Research Article

Risk Assessment of Debris Flows in Small Watersheds on the Northeast Margin of Qinghai-Tibet Plateau—A Case Study of Zhujiagou Watershed

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Received 19 November 2021; Accepted 18 January 2022; Published 8 February 2022

Academic Editor: Yonghui Wu

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In the Qinghai-Tibet Plateau, fractures and fault zones have developed in this area, where earthquakes and extreme rainfall frequently induce debris flow disasters, which seriously threaten the safety of the people and properties. In this study, Zhujiagou, Minxian County, Gansu Province in China, has a typical debris flow channel in a small watershed on the northeastern edge of the Qinghai-Tibet Plateau, which has been used as the case study for risk assessment. A debris flow-risk assessment method has been developed in this study. The fusion algorithm of entropy weight and coefficient of variation has been used to evaluate the susceptibility of debris flow in each tributary channel in the watershed. Further, numerical simulation of the debris flow events at the main channel and at the high-prone debris flow tributary channel has been carried out. The "7.18" Zhujiagou debris flow event has been used to verify that the accuracy of the numerical simulation is higher than 74.12%. This method has been applied to design the Zhujiagou debris flow-risk zoning under extreme rainfall conditions, aimed at forming a set of debris flow-risk evaluation system suitable for this type of small watershed. The results show that the peak single-width clear water flow at the mouth of the channel, the length of the channel, and the shallow surface rock formation are the main factors influencing the susceptibility of debris flow. The main tributaries of the watershed are Hagu channel, Zhuling channel, Songshu channel, and Langia channel which are all high-prone debris flow channels. The Zhujiagou debris flow accumulation fan under the designed 1% rainfall frequency will block the Taohe, which will threaten the safety of the residents and properties near the channel, at the mouth of the channel and in the urban area on the opposite bank of the Taohe. Compared with Hagugou, Zhulinggou, and Songshugou, the low-risk area is Langjiagou. The research results of this study can be used for evaluation methods and as a basis for preventing debris flow disasters on the northeastern edge of the Qinghai-Tibet Plateau.

1. Introduction

The northeastern margin of the Qinghai-Tibet Plateau is located in the west extension of the West Qinling tectonic belt in China [1]. It is located at the intersection of the north-south seismic belt and the Qilianshan seismic belt. There are developed active faults, strong seismic activities, and frequent mountain disasters. Mountain towns located here, such as Minxian County, Wudu, and Gansu, are mostly mud-rock flow areas [2–6]. Mud-rock flow disasters have severely restricted the economic and social developments in the region.

Zhujiagou in Minxian County, Gansu Province, is a typical small watershed with a debris flow channel on the...
northeastern edge of the Qinghai-Tibet Plateau in China. Debris flow disasters have occurred many times in the past [7]. In recent years, affected by the 2008 Wenchuan earthquake, and the 2013 "7.22" Minxian-Zhangxian Ms6.6 earthquake, the material sources in Zhujiajou have increased sharply, leading to a sharp increase in the risk of debris flow in this small watershed. It is very likely to erupt again. Large-scale debris flow disasters greatly threaten the lives and properties of residents in the river basin and urban areas. Therefore, it is urgently required to carry out a debris flow disaster risk assessment of the watershed so as to provide a scientific basis for disaster prevention and mitigation.

Debris flow-risk assessment methods can be roughly divided into two types: multifactor superposition method [5, 8–14] and numerical simulation method [15–20]. The differences between the two methods are as follows: (1) evaluation methods: for the multifactor superposition method, it is based on the data influencing factors of a debris flow. It is therefore necessary to carry out a comprehensive evaluation of the basin, which directly reflects the overall risk of the basin. For the numerical simulation method, it is based on the simulation of the mud depth and velocity of the debris flow eroding in the basin. It focuses on the inversion of the dynamic process of the debris flow, and uses this as a basis for risk assessment; (2) scope of application: for the multifactor superposition method, it is suitable for large, medium, and small watersheds. For the numerical simulation method, it is more suitable for small watersheds or specific valleys; and (3) evaluation purposes: for the multifactor superposition method, it is aimed at evaluating the occurrence of debris flows in each watershed in the future. For the numerical simulation method, it focuses on combining the intensity of the debris flow with the recurrence period [5, 6, 17, 21–23], simulating the movement process of the debris flow at different frequencies, and predicting the movement characteristics and accumulation area of the debris flow.

