Discrimination of debris flow in narrow-steep type and wide-gentle type gullies in Wenchuan meizoseismal area

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The debris flow disasters in the Wenchuan meizoseismal area are dominantly triggered by the gully-type debris flow. Research on its classification method can be of great theoretical value and practical significance for developing targeted prevention measures. The current empirical classification method has some disadvantages, such as inconsistent discrimination criteria and poor practicability. In this paper, in order to overcome these drawbacks, the topography, rainfall, and source characteristics data of 176 gully-type debris flows in the Wenchuan "5.12" meizoseismal area since 2008 were collected and divided into the narrow-steep, transitional, and wide-gentle types based on field investigation. The narrow-steep type gullies are mainly concentrated in small catchments with severe erosion. In contrast, the wide-gentle type gullies are often characterized by big catchments, gentle vertical slopes, and debris flows movement dominated by deposition. An empirical discrimination method for debris flow gullies is proposed based on the characters of the gullies in the meizoseismal area, and a mathematical discrimination model named Gully Geomorphology Index (GGI) is also constructed. The results from existing cases indicated that both methods were accurate to discriminate between the narrow-steep and wide-gentle debris flow gullies. According to the empirical discrimination method, among the 176 channel-type debris flows, the numbers of narrow-steep, transitional, and wide-gentle channel types are 105 (59.66%), 12 (6.82%), and 59 (33.52%), respectively. While for the GGI method, the value 0.05 and 0.10 were defined as the threshold of the three types, and the distribution of the results is 104 (59.09%) for the narrow-steep type, 16 (9.09%) for the transitional type, and 56 (31.82%) for the narrow-steep type, which can better classify the transitional type gullies and is more practical. We hope that the discrimination methods proposed in this paper will help better understand the disaster-causing mechanism and improve the prevention measures of debris flow in the Wenchuan meizoseismal area.

1 Introduction

Since the 2008 "5.12" earthquake, mega flash floods and debris flows have occurred in Wenchuan, Dujiangyan, Mianzhu, and other strong seismic regions for many years, causing huge losses to local people's lives and properties (Fan et al., 2018). Debris flow is one of the main types of post-earthquake secondary disasters, of which abundant source material was produced and the critical rainfall threshold was consequently reduced by the activating effect of the earthquake (Koi et al., 2008; Wu et al., 2011; Tang et al., 2012; Yin et al., 2015; Qi et al., 2020). Many researchers have studied the area. Lombardo et al. (2019) retrieved the pattern of the ground motion through the landslides the Wenchuan earthquake itself triggered. Loche et al. (2022) studies the post-seismic response of a small area. According to the previous studies, the active period of debris flow after the earthquake will be 5–30 years (Tang et al., 2009; Huang and Li 2014; Zhang et al., 2014; Xiong et al., 2020), so it can be seen that the Wenchuan meizoseismal area is still in the high incidence period of post-earthquake debris flow. Debris flow gully can be generally divided into formation area, circulation area and accumulation area (Qu and Xiao, 2018). As the Wenchuan meizoseismal area is located in China's one and two-step boundary line in the Hengduan mountain range, the valleys are steep, the generation and concentration of runoff are urgent. Therefore, the outbreak of debris flow in this region after the earthquake is likely to be the gully type. Due to the different geomorphological characteristics of different channels, the formation of the channel debris flow disaster-causing mechanism and disaster-causing mode also differ. The current debris flow discrimination method have been unable to meet the requirements for the meizoseismal area debris flow disaster control, so there is an urgent need to effectively identify the type of debris flow to develop different types of prevention engineering in this region.

In past years, debris flow researches mainly focused on two types of debris flows: Slope debris flow and gully debris flow. Debris flows that have occurred after the Wenchuan earthquake in Southwest China have different formation mechanisms, erosion, deposition characteristics, and secondary disaster chain (Han 2016). Several research teams have studied the type of debris flows in this region. Yang et al. (2012) proposed the concept of narrow-steep channel type debris flow after studying 67 mudslide ditches that occurred in five areas of the Wenchuan meizoseismal area from 2008 to 2013 and analyzed their unique management difficulties and corresponding prevention and control countermeasures (Yang et al., 2015; Yang et al., 2020). Based on the characteristics of 13 debris flows along the Duwen Expressway in 2013, Han (2016)

divided the channel-type debris flows into two categories, narrow-steep and wide-gentle, and discussed their disaster mechanism. For each of them, the prevention measures were then given by Han et al. (2018). After analyzing the parameters of 145 debris flows that erupted after the Wenchuan Earthquake, Chen et al. (2018) proposed the concept of urgent-steep gully debris flows, summarized their motion and dynamic characteristics, and Li et al. (2020) studied their initiation characteristics through flume experiment. The above-mentioned "narrow-steep" and "urgent-steep" gullies refer to a kind of debris flow gully with a small watershed area, narrow flow channel, and steep channel gradient, in which the debris flow erupts, moves swiftly and violently. The term "narrow" describes the character of the width of the overall watershed and flow channel, while "urgent" and "steep" are used to indicate both the overall and the flow channel gradient. Therefore, we use narrow-steep type to describe this kind of debris flow gully, while the gullies with opposite characteristics are defined as a wide-gentle type.

Accurate classification of gullies in the meizoseismal area can help promote the mechanistic understanding of debris flow further and thus improve engineering management. To date,

FIGURE 1
Distribution of the 58 debris flow gullies in Wenchuan.
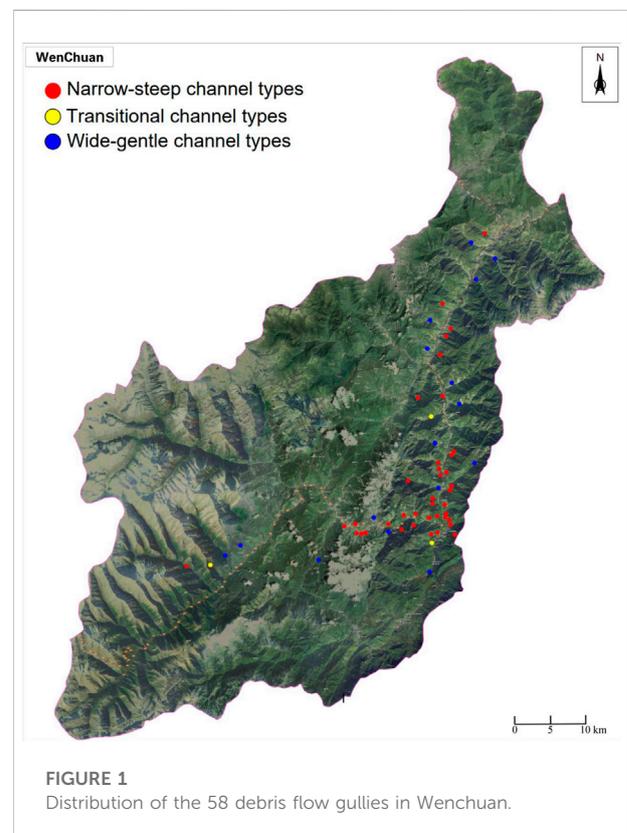
the identification of gully-type debris flows in the meizoseismal area is mainly based on the empirical methods proposed by different scholars. The main defects associated with these methods include the inconsistent selection of indicators and the conflicting identification rules. In addition, the gully-type debris flows in seismic regions are mainly divided into two categories: "narrow-steep/urgent-steep/steep" and "wide-gentle." However, field investigations found that the current empirical methods could not identify debris flows with characteristics in between. Hence, in order to address the deficiencies of the empirical discrimination method in the selection of indicators, discrimination criteria, classification, method operation, and other aspects, several improvements are made on the empirical discrimination method in this paper by combining the characteristics of the indicators of 176 debris flows in the meizoseismal areas. During the "5·12″" earthquake, Wenchuan was the area most affected by the earthquake and also had a high incidence of debris flows. Figure 1 shows the distribution of the 58 debris flow gullies in the Wenchuan area. On this basis, a gully geomorphological index (GGI) discrimination model is proposed. The results show that the model has good operability and accuracy and is of significant guidance to further research on the mechanism of disaster and its prevention and control.

