



A multivariate statistical method for susceptibility analysis of debris flow in southwestern China

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Abstract. Southwestern China is characterized by many steep mountains and deep valleys due to the uplift activity of the Tibetan Plateau. The 2008 Wenchuan earthquake left large amounts of loose materials in this area, making it a severe disaster zone in terms of debris flow. Susceptibility is a significant factor of debris flows for evaluating their formation and impact. Therefore, there is an urgent need to analyze the susceptibility to debris flows of this area. To quantitatively predict the susceptibility of the area to debris flows, this study evaluates 70 typical debris flow gullies, which are distributed along the Brahmaputra River, Nujiang River, Yalong River, Dadu River, and Ming River, as statistical samples. Nine indexes are chosen to construct a factor index system and then to evaluate the susceptibility to debris flow. They are the catchment area, longitudinal gradient, average gradient of the slope on both sides of the gully, catchment morphology, valley orientation, loose material reserves, location of the main loose material, antecedent precipitation, and rainfall intensity. Following this, an empirical model based on the Type I quantification theory is established for susceptibility prediction for debris flows in southwestern China. Finally, 10 debris flow gullies upstream of the Dadu River are analyzed to verify the reliability of the proposed model. The results show that the accuracy of the statistical model is 90 %.

other structural facilities. China has a chiefly mountainous topography and is one of the most debris-flow-prone countries in the world. Up to March 2019, approximately recorded 50 000 debris flows have occurred in China (Di et al., 2019). A significant percentage of these debris flows are distributed in southwestern China, particularly in the Wenchuan earthquake area, where large amounts of loose material were produced by the earthquake-induced landslides (Xu et al., 2012; Huang et al., 2015; Dai et al., 2017).

Due to the complex nature of debris flows, it is quite difficult to fully understand their initiation mechanism and precisely forecast their occurrence (Brayshaw and Hassan, 2009; Gao et al., 2019). The uncertainty of debris flows poses a significant threat to human life in downstream areas (Schürch et al., 2011). Debris flow susceptibility expresses the occurrence possibility of debris flow in an area with respect to its geomorphologic characteristics (Kappes et al., 2011; Bertrand et al., 2013). Therefore, susceptibility analysis is an essential step for conducting risk assessments of debris flow hazards (Di et al., 2019; Zou et al., 2019).

Debris flow susceptibility analyses include two steps: (1) identification of the potential source areas and (2) prediction of the possible deposition areas (Kang and Lee, 2018). In the literature, a large number of prediction models have been proposed for the susceptibility analyses of debris flows. For the first step, statistical models that use various environmental factors contributing to possible instabilities are well established. For example, Blahut et al. (2010) performed susceptibility assessment for the source areas of landslide-induced debris flows in the Valtellina Valley based on bivariate statistics. Bertrand et al. (2013) used two multivariate statistical

1 Introduction

Debris flows are a common geological hazard in mountainous areas that transport large amounts of sediment down-slope and cause serious damage to dwellings, roads, and

models, a linear discriminant analysis (LDA) and a logistic regression (LR), to analyze the debris flow susceptibility of upland catchments. Jomelli et al. (2015) proposed a Bayesian hierarchical probabilistic model to investigate how debris flows respond to environmental and climatic variables in the French Alps. Carrara et al. (2008) discussed the application of different statistical models to debris flows in Val di Fassa, Trentino, Italy. Lucà et al. (2011) compare bivariate and multivariate statistical models for the evaluation of gully susceptibility in northern Calabria, southern Italy, and concluded that multivariate statistical models were found to be the best model for predicting the debris flow susceptibility of the study area. For the second step, the concept “angle of reach” was widely used in the empirical models to predict the run out distance of debris flows (Hürlimann et al., 2012; Horton et al., 2013). Recently, many numerical models have been proposed to simulate the propagation of debris flows and predict the deposition area. For example, Pirulli and Sorbino (2008) analyzed the propagation of potential debris flows in southern Italy using two numerical codes RASH3D and FLO2D. Beguería et al. (2009) proposed a two-dimensional model based on numerical integration of the depth-averaged motion equations to predict debris flow propagation over complex terrain near Lienz, East Tyrol, Austria. Huang et al. (2015) presented a numerical model based on the smoothed particle hydrodynamic (SPH) method to calculate the run out distance of catastrophic debris flows that occurred in the Wenchuan earthquake area. Gregoretti et al. (2016) used a cell model to simulate a debris flow that occurred on the Rio Lazer. Moraci et al. (2017) performed debris flow susceptibility zoning of debris flows in the Province of Reggio Calabria based on the SPH method. Some recent analysis methods of debris flow susceptibility can be found in Cama et al. (2017), Prieto et al. (2018), and Rosatti et al. (2018).

The previous studies mentioned above have attempted to conduct debris flow susceptibility analysis in specified regions. Southwestern China is characterized by steep mountains and deep valleys, and is strongly affected by the uplift activity of the Tibetan Plateau. Moreover, southwestern China has abundant loose material after the 2008 Wenchuan earthquake. Therefore, a series of large-scale debris flows have been occurred during the rainy seasons in southwestern China (Wu et al., 2019). In the literature, many models for debris flow risk prediction in this area have been proposed. For example, Xu et al. (2012) assess debris flow susceptibility based on an information value model and Geographic Information System (GIS) in Sichuan, China. Wang et al. (2016) adopted a self-organizing map method to analyze the susceptibility to debris flows at the Wudongde Dam site in southwestern China. Li et al. (2017) carried out a susceptibility analysis on debris flows also in the Wudongde Dam area using the fuzzy *C*-means algorithm (FCM). Recently, Liu et al. (2018) presented a comprehensive risk assessment model based on semiquantitative methods to quan-

tify the risk level of each zone in southwestern China. Di et al. (2019) developed a gradient boosting machine (GBM) to predict the susceptibilities of debris flows in southwestern China. Wu et al. (2020) implemented logistical regression models to identify the areas that are susceptible to debris flow formations in Sichuan Province, China. Through the above research, some promising results have been achieved concerning the susceptibility analysis of the debris flows in southwestern China. This work aims to provide a multivariate statistical method for susceptibility analysis of debris flow in southwestern China. A total of 70 debris flow gullies in southwestern China were analyzed, and nine key indicators were extracted through the initial analysis of the debris flows. Through multivariate statistics, an empirical formula of susceptibility was established, which was then validated with the data of the 10 debris flow gullies upstream of the Dadu River. It is worth noting that this work is confined to identifying the potential debris flow source areas in southwestern China and neglects the run out of the phenomenon.