In this study, the above two types of methods have been combined. Through a detailed field investigation and data analysis, a multifactor superposition method combining entropy weight and coefficient of variation has been used to evaluate the susceptibility of Zhujiajou debris flow. On this basis, heavy rainfall conditions are carried out \((P = 1.6\%, \ P = 1\%)\). Numerical simulation of a mud-rock flow movement in Xiazhujiagou and its high-prone debris flow tributary channels has been verified by the comparison with field survey data. Finally, the risk zoning has been carried out based on the flow velocity, mud depth, and accumulation range. The results of this study can be used as a basis for the prevention and control of local debris flow disasters.

Zhujiajou is located in the northern part of the city of Minxian County, Gansu Province, China. It is a first-level tributary of the Taohe River. The drainage area is about 14 km², and the main channel is about 6.7 km long. It is separated from the county seat by a river. The basin is located on the northeastern margin of the Qinghai-Tibet Plateau, which is the intermediate transition zone of strain transmission and structural transformation between the East Kunlun fault zone and the northern margin of West Qinling. The Malutan fault is a high-angle thrust and a right-lateral strike-slip fault, inclined to the northeast, with an inclination of about 55°-70°. The hanging wall of the fault is dominated by the Permian carbon slate intercalated with quartz sandstone and siltstone. The surface layer is weathered. The thickness of the crust is 2–3 m, belonging to the medium-hardness massive clastic rock group. The footwall is dominated by the Triassic slate, sandy slate, and siltstone. The surface layer is severely weathered, and the thickness of the weathered crust is 5–8 m, which is weak. The strong surface rock and soil mass have been disturbed by earthquakes. The structure is therefore loose, and the trigger threshold of collapse and landslide has been lowered.

The terrain of Zhujiajou is high in the north and low in the south. It belongs to the middle-low mountain landform of tectonic erosion and denudation in the northern part of West Qinling. The altitude is between 2276 and 3017 m, and the relative height difference is 741 m. It is wide, extending from north to south in a curved shape. The section of the drainage basin changes from “V” to “U.” There are 33 gullies and 17 branch channels on both sides of the bank, including Langjiagou, Songshugou, Zhulinggou, and Hagugou. It is the main tributary of Zhujiajou. The basin is located in the transitional zone between temperate semihumid and alpine humid climate. The annual average precipitation is 560.8 mm. The precipitation is concentrated in May to September, accounting for more than 78% of the total annual precipitation. Most of it is short-term heavy rainfall in summer. Frequent activities to stimulate mudslides seriously threaten the safety of the residents and properties in the urban areas and river basins.

In summary, Zhujiajou has always been an important area for implementing debris flow prevention and mitigation in Minxian County. During the reconstruction after the devastating hail torrents and mudslides in Minxian County and the reconstruction after the Minxian-Zhang County earthquake, the drainage channels have been constructed at the mouth of Zhujiajou, Songshuzhigou, Langjiazhigou, Wangjiazhigou, and Songshusongshugou. Three blocking dams were built in Songshugou and one blocking dam was built in Wangjiazhigou. A geological schematic map of the Zhujiajou channel is shown in Figure 1.

2. Evaluation of Debris Flow Susceptibility Based on the Fusion Algorithm of Entropy Weight and Coefficient of Variation

2.1. Headings Principle of Fusion Algorithm. Information entropy, used to measure the uncertainty of things [24], can be expressed in the field of geological disasters as an impact factor carrying information entropy, which is inversely proportional to the probability of disaster occurrence. The process of calculating entropy weight through information entropy is as follows:

(1) Establish a standardized evaluation matrix:

\[
X = [x_{ij}]_{m \times n},
\]
In the formula, \( m, n, \) and \( x_{ij} \) represent the number of evaluation objects, the number of evaluation factors, and the standard value of the \( j \)th factor of the \( i \)th evaluation object, respectively.

(2) Determine the information entropy weight of the \( j \)th factor:

\[
\begin{align*}
e_j &= -\frac{1}{\ln m} \sum_{i=1}^{m} \frac{x_{ij}}{\sum_{j=1}^{n} x_{ij}} \ln \left( \frac{x_{ij}}{\sum_{j=1}^{n} x_{ij}} \right) \quad (2) \\
w_{ij} &= \frac{1 - e_j}{n - \frac{\sum_{j=1}^{n} e_j}{n}}.
\end{align*}
\]

where \( e_j \) is the information entropy of the \( j \)th factor and \( w_{ij} \) is the entropy weight of the \( j \)th factor.