2 Analysis of debris flow discriminant indicator

The quantitative indicators to describe the topography of debris flow gullies are divided into the planimetric indicators and spatial elevation indicators (Liao et al., 2011). The main indicators that can describe the feature of "narrow" are planimetric indicators, such as watershed area, watershed length, average watershed width, watershed integrity coefficient, average channel width, and main channel length. These metrics can be accessed through GIS (Chowdhuri et al., 2020; Pal et al., 2020; Roy et al., 2020). The main indicators that can describe the feature of "steep" are spatial elevation indicators, such as the relative elevation of the watershed, the average vertical slope of the catchment, and the slope of both sides of the trench. The meaning of the indicators is shown as follow:

(1) Drainage area F: The drainage area is the area enclosed by the watershed and represents the catchment capacity of the watershed. Its scale reflects the extent of debris flow gully development. If the other conditions remain invariant, the larger the watershed area, the greater the catchment capacity, the more sources of loose solids the watershed contains, and the greater the size and destructive capacity of the resulting debris flows (Li et al., 2014).

(2) Watershed length, average width, and watershed integrity factor: watershed length refers to the axial length of the watershed, which is generally the same as the main gully length when studying the debris flows (Wang et al., 2020). Since the watershed is mostly irregular in shape, the width characteristic is often expressed as the average watershed width B, which is determined as $B = F/L$, where L is the main channel length. The watershed integrity coefficient reflects the morphological characteristics of the watershed, which is determined as $\delta = F/L^2$. The smaller the coefficient, the narrower the watershed. The watershed integrity coefficient is very closely related to the formation of debris flows. When $\delta < 1$, the shape of the watershed is narrow and the river slope is steep, which can easily lead to side slope collapse and accumulation in the riverbed, providing the material source conditions for debris flow generation (Zhou 1991; Chang et al., 2009).

(3) Average channel width: The average channel width is mainly dependent on the watershed's shape and the average width; it is positively correlated to the latter. The bottom width is usually measured to calculate the average width. However, most of the narrow steep debris flow gully has a profile for the V-shaped section, and the actual channel width under this section varies with the scale of the debris flow. The larger the scale, the greater the average channel width. Thus, it is difficult to determine the width of the flow channel in the event of a debris flow and unreasonable to use only the bottom width as the proxy for the average channel width. Therefore, the average watershed width is selected to represent the width information.

(4) Relative elevation difference of the catchment: the relative height difference of the watershed quantitatively reflects the spatial height variation of the debris flow gully. The more significant the difference in elevation, the greater the potential energy converted into kinetic energy, and the stronger the athletic ability for debris flow (Wang et al., 2020).

(5) Average vertical slope of the channel I: vertical slope reflects the steepness of the gully, generally using the average longitudinal ratio of the original area and circulation area to represent (Li et al., 2014; Wang et al., 2020). The high average vertical slope indicates that the gully is in the formative-developmental stage in geomorphological development. With narrow gully and severe erosion, debris flow frequently occurs (Wang et al., 2020).

In summary, we selected the watershed area, the average watershed width, the watershed integrity coefficient, and the main channel length to represent the character of width. The relative elevation of the watershed and the average vertical slope of the catchment are selected to represent the character of the slope.

TABLE 1 The existing empirical discrimination methods for channel-type debris flow in the meizoseismal area.

Type of gully	Watershed area (km²)	Watershed integrity coefficient	Average channel width(m)	Relative elevation difference of catchment(m)	Average vertical slope of the channel (‰)	References
Narrow-steep	≤5	≤0.4	—	≥1000	≥300	Yang et al. (2015)
	<10	—	<30	—	>300	Han (2016), Han et al. (2018)
	<3.5			767–2238	>400	Li et al. (2020)
	<5	<0.4	—	—	>300	Chen et al. (2018)
Wide-gentle	>10	—	>50	—	<200	Han (2016)

3 Topographical features of the debris flow gully in the meizoseismal area

Table 1 summarizes previous studies' existing empirical discrimination methods for debris flow gullies. Still, for many gullies, like Anjia gully (F=9.17km², I= 434‰, δ=0.28, the width in circulation area: 10–30 m) and Bayi gully (F=8.63 km², I=366‰, δ=0.44), they have a typical character of narrow-steep gullies such as large longitudinal gradient and narrow circulation area. Although they are not fully meeting the specific parameters given in Table 1, they should also be classified as narrow-steep gullies (Zhao et al., 2021). In addition, the different indicators and criteria proposed by other investigators may result in the same gully being classified as different types by using different empirical discrimination methods. Due to different types of gullies having different disaster-causing mechanisms, this discriminant bias will significantly impact the later theoretical research and engineering control. For instance, wide-gentle gullies are always dominated by siltation, and the treatment engineering measures are often adopted as intercepting sources in the upstream and drainage in the downstream.

