

A 10-min rainfall prediction model for debris flows triggered by a runoff induced mechanism

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Abstract Debris flows are triggered every year in the Jiangjia Gully, Yunnan Province, China. High-intensity short duration rainfall was the main triggering factor for these gully type debris flows which are triggered by a runoff induced mechanism. The 10-min rainfall intensity is considered as the trigger. A revised prediction model with factors related to hydrology (rainfall) is introduced for this kind of gully type debris flows and applied to the Jiangjia Gully. A 10-min rainfall coefficient intensity is proposed based on the observational data of Jiangjia Gully, and a minimum 10-min rainfall intensity for triggering debris flow is presented. The Jiangjia data were used also to assess critical boundaries between three probability classes of debris flow initiation. The model was successfully validated in debris flow gullies with the same initiation mechanism in other areas of southwest China. The generic character of the model is explained by the fact that its factors are partly based on the initiation mechanisms and not only on the statistical analyses of a unique variety of local factors. The research provides a new way to predict the occurrence of debris flows initiated by a runoff induced mechanism.

Keywords 10-min rainfall intensity · Prediction model · Debris flow · Runoff mechanism

Introduction

The gully-type debris flows are dangerous and cause enormous risks (Yu et al. 2013). This category of debris flows occurs in areas with significant gully topography (Liu et al. 2009). Since 1960, debris flows were observed year after year in the Jiangjia Gully in the Yunnan Province, China (Wu et al. 1990). These gully-type debris flows were triggered by flash floods, which are generated by runoff from low-permeability surfaces during rain storms. At a critical discharge, loose sediments are mobilized, which can transform into a debris flow (Kean et al. 2013). The initiation of a debris flow by a runoff effect can be facilitated by the accumulation in very steep channels of abundant solid materials from old landslides, soil, talus, or dumped material deposits. High-speed water flows, generated during unusually intense rainstorms, can generate an extra shear force along the steep debris surface. In addition to the component of the driving force induced by the weight of the sediment, the material may destabilize and may initiate a debris flow (Johnson and Rodine 1984).

To mitigate and prevent hazards induced by debris flows and related risks, one must understand the formation of these to make reliable forecasts. Yu et al. (2013) introduced a formation model for gully type debris flows for the Chenyoutan River Watershed with factors related to topography, geology, and rainfall. Their model consists of three critical values to make four probability classes of debris flow occurrence. Yu et al. (2014) developed a prediction model for runoff induced debris flows using 1-h rainfall intensities for the hydrological factor because no other data were available. The model was successfully validated in debris flow gullies with the same initiation mechanism in other areas of southwest China. However, Yu et al. (2014) pointed out that 10-min rainfall intensities

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should be used in the prediction model to get better results of the prediction of debris flows with a runoff induced mechanism.

Kean et al. (2011) pointed that the post-fire debris flow stage was best cross correlated with time series of 5-min rainfall intensity, and lagged the rainfall by an average of just 5 min. Kean et al. (2013) described debris flow surge characteristics at Chalk Cliffs during events with low, intermediate, and high peak 5-min rainfall intensity. They found that the short-duration rainfall intensity is very important in the triggering of debris flows. Wu et al. (1990) indicated that the 10-min rainfall intensity is strongly correlated with the triggering of runoff induced debris flows. Also Zhang and Liu (1989) discovered that the 10-min rainfall intensity had a good relationship with the triggering of debris flows in the Hunshui Gully, (Yunnan, China). Tan and Yang (1984) pointed that the triggering of debris flows in Yaan (Sichuan, China) could be related to a combination of the 1-h and 10-min rainfall intensity. Gao and Qi (1997) indicated that the debris flows were triggered during small, intermediate, and large accumulations of rainfall in the Macao Gully (Gansu Province, China), but the key triggering threshold was the 10-min rainfall intensity. LIGC and TSIG (1982) related the triggering of debris flows in the Liuwan Gully (Gansu Province, China) with the cumulative rainfall and 10-min rainfall intensity and found a better correlation with the 10-min rainfall intensity. Tan (1989) compared the degree of correlation of the cumulative rainfall, the 1-h rainfall intensity, and the 10-min rainfall intensity with the triggering of 250 debris flows in 35 gullies in the southwest of China. He pointed out that the 1-h rainfall intensity has the same importance as the 10-min rainfall intensity in triggering debris flows. Yu (2011) used 10-min rainfall intensity to estimate run-off discharge, and could predict the occurrence of debris flows in the Jiangjia Gully (Yunnan, China).

One can conclude that the above presented prediction models for the triggering of debris flows with a runoff induced mechanism are mainly based on a relationship with the 10-min rainfall intensity. However, these empirical models, which are based only on local rainfall data cannot be used for prediction in other regions because other factors related to topography and geology were not considered. Yu et al. (2014) presented a more generic prediction model where the selected factors related to hydrology, catchment morphology, geology, and materials are based on the initiation mechanisms of these rainfall induced debris flows. However, they were not able to include in their model the 10-min rainfall intensity, which seems to give the best meteorological relationship with the triggering of debris flows.

Therefore in this study, a revised prediction model with a refined 10-min rainfall intensity is introduced for run-off

induced debris flows. The revised model will be calibrated on debris flows, which occurred from 1978 to 1984 in the Jiangjia Gully. The generic character of the model, including topographical and geological factors, was tested through validation on debris flows, which were triggered in other regions in southwest China.

Description of the debris flows in Jiangjia Gully

The Jiangjia Gully is located in Yunnan Province, China (Fig. 1). Since 1960, debris flows occurred year after year in the Jiangjia Gully, with an average temporal frequency of 12 times/year. The debris flows in the Jiangjia Gully are triggered by a runoff mechanism (Yu 2011). The catchment of the Jiangjia Gully has an area of 32.6 km² (upstream of the observation site, which is about 3 km downstream of the junction of the two tributaries), and consists of two tributaries: the Duozhao Gully and the Menqian Gully. The catchment has an east–west orientation and is a tributary of the Xiaojiang River, a main branch of the Jingsha River. The lowest altitude in the Jiangjia Gully is 1300 m and the highest peaks in the catchment have an altitude 3500 m. The inclination angle of the channel (where debris flows are initiated) is more than 10°. Rainstorms always produce large volumes of run-off and large flood discharges.

Sandstones and slates are major lithological units in the Jiangjia Gully. They are exposed in the source area and transport area and these units cover about 80 % of total catchment area. Dolomites lying discordant on the sandstone and slate layers form the other lithological unit. They are exposed in the source area. The area of the Jiangjia Gully is part of an old intricate tectonic system,

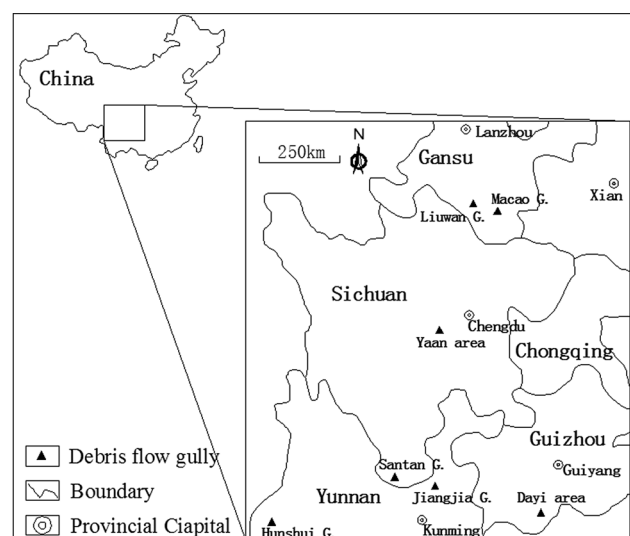


Fig. 1 Distribution of seven series of debris flow gullies in Southwest of China

characterized by intense geotectonic and frequent seismic activity. Due to tectonism and seismic activity, the rocks have been folded and faulted as well as strongly sheared. The Jiangjia Gully is located along the well-known Great Xiaojiang Fault. It is accompanied by two other faults and a number of secondary faults crossing the lithological units in the catchment, which caused over a wide area a severe cracking of the rocks. (Wu et al. 1990). The statistics of historical earthquakes give the study area a general seismic intensity of IX (NSBC 1990). The vegetative cover is bad (or sparse) in the source area of Jiangjia Gully (Wu et al. 1990).