The coefficient of variation is a normalized measure that expresses the degree of dispersion of the probability distribution. In the evaluation system, the greater the coefficient of variation of a factor, the more the factor can represent the difference within the system, and the greater the impact on the evaluation results. The weight of the coefficient of variation of the \( j \)th factor is as follows:

\[
w_{2j} = \frac{C_{v_j}}{\sum_{j=1}^{n} C_{v_j}}, \quad (3)
\]

where \( C_{v_j} \) is the coefficient of variation of the \( j \)th factor and \( w_{2j} \) is the weight of the coefficient of variation of the \( j \)th factor.

Relative entropy (Equation (4)) can be used to measure the difference between two sets of discrete vectors.

\[
h_{(x,y)} = \sum_{i=1}^{n} x_i \log \frac{x_i}{y_i}, \quad (4)
\]

where \( x_i \in X = (x_1, x_2, \ldots, x_n), y_i \in Y = (y_1, y_2, \ldots, y_n), x_i y_i \geq 0, i \in [1, n], \) and \( 1 = \sum_{i=1}^{n} x_i \geq \sum_{i=1}^{n} y_i. \)

According to the definition of relative entropy, the fusion vector \( W = (w_1, w_2, \ldots, w_n) \) and the vector group to be evaluated \( W_{\text{pre}} \) are introduced to minimize the sum of the distance between this vector, the weight vector of the entropy weight method, and the weight vector of the coefficient of variation method [13]. A distance planning model is established to solve the fusion weight:

\[
\begin{align*}
\min H(w) &= \sum_{j=1}^{p} \sum_{i=1}^{n} w_i \log \frac{w_i}{w_{ji}} \\
\sum_{i=1}^{n} w_i &= 1, w_i &> 0, w_j \in W = (w_1, w_2, \ldots, w_n).
\end{align*}
\]

In the formula, the physical meanings of \( p \) and \( n \) are the number of disaster evaluation models and the number of disaster evaluation factors, respectively, and \( w_i \) is the fusion weight of the \( j \)th factor.

2.2. Influencing Factors of the Susceptibility of Debris Flow.

Starting from the formation conditions of debris flow, precipitation, valley, and provenance, the main factors affecting the development of debris flow are shape coefficient, watershed area, distance from the valley centroid to a fault, valley density, channel length, main channel profile drop, and channel. There are a total of 12 evaluation factors for the peak clear water flow per unit width, source distribution, relative height difference, average slope of the basin, vegetation coverage, and shallow engineering rock formations. The actual values of all the factors are shown in Table 1.