In contrast, for the narrow-steep gullies, erosion is the main disaster. Consolidating the slope and bed of the gully and building a retaining dam at the gully outlet are effective methods for disaster control (Han 2016). Using treatment measures without considering the gully type may cause severe damage. Taking the Wenjia gully (F=7.81 km², L=3.25 km, H=1519 m) for example, it built many check dams to prevent the debris flow, while the debris flow occurred on 13 August 2010 filled many check dams and eventually destroyed the dams at the outlet, which caused 7 casualties, 39 injured, and 497 houses buried (Liu et al., 2017). Therefore, in order to discriminate the type of gullies more precisely, the topographical features of gullies are analyzed from six indicators based on the 176 cases.
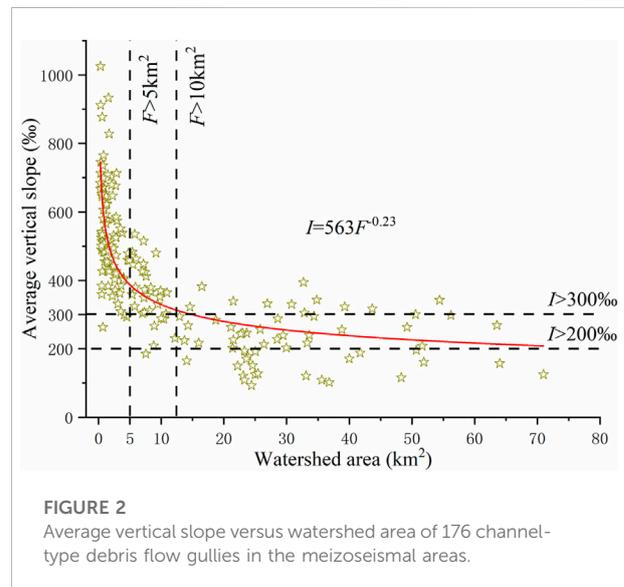

FIGURE 2
Average vertical slope versus watershed area of 176 channel-type debris flow gullies in the meizoseismal areas.

3.1 Watershed area

The watershed area distribution of the 176 cases is shown in Figure 2, The gullies with $F < 5$km², $5 \leq F \leq 10$km² and $F > 10$km² are accounting for 48.30%, 15.91%, and 35.80%, respectively, suggesting that one of the characteristics of channel-type debris flow in the meizoseismal area is tended to be a small watershed. This is because the meizoseismal area is located in middle-high gorge areas, where the topography is presented to be eroded landform and small-scale gullies densely distributed. Plenty of sources generated after the earthquake contributed to the transformation of these small-scale gullies into debris flow gullies (Ni et al., 2014). Table 1 shows that the gullies have been divided into two groups in previous studies, i.e., the wide-gentle gullies and the narrow-steep gullies (Yang et al., 2015; Chen et al., 2018), according to the value of the watershed area F. However, different investigators have used different F values to distinguish these two gullies types,

e.g., $F = 5km^2$ was suggested by Yang and Chen et al., while $F = 10km^2$ was preferred by Han (2016). Qu and Xiao (2018) also proposed that the range of watershed area of narrow-steep gullies area is between 0.3 and 10 km^2 and with an average value of 3 km^2 based on collected 145 gullies in the meizoseismal. There is a common view that narrow-steep gullies have watershed areas lower than 10 km^2, and the smaller the watershed area, the better it fits the features of narrow-steep gullies. Therefore, the condition $F < 5km^2$ can reflect more the character of the narrow-steep type. While for the gullies with a watershed area between 5 and 10 km^2 often have characters between wide-gentle and narrow-steep, defined as a transitional type. Thus, we propose that the corresponding threshold values of watershed area for the narrow-steep, transitional, and wide-gentle gully debris flows are $F < 5km^2$, $5 \leq F \leq 10km^2$, and $F > 10km^2$, respectively.

3.2 Average vertical slope of the channel

The average vertical slope of the channel is the key indicator controlling the formation and movement of debris flow. Takahashi (1980) found that when the vertical slope of the gully in the original area is above 286‰, the rainwater collected in the catchment area plays a more significant role in the occurrence of debris flows. The Institute of Mountain Hazards and Environment (IMHE) investigated the debris flow along Chengdu-Kunming railway and presented that the steep gully can be defined when the average vertical slope is greater than 250‰ (Chengdu Institute of mountain hazards and environment and Chinese Academy of Sciences, 1989); Specification of Geological Investigation for Debris Flow Stabilization (DZ/T2006) stipulates that a gully bed with a vertical slope greater than 12° (213‰) is highly susceptible to debris flow (resources 2006). Among the 176 cases in the meizoseismal area, 67.61% have an average vertical slope greater than 300‰, indicating that most debris flow gullies are steep, which endowed the debris flow a large amount of kinetic and potential energy, causing large-scale scouring and deposition. The Scholars (Chen et al., 2018; Han et al., 2018) often used the average vertical slope $I > 300$‰ as a criterion to determine narrow-steep channel debris flows (Table 1), while Han et al. proposed that the average vertical slope $I < 200$‰ is likely to generate wide-gentle channel debris flow. So in this study, we adopted the existed views and defined that the average vertical slope between 200‰ and 300‰ belongs to transitional type gullies.

Figure 2 shows that the gully average vertical slope tends to decrease with the increasing watershed area, and their relationship satisfies the curvilinear distribution of the dimensionless power function (Qu and Xiao 2018; Lyu et al., 2022). 68.91% of the gullies with the average vertical slop $I > 300$‰ are gathered in the watershed area $F < 5km^2$,
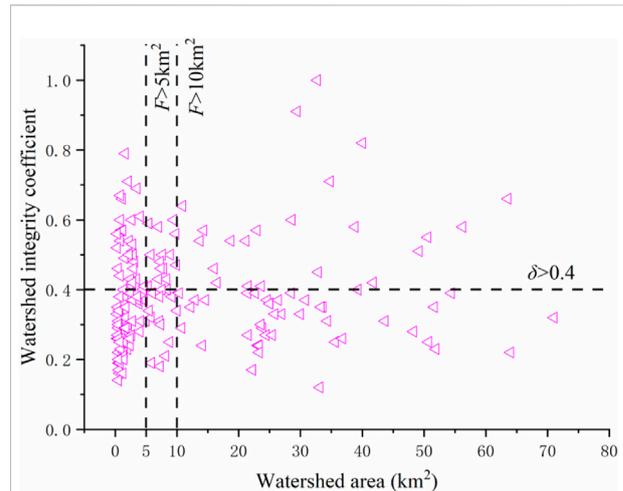

FIGURE 3
Watershed integrity coefficients versus watershed area of 176 channel-type debris flow gullies in the meizoseismal areas.
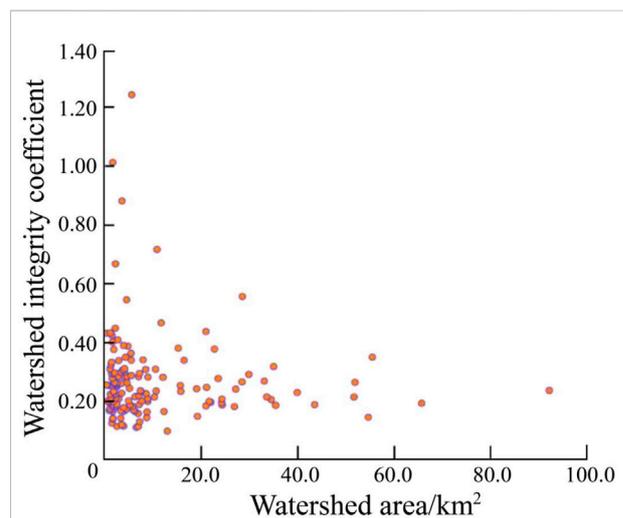
FIGURE 4
Watershed integrity factor and catchment area of 145 channel-type debris flows in the meizoseismal area (Chen et al., 2018).

representing the narrow-steep debris flow gully. 95.65% of gullies with the average vertical slop $I < 300$‰ are clustered in the watershed area $F > 10km^2$, representing wide-gentle gullies. This phenomenon can be explained as when the watershed area is small, the gully is in the formation-development stage, the effect of water flow downcutting erosion is severe, shaping high slope gradients and gully-bed ratios; With the increasing of the catchment area, the gullies evolution comes to an end, the degree of channel incision decreases, making it hard to satisfy the hydrodynamic conditions required to initiate a debris flow.