The rainfall in the upper reaches of the Jiangjia Gully strongly differs between the dry and wet season. Intensive rainstorms are concentrated in the wet season in the rainy summer months of June, July, and August (Wu et al. 1990). The center of the rain storms is most of the times located in the upstream part of the catchment at altitudes between 2400 and 3300 m, which is the source area of the debris flows. The average annual rainfall in the source area is obtained from two nearby rainfall stations: the Yinmin station, located at an altitude of 2410 m with an average annual rainfall of 1130 mm, and the Luoxue station, at an altitude of 3228 m with an average annual rainfall of 1159.4 mm (Du et al. 1987). The mean of these two values (1144.7 mm) is considered as the average annual rainfall in the formation area of the Jiangjia Gully.

The rainfall data was collected together with the debris flow events in the two tributaries: the Duo Zhao Gully and the Menqian Gully from 1978 to 1984 (Wu et al. 1990). The observation site for debris flows is located in the middle part of the catchment, downstream of the junction of the Duo Zhao Gully and the Menqian Gully. This means that nobody could decide whether a debris flow originated from the Duo Zhao or the Menqian tributary or from both. The collected rainfall data include the cumulative precipitation until the start of the debris flow and the amount of rainfall in the 10 min before the start of the debris flow, from one of these two tributaries. The rainfall data for 58 rainfall events with debris flows and 18 large rainfall events without debris flow are given in Table 1.

The prediction factors of debris flows with a runoff induced mechanism

The basic ideas behind the three prediction factors used in this study are the same as those in Yu et al. (2014), but there are, as explained above, some refinements of the rainfall factors.

The topographic factor

Yu et al. (2011, 2013, 2014) obtained a dimensionless topographic factor describing the role of topography in the formation of debris flows with a runoff induced mechanism (Eq. 1):

$$T = FJ \left(\frac{A}{A_0} \right)^{0.2} = J \left(\frac{A}{L^2} \right) \left(\frac{A}{A_0} \right)^{0.2} \tag{1}$$

in which *T* is the dimensionless topographic factor of the source (formation) section of the gully where the debris flows are initiated; *F* ($=A/L^2$) is the form factor with *A*: the area (km²) and *L* (km): the length of the channel in the source section. *J* is the average slope gradient of the channel in the source section; *A*₀ is the unit area of the gully in the source section ($=1 \text{ km}^2$).

The stream length is determined by accumulating the length of a series of straight line segments along its flow direction. The form factor is calculated as the ratio between the area of the formation section and the square of the stream length in the formation section. The form factor is highly related to the distribution of the hydrograph: a larger form factor produces a larger discharge and velocity than a smaller form factor. Therefore, under the same conditions, a watershed area with a large form factor has a higher likelihood to generate debris flows (Chang 2007). The average slope of a stream is calculated as the elevation difference between the upslope end of the stream and the outlet of the section, divided by the stream length. These parameters also influence the surface flow discharge and the flow velocity and thus the resulting down slope movement of sediments.

The topographic factors were calculated using a 1:50,000 topographic map. The values of the area of the source section *A*, the form factor *F*, the length of the channel in the source section *L*, the average slope gradient of channel in the source section *J* for the Duo Zhao Gully are 13.9 km², 0.515, 5.2 km, 0.279, respectively. The values of *A*, *F*, *L*, *J* for the Menqian Gully are 10.42 km², 0.636, 4.05 km, 0.292, respectively. So the values of the topographic factor *T* for the Duo Zhao Gully and the Menqian Gully are 0.297, and 0.244, respectively.

The geological factor

Yu et al. (2014) obtained a dimensionless geologic factor to represent the role of geology in the formation of debris flows triggered by flash floods in channels. The geological factor contains a firmness coefficient (*F*₀) for the lithology and some correction coefficients:

$$G = F_0 C_1 C_2 C_3 C_4 \tag{2}$$

Table 1 Parametric values related to rainfall factors and the presence of debris flows in gullies in the Jiangjia G., Hunshui G., Santan G., Liuwan G., and Macao G.

No.	Name	<i>B</i> (mm)	<i>I</i> ₁₀ (mm)	Debris	No.	Name	<i>B</i> (mm)	<i>I</i> ₁₀ (mm)	Debris	No.	Name	<i>B</i> (mm)	<i>I</i> ₁₀ (mm)	Debris
1	Jiangjia	14.9	4.9	Yes	63	Jiangjia	17.3	1.3	No	125	Hunshui	81.5	7.8	Yes
2	Jiangjia	31.75	3.75	Yes	64	Jiangjia	24.6	2.6	No	126	Hunshui	89.5	12.2	Yes
3	Jiangjia	38.9	2.9	Yes	65	Jiangjia	29	3	No	127	Hunshui	85	12.8	Yes
4	Jiangjia	54.3	1.3	Yes	66	Jiangjia	28.5	2.5	No	128	Santan	28.5	8.4	Yes
5	Jiangjia	54.8	0.8	Yes	67	Jiangjia	34.4	2.4	No	129	Santan	29	9.5	Yes
6	Jiangjia	61.7	0.7	Yes	68	Jiangjia	36.3	2.3	No	130	Santan	35	10.5	Yes
7	Jiangjia	39.9	2.9	Yes	69	Jiangjia	43.6	1.6	No	131	Santan	30.5	10.9	Yes
8	Jiangjia	10.1	8.1	Yes	70	Jiangjia	41	1	No	132	Santan	26	12.1	Yes
9	Jiangjia	10.5	7.5	Yes	71	Jiangjia	22.7	4.7	No	133	Santan	34	12	Yes
10	Jiangjia	16.9	5.9	Yes	72	Jiangjia	19.4	4.4	No	134	Santan	40	11.8	Yes
11	Jiangjia	18	6	Yes	73	Jiangjia	33.6	3.6	No	135	Santan	41	11.8	Yes
12	Jiangjia	18.5	5.5	Yes	74	Jiangjia	32.2	3.2	No	136	Santan	42.5	11.1	Yes
13	Jiangjia	23.9	6.9	Yes	75	Jiangjia	51.2	1.2	No	137	Santan	7.5	0.3	No
14	Jiangjia	23.1	6.1	Yes	76	Jiangjia	47.1	1.1	No	138	Santan	10	0.8	No
15	Jiangjia	26.2	6.2	Yes	77	Hunshui	53	3	Yes	139	Santan	11	0.7	No
16	Jiangjia	34	9	Yes	78	Hunshui	54	4	Yes	140	Santan	8.5	2.7	No
17	Jiangjia	33.6	6.6	Yes	79	Hunshui	56	6	Yes	141	Santan	14.5	2.9	No
18	Jiangjia	35	6	Yes	80	Hunshui	57.5	2.9	Yes	142	Santan	17	3.5	No
19	Jiangjia	34.1	4.1	Yes	81	Hunshui	60	4.3	Yes	143	Santan	15	3.9	No
20	Jiangjia	40.1	4.1	Yes	82	Hunshui	63.5	2.5	Yes	144	Santan	11.5	3.5	No
21	Jiangjia	45.2	5.2	Yes	83	Hunshui	65.5	6.7	Yes	145	Santan	9	3.8	No
22	Jiangjia	50	6	Yes	84	Hunshui	67	14	Yes	146	Santan	7	3.5	No
23	Jiangjia	48.2	5.2	Yes	85	Hunshui	74	5	Yes	147	Santan	14.5	5	No
24	Jiangjia	52.7	4.7	Yes	86	Hunshui	76	5.8	Yes	148	Santan	10	5.6	No
25	Jiangjia	58.5	3.5	Yes	87	Hunshui	76.5	4.3	Yes	149	Santan	9	5.3	No
26	Jiangjia	59.9	2.9	Yes	88	Hunshui	86.5	2.5	Yes	150	Santan	7	5.5	No
27	Jiangjia	20.4	5.4	Yes	89	Hunshui	90	2.8	Yes	151	Santan	6	5.9	No
28	Jiangjia	49	3	Yes	90	Hunshui	89.5	3.6	Yes	152	Santan	8	6.2	No
29	Jiangjia	29.1	7.1	Yes	91	Hunshui	90	4.9	Yes	153	Santan	14.5	6.2	No
30	Jiangjia	57.6	1.6	Yes	92	Hunshui	90	6.7	Yes	154	Santan	16.5	6.1	No
31	Jiangjia	24.8	4.8	Yes	93	Hunshui	90	8.1	Yes	155	Santan	26.5	5.4	No
32	Jiangjia	30.3	5.3	Yes	94	Hunshui	90	8.9	Yes	156	Santan	33	5.8	No
33	Jiangjia	23.9	4.5	Yes	95	Hunshui	35	5	Yes	157	Santan	31.5	6.9	No
34	Jiangjia	25.3	3.5	Yes	96	Hunshui	46.5	8.1	Yes	158	Santan	30.5	7.3	No
35	Jiangjia	26.8	4.9	Yes	97	Hunshui	46	9.6	Yes	159	Santan	26	8	No
36	Jiangjia	24.1	3.6	Yes	98	Hunshui	48	7.2	Yes	160	Santan	24	7	No
37	Jiangjia	53.5	2.2	Yes	99	Hunshui	50	4.9	Yes	161	Santan	14	8.9	No
38	Jiangjia	24	5.8	Yes	100	Hunshui	53	4.5	Yes	162	Santan	9	9	No
39	Jiangjia	40.1	8	Yes	101	Hunshui	50.5	8	Yes	163	Santan	9.5	9.5	No
40	Jiangjia	41.9	2.1	Yes	102	Hunshui	54	7.6	Yes	164	Santan	9.5	9.5	No
41	Jiangjia	32.5	3.9	Yes	103	Hunshui	56	5.8	Yes	165	Santan	10	10	No
42	Jiangjia	5.6	2.6	Yes	104	Hunshui	60	3.5	Yes	166	Santan	10.2	10.2	No
43	Jiangjia	26.9	7.3	Yes	105	Hunshui	62.5	5.5	Yes	167	Santan	11	11	No
44	Jiangjia	36.5	3.4	Yes	106	Hunshui	62	6.1	Yes	168	Liuwan	13.3	4.2	Yes
45	Jiangjia	25.2	6.8	Yes	107	Hunshui	67.5	3.3	Yes	169	Liuwan	3.45	2.3	Yes
46	Jiangjia	28.6	5.6	Yes	108	Hunshui	75	4	Yes	170	Liuwan	3.2	0.6	Yes
47	Jiangjia	48.6	1.5	Yes	109	Hunshui	77	5.2	Yes	171	Liuwan	3	2	Yes