Due to the small area of the study area, the rainfall in the tributaries during the same period of rainfall is close to each other. Therefore, rainfall has not been used as an evaluation factor. However, for the one-time short-duration and heavy rainfall that causes a mud-rock flow, the rainwater in the basin has short-term infiltration and little evaporation. Most of the surface runoff is used to stimulate the source to start and finally flows out through the channel mouth. So, the peak value of clear water flow per unit width at the channel
| Number | Shape factor | Drainage area, km² | Valley centroid fault distance, m | Valley density | Channel length, km | Main ditch, %o | Water flow, m³/s | Provenance distribution | Relative height difference | Slope | Vegetation coverage | Rock group |
|-------|--------------|---------------------|---------------------------------|---------------|------------------|---------------|----------------|----------------------|--------------------------|-------|-------------------|------------|
| 1     | 1.15         | 0.989               | 2262                            | 2.18          | 1192             | 94.75         | 0.35           | 1.70                 | 324                      | 20.41 | 3.42             | Medium weathered hard massive clastic rocks |
| 2     | 1.32         | 0.298               | 1417                            | 3.53          | 1051             | 235.85        | 0.06           | 1.08                 | 288                      | 21.52 | 2.14             | Medium weathered hard massive clastic rocks |
| 3     | 1.36         | 0.246               | 939                             | 2.12          | 521              | 210.37        | 0.15           | 2.56                 | 240                      | 16.07 | 0.00             | Medium weathered hard massive clastic rocks |
| 4     | 1.14         | 0.102               | 2414                            | 2.07          | 1438             | 198.15        | 0.48           | 4.04                 | 356                      | 20.88 | 5.34             | Medium weathered hard massive clastic rocks |
| 5     | 1.32         | 0.224               | 1188                            | 4.70          | 541              | 211.88        | 0.01           | 30.89                | 284                      | 18.15 | 4.50             | Medium weathered hard massive clastic rocks |
| 6     | 1.13         | 0.292               | 1401                            | 1.19          | 2761             | 174.17        | 1.14           | 7.30                 | 550                      | 21.12 | 15.86            | Medium weathered hard massive clastic rocks |
| 7     | 1.08         | 0.266               | 98                              | 2.48          | 660              | 254.17        | 0.31           | 1.57                 | 250                      | 20.29 | 0.00             | Strong weathering of gully head in gully mouth |
| 8     | 1.34         | 0.300               | 398                             | 3.79          | 712              | 317.37        | 0.07           | 5.08                 | 412                      | 21.43 | 6.78             | Strong weathering of gully head |
| 9     | 1.13         | 0.166               | 143                             | 0.96          | 127              | 242.57        | 0.06           | 1.11                 | 204                      | 22.30 | 0.00             | Strong weathering of gully head in gully mouth |
| 10    | 1.15         | 0.327               | 631                             | 4.59          | 1502             | 86.51         | 0.14           | 2.66                 | 306                      | 24.46 | 29.39            | Hard layered fractured rock in strong weathering |
| 11    | 1.21         | 0.150               | 322                             | 2.80          | 419              | 338.74        | 0.04           | 1.08                 | 240                      | 24.43 | 2.55             | Hard layered fractured rock in strong weathering |
| 12    | 1.21         | 0.206               | 832                             | 1.60          | 1287             | 108.74        | 0.84           | 8.84                 | 570                      | 23.84 | 2.52             | Strong weathering in gully head |
| 13    | 1.31         | 0.283               | 318                             | 1.97          | 555.84           | 395.80        | 0.07           | 1.06                 | 388                      | 23.12 | 7.88             | Strong weathering in gully head |
| 14    | 1.24         | 0.254               | 759                             | 4.53          | 622.09           | 252.38        | 0.06           | 1.13                 | 309                      | 26.40 | 20.67            | Hard layered fractured rock in strong weathering |
| 15    | 1.19         | 0.247               | 773                             | 2.00          | 188.07           | 297.76        | 0.05           | 1.02                 | 323                      | 23.23 | 15.36            | Hard layered fractured rock in strong weathering |
| 16    | 1.11         | 0.209               | 796                             | 1.57          | 327.14           | 247.60        | 0.41           | 0.64                 | 291                      | 23.73 | 3.65             | Medium weathered hard massive clastic rocks |
| 17    | 1.19         | 0.361               | 1625                            | 2.59          | 289.24           | 190.15        | 0.37           | 4.97                 | 318                      | 21.70 | 3.16             | Medium weathered hard massive clastic rocks |
mouth can directly reflect the runoff generation and the confluence capacity of the basin. The historical maximum daily rainfall near the basin is 61.5 mm (May 10, 2010). According to the daily rainfall data from June to August 2020 provided by the Minxian Meteorological Bureau, the rainfall of 59.3 mm on July 18 is the maximum precipitation during the 2020 local rainy season. In this study, based on the Rain Module of the software FLO-2D, the rainfall distribution is shown in Figure 2. The SKK model suitable to be used for small watersheds in the western mountainous area has been selected [25]. Further, the “7.18” heavy rainfall-runoff simulation in Zhujiagou has been carried out, and the peak value of clear water runoff at the mouth of each tributary has been extracted. The peak values of the flow process are shown in Table 1.

According to the industry standards [26] and related research results [27, 28], these factors, which are listed in Table 2, have been divided into four levels: strong (IV), medium (III), weak (II), and underdeveloped (I). Then, by substituting the grading results into the fusion algorithm, the weight has been calculated. The grading standards and the weight calculation results are shown in Table 2. Further, the grading results are also shown in Figure 3.