2 Characteristics of the debris flows in the study area

Southwestern China is characterized by steep mountains and deep valleys and is strongly affected by the uplift activity of the Qinghai–Tibet Plateau. Furthermore, there is abundant loose material and rainfall in this area. Therefore, it is a severe disaster zone in terms of debris flow. In the past 3 years, 70 typical debris flows distributed along the Brahmaputra River, Nujiang River, Yalong River, Dadu River, and Ming River are investigated. The location of the debris flows is shown in Fig. 1, and some typical debris flows are shown in Fig. 2. Based on the field investigation, the characteristics of the five water catchments are summarized as follows.

1. Upstream of the Brahmaputra River, 18 debris flow gullies along the Dagu River and Jiexu River are investigated. The lithology in this area is the irruptive rock of the late Yanshanian–Himalayan epoch, with a wide distribution of granodiorite. The average annual rainfall in this area is about 540 mm and concentrates mostly in summer. Large-scale ice-melting-type debris flow once occurred in this region. However, in recent years, the debris flows in this area are mainly caused by precipitation. Material reserves are abundant in the valleys, whereas unstable materials are found less frequently and the deposit zone is small. It is found that most of the debris flows in this area are in the decline phase, and that most debris flow gullies are in the low-frequency category.
2. In the midstream of the Nujiang River catchment, 11 debris flow gullies located in the Zuogong River section are investigated. The stratum mainly includes the Permian Nacuo group slate and Triassic Wapu group marble. As this region is located in the subtropical zone

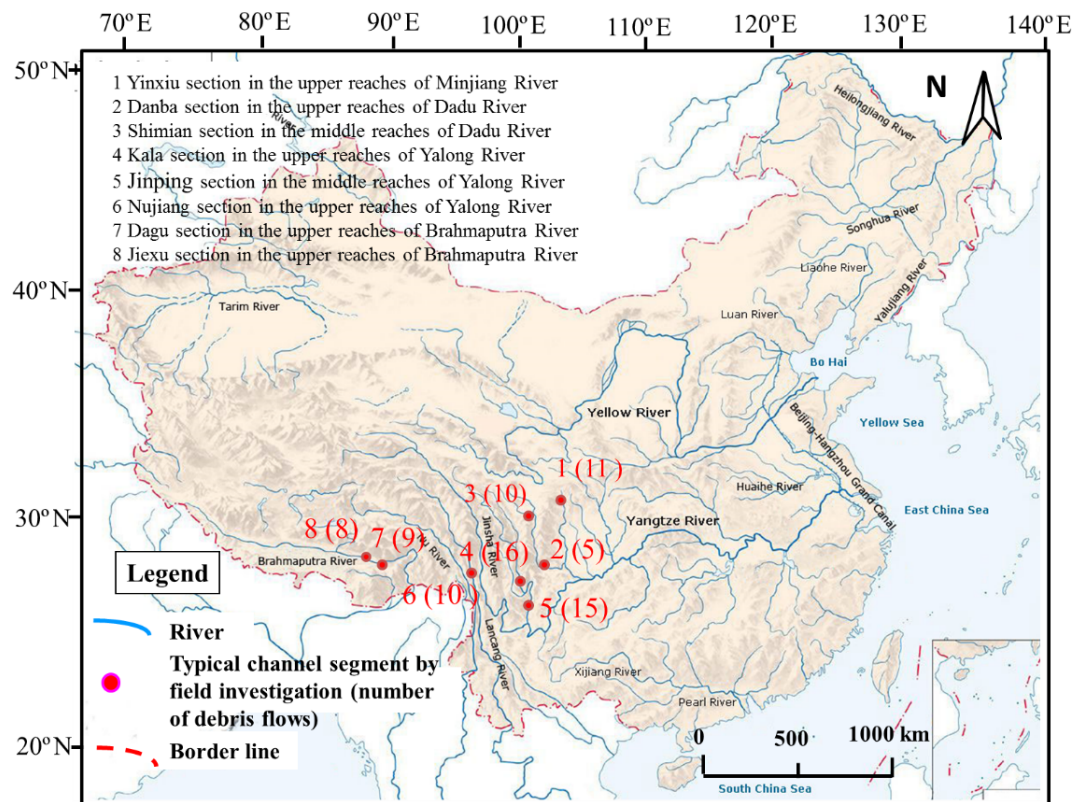


Figure 1. Distribution of the 70 debris flow gullies investigated in southwestern China (the base map is from Zhao, 2014). Publisher's note: Please note that the above figure contains disputed territories.

south of the Himalayas, it is characterized by a humid climate and plentiful precipitation. This leads to an extensive distribution of debris flow gullies.

3. Midstream in the Yalong River catchment, 27 debris flow valleys are investigated, which belong to a plateau climate zone with complex meteorological and hydrological conditions. The concentricity and suddenness of rainfall provide hydraulic conditions for the debris flow breakouts. Collapses and landslides in the valley occur frequently, which provide abundant material resources for the debris flow occurrence. Moreover, the debris flow activity is intensified by unreasonable human engineering activities, such as deforestation and accumulation of highway waste residue.
4. In the Dadu River catchment, 42 gullies in the midstream and the upstream are surveyed. This area is characterized by intense new tectonic movement, high earthquake intensity, and rock fragmentation on the mountain surface. Debris flow, collapse, and other geological disasters are widely distributed, and the deposit zone of the debris flow is large. The maturity of the valley is high.
5. In the Minjiang River catchment, the Wenchuan River section are surveyed, and 32 debris flows are investi-

gated. This region is characterized by abundant loose materials, frequent debris flows, and a high possibility of the breakout of large-scale debris flows. Most of these debris flows are intensive in activity and have not declined in recent times.

3 Methodology

3.1 Investigation and statistical data

In total, 70 debris flow gullies distributed in five water catchments in southwestern China were investigated from the gully outlet to the watershed over the past 3 years. This work includes the investigation of the watershed terrain, geological structure, outbreak scale, loose material distribution, processes of occurrence and movement, frequency of debris flows, and so on. The role of each factor causing instability of the source materials are analyzed.