Table 1 continued

No.	Name	<i>B</i> (mm)	<i>I</i> ₁₀ (mm)	Debris	No.	Name	<i>B</i> (mm)	<i>I</i> ₁₀ (mm)	Debris	No.	Name	<i>B</i> (mm)	<i>I</i> ₁₀ (mm)	Debris
48	Jiangjia	22.7	8.5	Yes	110	Hunshui	77	8.2	Yes	172	Liuwan	4.35	2.9	Yes
49	Jiangjia	26.2	3.5	Yes	111	Hunshui	83	3.3	Yes	173	Liuwan	8.9	4	Yes
50	Jiangjia	33.9	2.2	Yes	112	Hunshui	90	4.5	Yes	174	Liuwan	15.5	0.7	Yes
51	Jiangjia	43.9	2.9	Yes	113	Hunshui	89	9.3	Yes	175	Liuwan	21.6	0.8	Yes
52	Jiangjia	23.5	4	Yes	114	Hunshui	67.5	2.8	Yes	176	Liuwan	34.4	2	Yes
53	Jiangjia	20.9	3.9	Yes	115	Hunshui	32	4.4	Yes	177	Liuwan	5.5	5.5	Yes
54	Jiangjia	45.4	1.9	Yes	116	Hunshui	36	4	Yes	178	Liuwan	2.1	1.4	Yes
55	Jiangjia	14.3	2.8	Yes	117	Hunshui	47.5	3.2	Yes	179	Liuwan	1.35	0.9	Yes
56	Jiangjia	16.4	4.4	Yes	118	Hunshui	52	4	Yes	180	Liuwan	4.2	2.2	Yes
57	Jiangjia	30.9	2.9	Yes	119	Hunshui	60	2.6	Yes	181	Macao	23	23	Yes
58	Jiangjia	44.6	1.6	Yes	120	Hunshui	63.5	3.8	Yes	182	Macao	21.8	5.8	Yes
59	Jiangjia	12.3	5.3	No	121	Hunshui	66	3.6	Yes	183	Macao	11	1	Yes
60	Jiangjia	17	4	No	122	Hunshui	68	8.2	Yes	184	Macao	2.5	2.5	Yes
61	Jiangjia	8.7	1.2	No	123	Hunshui	67.5	9.5	Yes	185	Macao	20.9	0.9	No
62	Jiangjia	8.7	4.3	No	124	Hunshui	82	2.8	Yes					

B cumulative rainfall before the triggering of the debris flows, *I*₁₀ the 10-min rainfall

in which *G* is the dimensionless geologic factor; *F*₀ is the average firmness coefficient of the lithology in the source section of the gully; *C*₁ is a correction coefficient for seismic intensity in the source section of the gully; *C*₂ is a correction coefficient for tectonics (faults); *C*₃ is the correction coefficient for physical weathering; *C*₄ is the correction coefficient for chemical weathering (Yu et al. 2014).

The average firmness coefficient for lithology *F*₀ is based on the Protodrakonov coefficient (Protodyakonov 1962) for rock strength (Yu et al. 2014). The harder the rock, the greater the particle size of the solid material, and the longer the accumulation time and thus the more difficult to trigger debris flows. On the other hand, soft rocks have a larger potential to supply solid source material delivered by landslides. The smaller the particle size of solid materials, the faster the deposition of source material, and the easier debris flows are activated (Yu et al. 2013). The correction coefficients *C*₁, *C*₂, *C*₃, and *C*₄ (see Eq. 2) of, respectively, the seismic intensity, tectonics (faults), physical weathering, and chemical weathering in the formation area of the gullies (Yu et al. 2014). The seismic intensity in the study area is VI, which gives a correction coefficient *C*₁ of 1 (see Table 3 in Yu et al. 2014). The physical weathering scores are based on the data of the average annual rainfall and temperature in the study area, and the figure of the weathering classification with average annual rainfall and temperature are provided by Fookes et al. (1971). The chemical weathering is a second factor which plays a role.

The intensity of the chemical weathering is controlled by the amount of CO₃²⁻ in rocks such as in limestones, dolomites, etc. (Yu et al. 2014). Chemical weathering in limestone leads to the formation of cracks which hampers the formation of surface runoff (Yu et al. 2014). Therefore, the stronger the chemical weathering, the more difficult it is to form runoff-induced debris flows. So the coefficient *C*₄ increases with increasing intensity of chemical weathering (see Yu et al. 2014).

The values of this coefficient for the Jiangjia Gully is *F*₀ = 2 because the three faults crossing the catchment have severely cracked the rocks over a wide area. Therefore these crashed rocks got the same value as extremely weathered granite (Yu et al. 2014). The correction coefficients *C*₁, *C*₂, *C*₃, and *C*₄ (see Eq. 2) of, respectively, the seismic intensity, tectonics (faults), physical weathering, and chemical weathering in the formation area are 0.9, 0.9, 1, and 1, respectively. The resulting final geologic value for Jiangjia Gully is therefore *G* = 1.62.

The rainfall factor

Short-duration high-intensity rainfall is the main triggering factor for the gully type debris flows (Shieh et al. 2009; Wu et al. 1990; Tan and Han 1992). Yu et al. (2014) used the 1-h rainfall intensity and cumulative precipitation in the period before the triggering of the debris flow to describe the critical rainfall index for runoff induced debris flows.

$$R^* = B + KI \tag{3}$$

in which R^* is the critical rainfall index (mm); B is the cumulative precipitation, until the start of the debris flow (mm); I is the amount of rainfall in the hour before the start of the debris flow (mm); K in Eq. 3 (see: Shieh et al. 2009; Wu et al. 1990; Tan and Han 1992) is an indicator for the role of rainfall intensity. Yu et al. (2013, 2014) pointed that the coefficient K is 12.5 for the 1 h prediction model.