3.3 Watershed integrity coefficient

Previous studies often used $\delta < 0.4$ as a condition to verdict narrow-steep gullies (Yang et al., 2015). Figure 3 plots the watershed integrity coefficients against a catchment area for all the cases. 60.80% of the 176 gullies have watershed integrity coefficients less than 0.4. From the aspect of the watershed area, there are 85 debris flow gullies with a catchment area $F < 5km^2$, of which 63.53% (i.e., 54) had a watershed integrity coefficient $\delta < 0.4$; and of the 63 debris flow ditches with a watershed area $F > 10km^2$, 65.08% (i.e., 41) had a catchment integrity factor $\delta < 0.4$. So, it can be seen that regardless of the size of the watershed, the watershed integrity coefficients in the meizoseismal area showed a predominance of less than 0.4. In addition, Chen et al. (2018) analyzed the relationship between the watershed integrity coefficient and the watershed area for 145 channel-type debris flow gullies in the meizoseismal area. The results are replotted in Figure 4. which shows that the watershed integrity coefficient $\delta < 0.4$ is accounting for 75%; Qu and Xiao (2018) also found that the watershed integrity coefficient of channel-type gullies in the meizoseismal area is gathered between 0.1 and 0.4 and with an average value of 0.26, which indicates that $\delta < 0.4$ in strong seismic areas is a common phenomenon, there is no clear relationship between the watershed integrity coefficient and the watershed area, using this condition to represent the feature of "narrow" is inadequate. Thus, this study only used the watershed integrity coefficient as a reference index.

3.4 Relative elevation difference of catchment

Yang et al. used the condition $H > 1000m$ to discriminate the character of narrow-steep gullies. However, 139 out of the 176 watersheds have a relative height difference $H > 1000m$, accounting for 78.98%. This indicates that this condition is a common characteristic of channel-type debris flows in the meizoseismal area. Qu and Xiao (2018) proposed that the relative height difference range of narrow-steep gullies is between 896m and 2586 m where $H > 1000m$ could represent the characteristic of "steep" However since the meizoseismal area belongs to the alpine-gorge area., many wide-gentle gullies also present high relative elevation differences (e.g., Taoguan gully, watershed area: 50.86 km^2, relative elevation difference:2901 m). Thus, since this condition does not distinguish well between the two types of gullies, it is therefore used as a reference in the discrimination method.

3.5 Main channel length and average watershed width

The length of the main channel determines the flow length of the debris flow and the volume of erosion sources along the way,

reflecting its energy and destructive power. From the 176 cases, 109 (61.9%) have a main gully length less than 5 km, showing the short gully is the main feature of the debris flow gullies in the meizoseismal area. Figure 5 indicates that the main channel length and watershed area satisfies a linear distribution with a positive correlation (R^2=0.84). Their control effect on debris flow outbreaks is similar. With the decrease of the watershed area, the main channel length gets short, making it unfavorable to store loose material while conducive to debris flow initiation. Under the condition of narrow-steep gully F<5 km^2, the main gully length satisfies L<5 km. Since the main gully length strongly correlates with the watershed area, L<5 km is used in this paper as a secondary discriminant condition.

The equation B=F/L can calculate the average watershed width because the main channel length is consistent with the watershed length. Figure 5 shows 63.6% (112) gullies are satisfied with condition B<2 km, indicating that the long-narrow basin form is typically characteristic of gullies in the meizoseismal area. The relationship of watershed area and average watershed width satisfy a linear distribution (R^2=0.83) and under the condition of F<5 km^2 for narrow-steep gullies, the average basin widths all satisfy B<2 km, so B<2 km is used as a secondary discriminant.

4 Rainfall and source characteristics

Wenchuan meizoseismal area belongs to tectonically eroded mid-alpine landscapes, and the topography significantly influences the climate. When encountering mountains, the air current lift results in clouds and rainfall, so the precipitation and rainy days increase with mountain elevation (Gu et al., 2005). Local heavy rainfall is mainly concentrated in the debris flow gullies catchment area. Therefore, the heavy rainfall that triggers debris flow is characterized by concentrated precipitation areas, rapid confluence, and uneven spatial distribution, which are highly favorable to the occurrence of debris flows (Zhang et al., 2014).

The rainfall in Wenchuan meizoseismal area is abundant. The average annual precipitation for the last 56 years is 719. 70 mm, with a large inter-annual variation and an oscillating upward trend. Statistics show that the average annual rainfall before the earthquake was about 716 mm, and the average annual rainfall from 2008 to 2017 after the earthquake was 752. 61 mm, which has increased by 5. 17% compared with the pre-earthquake period. With more precipitation, the loose hills are more prone to geological hazards (Guo et al., 2017). As shown in Figure 6, precipitation during the year was mainly concentrated between June and September. Approximately 70% of precipitation occurs in this period (Tang et al., 2016). Previous studies found that the critical rainfall intensity of debris flow is between 15.8 and 56.5 mm/h in the Wenchuan meizoseismal area. Also, the annual thresholds for debris flows have increased each year over the past years loose vegetation recovered (Guo et al., 2016).
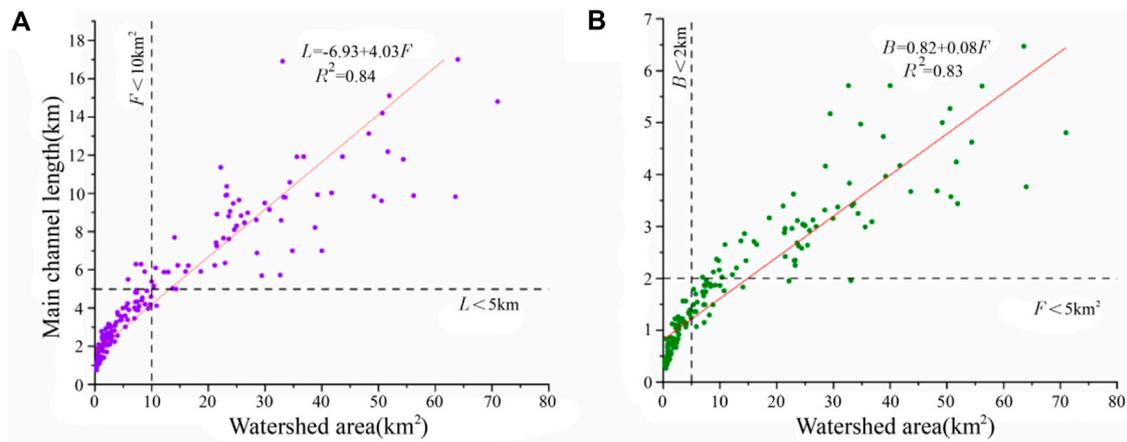
FIGURE 5
(A) Main channel length versus Watershed area **(B)** Average watershed width versus Watershed area.
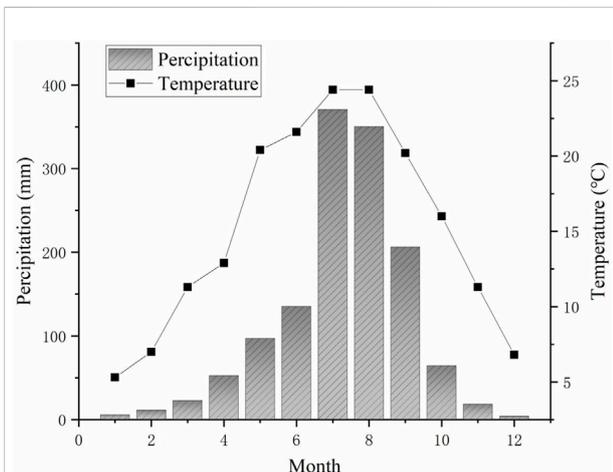