The antecedent precipitation can reduce the soil shear strength, and has an important influence on the formation and the scale of debris flows (Shieh et al., 2009). Therefore, the precipitation data before the outbreak of debris flows was collected from local meteorological bureaus and used as one of the main influence factors to assess the susceptibility of debris flows in this study. In this work, the antecedent



Figure 2. Typical debris flows in the study area.

precipitation is classified into three categories: inadequate, medium, and adequate. The classification criteria are listed in Table 1.

3.2 Field test

Bulk density tests and soil screening tests are carried out in the 70 debris flow deposit areas. Figure 3 shows the results of the bulk density tests. The bulk densities of the soil material in the debris flow deposits are mainly between 1.3 and 1.8 g cm⁻³, and the average bulk density is about 1.48 g cm⁻³. The results of the screening test show that the material composition in the deposit zone is mainly composed of block gravel mixed soil, the content of the block gravel is 30 %–50 %, the content of silt and clay is about 20 %–40 %, and the rest of the deposit material is breccia. The reason for the high content of coarse stone soil is that the collapse phenomenon is quite common due to the active crustal movement in the study area.

3.3 Drilling and geophysical prospecting

The geologic condition in the active debris flow gullies in southwestern China is very complicated. To investigate the material composition and the thickness of the deposit area, the geological drilling was conducted in the active debris flow gullies along the Dadu River, Yalong River, Yaluzangbo River, and Minjiang River. The drilling information, such as

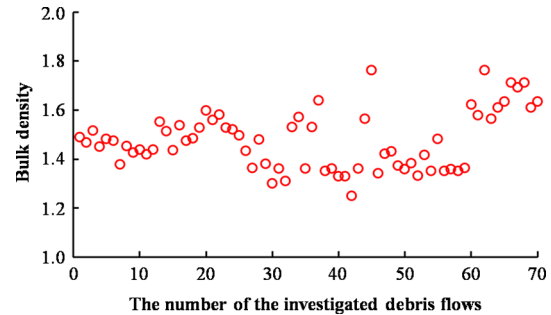


Figure 3. Density characteristics of debris flow deposits in the study area.

the drilling location, drilling depth, and soil characteristics, are provided in Table 2.

3.4 Statistical technique

The statistical techniques can be grouped into bivariate and multivariate methods. A bivariate statistical method analyses each parameter individually; therefore, the calculation and application in bivariate statistical models are straightforward and efficient (Suzen and Doyuran, 2004). On the other hand, a multivariate statistical method considers the interaction of all parameters in controlling the occurrence of a phenomenon and is considered one of the best methods in predicting debris

Table 1. Qualitative grading criteria of antecedent precipitation.

Classification	Standard of classification
Inadequate	There is no antecedent precipitation or very little antecedent precipitation, which is not enough to make the surface soil moist.
Medium	The antecedent precipitation is intermittent or lower, and the soil is wet or muddy.
Adequate	The precipitation lasts for several days, and the soil layer is full of water. Water accumulated in some low-lying areas, and the drainage is not smooth.

flow susceptibility (Lucà et al., 2011). Hayashi's quantification theory is a well-known multivariate statistical method developed by Hayashi (1961). The Type I quantification theory applies multiple linear regression methods, which can simultaneously process qualitative and quantitative variables, and evaluate the weight of each variable. Therefore, it is widely used in various fields (Matsumura, 2004; Ishihara et al., 2007; Inoue et al., 2009; Shen and Chen, 2018). In this method, the qualitative and quantitative variables can be mutually transformed based on a reasonable principle. Therefore, this method has very good applicability for processing the quantitative and qualitative influencing factors of debris flow risk.

In Hayashi's Type I quantification theory, qualitative variables are termed items. All possibilities for each item are termed categories. A dummy variable $\delta_i(j, k)$ is introduced in the method to express the response of an item and the category for each sample:

$$\delta_i(j, k) = \begin{cases} 1, & \text{if response of } i\text{th sample in the category } k \text{ of} \\ & \text{item } j \text{ to the corresponding external criterion;} \\ 0, & \text{otherwise} \end{cases} \quad \begin{cases} i = 1, 2, \dots, n; \\ j = 1, 2, \dots, m, \end{cases} \quad (1)$$

where n is the number of samples and m denotes the number of items.

The response matrix \mathbf{X} can be expressed as a $n \times p$ order matrix composed of all categories $\delta_i(j, k)$:

$$\mathbf{X} = \begin{pmatrix} \delta_1(1,1) \cdots \delta_1(1,r_1) & \delta_1(2,1) \cdots \delta_1(2,r_2) & \cdots & \delta_1(m,1) \cdots \delta_1(m,r_m) \\ \delta_2(1,1) \cdots \delta_2(1,r_1) & \delta_2(2,1) \cdots \delta_2(2,r_2) & \cdots & \delta_2(m,1) \cdots \delta_2(m,r_m) \\ \vdots & \vdots & \ddots & \vdots \\ \delta_n(1,1) \cdots \delta_n(1,r_1) & \delta_n(2,1) \cdots \delta_n(2,r_2) & \cdots & \delta_n(m,1) \cdots \delta_n(m,r_m) \end{pmatrix}. \quad (2)$$

To establish a quantitative analysis model, the qualitative and quantitative in situ observations are used to fit the linear relationship between the concerned independent variable and the dependent variable. In Hayashi's Type I quantification theory, the random variable changes with the m variables:

$$y_i = \sum_{j=1}^m \sum_{k=1}^{r_j} \delta_i(j, k) b_{jk} + \varepsilon_i, \quad i = 1, 2, \dots, n, \quad (3)$$

where y_i represents the susceptibility of the i th debris flow gully, r_j is the number of categories of the item j , b_{jk} is a

constant coefficient depending on category k in item j , and ε_i is a random error.

To establish an analysis model of debris flow susceptibility, some necessary steps should be followed based on Hayashi's Type I quantification theory: (1) building an index system, (2) selecting samples and assigning values, (3) establishing the analysis model using single slopes, (4) conducting a significance test of the regression equation and each variable, and (5) applying this analysis model to regional debris flow hazards evaluation.