2.3. Evaluation Results of the Susceptibility of Debris Flow. After the multifactor superposition calculations, the evaluation results of the debris flow susceptibility of the micro-watershed in Zhujiagou are between 0.424 and 0.624, and the natural discontinuity method in statistics has been used to classify the channels (Figure 4): high-prone debris flow channel (0.526, 0.624), medium-prone debris flow channel (0.464, 0.526), and low-prone debris flow channel [0.424, 0.464]. Combining with the field investigation and the analysis in August 2020, the main tributary channels in the basin are Hagu, Zhuling, Songshugou, and Langjia-gou channels which are all channels that are highly prone to debris flow.

3. Risk Assessment of Zhujiagou Debris Flow Based on FLO-2D

Considering the proneness to debris flow in the tributary channel in Zhujiagou and the accuracy of the acquired ALS012.5 m digital elevation data (DEM), the main tributary channels with high probability of debris flow in the study area have been selected: Hagu channel, Zhuling channel, and Songshu channel. Lang carried out the evaluations on the home channel and the main channel.

3.1. Working Condition Setting and Calculation Parameters. The software FLO-2D is based on non-Newtonian fluid and uses the central finite difference method to solve the fluid motion control equations iteratively, thereby simulating the motion process of a flood and debris flow [17]. The calculation conditions are set as follows:

3.1.1. Rainfall Conditions. According to the daily precipitation data of Minxian from 1981 to 2010, the index extrapolation method has been used to fit the annual rainfall frequency curve (Figure 5) in Minxian (Equation (6)). It can be seen that the largest single-day rainfall in the Zhuijiagou Basin in 2020 is 59.3 mm: “7.18” heavy rainfall, with an annual rainfall frequency of 1.6%, which is a 50-year heavy rain event. This rainfall has been set as the simulation condition. In addition, according to Equation (6), a single-day rainfall of 99.38 mm has been selected as the once-in-a-hundred-year extreme precipitation condition for simulation.

\[ R = 1.2P^{0.9518} - 1.699, \]  

where \( R \) is the rainfall, \( P \) is the annual rainfall frequency, and the confidence probability of the fitting formula is 95%.

3.1.2. Conditions for Prevention and Control Projects. After the “5.10” severe hail and the “7.22” Minxian-Zhangxian earthquake, the debris flow in Zhujiagou has increased
Table 2: Development grade and weights of the rating factors.

| Impact factor                     | Strong development (IV) | Medium development (III) | Weak development (II) | Underdevelopment (I) | Entropy weight | Coefficient of variation weight | Right to integration |
|-----------------------------------|-------------------------|--------------------------|-----------------------|----------------------|----------------|-------------------------------|---------------------|
| Shape factor                      | <1.1                    | 1.1~1.25                 | 1.25~1.37             | >1.37                | 0.084          | 0.060                         | 0.062               |
| Drainage area                     | 0.2~5                   | 5~10.0                   | <0.2; 10~100          | >100                 | 0.084          | 0.038                         | 0.039               |
| Valley centroid fault distance    | 0                       | <5                       | 5.0~10                | >10                  | 0.084          | 0.044                         | 0.046               |
| Valley density                    | >6                      | 6~4.0                    | 4~2.0                 | <2.0                 | 0.083          | 0.114                         | 0.119               |
| Length of main groove             | >10                     | 10~5.0                   | 5~1.0                 | <1                   | 0.082          | 0.132                         | 0.137               |
| Main ditch                        | >213                    | 213~105                  | 105~52                | <52                  | 0.084          | 0.058                         | 0.060               |
| Water flow                        | >1.1365                 | 1.1365~0.7725            | 0.7725~0.3085         | <0.308465            | 0.080          | 0.189                         | 0.196               |
| Provenance distribution           | >10                     | 10~5                     | 5~1                   | <1                   | 0.084          | 0.088                         | 0.092               |
| Relative height difference        | >500                    | 500~300                  | 300~100               | <100                 | 0.084          | 0.072                         | 0.075               |
| Average slope of the basin        | >32                     | 25~32                    | 15~25                 | <15                  | 0.084          | 0.046                         | 0.047               |
| Vegetation coverage               | <10                     | 10~30                    | 30~60                 | >60                  | 0.084          | 0.036                         | 0.037               |
| Rock group                        | Strongly weathered stratified cataclastic rock (0.75, 1) | Strong weathering and moderate weathering (0.5, 0.75) | Strong weathering and moderate weathering (0.25, 0.5) | Moderately weathered massive clastic rock (0, 0.25) | 0.082 | 0.123 | 0.128 |
| Range                             | 0.875                   | 0.625                    | 0.375                 | 0.125                |                |                              |                     |
| Value                             |                         |                          |                       |                      |                |                              |                     |

Range: [0.125, 0.875]
significantly, and the adjacent county seat is at a greater risk.