FIGURE 6
Average temperature and precipitation in the meizoseismal area from 1965 to 2015.

Debris flow outbreaks result from the combined effect of the previously accumulated rainfalls and the recent rainfalls (Jiang et al., 2021; Li et al., 2021). The short duration with high-intensity rainfall plays a decisive role in triggering debris flows. This precipitation process can rapidly form larger flood peaks within a certain range of the debris flow basin, which induces the loose deposits to be piled up in the gully or washed out. Besides, the continuous light rainfall that often occurs during the rainy season in the meizoseismal areas saturates the water content of loose soil, increases its volume weight, reduces its shear strength and stability, resulting in a reduction in the critical rain intensity required to trigger debris flow, which facilitates debris flow activity.

The sources in the study area are mainly divided into landslide accumulation sources, channel accumulation sources, and slope erosion sources. Due to the increase in adverse geological phenomena caused by the strong earthquake, both the landslide deposit and channel deposit sources increased significantly. The proportion of dynamic storage also increased, providing a large amount of loose material for debris flow formation, resulting in a significant increase in the risk of channel-type debris flow in the meizoseismal area (Chen et al., 2012). In addition, during the earthquake, the mountain body was cracked and loosened under seismic waves, resulting in many critical slope bodies that were cracked but not slippery. Under the action of rainfall and self-weight, those potential sources will be disintegrated and piled up in the gully, recharging the sources in stages.

In terms of the source distribution, gully-type debris flow in the meizoseismal area has a concentrated source distribution, mainly accumulating in the gully, which is unstable. Compared to the wide-gently gullies, the narrow-steep gullies have a smaller catchment area but a larger storage capacity per unit area. For example, compared with Qipan gully, which has a watershed area of 54.2 km^2 and a dynamic storage capacity of 130,000 m^3/km^2 of loose material per unit area, the narrow-steep Maliu gully has a watershed area of 1.6 km^2 and a dynamic storage capacity of 940,000 m^3/km^2 of loose material per unit area, and the "7.10" debris flow washed out 100.58 million m^3 of solid material at one time (Zhang et al., 2012).

Five typical gully-type debris flows gullies were selected from the two massive debris flows in Yingxiu Township, Mianhao Township, and Yinxing Township in the Wenchuan meizoseismal area 2010.08.13 and 2013.07.10. The screening experiment was carried out on these gullies, and the gradation curves were obtained as shown in Figure 7. The gradation of solid particles from the deposition

FIGURE 7
(A) The gradation curves of five gullies (B) Clay mineral composition of the deposit source in the meizoseismal area.
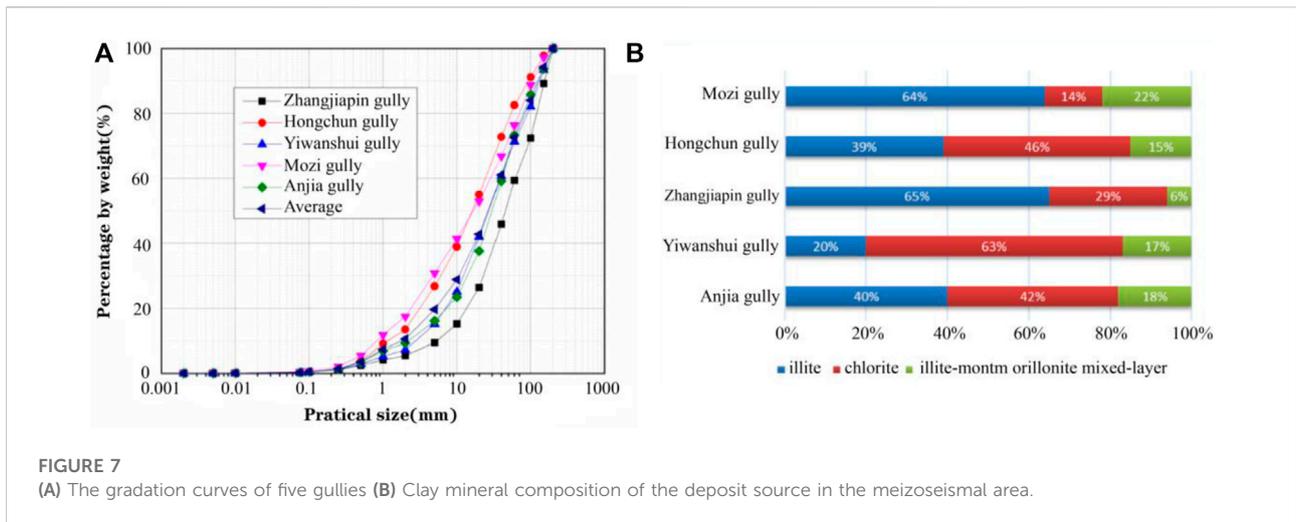
sources in the meizoseismal area is widely distributed and has good continuity. The gradation curves have an inhomogeneity coefficient greater than 5 and a curvature coefficient between 0.95 and 3, with no missing particle groups. The content of fine particles less than 0.075 mm is less than 0.5%, and the content of sticky particles less than 0.005 mm is less than 0.11%, with slight differences between different gullies. Most of the source particle size is smaller than pre-earthquake, and the loose solid material is mainly the mixture of block gravel and soil. The proportion of rock blocks is large, while the total amount of less than 200 mm blocks is also relatively large, which is easy to initiate.