Yu et al. (2013) used the annual precipitation to normalize the critical rainfall in the Chenyoulan River Watershed. The normalization is very important because rainfall values vary widely between the different areas. The difference may be reduced by introducing a good normalization. Only annual precipitation is not enough to normalize the rainfall. The coefficient of variation represents the local heterogeneity of rainfall. The larger the coefficient of variation, the more heterogeneous is the rainfall. The coefficient of variation was introduced for the normalization of the rainfall factor by Yu et al. (2014).

Yu et al. (2014) normalized the critical rainfall with the annual precipitation and the coefficient of variation of 10-min rainfall (when available) to obtain the dimensionless rainfall factor R (Eq. 4):

$$R = \frac{R^*}{R_0 C_v} = \frac{B + KI}{R_0 C_v} \quad (4)$$

in which R is the dimensionless rainfall factor; R_0 is the annual precipitation of the site (mm); C_v is the coefficient of variation of 10-min rainfall. In the Jiangjia Gully the coefficient of variation for the 10-min rainfall: $C_v = 0.33$.

In this study, the 1-h rainfall I in Eq. 3 will be replaced by the 10-min rainfall I_{10} . As a consequence, the coefficient K is not the same as in the 1 h prediction model. The coefficient K will be determined with the data of the Jiangjia Gully by distinguishing the presence and absence of debris flows.

Huang (2002) and Lee et al. (2013) 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. The rainfall event ends when any one of these conditions is meeting in this study. Because it is difficult to know the exact time of each debris flow triggered, the cumulative precipitation B and the high intensity rainfall I are determined by the maximum value of the critical rainfall index R^* in the rainfall events (the time of maximum R^* must be before the debris flow triggered). This situation happened only in the determination of rainfall data in the Dayi area. For the rainfall data in the Jiangjia Gully, Hunshui Gully, Santan Gully, Liuwan Gully, Macao Gully, and Yaan area, the cumulative

precipitation B and the high intensity rainfall I are obtained by the references.

The calibration of the 10-min prediction model in the Jiangjia Gully and the validation in some areas of Southwest China

Model calibration in the Jiangjia Gully

Yu et al. (2014) obtained a formation model with data of debris flows with a runoff induced mechanism in the Dayi area for a rainfall storm in 2011. With the refined rainfall factor proposed in this study, a revised prediction model for debris flows is obtained using the data of 1978–1984 in the Jiangjia Gully. The prediction factor P as a function of T (Eq. 1), G (Eq. 2), and R (Eq. 4) is obtained by empirical statistic analyses (Yu et al. 2014) (Eq 5):

$$P = RT^{0.2}/G^{0.5} \geq C_r \quad (5)$$

in which P is the prediction factor expressing the probability of debris flow occurrence; C_r is a critical value marking the limit of a certain probability class for the prediction of debris flows (see: Yu et al. 2014).

To refine the 10-min rainfall prediction model, the coefficient K in Eqs. 3 and 4 must be determined first. Wu et al. (1990) concluded that the coefficient K varies between 8.1 and 10.2 for the debris flows in Jiangjia Gully. Tan (1989) obtained values for the K coefficient between 6.3 and 8.1 for 35 debris flow catchments in southwest China. In this study, the 10-min rainfall and the cumulative rainfall associated with the occurrence of debris flows in the Jiangjia Gully form the basis for determining the coefficient K by distinguishing the presence and absence of debris flows. The cumulative precipitation and the amount of 10-min rainfall before the start of the debris flow in Jiangjia Gully are listed in Table 1. Figure 2 shows a scatter plot of the cumulative precipitation B against the 10-min rainfall I_{10} for all the data between 1978 and 1984 in the Jiangjia Gully. A line was drawn to separate the points with and without debris flows: beyond this line points with debris flows are dominant over points with no debris flows. The line ($R^*_1 = 50$ mm in Fig. 2) has two intersections with longitudinal coordinate (I_{10}) and horizontal ordinate (B), which delivers the value of the coefficient K : $K = B/I_{10} = 8$. The second line ($R^*_2 = 63$ mm in Fig. 2) is parallel with the first line ($K = 8$). Points without debris flows are not present beyond the second line. The value of $K = 8$ is falling in the middle of range of K values found by Wu et al. (1990) and Tan (1989). Almost all (56 out of a total of 58 = 96.6 %) “debris flow points”

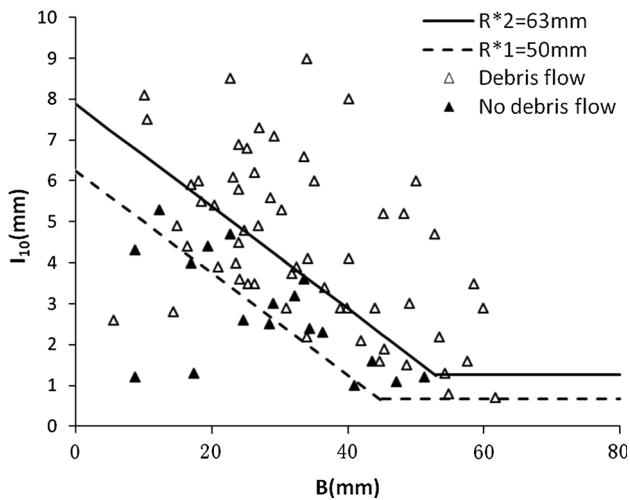


Fig. 2 Scatter plot of B against I_{10} for debris flow from 1978 to 1984 in Jiangjia Gully

lie beyond the critical line $R^*_1 = 50$ mm in Fig. 2 while 63.8 % (37 out of a total of 58) of “debris flow points” lie beyond the line, $R^*_2 = 63$ mm. There is no “no debris flow points” beyond the line, $R^*_2 = 63$ mm. These critical boundaries deliver a subdivision into three classes of the probability of debris flow occurrence. Debris flows are hardly triggered in the area with $R^* < 50$ mm. This area can be considered as a very low probability or safe area. Some debris flows (19 out of a total of 58, 32.8 %) are triggered in the area between $50 \text{ mm} \leq R^* < 63$ mm, which makes this area a medium probability or an alarm area. When $R^* \geq 63$ mm, debris flows are triggered in most rainfall events (37 out of 58, 63.8 %), which makes it a high probability area. In this area people have to be evacuated to safer places.

Therefore the 10-min prediction model can be express as Eq. 5 with the refined rainfall factor (Eq. 6):

$$R = \frac{R^*}{R_0 C_v} = \frac{B + 8I_{10}}{R_0 C_v} \tag{6}$$

in which I_{10} is the amount of rainfall in the 10-min before the start of the debris flow (mm).

There may be a minimum 10-min intensity for the triggering of these run-off induced debris flows. Wu et al. (1990) indicated that the minimum 10-min triggering intensity is 1 mm in the Jiangjia Gully. Zhang and Liu (1989) showed that the minimum 10-min rainfall is 1.8 mm in Hunshui Gully. Gao and Qi (1997) assessed for the Macao Gully a minimum 10-min intensity of 1 mm. A line parallel to the horizontal ordinate was drawn to obtain the first minimum 10-min intensity: below this line, there are no points with debris flows. This line is connected with the line: $R^*_1 = 50$ mm in Fig. 2 and the ratio of R^*_1 to Im_1 (the minimum amount of rainfall in the 10-min intensity) is

75. The second line parallel to the horizontal ordinate was drawn to obtain another minimum 10-min intensity: below this line, there are almost no points with debris flow. This line is connected with the line: $R^*_2 = 63$ mm in Fig. 2 and the ratio of R^*_2 to Im_2 (the second minimum amount of rainfall in the 10-min intensity) is 50. In this study, the minimum rainfall is obtained by the critical rainfall R^* from Fig. 2 (Eqs. 7, 8):

$$I_{m1} = R^*_1/75 \tag{7}$$

$$I_{m2} = R^*_2/50 \tag{8}$$

in which I_m is the minimum amount of rainfall in the 10-min intensity (mm). In the Jiangjia Gully, there are two the minimum 10-min rainfall values, $I_{m1} = 0.67$ mm, and $I_{m2} = 1.26$ mm, corresponding to the two critical rainfall values R^*_1 , and R^*_2 (see Fig. 2).