4 Model generation and results

4.1 Indexes and categories in the statistical model

There are many factors that affect debris flow formation and development. From the perspective of source material of the debris flows, the main influence factors are catchment area, loose material position, and loose material reserves. The antecedent precipitation and H_{1p} rainfall intensity are the main generating conditions of debris flows. Aside from this, the catchment morphology, longitudinal gradient, average gradient of slope on both sides of the gully, and valley orientation are the main factors affecting the development of debris flows. Therefore, these nine indexes (listed in Table 3) are selected in this study to assess the susceptibility of debris flows. Each factor is classified into certain categories according to the values shown in Table 4.

4.2 Sample quantification

A total of 70 debris flow gullies in southwestern China are selected as the sample to evaluate the performance of the statistical model. Detailed information about these debris flow gullies is given in Table 5. The values of the samples are assigned according to Eq. (1), and the response from each category is obtained. The sample data then can be transformed into a "0–1" reflection matrix.

Table 2. Information and results of the geological drilling in the study area.

No.	River	Debris flow gully	Coordinates	Drilling depth (m)	Soil characteristics exposed by drilling
1	Yalong River	Reshui Gully	28°24′08″ N 101°16′42″ E	15	The lithology is mainly metamorphic sandstone and carbonaceous slate, with a small amount of quartzite.
2	Yalong River	Reshui Gully	28°24′10″ N 101°16′44″ E	22	The percentage of boulder and gravel is about 40 %, which is slightly angular. Their particle sizes are
3	Yalong River	Reshui Gully	28°24′12″ N 101°16′45″ E	26	40–60 and 4–9 cm, respectively. The rest of the material is silty clay of medium density. The cementation state of the soil material in this area is good.
4	Yalong River	Shangtian Gully	28°24′08″ N 101°16′26″ E	21	The lithology is gravel soil of medium density. The percentage of gravel and coarse sand is 43 % and
5	Yalong River	Shangtian Gully	28°24′11″ N 101°16′29″ E	17	20 %, respectively, and the rest of the material is clay. The average thickness of the deposit in this area is about 19.0 m.
6	Dadu River	Shuikazi Gully	31°03′38″ N 101°52′07″ E	31	The thickness of the upper layer of the deposit is about 1.5 m, and the material is weakly cemented silty clay
7	Dadu River	Shuikazi Gully	31°03′39″ N 101°52′09″ E	36	with a small amount of gravel. The thickness of middle layer is about 2.0 m, and the material is clay
8	Dadu River	Shuikazi Gully	31°03′41″ N 101°52′11″ E	35	mixed with gravel containing a small amount of boulder. The particle size of the gravel, breccia, and boulder are 2–3, 10, and 40 cm, respectively. The soil content in this layer is up to 70 %. The lower layer is mainly composed of gravel and sand, and the particle size is relatively uniform, generally 5–8 cm. The roundness of the particles is good, and the content of fine particles is low.
9	Dadu River	Kaka Gully	31°00′11″ N 101°52′12″ E	21	The lithology is mainly mica quartz schist, which is slightly angular, grayish yellow, dry, and of medium density
10	Dadu River	Kaka Gully	31°00′15″ N 101°52′14″ E	19	The particle size of the boulder is 20–40 cm, accounting for about 40 % of the total. The boulder layer in this gully is mainly filled with silt and a small amount of gravel.
11	Brahmaputra River	Menda Gully	29°15′22″ N 92°25′12″ E	22	The deposit in this area is mainly composed of gravelly soil mixed with boulder. The average
12	Brahmaputra River	Menda Gully	29°15′23″ N 92°25′11″ E	26	particle size of the gravels is 15–20 cm, accounting for about 40 % of the total. The average particle size of block
13	Brahmaputra River	Menda Gully	29°15′24″ N 92°25′13″ E	29	stone is about 40–60 cm, accounting for about 10 %–20 % of the total. In addition, there are some sporadic boulders with an average particle size of 3–4 m.
14	Brahmaputra River	Zhuangnan Gully	29°15′39″ N 92°24′23″ E	16	The material is mainly composed of dense gravelly soil and a small amount of silt. The gravels with the
15	Brahmaputra River	Zhuangnan Gully	29°15′41″ N 92°24′24″ E	11	average particle size of 30–60 cm account for about 30 % of the total. The gravels with the average particle size of
16	Brahmaputra River	Zhuangnan Gully	29°15′42″ N 92°24′21″ E	17	15 cm account for about 10 % of the total. The rest is breccia soil, which has poor sorting performance and obvious miscellaneous accumulation characteristics.

Table 2. Continued.

No.	River	Debris flow gully	Coordinates	Drilling depth (m)	Soil characteristics exposed by drilling
17	Minjiang River	Banzi Gully	31°24′25″ N 103°31′49″ E	18	The deposit in this area is mainly composed of brown yellow gravel soil, which contains 10 % cobble, 45 % gravel, and 20 % coarse sand, with the rest made up of clay.
18	Minjiang River	Banzi Gully	31°24′27″ N 103°31′51″ E	24	
19	Minjiang River	Chutou Gully	31°20′21″ N 103°29′12″ E	14	The deposit zone in this area is 150 m long and 100 m wide. The soil material is of medium density and contains 30 % boulder and 70 % gravelly soil.
20	Minjiang River	Chutou Gully	31°20′22″ N 103°29′13″ E	17	
21	Minjiang River	Chutou Gully	31°20′25″ N 103°29′14″ E	13	

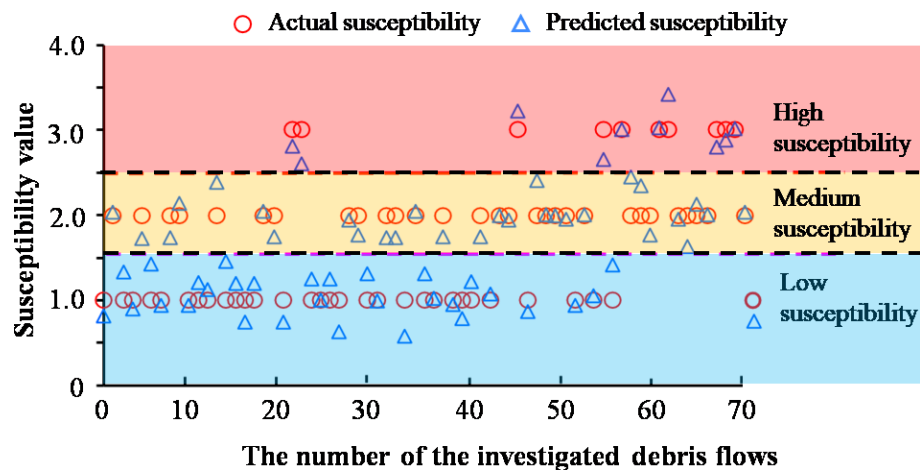


Figure 4. Typical characteristics of the Danba section in the upper reaches of the Dadu River.

