factors of influence: geology and rainfall.

The most sensitive range of slope gradient for the occurrence of debris flows with runoff-induced mechanism in the study area is 25° – 50° . This slope range includes almost all the slopes sensitive for the occurrence of landslides (20° – 40°), and part of slopes sensitive for rock fall ($>40^\circ$). This slope range also produces high runoff rates during rainfall. However, the sensitive gradients of slopes in other areas may be different because of the unique geological environment of the Longxi River catchment: (1) the study area is situated in the area hit by the strong Wenchuan earthquake, with a local seismic intensity of XI. The triggering fault of the Wenchuan earthquake crosses the Longxi River and divides the catchment into two parts: the hanging wall part and the footwall part. (2) Most debris flows were triggered in the northern part of the catchment with hard rock: granites and andsites. The gradient of the slopes in this area is larger than in areas with softer rock. Most of the catchments without debris flows in the southern part of the catchment are exposed to soft rock: sandstones, mudstones, and shales, with more gentle slope gradients. Debris flows are developed in gullies with large slope gradient, while gullies without debris flows have a lower slope gradient. More work should be conducted in the future to determine in detail the role of the slope gradient.

To confirm that the T-factor plays an important role in the formation of debris flows, more work should be done

in: (1) larger catchments with sizes in the range of 10–100 km²; (2) other catchments which were not influenced by earthquakes, and with different geological setting. Such catchments must have a large record of rainfall events which triggered many debris flows.

The geological and hydrological information used in this paper may contain errors due to the scale of the available geological map and the lack of detailed rainfall data in the study area. More detailed work with a larger scale geological map and more detailed rainfall data such as rainfall data derived from weather radar should be conducted in the future.

Conclusions

The large number of debris flow events in the Longxi River catchment, Dujiangyan, Sichuan, China due to a large rainfall event in August 2010 provided a good opportunity to study the influence of topographical factors on the triggering of debris flows by the runoff-induced mechanism. The rainfall conditions in the studied sub-catchments were roughly identical during this large rainfall event, and a number of groups of neighboring catchments with identical geological conditions could be selected. In this way, the effect of the topographical factors could be isolated and analyzed.

A new factor T is proposed as a single topographical indicator, which may be used as a threshold for the formation of gully-type debris flows. If further studies confirm that it can be applied with success in other areas, it will be helpful to understand the formation of debris flows with runoff-induced mechanism.

The following conclusions can be drawn from our study:

1. The major topographic factors related with the development of debris flows are the catchment form factor, the gradient of the stream channels, the size of the catchments. The topographical factor T is a combination of these three factors and the area percentage of the catchment of terrain slopes between 25° and 50°.
2. The threshold for initiation of debris flow in the form of the T -factor is also controlled by the local geological factor and the rainfall factor, which still have to be defined. When all three factors are known, one could predict by combination of them the conditions for the occurrence of debris flows.
3. The probability of debris flow formation caused by the runoff-induced mechanism increases with increasing T values.