With the critical rainfall R^* for the whole Jiangjia Gully and the T and G values for the two tributaries, one can with Eq. 5, obtain the critical value Cr: $C_{r1} = 0.082$, $C_{r2} = 0.103$ for Duozhao Gully, and $C_{r1} = 0.078$, $C_{r2} = 0.099$ for Menqian Gully. Because no detailed information is available on the triggering site of the investigated debris flows, the total catchment for C_{r1} the minimum value (=0.078) and for C_{r2} the maximum value (=0.103) were selected.

Validation in Southwest China

Also many runoff induced debris flows are triggered every year in southwest China. Some of them cause enormous damage and many casualties (Yu et al. 2010). Figure 1 shows the location of gullies with series of debris flows in southwest China (including the Jiangjia Gully): the Hunshui Gully, Santan Gully, Liuwan Gully, Macao Gully, and debris flows in the Dayi area and the Yaan area (the Luwang Gully, and the Ganxi Gully). These catchments will be used for the validation of the revised 10-min prediction model. The debris flows in these gullies and areas are all triggered by a runoff mechanism.

The Hunshui Gully

The Hunshui Gully is a high frequency debris flow gully located in the Yunnan Province, China. The catchment area of the Hunshui Gully is 4.5 km² (Zhang and Liu 1989). The topographical factor T is 0.34.

The Hunshui Gully is located along the Great Yingjiang Fault. Extremely strong weathered granites are exposed on the slopes (Zhang and Liu 1989). The statistics of historical earthquakes give the study area a general seismic intensity of VIII (NSBC 1990). The average firmness coefficient for the lithology F_0 is 2, $C_1 = 0.9$, $C_2 = 0.93$, $C_3 = 1$,

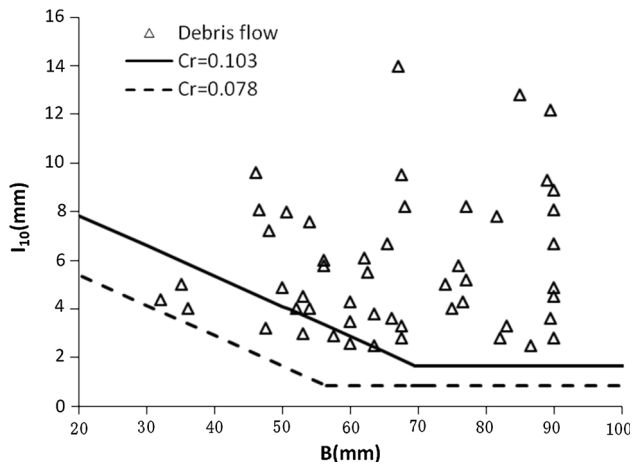


Fig. 3 Scatter plot of B against I_{10} for debris flow from 1976 to 1978 in Hunshui Gully

$C_4 = 1$, and the geological factor G is 1.674 (Yu et al. 2014).

The average annual rainfall is 1792.5 mm, and the coefficient of variation for the 10-min C_v is 0.28 in Hunshui Gully (Zhang and Liu 1989). The rainfall data, including the cumulative precipitation and the amount of 10-min rainfall before the start of the debris flow in Hunshui Gully, is listed in Table 1 (Zhang and Liu 1989).

Figure 3 shows a scatter plot of B against I_{10} for debris flows from 1976 to 1978 for the Hunshui Gully. In Fig. 3, the $R^*_1 = 63.2$ mm, and $R^*_2 = 82.8$ mm, $I_{m1} = 0.84$ mm, and $I_{m2} = 1.66$ mm, corresponding to the calibrated values for $C_{r1} = 0.078$, and $C_{r2} = 0.103$ in the Jiangjia Gully (Eqs. 5–8). All the debris flows lies beyond the critical line $C_{r1} = 0.078$ in Fig. 3 while 86.3 % (44 out of a total of 51) of the debris flows lie beyond the line, $C_{r2} = 0.103$.

Santan Gully

The Santan Gully is located in the south of the Sichuan Province, China. The catchment area of the Santan Gully is 1.66 km² (IMDE 1989). The topographical factor T is 0.236.

There are three faults crossing the Santan Gully catchment. Quartz sandstones, quartz siltstones, conglomerates, and limestones are exposed in the catchment (IMDE 1989). The statistics of historical earthquakes give the study area a general seismic intensity of VIII (NSBC 1990). The average firmness coefficient for lithology F_0 is 9.5, $C_1 = 0.9$, $C_2 = 0.93$, $C_3 = 1$, $C_4 = 1$, and the geological factor G is 7.95 (Yu et al. 2014).

The average annual rainfall is 812 mm, and the coefficient of variation for the 10-min C_v is 0.30 (IMDE 1989). The rainfall data, including the cumulative precipitation

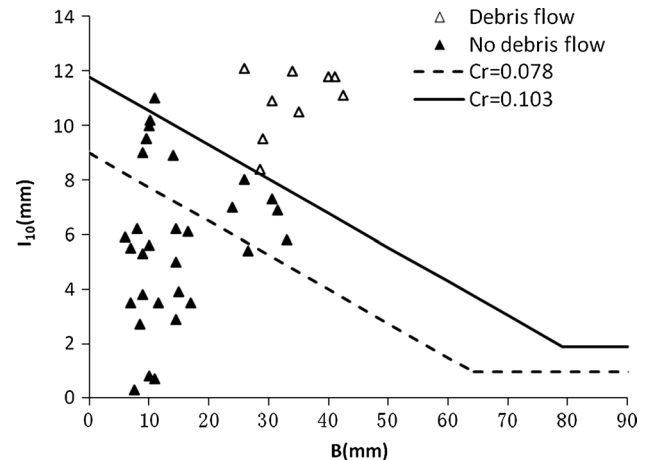


Fig. 4 Scatter plot of B against I_{10} for debris flow from 1975 to 1976 in Santan Gully

and the amount of 10-min rainfall in relation to the presence or absence of debris flows are listed in Table 1.

Figure 4 shows a scatter plot of I_{10} against B for debris flows and no debris flows from 1975 to 1976 in the Santan Gully. In Fig. 4, the $R^*_1 = 71.9$ mm, and $R^*_2 = 94.2$ mm, $I_{m1} = 0.96$ mm, and $I_{m2} = 1.88$ mm, corresponding to the calibrated $C_{r1} = 0.078$, and $C_{r2} = 0.103$ (Eqs. 5–8). All the debris flows lies beyond the critical line $C_{r2} = 0.103$ in Fig. 4 while 3.2 % (1 out of a total of 31) of the no debris flows lie beyond the line, $C_{r2} = 0.103$.

Liuwan Gully

The Liuwan Gully is a high frequency debris flow gully located in the south of the Gansu Province, China. The catchment area of the Liuwan Gully is 1.84 km² (LIGC and TSIG 1982). The topographical factor T is 0.405.

There are many landslides deposited in the Liuwan Gully (LIGC and TSIG 1982). The landslides provided a lot of sediments to trigger debris flows. The geological factor G is 0.5 (Yu et al. 2014).

The average annual rainfall is 550 mm, and the coefficient of variation for the 10-min C_v is 0.71 in Liuwan Gully (LIGC and TSIG 1982). The rainfall data, including the cumulative precipitation and the amount of 10-min rainfall before the start of the debris flows in Liuwan Gully, is listed in Table 1 (LIGC and TSIG 1982).

Figure 5 shows a scatter plot of B against I_{10} for debris flows from 1963 to 1964 in Liuwan Gully. In Fig. 5, the $R^*_1 = 25.9$ mm, and $R^*_2 = 34.0$ mm, $I_{m1} = 0.35$ mm, and $I_{m2} = 0.68$ mm, corresponding to the calibrated values of $C_{r1} = 0.078$, and $C_{r2} = 0.103$ (Eqs. 5–8). About half (46.2 %, 6 out of a total of 13) of the debris flows lies beyond the critical line $C_{r1} = 0.078$ in Fig. 5 while 30.8 %

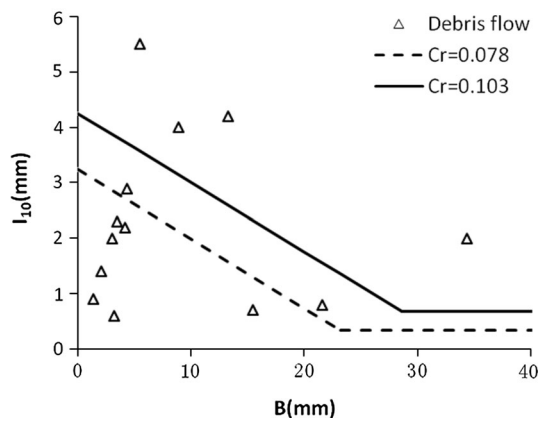


Fig. 5 Scatter plot of B against I_{10} for debris flow from 1963 to 1964 in Liuwan Gully

(4 out of a total of 13) of the debris flows lie beyond the line, $C_{r2} = 0.103$.