Table 3. The nine indexes used in the prediction model of debris flow susceptibility.

Symbol	Physical significance
x_1	Catchment area (km ²)
x_2	Longitudinal gradient (‰)
x_3	Average gradient of slope on both sides of gully (°)
x_4	Catchment morphology
x_5	Valley orientation
x_6	Loose material reserves (10 ⁴ m ³ km ⁻²)
x_7	Main loose material position
x_8	Antecedent precipitation
x_9	H_{1p} rainfall intensity (mm)

4.3 Statistical model based on Hayashi’s quantification theory

When the quantitative theory and regression analysis take the binary-state variables 0 and 1, the equation can be revised as the following linear regression expression:

$$y_i = a_0 + \sum_{j=1}^f a_j x_{ij} + \varepsilon_i \quad i = 1, \dots, n.$$

(4)

Based on Eq. (4) and matrix derivation regression calculation, the contribution values of each item are obtained, as shown in Table 6.

Substituting the numerical values in Eq. (4), the susceptibility prediction model of debris flow is established, which can be represented as follows:

Table 4. Grading criteria of the evaluation indexes in the prediction model of debris flow susceptibility.

Item	Category	Value
Catchment area x_1 (km ²)	x_{11}	$< 1 \text{ km}^2$
	x_{12}	$1\text{--}10 \text{ km}^2$
	x_{13}	$10\text{--}100 \text{ km}^2$
	x_{14}	$\geq 100 \text{ km}^2$
Longitudinal gradient x_2 (‰)	x_{21}	$< 100 \text{ ‰}$
	x_{22}	$100 \text{ ‰--}300 \text{ ‰}$
	x_{23}	$\geq 300 \text{ ‰}$
Average gradient of slope on both sides of gully x_3 (°)	x_{31}	< 30
	x_{32}	$30\text{--}40^\circ$
	x_{33}	$\geq 40^\circ$
Catchment morphology x_4 (–)	x_{41}	$Z < 0.3$
	x_{42}	$Z = 0.3\text{--}0.7$
	x_{43}	$Z \geq 0.7$
Valley orientation x_5 (–)	x_{51}	Sunny slope
	x_{52}	Shady slope
Loose material reserves x_6 ($10^4 \text{ m}^3 \text{ km}^{-2}$)	x_{61}	$< 1 \times 10^4 \text{ m}^3 \text{ km}^{-2}$
	x_{62}	$1\text{--}5 \times 10^4 \text{ m}^3 \text{ km}^{-2}$
	x_{63}	$\geq 5 \times 10^4 \text{ m}^3 \text{ km}^{-2}$
Main loose material position x_7 (–)	x_{71}	Upstream or tributary
	x_{72}	Middle and lower reaches
	x_{73}	Toe of gully
Antecedent precipitation x_8 (–)	x_{81}	Inadequacy
	x_{82}	Medium
	x_{83}	Adequacy
H_{1p} rainfall intensity x_9 (mm)	x_{91}	$< 30 \text{ mm}$
	x_{92}	$\geq 30 \text{ mm}$

Note that Z is the length to width ratio of the debris gully.

$$\begin{aligned}
 Y = & 0.573x_{11} + 0.821x_{12} + 0.910x_{13} + 0.875x_{21} \\
 & + 0.955x_{22} + 0.320x_{23} - 0.107x_{32} - 0.163x_{41} \\
 & + 0.135x_{42} + 0.213x_{43} - 0.136x_{51} - 0.174x_{52} \\
 & + 0.246x_{62} + 0.454x_{63} - 0.220x_{71} - 0.161x_{72} \\
 & + 0.034x_{82} + 0.071x_{83} - 0.038x_{91} + 0.043x_{92}. \quad (5)
 \end{aligned}$$

In Eq. (5), Y is the susceptibility for the debris flow, and the meanings of x_{11} , x_{12} , x_{13} , and other indexes are detailed in Table 4. Based on the statistical analysis of the debris flows that occurred in southwestern China, the susceptibility values are classified into three categories in the proposed model:

$$\begin{cases} Y < 1.5 & \text{Low susceptibility} \\ 1.5 \leq Y < 2.5 & \text{Medium susceptibility} \\ Y \geq 2.5 & \text{High susceptibility} \end{cases} \quad (6)$$

5 Validation and discussion

5.1 Fitting degree analysis

R_2 is the fitting degree, which is widely used to evaluate the accuracy of prediction models. As shown in Table 7, the fitting degree of the proposed model is 71.8 %, which shows that this model can precisely predict the susceptibility of debris flows in southwestern China.

5.2 Self-test coincidence rate

The values of each index are used in the established model to calculate the predicted values of the susceptibility based on Eq. (5), and then the predicted values are compared with the actual susceptibility. In this study, self-test coincidence rate is defined as the ratio of the predicted result to the actual susceptibility. As shown in Fig. 4, the predicted values of debris flow susceptibility are graded. For the calculated results listed in Table 8, the prediction accuracy for the low-

Table 5. Sample data for debris flow examples from southwestern China.