Webb et al. (2008) investigated the relationship between the clay mineralogy and major-cation chemistry of fine-grained bedrock units and the occurrence of debris flows on the entire Colorado Plateau, finding that the debris flow producers are uniformly low in montmorillonite (5%) and high in illite and kaolinite (71%); conversely, fine-grained bedrock that does not produce debris flows has lower illite and kaolinite (25%) and higher montmorillonite (51%) content. Analysis of the clay mineral composition of the deposit source in the meizoseismal area by X-ray diffraction experiments revealed that it is mainly composed of three clay minerals (Figure 7): illite, chlorite, and illite-montmorillonite mixed-layer, with an average content of 45.6%, 38.8%, and 15.6% respectively. The total contents of illite and chlorite are over 75%, while the contents of illite-montmorillonite mixed-layer are below 25%, which indicates the clay mineral composition in the meizoseismal area is favorable to the formation of debris flow.

5 Discrimination method of gully-type debris flows in the meizoseismal area

Identifying the gullies type plays a vital role in understanding the mechanism of debris flow and designing corresponding

prevention engineering. The existing discrimination methods are always empirical and have defects such as inconsistent selection of indicators and conflicting identification rules. Based on the topographic feature of the 176 gullies in the meizoseismal area, the research for the discrimination method of debris flow gullies was carried out in this section.

The watershed area and average vertical slope of the channel, which reflect the character of width and slope, are selected as the main discrimination indicators in empirical discrimination. The average watershed width and main channel length are selected as secondary discrimination indicators. Table 2 shows the discrimination method. When the two main indexes belong to the same category, they can be discriminated directly. When one main index belongs to transitional, while the other one belongs to the other type, it can be discriminated to be narrow-steep or wide-gentle type. When there is a conflict between the two main indexes, comprehensive empirical discrimination should be made based on the specific values of the two indicators combined with the secondary index.

In using the empirical discriminant method to discriminate channel-type debris flows in the meizoseismal areas, the traditional empirical method needs to rely on the subjective human experience to make comprehensive judgments, particularly for cases where the results of two discriminant indicators are inconsistent. Take the Banqiao gully (watershed area: 26.96 km², average vertical slope: 332‰) as an example. It has the characteristics of "steep" as the slope exceeds 300‰; however, its watershed area is much larger than 10 km², which indicates the "wide" characteristic is more prominent, so it is categorized as the wide-gentle type. Although the empirical discrimination method can identify the gully type, it relies on subjective experience because of the terrain complexity, which reduces the applicability of the method. Therefore, based on the empirical discriminant method, a novel mathematical discriminant model is proposed by further analyzing and selecting the key discriminant indicators.

TABLE 2 Improved empirical discrimination model.

Indicators	Narrow-steep type	Transitional type	Wide-gentle type
Watershed area (km^2)	≤5	5–10	>10
Average vertical slope of the channel (‰)	>300	200–300	<200
average watershed width (km)	<2		>2
main channel length (km)	<5		>5

TABLE 3 Verification of Discrimination Results of Empirical method and GGI.

Name	L/km	F/km^2	B/km	Factor	H/m	I/‰	GGI	Empirical method	GGI	Han (2016)
Taoguan gully	14.20	50.86	3.58	0.25	2901	197.00	0.02	WG	WG	WG
Qipan gully	15.10	54.20	3.59	0.24	3050	192.00	0.02	WG	WG	WG
Chutou gully	8.90	21.70	2.44	0.27	2952	184.00	0.06	WG	T	WG
Xinqiao gully	5.00	14.30	2.86	0.57	2110	267.90	0.05	WG	T	WG
Yanglin gully	5.50	7.95	1.45	0.26	2124	386.00	0.18	NS	NS	NS
Sucun gully	4.25	5.79	1.36	0.32	2275	455.00	0.29	NS	NS	NS
Anjia gully	4.90	9.17	1.87	0.38	2350	417.00	0.14	NS	NS	NS
Lianshandaqiao gully	1.34	0.60	0.45	0.33	1159	483.00	4.31	NS	NS	NS
Huaxi gully	5.15	10.39	2.02	0.39	1897	287.00	0.09	T	T	WG
Mozi gully	4.00	7.40	1.85	0.46	1696	424.00	0.12	NS	NS	NS
Wayao gully	2.78	1.21	0.44	0.16	1796	646.04	3.41	NS	NS	NS
Futang gully	1.30	1.12	0.86	0.66	851	654.62	0.88	NS	NS	NS
Zhangjiapin gully	2.20	1.71	0.78	0.35	937	425.91	0.71	NS	NS	NS

Note: NS: narrow-steep channel debris flow; WG: wide-gentle channel debris flow; T: transitional channel debris flow.

There are two functional relations in the four indicators describing the width of the gully (including watershed area, average watershed width, watershed integrity coefficient, and main channel length), displayed as $\delta = F/L^2$ and $B = F/L$. So, any two indicators can deduce all the massages of the width of the gully. Similarly, a functional relationship exists between the average vertical slope of the channel and the relative elevation difference of catchment (i.e., I=H/L). So, we use two width indicators and one slope indicator to construct the mathematical function. Previous studies (Qu and Xiao 2018) found that the smaller the watershed area and the bigger the relative elevation difference, the more it fits the characteristics of narrow-steep gullies. When the area is fixed, the smaller the average width of the watershed, the more it fits the narrow-steep gullies. Therefore, the gully geomorphic index (GGI) is defined as the coefficient of discrimination, as shown in Eq. 1.

$$GGI = \frac{1}{F} * \frac{H}{B} = \frac{HL}{F^2} \qquad (1)$$

From the classification criteria of the improved empirical discrimination method, the narrow-steep gullies have characteristics of $F < 5\text{km}^2$, $B < 2\text{km}$ and $H > 1000\text{m}$, while the wide-gentle gullies have characteristics of $F > 10\text{km}^2$, it is

possible to define $GGI > 0.10$ as the narrow-steep channel debris flow. The same token $GGI < 0.05$ is used for the wide-gentle channel debris flow and $0.05 \leq GGI \leq 0.10$ the transition channel.

Han et al. (2018) investigated 13 debris flows gullies outbreaking along the Duwen expressway on 10 July 2013, and classified them into two categories: wide-gentle and narrow-steep type by analyzing their characteristics. Table 3 verified the accuracy of the two discrimination methods proposed in this paper by applying them to the 13 gullies. For narrow-steep gullies (e.g., Mozi gully, Anjia gully), both methods can identify them well, while for wide-gentle gullies, there are a few differences between the discriminant method and the results from Han, et al. The inconsistence gullies like Huaxi gully (main channel length: 5.15 km, watershed area: 10.39 km^2, average vertical slope: 287%) are charactered by medium-scale watershed area and relative gentle slope, which is defined as a transitional type. The discrimination methods proposed in this paper can better reflect the overall characteristics of gullies, then facilitates the targeting of prevention engineering.