Macao Gully

The Macao Gully is a high frequency debris flow gully and located in the south of the Gansu Province, China. The catchment area of the Macao Gully is 13.5 km² (Gao and Qi 1997). The topographical factor T is 0.104.

Many landslide material was deposited in the Macao Gully (Gao and Qi 1997). The landslides provided an abundant amount of sediments for the initiation of debris flows. The geological factor G is 0.5 (Yu et al. 2014).

The average annual rainfall is 495 mm, and the coefficient of variation for the 10-min C_v is 0.67 in Macao Gully (Gao and Qi 1997). The rainfall data, including the cumulative precipitation and the amount of 10-min rainfall in relation to the presence or absence of debris flows in the Macao Gully, is listed in Table 1 (Gao and Qi 1997).

Figure 6 shows a scatter plot of I_{10} against B for debris flows and no debris flows from 1986 to 1989 in the Macao Gully. In Fig. 6, the $R^*_{1} = 28.9$ mm, and $R^*_{2} = 37.9$ mm, $I_{m1} = 0.39$ mm, and $I_{m2} = 0.76$ mm, corresponding to $C_{r1} = 0.078$, and $C_{r2} = 0.103$ (Eqs. 5–8). Half (50 %, two out of a total of four) of the debris flows lies beyond the critical line $C_{r2} = 0.103$ in Fig. 6 while all (one out of a total of one) points without debris flows lies below the line, $C_{r1} = 0.078$.

Debris flows in Dayi area

During a rainstorm from June 5 to June 6, 2011, many debris flows were triggered within and outside the Dayi area in the south of the Guizhou Province. There are 66 gullies located downstream of Dayi town. The debris flows in these gullies were distinguished in three classes: (1) 22

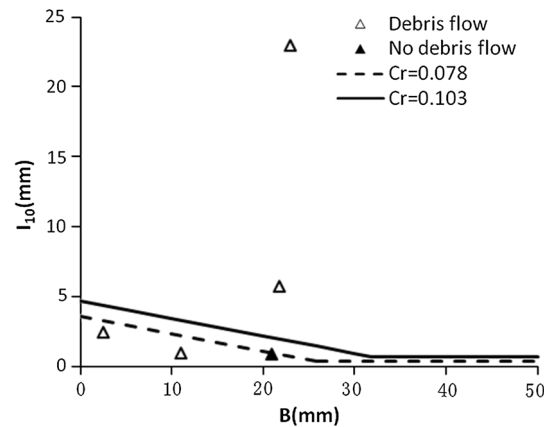


Fig. 6 Scatter plot of B against I_{10} for debris flow from 1986 to 1989 in Macao Gully

gullies were classified as “no debris flow”, (2) 25 gullies were classified as ‘debris flow’, and (3) 19 gullies were classified as “uncertain” because there was no clear indication of entrainment of material in the channels (Yu et al. 2014).

The lowest altitude in the Dayi area is 710 m, and the highest peaks in the catchment have altitudes between 1500 and 1600 m. The slope gradients of the channels in the upstream part of the gullies are very large, some of them are larger than 35°. No debris flow were triggered in channels with a slope gradient larger than 35° because of the lack of loose source material (Yu et al. 2014). The values of the topographical factor T ranges between 0.046 and 0.661. The T -values for each gully are listed in Table 2 (Yu et al. 2014).

There are only two lithological units in this area: hard siltstones interbedded with thin mudstones with a thickness ratio of 3–4 to 1. There is no fault in the study area. The statistics of historical earthquakes give the study area a general seismic intensity of VI (NSBC 1990). The average firmness coefficient for lithology F_0 is 7.11, $C_1 = 1$, $C_2 = 1$, $C_3 = 1$, $C_4 = 1$, and the geological factor G is 7.11 (Table 2) (Yu et al. 2014).

The average annual rainfall lies in a range between 1210 and 1320 mm, and the coefficient of variation for the 10-min C_v is 0.40 in Dayi area. The catastrophic rainfall event of June 5–6, 2011, started at 22:00; the maximum 10-min rainfall was 27 mm. The rainfall data for the 66 gullies, including the 10-min rainfall, and cumulative rainfall before the triggering of the debris flows were obtained by interpolation of the rainfall data of the Dayi and Xintun station (see Table 2) (Yu et al. 2014).

Since the values of R^*_{1} and R^*_{2} are variables in the study area with different gullies and not in one gully, no I_{10} – B plot can be made, but only a $T^{0.2}/G^{0.5}$ versus R plot. Figure 7 shows a scatter plot of $T^{0.2}/G^{0.5}$ against R for

Table 2 Parametric values related to different debris flow prediction factors and the presence of debris flows in gullies in the Dayi area, and Yaan area (Luwang G., and Ganxi G.)

Area	Name	R_0 (mm)	B (mm)	I_{10} (mm)	T	G	R	P	Debris
Dayi	1	1320	116	26.4	0.177	7.11	0.62	0.164	Uncertain
Dayi	2	1320	114.9	26.2	0.094	7.11	0.614	0.144	No
Dayi	3	1320	114.8	26.1	0.135	7.11	0.613	0.154	No
Dayi	4	1320	114.8	26.1	0.109	7.11	0.614	0.148	Yes
Dayi	5	1320	113.2	25.8	0.09	7.11	0.605	0.14	Yes
Dayi	6	1320	111.5	25.4	0.165	7.11	0.596	0.156	Yes
Dayi	7	1320	112.2	25.5	0.146	7.11	0.599	0.153	Uncertain
Dayi	8	1320	111.8	25.4	0.109	7.11	0.597	0.144	Uncertain
Dayi	9	1320	108.3	24.6	0.129	7.11	0.578	0.144	Yes
Dayi	10	1320	106.2	24.1	0.203	7.11	0.567	0.154	Uncertain ^a
Dayi	11	1320	104.6	23.7	0.156	7.11	0.558	0.144	Uncertain
Dayi	12	1320	103.4	23.5	0.138	7.11	0.551	0.139	Yes
Dayi	13	1320	101.1	22.9	0.157	7.11	0.539	0.14	Uncertain
Dayi	14	1320	107.9	24.5	0.166	7.11	0.576	0.151	Yes
Dayi	15	1320	112.2	25.5	0.09	7.11	0.6	0.139	Yes
Dayi	16	1320	104.6	23.7	0.108	7.11	0.558	0.134	Yes
Dayi	17	1280	90.5	20.4	0.216	7.11	0.495	0.137	Yes
Dayi	18	1280	93.2	21	0.1	7.11	0.511	0.121	Yes
Dayi	19	1280	95.3	21.5	0.07	7.11	0.523	0.115	Uncertain
Dayi	20	1280	97.9	22.2	0.066	7.11	0.537	0.117	Yes
Dayi	21	1280	99.5	22.5	0.046	7.11	0.547	0.111	Yes
Dayi	22	1280	101.1	22.9	0.453	7.11	0.555	0.178	Uncertain
Dayi	23	1280	106.1	24.1	0.284	7.11	0.584	0.17	No
Dayi	24	1280	104.7	23.7	0.183	7.11	0.575	0.154	Uncertain
Dayi	25	1280	100.1	22.7	0.228	7.11	0.55	0.153	No
Dayi	26	1280	95.9	21.7	0.238	7.11	0.526	0.148	No
Dayi	27	1280	83.4	18.7	0.27	7.11	0.455	0.131	Uncertain
Dayi	28	1220	77.2	17.3	0.047	7.11	0.441	0.09	Yes
Dayi	29	1220	72.2	16.1	0.212	7.11	0.412	0.113	Uncertain
Dayi	30	1220	69.9	15.5	0.259	7.11	0.398	0.114	Uncertain
Dayi	31	1220	67.5	15	0.177	7.11	0.384	0.102	No
Dayi	32	1210	61	13.4	0.091	7.11	0.348	0.081	Yes
Dayi	33	1210	58.2	12.8	0.396	7.11	0.331	0.103	Uncertain
Dayi	34	1210	58.6	12.8	0.548	7.11	0.333	0.111	No
Dayi	35	1210	54.9	12	0.232	7.11	0.311	0.087	Uncertain
Dayi	36	1210	51.7	11.2	0.256	7.11	0.292	0.083	No
Dayi	37	1210	52.4	11.4	0.279	7.11	0.296	0.086	Yes
Dayi	38	1210	49.9	10.8	0.231	7.11	0.281	0.079	Yes
Dayi	39	1210	55.5	12.1	0.61	7.11	0.315	0.107	Uncertain
Dayi	40	1210	57	12.5	0.277	7.11	0.324	0.094	Yes
Dayi	41	1210	60.9	13.4	0.661	7.11	0.347	0.12	Yes
Dayi	42	1210	63.4	14	0.262	7.11	0.362	0.104	Yes
Dayi	43	1220	65.3	14.4	0.325	7.11	0.37	0.111	No
Dayi	44	1220	66.2	14.7	0.089	7.11	0.376	0.087	No
Dayi	45	1220	72.1	16	0.206	7.11	0.411	0.112	Yes
Dayi	46	1220	76	17	0.41	7.11	0.434	0.136	Yes
Dayi	47	1220	71.9	16	0.2	7.11	0.41	0.111	No ^a
Dayi	48	1220	73	16.3	0.126	7.11	0.416	0.103	No ^a
Dayi	49	1220	74.2	16.6	0.155	7.11	0.423	0.109	No ^a