Dingxi Land and Resources Bureau is effective in preventing
and controlling geological disasters. See Table 3 for the con-
struction measures in the simulation area.

Rainfall and the control engineering conditions are com-
bined to simulate the hazards of debris flows in the high-
prone debris flow channels under three working conditions:
(1) 7.18” heavy rainfall (once in 50 years) when there is no
control project, (2) 7.18” heavy rainfall (once in 50 years)
when there is no control project and debris flow erupts,
and (3) when there is a prevention and control project, there
is a heavy rainfall and debris flow erupts in a hundred years.
The working conditions (1) and (2) have been used as the
control group to evaluate the effectiveness of the engineering
measures. The working conditions (2) and (3) have been
used as the control group to analyze the movement trend
of the debris flow under the extreme weather conditions.
The extreme working condition (3) has been used as the tar-
get group for risk division.

The parameters required for the calculations have been set
as follows: (1) severity and volume concentration: according
to the results of Guoying et al. [7] in Zhujiagou,
the bulk density of debris flow in Zhujiagou, Langjiagou,
Songshugou, Zhulinggou, and Haguou are 17.46, 17.59,
17.53, 16.16, and 17.16 m$^3$, respectively. The average bulk
density of the watershed is 17.2 kN/m$^3$. The average gravity
is Gs = 2.6 g/cm$^3$. The average void ratio in the watershed
has been calculated, and it is e = 1.228. The volume concen-
tration is CV = 0.463, corresponding to the mud-sand ratio
Rns = 0.70; (2) laminar flow resistance coefficient: this study
refers to the research of Shengshan et al. [11], who used the
engineering geology analogy method to determine the lami-
nar flow resistance coefficient K = 2280; (3) yield stress and
viscosity coefficient: using the parameters in (1), the simulta-
neous calculation formulas of viscosity coefficient η (Pas)
and yield stress τy (kPa) and Yuyi et al. [29] unified the
mud-sand ratio-volume concentration rheological param-
eter relationship (Equation 7); α1, α2, β1, and β2, are 0.0122,
0.0156, 17.41, and 18.28, respectively, and η and τy are
30.146 and 56.992, respectively. In the formula, η is the vis-
cosity coefficient, τy is the yield stress, CV is the volume concen-
tration, Rns is the ratio of mud to sand, and α1, α2, β1, and β2 are the experimental coefficients; (4) manning rough-
ness coefficient: using Yuyi et al.’s [18] unified resistance
roughness coefficient characterization formula, and combin-
it with the actual investigations, the mud depths, h, of the
main channel, Langjia channel, Songshu channel, Zhuling
channel, and Hagu channel are 1.7, 1.3, 1.3, 1.5, and 1.2 m,
respectively. The manning coefficients, nc, of the five chan-
nels are 0.29, 0.14, 0.14, 0.22, and 0.10, respectively; and
(5) catchment point and debris flow process curve: the col-
lection point has been taken from the debris flow of each
channel. At the top of the circulation area and at the bottom
of the formation area, the clear water flow line at the catch-
ment point and the amplification factor BF = 1/(1 − CV) =

![Figure 3: Quantitative classification of factors’ susceptibility.](source)

- (a) Watershed area
- (b) Longitudinal gradient of gully
- (c) Distance from valley centroid to fault
- (d) Height difference
- (e) Gully density
- (f) Peak single-width clear-water flow at the gully mouth
- (g) Shape coefficient
- (h) Average slope
- (i) Source distribution
- (j) Shallow rock group
- (k) Vegetation coverage
- (l) Gully length
Figure 4: Assessment results of debris flow susceptibility in Zhujia channel.

Figure 5: Fitting curve of annual frequency of rainfall in Minxian County.