No.	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	Susceptibility
1	0.77	567	35	Long strip	SE	8.05	Upstream	Inadequate	26.38	Low
2	13.3	366	28	Ellipse	SE	10.04	Upstream	Inadequate	26.38	Medium
3	2.62	624	37	Long strip	SE	4.39	Upstream	Inadequate	26.38	Low
4	2.47	624	36	Long strip	SE	26.06	Middle and lower reaches	Inadequate	26.38	Low
5	71.64	194	22	Ellipse	S	8.06	Upstream	Inadequate	26.38	Medium
6	18.89	344	35	Suborbicular	NE	3.08	Upstream	Inadequate	26.38	Low
7	13.01	404	36	Ellipse	NW	3.43	Upstream	Inadequate	26.38	Low
8	43.51	199	28	Suborbicular	NE	4.01	Upstream	Inadequate	26.38	Medium
9	38.4	251	37	Long strip	SE	5.38	Upstream	Inadequate	26.38	Medium
10	4.04	412.53	37	Long strip	NE	6.15	Upstream	Inadequate	26.38	Low
11	1.39	480	35	Long strip	N	7.85	Upstream	Inadequate	26.38	Low
12	1.62	569.4	36	Long strip	S	19.11	Middle and lower reaches	Inadequate	26.38	Low
13	13.23	280.61	31	Ellipse	N	3.07	Middle and lower reaches	Inadequate	26.38	Medium
14	2.48	536.68	41	Long strip	S	22.63	Upstream	Inadequate	26.38	Low
15	5.15	507.69	39	Ellipse	S	10.74	Upstream	Inadequate	26.38	Low
16	1.25	630.34	43	Suborbicular	NE	6.44	Middle and lower reaches	Inadequate	26.38	Low
17	135.6	139.46	30	Suborbicular	NE	3.91	Upstream	Inadequate	26.38	Low
18	53.42	169.87	30	Ellipse	SW	1.89	Middle and lower reaches	Adequate	32.85	Medium
19	169.72	121.62	25	Ellipse	S	0.98	Branch trench, upstream	Adequate	32.85	Medium
20	15.53	171.2	36	Long strip	N	3.24	Upstream	Adequate	32.85	Low
21	31.35	171	33	Ellipse	NE	2.74	Middle and lower reaches	Adequate	32.85	High
22	7.37	462.11	35	Suborbicular	NE	7.06	Middle and lower reaches	Adequate	32.85	High
23	20.99	235.79	25	Ellipse	SW	1.47	Upstream	Adequate	32.85	Low
24	275.41	60	23	Ellipse	SE	0.89	Upstream	Adequate	32.85	Low
25	211.4	94	34	Ellipse	NW	1.04	Tributary	Medium	32.85	Low
26	8.89	256	36	Long strip	SW	3.79	Upstream	Adequate	32.85	Low
27	28.91	190	31	Ellipse	SE	2.20	Middle and lower reaches	Adequate	32.85	Medium
28	34.84	158	43	Long strip	SW	0.90	Middle and lower reaches	Adequate	42.2	Medium
29	102.7	110	29	Long strip	NE	0.75	Middle and lower reaches	Adequate	42.2	Low
30	84.81	146.2	32	Ellipse	NE	0.78	Branch trench	Adequate	42.2	Low
31	132.02	129.5	35	Ellipse	SW	0.42	Upstream	Adequate	42.2	Medium
32	5.5	318.01	33	Ellipse	NE	6.37	Middle and lower reaches	Adequate	42.2	Medium
33	124.3	117.9	26	Ellipse	SW	1.37	Branch trench, upstream	Adequate	42.2	Low
34	26.2	203.9	36	Ellipse	SE	3.85	Upstream	Adequate	42.2	Medium
35	29.56	205.1	32	Long strip	SW	1.84	Upstream	Adequate	42.2	Low
36	80.34	119.1	38	Long strip	NE	1.51	Branch trench, upstream	Adequate	42.2	Low
37	8.45	301.5	37	Ellipse	NE	2.06	Upstream	Adequate	42.2	Medium
38	16.26	217.1	36	Long strip	SE	1.15	Branch trench, upstream	Adequate	42.2	Low
39	77.5	138.5	41	Long strip	NE	1.22	Upstream	Adequate	42.2	Low
40	23.1	235.52	24	Long strip	SW	1.68	Upstream	Adequate	42.2	Low
41	47.01	166	30	Ellipse	NE	1.69	Toe of gully	Adequate	42.2	Medium
42	83.11	125	31	Ellipse	NE	0.40	Upstream	Adequate	42.2	Low
43	21.11	238	32	Ellipse	SW	0.87	Upstream	Adequate	42.2	Medium
44	73.11	156	32	Ellipse	SE	1.10	Middle and lower reaches	Medium	43.12	Medium
45	64.7	144	33	Ellipse	NW	0.78	Toe of gully	Medium	43.12	High
46	21.87	242.95	36	Ellipse	NW	1.55	Branch trench, upstream	Medium	43.12	Low
47	3.5	530.4	42	Ellipse	NW	8.34	Middle and lower reaches	Medium	43.12	Medium
48	26.66	296.6	33	Ellipse	SE	4.70	Middle and lower reaches	Medium	43.12	Medium
49	32.23	178.35	30	Suborbicular	S	5.91	Middle and lower reaches	Medium	28.47	Medium
50	40.03	164.6	31	Ellipse	SE	5.59	Middle and lower reaches	Medium	28.47	Medium
51	3.25	235.43	35	Ellipse	NW	2.18	Upstream	Medium	28.47	Low
52	351.2	92.4	24	Ellipse	S	10.37	Branch trench	Medium	28.47	Medium
53	8.85	220.35	36	Suborbicular	NW	4.01	Branch trench, upstream	Medium	28.47	Low
54	25.31	203.62	30	Long strip	S	4.75	Middle and lower reaches	Medium	28.47	High
55	1.78	214.58	28	Suborbicular	NE	0.73	Upstream	Medium	28.47	Low
56	5.8	246.48	34	Ellipse	SW	15.79	Middle and lower reaches	Medium	28.47	High

Table 5. Continued.