Table 2 continued

Area	Name	R_0 (mm)	B (mm)	I_{10} (mm)	T	G	R	P	Debris
Dayi	50	1220	74.8	16.7	0.223	7.11	0.427	0.119	No ^a
Dayi	51	1220	76.2	17	0.162	7.11	0.435	0.113	No ^a
Dayi	52	1220	77.3	17.3	0.221	7.11	0.442	0.122	No ^a
Dayi	53	1220	76.6	17.1	0.127	7.11	0.437	0.109	No
Dayi	54	1220	77.8	17.4	0.145	7.11	0.444	0.113	No ^a
Dayi	55	1220	80	17.9	0.152	7.11	0.458	0.118	No ^a
Dayi	56	1280	82.9	18.6	0.112	7.11	0.452	0.11	Uncertain
Dayi	57	1280	84.5	19	0.105	7.11	0.462	0.11	Uncertain
Dayi	58	1280	86.6	19.5	0.135	7.11	0.473	0.119	Yes
Dayi	59	1280	89.1	20.1	0.127	7.11	0.488	0.121	Uncertain
Dayi	60	1280	91.8	20.7	0.306	7.11	0.503	0.149	No ^a
Dayi	61	1280	94.1	21.3	0.155	7.11	0.516	0.133	Yes
Dayi	62	1280	97.8	22.1	0.168	7.11	0.537	0.141	No ^a
Dayi	63	1280	98.1	22.2	0.091	7.11	0.538	0.125	Yes
Dayi	64	1320	103.1	23.4	0.101	7.11	0.549	0.13	No
Dayi	65	1320	104	23.6	0.151	7.11	0.554	0.142	Uncertain ^a
Dayi	66	1320	106.8	24.2	0.196	7.11	0.57	0.154	Yes
Yaan	Luwang	1718	81.6	26.6	0.048	7.14	0.490	0.100	Yes
Yaan	Luwang	1718	28	28	0.048	7.14	0.419	0.085	No
Yaan	Ganxi	1718	81.6	26.6	0.062	7.14	0.490	0.105	Yes
Yaan	Ganxi	1718	28	28	0.062	7.14	0.419	0.090	No

T , G , and R are data pertaining to the formation (source) area of the gullies

R_0 the annual precipitation of the site, B cumulative rainfall before the triggering of the debris flows, I_{10} the 10-min rainfall

^a Average slope in channel is large than 0.7

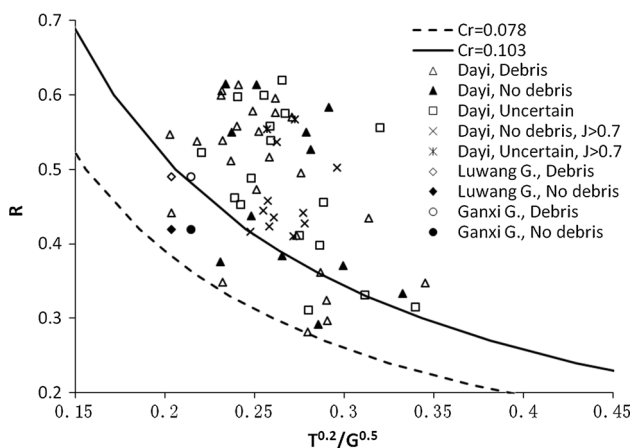


Fig. 7 Scatter plot of $T^{0.2}/G^{0.5}$ against R for debris flow in 2011 in Dayi area and Yaan area (Luwang Gully and Ganxi Gully)

debris flows of June 6, 2011 in Dayi area and Yaan area. In Fig. 7, the range of R^*_1 is from 109.4 to 196.7 mm, R^*_2 is from 144.4 to 259.8 mm, I_{m1} is from 1.5 to 2.6 mm, and I_{m2} is from 2.9 to 5.2 mm, corresponding to $C_{r1} = 0.078$, and $C_{r2} = 0.103$ (Eqs. 5–8). All the debris flows in Fig. 7

lie beyond the critical line $C_{r1} = 0.078$ while 80 % (20 out of a total of 25) of the debris flows lie beyond the line, $C_{r2} = 0.103$. But 75 % (9 out of a total of 12) points with no debris flows lie also beyond the line, $C_{r2} = 0.103$.

Debris flows in Yaan area

During the rainstorm of Nov. 2, 1979, two debris flows were triggered in the Luwang Gully, and the Ganxi Gully, in the Yaan area in the Sichuan Province (Tan and Yang 1984). The catchment area of the Luwang Gully, and Ganxi Gully are 2.49 and 10.47 km², respectively (Tan and Yang 1984). The topographical factor T are 0.048, and 0.062, respectively (Yu et al. 2014).

There are two faults crossing the Luwang and Ganxi Gully consisting of sandstones (Tan and Yang 1984). The statistics of historical earthquakes give the study area a general seismic intensity of VII (NSBC 1990). The average firmness coefficient for lithology F_0 is 8, $C_1 = 0.93$, $C_2 = 0.96$, $C_3 = 1$, $C_4 = 1$, and the geological factor G is 7.14 (Yu et al. 2014).

The average annual rainfall is 1718 mm, and the coefficient of variation for the 10-min C_v is 0.35 in the Luwang

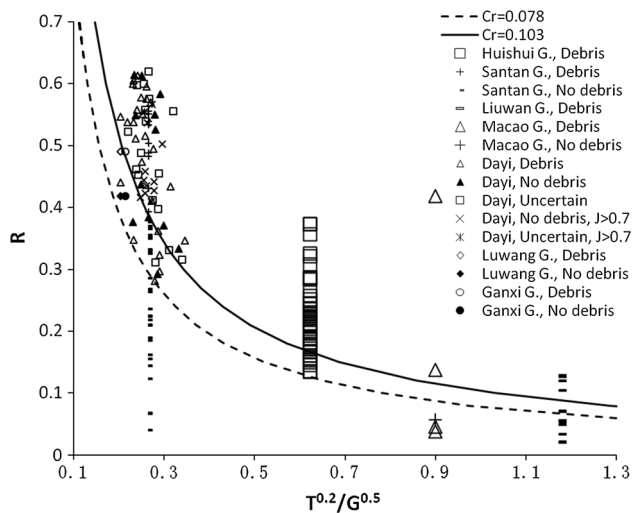


Fig. 8 Scatter plot of $T^{0.2}/G^{0.5}$ against R for debris flow in all validation

Gully, and Ganxi Gully (Yu et al. 2014). The rainfall data, including the cumulative precipitation and the amount of 10-min rainfall before the start of the debris flows and no debris flows in the Luwang Gully, and Ganxi Gully, is listed in Table 2 (Tan and Yang 1984).