Table 3: Parameters of debris flow control project in study area.

| Ditch          | Project          | Main structural parameters                          |
|----------------|------------------|----------------------------------------------------|
| Zhujiagou      | Row guide groove | Slot length 460 m, groove depth 2.7 m, trend NS    |
| Langjiagou     | Row guide groove | Slot length 600 m, groove depth 2.7 m, trend EN-WS |
| Songshugou     | No. 1 stop dam   | Dam length 18 m, height of dam 7.5 m, trend NW-SE  |
| Songshugou     | No. 2 stop dam   | Dam length 33.5 m, height of dam 7.5 m, trend WN-ES|
| Songshugou     | No. 3 stop dam   | Dam length 33 m, height of dam 7.5 m, trend NW-SE  |
1,862 have been extracted from the “7.18” rainfall-runoff simulation, and the debris flow process curve at the point has been obtained (Figure 6).

3.2. Simulation Results. The simulation of the debris flow movement process in Zhujiagou under actual rainfall conditions has been verified (Table 4). The simulation accuracy is higher than 74.12%. This is an indication the simulation can reflect the movement characteristics and accumulation range of the debris flow in the area under the “7.18” rainfall conditions. The prediction of the debris flow is more credible under the rain conditions. From the simulation results, it can be seen that (1) when the “7.18” heavy rainfall (Figures 7(a), 7(b), 7(d), and 7(e)), the maximum mud velocity is 6.03 m/s, and the maximum mud depth is 4.88–8.07 m, which is located in the middle of the channel accumulation fan and channel junction. Under the engineering conditions, the maximum mud velocity is 4.54 m/s, and the maximum mud depth in front of the three blocking dams is 7.42–8.58 m. The section from Langjiagou to the main drainage channel is affected by the rear recharge and front movement. The depth of the siltation reaches 4.2–5.75 m, and the maximum depth of the channel deposit area is 3.23 m. The blocking dam and the drainage channel play the roles of intercepting the back siltation, deceleration, and diversion control. (2) When heavy rainfall occurs once in a hundred years (Figures 7(c) and 7(f)), hydrodynamic conditions are enhanced. Rainwater wets the channel. Mud velocity in Zhujiagou increases, mud depth increases, and debris flow material rushes out of the channel, which blocks the Tao River. Hence, the county seat of Minxian County is threatened directly.

3.3. Risk Assessment of Debris Flow. The field investigations show that Zhujiagou debris flow has obvious straightness and climbability. The damage forms are the washout, siltation of farmland, residential buildings, highways, and squeezed rivers. Mud velocity, depth, and risk are positively correlated. Referring to Shengshan et al.’s [16] working experience in the Eryang River Basin in Minxian County (Table 5), under the once-in-a-hundred-year heavy rainfall conditions and the “7.18” heavy rainfall conditions in 2020, the Zhujiagou debris flow was classified as dangerous.

In the risk of debris flow, the results show that the total area of the debris flow on “7.18” is 371,875 m². The high-risk area accounts for 45.72% of the total area of the...
dangerous area. The middle and lower reaches of the main channel are all within the high-risk area. The area is restricted to the trough to prevent the accumulation of the fans from forming. In addition, the three blocking dams in Songshugou are highly dangerous since they block the back siltation. The medium-risk area accounts for 30.70% of the total area of the dangerous area and is distributed in Songshugou, Zhulingou, and the upstream area of the main channel, around the exit of the drainage channel. The low-risk area accounts for 23.58% of the total area of the dangerous area and is distributed in Hagugou and Langjiagou. Under the probability of \( P = 1% \), the total area of the debris flow danger zone is 500,625 m\(^2\), which is 34.62% larger than that under the “7.18” rainfall condition. Among them, the high-risk area accounted for 71.62% of the total area, an increase of 188,525 m\(^2\), which was manifested as the increased danger at the head of the main channel. The buildings along the main channel of Zhujiajagou were vulnerable to the threat of mudslides and the formation of alluvial fans at the mouth of the channel, which mainly threatened Tao. There are buildings within 30 m between the mouth of Hebei Angou and the south bank. The area of the medium-dangerous zone accounts for about 18.34% of total area including Zhulingou, Hagugou, and Songshugou. However, the blocking project in Songshugou is full of silt and exceeds the limit state, causing high risk in the surrounding area. The area of the low-risk zone accounts for about 10.04% of the total area. The overall risk of Langjiagou is low, and the drainage and drainage facilities at the channel mouth can still continue to flow backwards. The Zhujia channel debris flow-risk zoning map is shown in Figure 8.