The discrimination methods are applied to the 176 cases, and the results are shown in Tab X. For the empirical discrimination method, the number of narrow-steep channel type, transitional channel type, and wide-gentle channel type is 105 (59.66%), 12
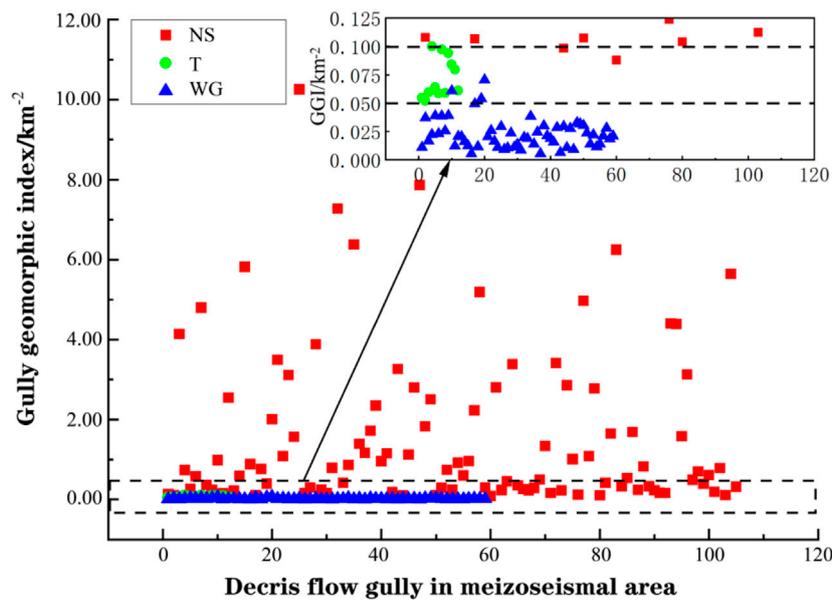
FIGURE 8
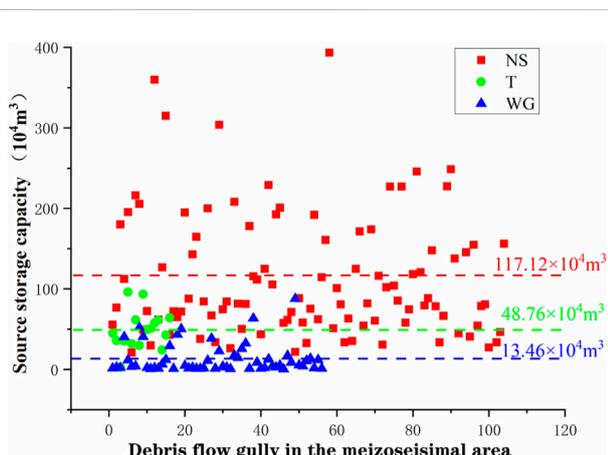The classification results of 176 gullies by the two methods.

FIGURE 9
The source reserves of the three types of debris flow gully.

(6.82%), and 59 (33.52%), respectively. While for GGI, the distribution of the result is 104 (59.09%), 16 (9.09%), and 56 (31.82%), respectively. Figure 8 shows the classification results of 176 gullies by the two methods, which is essentially in agreement.

Figure 9 shows the amount of source storage per km² for three types of debris flow gullies. The average volume of narrow-steep, transitional, and wide-gentle debris flow gully are 117.12×10^4 m³/km², 48.76×10^4 m³/km², and 13.46×10^4 m³/km², respectively. The source storage capacity per unit area of narrow-steep debris flow gully is 8.7 times greater than that of the wide-

gentle type, which indicates the narrow-steep gully is more prone to debris flow occurrence.

6 Discussion

Narrow-steep debris flow gullies are always taking the shape of "V", characterized by small watershed area (F < 5 km²), large longitudinal slope (I>300‰), significant relative height difference (H>1000), and the main channel length is generally less than 5 km (Figure 10). The bank slope is steep, leading the runoff generation and concentration rapidly and the source transport fast, thus the debris flow outbreaks suddenly. Due to the narrow width of the gully (5–30 m), it is more likely to erode the bank slope (Lyu et al., 2017), which further enhances the destructive capacity of debris flow. In the aspect of movement characteristic, the narrow-steep type debris flow is characterized by downward erosion and retrogressive erosion owing to the steep terrain, with no chance for deposition. Therefore, the focus of management should be on the control of undercutting and anadromous erosion of the gully.

Wide-gentle debris flow gullies are mostly "U" shaped, with characters of big watershed area (F>10 km²), gentle longitudinal gradient (I<200‰), and long main channel length (Figure 10). Generally, this type has broad gully bottom and multiple tributary ditches, which tend to form cascade failure under heavy rainfall. The movement characteristic of wide-gentle type debris flow is mainly deposition. The scale of the outflow
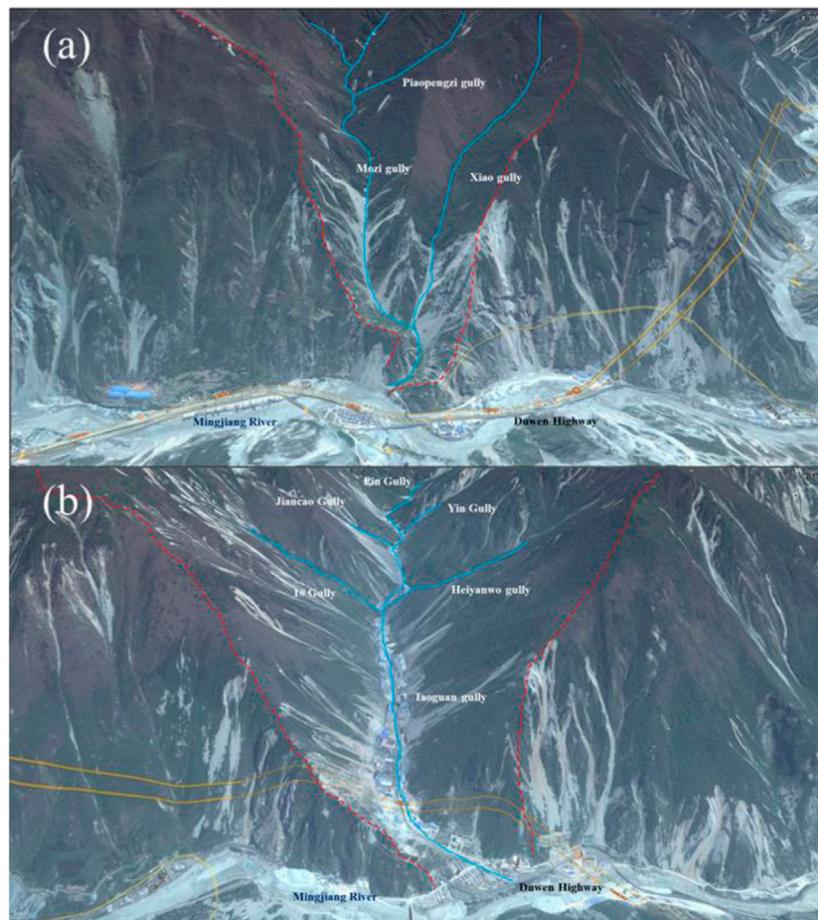
FIGURE 10
The typical narrow-steep and wide-gentle debris flow gullies: **(A)** The typical narrow-steep debris gully: Mozi gully (the watershed area: 7.4 km², the average vertical slope: 424‰, with "V" shaped section) **(B)** The typical wide-gentle debris gully: Taoguan gully (the watershed area: 50.86 km², the average vertical slope: 197‰, with "U" shaped section).

is huge, so it permanently blocks the river and forms barrier lakes. The multi-stage dam can effectively prevent the formation of barrier lakes and reduce the risk of collapse.