No.	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	Susceptibility
57	7.6	230.09	42	Ellipse	S	17.34	Middle and lower reaches	Medium	28.47	Medium
58	1.7	140.37	36	Long strip	SE	136.82	Middle and lower reaches	Medium	28.47	Medium
59	53.27	132.43	32	Ellipse	SE	10.33	Upstream	Medium	28.47	Medium
60	14.15	178.6	28	Suborbicular	SW	55.50	Middle and lower reaches	Adequate	41.1	High
61	1.48	244.2	33	Suborbicular	SW	32.81	Middle and lower reaches	Adequate	41.1	High
62	0.89	256.8	38	Suborbicular	SW	18.81	Middle and lower reaches	Adequate	41.1	Medium
63	0.98	243.2	35	Suborbicular	SW	12.70	Middle and lower reaches	Adequate	41.1	Medium
64	3.73	120	24	Long strip	SW	9.51	Upstream	Adequate	41.1	Medium
65	3.37	450.9	40	Ellipse	SE	8.80	Upstream	Adequate	41.1	Medium
66	0.57	207.7	31	Suborbicular	SW	36.89	Middle and lower reaches	Adequate	41.1	High
67	3.02	488.8	42	Ellipse	SE	20.99	Middle and lower reaches	Adequate	41.1	High
68	7.59	352	28	Ellipse	NE	19.26	Middle and lower reaches	Adequate	41.1	High
69	32.04	223	23	Ellipse	NW	13.67	Middle and lower reaches	Adequate	41.1	High
70	3.27	235	35	Ellipse	NE	9.29	Upstream	Adequate	41.1	Low

Table 6. Score values of each index after normalization.

Item	Category	Value
Catchment area x_1 (km ²)	x_{11}	< 1 km ²
	x_{12}	1–10 km ²
	x_{13}	10–100 km ²
	x_{14}	≥ 100 km ²
Longitudinal gradient x_2 (‰)	x_{21}	< 100 ‰
	x_{22}	100 ‰–300 ‰
	x_{23}	≥ 300 ‰
Average gradient of slope on both sides of gully x_3 (°)	x_{31}	< 30
	x_{32}	30–40°
	x_{33}	≥ 40°
Catchment morphology x_4 (–)	x_{41}	$Z < 0.3$
	x_{42}	$Z = 0.3–0.7$
	x_{43}	$Z ≥ 0.7$
Valley orientation x_5 (–)	x_{51}	Sunny slope
	x_{52}	Shady slope
Loose material reserves x_6 (10 ⁴ m ³ km ^{–2})	x_{61}	< 1 × 10 ⁴ m ³ km ^{–2}
	x_{62}	1–5 × 10 ⁴ m ³ km ^{–2}
	x_{63}	≥ 5 × 10 ⁴ m ³ km ^{–2}
Main loose material position x_7 (–)	x_{71}	Upstream or tributary
	x_{72}	Middle and lower reaches
	x_{73}	Toe of gully
Antecedent precipitation x_8 (–)	x_{81}	Inadequate
	x_{82}	Medium
	x_{83}	Adequate
H_{1p} rainfall intensity x_9 (mm)	x_{91}	< 30 mm
	x_{92}	≥ 30 mm

Table 7. Quantitative model eigenvalue.

Model	R^2	Standard deviation
1	0.749	0.289

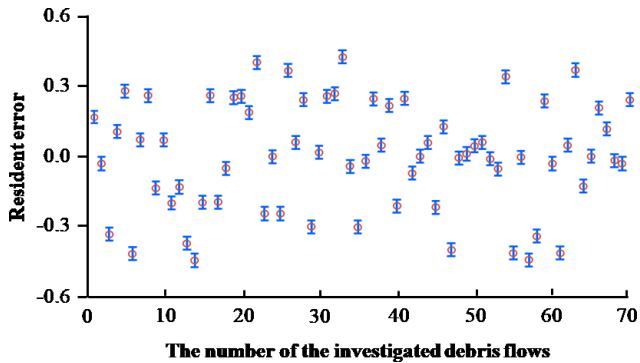


Figure 5. Comparison of actual susceptibility and predicted actual susceptibility.

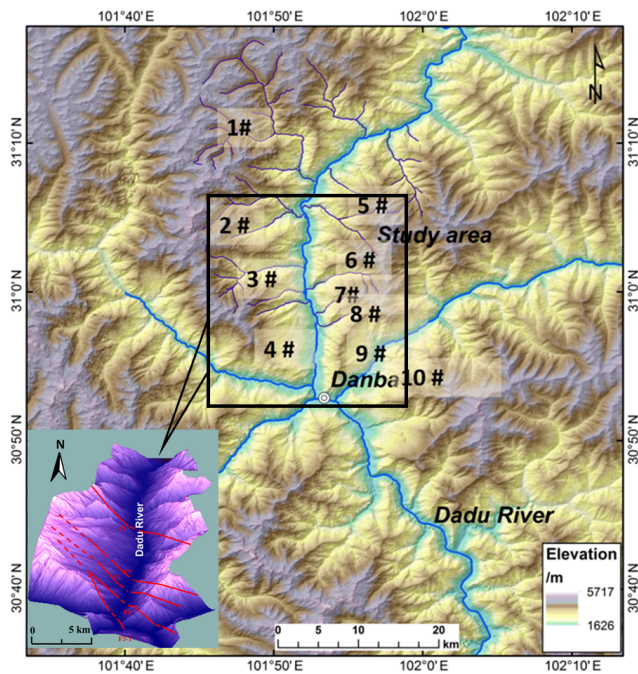
susceptibility, medium-susceptibility, and high-susceptibility debris flows are 78.5 %, 92.3 %, and 82.0 %, respectively, which indicates that the proposed model can predict the debris flow susceptibility well.

5.3 Residual error analysis

Residual error is the difference between a group of values observed and their arithmetical mean. As shown in Fig. 5, the residual error of the model mainly fluctuates by ±0.45, which indicates that the regression line can fit the field value well, and the residual frequency is approximately close to the normal distribution.

Table 8. Prediction model accuracy.

Category	Low	Medium	High
Accuracy (%)	78.5	92.3	82.0

**Figure 6.** Residual distribution in the regression model of debris flow susceptibility.

5.4 Verification of proposed model

The Kaka basin is located on the upper part of the Dadu River, southeast of the Qinghai–Tibet Plateau. The valley is deep and the river runs from north to south. The regional topography is characterized by high altitudes in the east and low altitudes in the west. The terrain is composed of high mountains with elevations of 2000 m. There are three layers of wide valley mesas, and the uplift of mountains and river erosion is significant in this area. The river elevation in the Kaka basin is approximately 1800 m, the river width is 140–185 m, and the slope angle is approximately 45–60°. The main faults are denoted as F1, F5, F5-1, F6, and F7 in Fig. 6. The strike is in a northwest direction, and they have a 40–60° angle with the river. A series of debris flow gullies have occurred in the basin.