Figure 7 shows a scatter plot of $T^{0.2}/G^{0.5}$ against R for the Luwang Gully, and Ganxi Gully. In Fig. 7, the $R^*_1 = 230$ mm, and $R^*_2 = 303.8$ mm, while $I_{m1} = 3.1$ mm, and $I_{m2} = 6.1$ mm in the Luwang Gully. The $R^*_1 = 218.6$ mm, and $R^*_2 = 288.6$ mm, with $I_{m1} = 2.9$ mm, and $I_{m2} = 5.8$ mm in the Ganxi Gully, corresponding to $C_{r1} = 0.078$, and $C_{r2} = 0.103$ (Eqs. 5–8). In Fig. 7, all the debris flows lie beyond the critical line $C_{r1} = 0.078$ while half of the debris flows lies beyond the critical line $C_{r2} = 0.103$. All the points with no debris flows lie below the line, $C_{r2} = 0.103$.

Figure 8 shows the validation of the 10-min prediction model for the selected areas in southwest China. The two calibrated critical C_r lines subdivide classes with almost the same probability in the Jiangjia Gully and areas in SW China: most of the debris flows lies beyond the critical line $C_{r1} = 0.078$ while most of the “no debris flows” lie below the line, $C_{r2} = 0.103$. The 10-min prediction model obtained from a series of rain events with debris flows in Jiangjia Gully, in the Yunnan Province is applicable in other areas in the southwest of China, and may be also a good predictor in other areas.

Discussion

Landslides, channel bed erosion, and destruction of natural dams are three common causes that trigger debris flows (Takahashi 2000). In this study area, only the runoff

induced mechanism (channel bed erosion) is considered as the trigger mechanism of debris flows in the study area. The proposed 10-min prediction model is not suitable for the other mechanisms of debris flow formation.

Observations during many years on the debris flows in the Jiangjia Gully provided an unprecedented amount of data to establish a 10-min rainfall model for the prediction of debris flows with a runoff induced mechanism. Calibration of the model on the Jiangjia data delivered to critical lines and three probability classes ($C_{r1} = 0.078$ or $R^*_1 = 50$ mm, $C_{r2} = 0.103$ or $R^*_2 = 63$ mm, see Fig. 2). Two debris flows (2 out of a total of 58, 3.4 %) appeared in the lowest probability class below the line $C_{r1} = 0.078$. In the highest probability class above the line $C_{r2} = 0.103$ only debris flows are found and no single point with an absence of debris flow. Neglecting the 3.4 % error, the distinction of the probability of occurrence of debris flows by means of the 10-min rainfall prediction factor P is acceptable.

In the high probability domain indicated by the model ($P \geq 0.103$) for the Daya events, still some gullies with absence of debris flows were found. The points with “No debris, $J > 0.7$ ” and “Uncertain, $J > 0.7$ ” in Fig. 7 represent however unrealistic (false) values because debris flows cannot take place whatever the values of the geological and rainfall factor because of the lack of source material in this steep channels (Yu et al. 2014). Without the “false” data for $J > 0.7$, there are still nine gullies with absence of debris flows in the high probability area ($P \geq 0.103$) during the Daya event, which we cannot explain. Future work is needed to give an clarification for these cases.

In the low probability domain ($P < 0.078$) for debris flows in the Liuwan Gully and Macao Gully, still nine points with presence of debris flows (Figs. 5, 6) were found, which cannot be explained either. But for some data below the critical line, $C_{r1} = 0.078$, the rainfall intensities of 10-min seem too low to trigger debris flows. This may be caused by some errors in the observed rainfall data.

The two calibrated critical C_r lines subdivide classes with almost the same probability in the Jiangjia Gully and also in the validation areas in SW China. In these six validation regions (debris flow gullies), most of the debris flows lies beyond the critical line $C_{r1} = 0.078$ except seven debris flows (53.8 %, 7 out of a total of 13) in Liuwan Gully, and two debris flows (50 %, two out of a total of four) in Macao gully. But for all debris flows in the six regions, only 9.7 % (9 out of a total of 93) debris flow points lie below the critical line $C_{r1} = 0.078$. Most of the points with no debris flows (78.3 %, 36 out of a total of 46) lies below the critical line $C_{r2} = 0.103$. Of the 10 false points of no debris flows, one point lies in the Santan Gully, and nine points are found in the in the Daya area.

The validation of the prediction model in southwest China was reasonable good notwithstanding the fact that the characteristics of these gullies are quite different from those of the calibration area. The 10-min prediction model obtained from a series of rain events with debris flows in the Jiangjia Gully, in the Yunnan Province is applicable in other areas in the southwest of China, and may be also a good predictor in other areas.

The critical rainfall index R^* has a large range in the calibration and validation areas: from 25.9 to 230 mm for R^*_{1} , and from 34 to 303.8 mm for R^*_{2} . The maximum value is nearly nine times larger than the minimum value. This is due to the difference in values of the topographical, geological, and rainfall factors in these areas.

One can observe that the large critical rainfall index R^* (for example, $R^* > 200$ mm) is related to areas with a low temporal frequency of debris flows (occurring once in 20 years or more, Han et al. 2011) like the Luwang Gully, Ganxi Gully, and Dayi area (Yu et al. 2014), while a low critical rainfall index R^* (for example, $R^* < 80$ mm) is associated with areas with a high or extremely high debris flow frequency (occurring once in 1–5 years or several times each year, (Han et al. 2011) like the Jiangjia Gully, Hunshui Gully, Liuwan Gully, and the Macao Gully. This points to a relationship, which may be established between the critical rainfall index R^* and the temporal frequency of debris flows. This should be verified by future studies with new data.

Kean et al. (2013) classified rainfall intensity as follows: low, <30 mm per hour; intermediate (>30 and <60 mm), and high (>60 mm). If this class limits are transferred to a 10-min rainfall intensity, the corresponding classes are: <5 mm: low intensity, >10 mm: high intensity, and between 5 and 10 mm in 10-min: intermediate intensity. In this study, a low intensity 10-min rainfall may trigger debris flows in combination with a small amount of cumulative rainfall as was observed in the Liuwan Gully and Macao Gully (see Figs. 5, 6). In the Luwang Gully and the Ganxi Gully a very large rainfall intensity of 10-min was observed (28 mm), without a debris flow (see Table 2). This may be caused by the well developed vegetative cover in the Luwang Gully and the Ganxi Gully. The classification only based on intensity by Kean et al. (2013) is a relative classification which is only valid at a specific location. However the critical rainfall intensities for the triggering of debris flows may change per location. For the debris flows, a 5 mm per 10 min intensity triggered debris flows in the Liuwan Gully and Macao Gully while in the Yaan and Dayi area a 10 mm intensity was not enough to trigger debris flows. The critical value C_{r2} is 32.1 % higher than the critical value C_{r1} (Eq. 5), which shows a moderate performance of the prediction model. For a more accurate

prediction of the occurrence of debris flows, more research is needed to reduce the difference between C_{r1} and C_{r2} .

Conclusions

Short-duration, 10-min high-intensity rainfall was the main triggering factor for debris flows with a runoff induced mechanism in the Jiangjia Gully, Yunnan, China. This research proposed a 10-min rainfall prediction model for debris flows based on a refined rainfall factor in combination with topographical and geological factors. These dimensionless factors are not totally deduced from statistical analyses in a given area but are partly based on the mechanisms behind the formation of debris flows. The model was calibrated on 76 rainfall events in the Jiangjia Gully. The prediction model has a generic nature, because it could be validated with reasonable success in other areas of southwest China with complete different gully characteristics.

The 10-min rainfall prediction model offers a new and exciting way to forecast the probability of occurrence of runoff induced debris flows. However, to improve the understanding of the occurrence and triggering mechanisms of debris flows, future research is needed to discover the reason for the miss classification of the absence of debris flows in the high probability domain (large P value), the presence of debris flows in the low probability domain (low P -value), the vegetative cover, and to reduce the difference between the critical probability values.

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