The current large-scale debris flow with a large watershed area, long main channel length, and gentle longitudinal slope are the future development trend of some small-scale debris flow with a small watershed area, short main gully length, and steep longitudinal slope. Lyu et al. (2022) found that the frequency of debris flow occurrence is closely related to the stage of gully evolution. As the watershed area grows, the frequency gradually increases until the watershed area reaches medium scale, which is assumed to be the morphologically most active gullies with the highest growth and incision rate. Then, as the watershed area further grows, the watershed morphology gradually stabilizes, and the mudflow frequency decreases affected by the milder gully gradient (Stock and Dietrich, 2006). From

the perspective of the gully evolution stage, the narrow-steep debris flow gully is currently in its young-adult stage. With the strong downward erosion, lateral erosion, and retrogressive erosion, the gully gradually becomes longer and wider, reflecting the characteristics of transitional debris flow gully as the gully evolution enters its late stage, the debris flow gully evolute to wide-gentle debris flow gully with low frequency of debris flow occurrence.

Comparing the results of the mathematical model and empirical discriminating method on 176 samples, it was found that for all three types of gullies, the results from these two methods were generally consistent with each other. Several inconsistent cases (Table 4) were found at the boundaries of the discriminant criteria, which have a character between narrow-steep and wide-gentle types. It can be seen that compared with the empirical discriminating method, the mathematical model (GGI) can

TABLE 4 The inconsistent gullies with the two methods.

Name	Main channel length (km)	Watershed area (km²)	Average channel width (km)	Watershed integrity factor	Relative elevation difference of catchment(m)	Average vertical slope of the channel (‰)	Gully geomorphic index	Improved empirical discrimination
Shilong Gully	3.91	7.3	1.87	0.48	1200	307	T	NS
Huaxi Gully	5.15	10.39	2.02	0.39	1478	287	T	WG
Dongguacao Gully	5.88	12.92	2.20	0.37	1730	294	T	WG
Hualin Gully	5.88	12.2	2.07	0.35	1360	231	T	WG

better classify the transitional type gullies. And form the aspect of operativity, the mathematical model is more practical and thus can be better used in the later remediation of debris flows in the meizoseismal area.

The preventive measures taken for different types of debris flow gullies are also different. For the wide-gentle gully type of debris flow, the management concept of "stopping mainly, supplemented by drainage" is used. For the narrow-steep type gully debris flows, the management concept of "consolidating the source and slope in the gully and stopping the siltation at the mouth of the gully" is used (Han 2016). For transitional mudslides, the above engineering measures can be chosen according to the actual situation.

In this paper, the proposed methods for classifying the gullies type in the meizoseismal area are based on the geomorphological perspectives. The sample quantity and study area restrict them. Further research should be conducted by expanding the sample size, combining DEM data with deep learning neural network algorithm (Chowdhuri et al., 2021; Saha et al., 2021; Chakrabortty et al., 2022).

7 Conclusion

Debris flow is a natural disaster that is widely distributed in some areas of the world with special topography and geomorphological conditions. Different types of debris flows should be subject to different control measures. Therefore, the study of mudslide discrimination methods is crucial. This paper collected 176 channel-type debris flow events in the meizoseismal area since 2008. Based on the analysis of gully character, two discrimination methods were proposed, and the following conclusions can be drawn:

(1) The gully-type debris flows in the meizoseismal area are characterized by small watershed areas, long strips, and steep longitudinal slopes, most of which have relative height differences greater than 1000 m, making them highly susceptible to debris flow. The short-duration, high-intensity rainfall in concert with continuous light rainfall is more conducive to debris flow formation. Besides, due to the earthquake disturbance, the sources in the meizoseismal area have increased significantly compared to the pre-earthquake period, and the clay mineral composition is favorable to the formation of debris flow.

(2) The debris flow gullies in meizoseismal area are classified as narrow-steep, transitional and wide-gentle types based on the topographical features. Narrow-steep debris flow gullies are mostly "V" shaped, with a small watershed area, steep channel slope, and narrow circulation channels. The debris flow moves fast in the channel, making it easy to form downward and lateral erosion. Wide-gentle debris flow gullies are mostly "U shape, with a larger basin area and gentler channel slope, the debris flow is easy to deposit in the channel, forming cascade failure and blocking the river. As the transitional stage of gully evolution, the transitional debris flow gully showed scour and deposition characteristics simultaneously. The source storage capacity per unit area of narrow-steep debris flow gully is 8.7 times greater than that of the wide-gentle type, indicating the narrow-steep gully is more prone to debris flow occurrence.

(3) The mathematical discrimination model named Gully Geomorphology Index (GGI) was constructed, and the value 0.05 and 0.10 were defined as the threshold of Narrow-steep, transitional and wide-gentle type gullies. Empirical method was applied to the 176 cases, showing the number of narrow-steep channel type, transitional channel type, and wide-gentle debris flow gullies are 105 (59.66%), 12 (6.82%), and 59 (33.52%), respectively. While for GGI, the distribution of discrimination results is 104 (59.09%), 16 (9.09%), and 56 (31.82%), which can better classify the transitional type gullies and is more practical.

At present, the world is encountering extreme climate and frequent natural disasters. The rapid identification of natural disasters is conducive to establishing a prevention and control system faster, and is of great significance to disaster prevention and reduction projects. The discrimination methods of narrow steep gully type debris flow and wide gentle gully type debris flow proposed in this paper greatly improve the speed of debris flow type discrimination, and the existing data show that these two methods have high reliability. We can use these two methods to construct numerical or experimental models of different debris flow gullies to further investigate their movement mechanisms and control measures. So as to promote the development of disaster prevention and reduction projects.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/supplementary material.

Author contributions

GX, DL, JJ, and QY planned the campaign; DL and JJ collected and analyzed the data; DL and MM wrote the manuscript draft; SQ, HL and QY reviewed and edited the manuscript.

Conflict of interest

JJ was employed by Sichuan Water Resources and Hydroelectric Investigation and Design Institute Co., Ltd, China. DL was employed by Yalong River Hydropower Development Company, Ltd, China.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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