A total of 10 typical debris flow gullies upstream of the Dadu River are selected as samples for the model validation (as shown in Fig. 7, and listed in Table 9). The accuracy of the established model is verified through the comparison with field investigation results. Table 9 provides the relevant basic data for the samples. Each secondary index is transformed into a 0–1 mode, and all the samples are adopted to construct

**Figure 7.** Distribution of debris flow gullies in the Dadu river basin.

a 9×26 matrix. Table 10 shows the predicted susceptibility from the proposed model, and the actual susceptibility obtained by the field investigation. The comparison shows that the accuracy rate of the model is 90 %, and only the prediction result of the Linong Gully deviates from the actual susceptibility. Therefore, detailed field investigation was then carried out to analyze the debris flow susceptibility in the Linong Gully.

Figure 8 shows the catchment of the Linong Gully. The total area of the catchment is about 10.09 km^2 , and the total amount of loose material is about $4.04 \times 10^6 \text{ m}^3$. The soil material, as shown in Fig. 9, is mainly composed of block and crushed stone. Their particle sizes are generally 10–40 cm. In the calculation process, the catchment area is quite large and the loose material per catchment area is relatively very small, as shown in Fig. 8. Based on the data, the prediction susceptibility of the Linong Gully is 2.421, which is very close to the high susceptibility threshold value 2.5. Therefore, although there is a minor deviation, it can still be concluded that the proposed model can perform well in predicting debris flow susceptibility in southwestern China.

6 Conclusions

Debris flows frequently occurred in southwestern China and resulted in severe damage to dwellings and lifelines. Based on Hayashi's Type I quantification theory, an initiation susceptibility model of debris flows in southwestern China was proposed in this work. The following conclusions can be drawn.

1. According to the topography and geomorphology characteristics in southwestern China, the following nine indexes were used as evaluation factors of debris flow initiation susceptibility: the catchment area, longitudinal gradient, average gradient of the slope on both sides

Table 9. Sample data from Kaka area upstream of the Dadu River.

No.	Ditch name	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9
1	Luotuo	227.1	102	25	0.745	SE	0.87	Middle and lower	Adequate	43.8
2	Qiongsan	84.90	200	28	0.907	SE	10.67	Middle and lower	Adequate	43.8
3	Shuikazi	49.78	209	31	0.534	SE	4.82	Middle and lower	Adequate	43.8
4	Bawang	11.84	310	32	0.219	SW	2.36	Upstream	Medium	43.8
5	Shenluo	4.54	455	33	0.580	NW	42.46	Toe of gully	Medium	43.8
6	Mueryue	35.81	206	36	0.376	NW	10.08	Upstream	Adequate	43.8
7	Sezu	4.23	613	42	0.812	NW	26.24	Middle and lower	Adequate	43.8
8	Muerluo	11.93	358	34	0.546	NW	9.98	Upstream	Medium	43.8
9	Yaneryan	30.01	242	34	0.382	SW	5.64	Middle and lower	Medium	43.8
10	Linong	10.09	332	35	0.448	NW	24.30	Middle and lower	Medium	43.8

Table 10. Comparison of predicted values and actual measured values.

Number	1	2	3	4	5	6	7	8	9	10
Calculated Y value	2.562	1.805	1.764	2.540	2.748	2.167	1.705	1.843	1.348	2.421
Predicted susceptibility	High	Medium	Medium	High	High	Medium	Medium	Medium	Low	Medium
Geological judgment of actual susceptibility	High	Medium	Medium	High	High	Medium	Medium	Medium	Low	High
Result	Right	Right	Right	Right	Right	Right	Right	Right	Right	Wrong

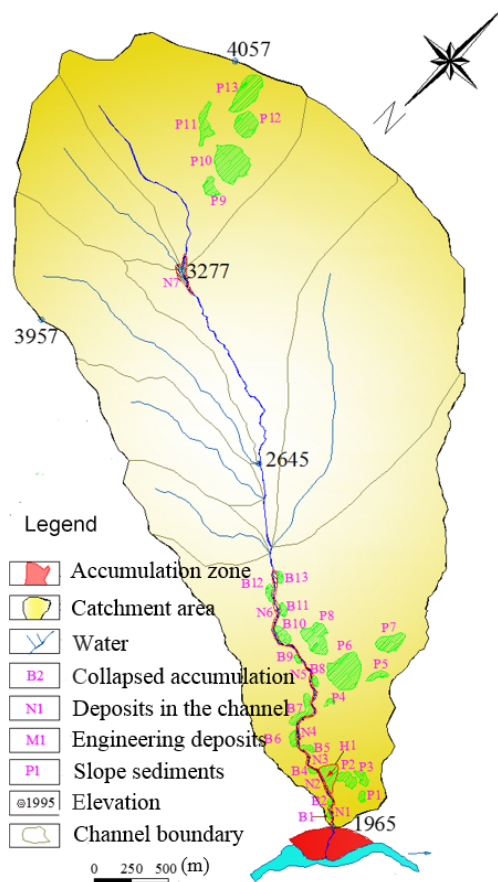


Figure 8. Distribution of loose deposits of Linong Gully.



Figure 9. Soil material in the Linong Gully deposit.

of the gully, catchment morphology, valley orientation, loose material reserves, location of the main loose material, antecedent precipitation, and rainfall intensity.

2. A total of 70 typical debris flow gullies distributed along the Brahmaputra River, Nujiang River, Yalong River,

Dadu River, and Ming River were investigated as statistical samples. The parameters of the prediction model were obtained based on Hayashi's quantitative theory and regression analysis.

3. The proposed model was applied to analyze the initiation susceptibility of 10 debris flow gullies located upstream of the Dadu River, and the result showed that the judgment coincidence rate is 90 %, indicating that the proposed model can accurately predict the initiation susceptibility of debris flow gullies in southwestern China.

Data availability. The data in this paper are not provided due to the confidentiality. Notwithstanding, the authors will try to address specific requests for scientific purposes.

Author contributions. FJ developed the model. RL did the field investigation. ZD prepared the manuscript with contributions from all co-authors.

Competing interests. The authors declare that they have no conflict of interest.

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