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References

- Akgun A, Dag S, Bulut F (2008) Landslide susceptibility mapping for a landslide-prone area (Findikli, NE of Turkey) by likelihood-frequency ratio and weighted linear combination models. *Environ Geol* 54:1127–1143
- Cannon SH, Gartner JE, Rupert MG, Michael JA, Rea AH, Parrett C (2010) Predicting the probability and volume of postwildfire debris flows in the intermountain western United States. *Geol Soc Am Bull* 122:127–144
- Catani F, Casagli N, Ermini L, Righini G, Menduni G (2005) Landslide hazard and risk mapping at catchment scale in the Arno River basin. *Landslides* 2:329–342
- Chang TC (2007) Risk degree of debris flow applying neural networks. *Nat Hazards* 42:209–224
- Chang TC, Chao RJ (2006) Application of back-propagation networks in debris flow prediction. *Eng Geol* 85:270–280
- Chang TC, Chien YH (2007) The application of genetic algorithm in debris flows prediction. *Environ Geol* 53:339–347
- Chen SC, Chen S, Wu CH (2012) The characteristic of the landslides in Shenmu watershed in Nantou County. *J Chin Soil Water Conserv* 43:214–226 (in Chinese with English abstract)
- Huang YT (2002) Characteristics of rains triggering debris flows in the Watershed of Chenyoulan Stream. Dissertation, National Cheng Kung University (Tainan)
- Kean JW, McCoy SW, Tucker GE, Staley DM, Coe JA (2013) Runoff-generated debris flows: observations and modeling of surge initiation, magnitude, and frequency. *J Geophys Res Earth Surf* 118:2190–2207
- Lan HX, Zhou CH, Wang LJ, Zhang HY, Li RH (2004) Landslide hazard spatial analysis and prediction using GIS in the Xiaojiang watershed, Yunnan, China. *Eng Geol* 76:109–128
- Lee MH (2006) A rainfall-based debris-flow warning analysis and its application. Dissertation, National Cheng Kung University (Tainan)
- Lee S, Pradhan B (2007) Landslide hazard mapping at Selangor, Malaysia using frequency ratio and logistic regression models. *Landslides* 4:33–41
- Lin JY, Hung JC, Yang MD (2002) Assessing debris-flow hazard in a watershed in Taiwan. *Eng Geol* 66:295–313
- Liu C, Dong J, Peng Y, Huang H (2009) Effects of strong ground motion on the susceptibility of gully type debris flows. *Eng Geol* 104:241–253
- Lopez JL, Perez D, Garcia R (2003) Hydrologic and geomorphologic evaluation of the 1999 debris flow event in Venezuela. In: Rickenmann D, Chen C (eds) *Debris flow hazards mitigation: mechanics, prediction, and assessment*. Millpress, Rotterdam, pp 1073–1083
- Lu GY, Chiu LS, Wong DW (2007) Vulnerability assessment of rainfall-induced debris flows in Taiwan. *Nat Hazards* 43:223–244
- Ranjan KD, Shuichi H, Atsuko N, Minoru Y, Takuro M, Katsuhiko N (2004) GIS-based weights-of-evidence modelling of rainfall-induced landslides in small catchments for landslide susceptibility mapping. *Environ Geol* 54:311–324

- Shen J, Zhu R, Liu W (2008) Possibility geological analysis of Gangou debris flow in Longchi Town in Dujiangyan induced by the earthquake of May 12 in Wenchuan. *J Mt Sci* 26:513–517 (in Chinese with English abstract)
- Su P, Wei F, Gu L, Ni H (2010) Characteristic and causes of group-occurring debris flow in Dechang County, Sichuan Province. *J Mt Sci* 28:593–606 (in Chinese with English abstract)
- Takahashi T (2000) Initiation and flow of various types of debris flow. In: Wieczorek GF, Naeser ND (eds) *Debris-flows hazard mitigation: mechanics prediction and assessment*. Balkema, Rotterdam, pp 15–25
- Tiranti D, Bonetto S, Mandrone G (2008) Quantitative basin characterisation to refine debris-flow triggering criteria and processes: an example from the Italian Western Alps. *Landslides* 5:45–57
- Tunusluoglu MC, Gokceoglu C, Nefeslioglu HA, Sonmez H (2008) Extraction of potential debris source areas by logistic regression technique: a case study from Barla, Besparmak and Kapi mountains (NW Taurids, Turkey). *Environ Geol* 54:9–22
- VanDine DF (1985) Debris flow and debris torrents in the Southern Canadian Cordillera. *Can Geotech J* 22:44–68
- Yu B, Yang Y, Su Y, Huang W, Wang G (2010) Research on the giant debris flow hazards in Zhouqu County, Gansu Province on August 7, 2010. *J Eng Geol* 18:437–444 (in Chinese with English abstract)
- Zhang Z, Zhang Z, Zhang S (2010) Formation conditions and dynamics features of the debris flow in Bayi Gully in Dujiangyan County. *Chin J Geol Hazard Control* 21:34–38 (in Chinese with English abstract)
- Zhong D, Xie H, Wang S (2004) *Debris flow in Beijing mountains*. Business Press, Beijing (in Chinese)