In general, the debris flow in Zhujiajagou is dangerous. It flows to the Taohe River in the rainy season every year. The debris flow material can then be silted at the intersection of the channel and the river, which raises the river bed. Under extreme meteorological conditions (see Figure 8(b)), there is a risk of blocking the Tao River and forming a barrier dam. The upstream water level will then increase and flood the urban area in Minxian County. In addition, the Longwangtai Hydropower Station is located 2.5 km downstream of the Zhujiagou channel. After the debris flow in the channel flows into the Tao River, there is a possibility of the Debris flow down into the reservoir area of the hydropower station, which will reduce the capacity of the reservoir.

### Table 5: Criteria for hazard zoning of debris flow.

| Dangerous | Deep mud, m | Associate | Mud depth and mud accumulation, m\(^2\)/s |
|-----------|-------------|-----------|------------------------------------------|
| High      | \( H \geq 1.5 \) | OR | \( VH \geq 1.5 \) |
| Moderate  | \( 0.5 < H < 1.5 \) | And | \( 0.5 < VH < 1.5 \) |
| Low       | \( 0.1 \leq H \leq 0.5 \) | And | \( 0.1 \leq VH \leq 0.5 \) |

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**Figure 7: Distribution of mud depth and mud velocity under different conditions.**

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4. Conclusions and Recommendation

(1) Through the evaluation of debris flow susceptibility based on the fusion algorithm of entropy weight and coefficient of variation in the study area, it is concluded that the susceptibility of debris flow in each tributary channel in the study area is mainly affected by the peak single-width clear water flow at the mouth of the channel, the length of the main channel, and the controlled conditions, such as the shallow surface rock formations. Among the 17 tributary channels in the area, there are 6 medium-high-prone debris flow channels, 5 medium-prone channels, and 6 low-prone channels. Among them, the main ones are the Hagu channel, Zhuling channel, Songshu channel, and Langjia channel. The tributary channels are all highly prone to debris flow.

(2) The results of the Zhujiagou debris flow-risk assessment under severe rainfall conditions ($P = 1\%$) show that the Zhujiagou debris flow-risk area is about 500,625 m$^2$, which is generally a high-risk area of debris flow. Among them, the high-risk areas account for 71.62% of total area, distributed in the main channel and the mouth of Zhujiagou and 30 m from the south bank of Taohe River. The medium-risk areas account for 18.34%, which are distributed in Songshuzhigou, Zhulinzhigou, and Haguzhigou. Low-risk zone accounts for 10.04% of the total area, which are distributed in Langjiazhi-gou. Comparing with the results of the "7.18" debris flow ($P = 1.6\%$) risk assessment, the main difference is the increase of 110.88% (188,525 m$^2$) in the high-risk area, and the main channel head and channel alluvial fans are the newly added high-risk areas.

(3) The numerical simulation results of the debris flow velocity and valley siltation show that below the 50-year rainfall intensity, the drainage channel at the mouth of Zhujiagou and the three blocking dams in Songshugou have played a role in the diversion and control of the debris flow in the channel. The deceleration effect was intercepted, but it has basically reached the limit of its ability. Under extreme rainfall conditions that occur once in a hundred years, there is a greater threat to the residents and houses near the channel, the county seat of Minxian County, and the downstream Longwangtai Hydropower Station. It is recommended to build a barrier dam and other prevention and control projects along the main channel and promptly remove the silt in the channel.

Data Availability

The original contributions presented in this study are all included in this manuscript; further inquiries can be directed to the corresponding authors.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This research was funded by the Second Comprehensive Scientific Investigation of the Qinghai-Tibet Plateau (No. 2019QZKK0902), General Project of Fujian Natural Science Foundation (No. 2020J01360), Fujian Province Young and Middle-Aged Teacher Education Research Project (Science and Technology) (No. JAT190759), Longyan City Science and Technology Planning Project (No. 2020-G-189), Fujian Provincial Education Department Project (No. JAT190759), Science and Technology Planning Project of Longyan City (No. 2020-2-009), Science and Technology Planning Project of Longyan City (No. 2020-2-010), and Natural Science Foundation of Fujian Province of China (No. 2020J01360).
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