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Research Article

Debris Flow Risk Assessment Method Based on Combination Weight of Probability Analysis

Li Li, Shi Xin Zhang, Shao Hong Li, Yue Qiang, Zhou Zheng, and Dong Sheng Zhao

Department of Civil Engineering, School of Civil Engineering, Chongqing Three Gorges University, Wanzhou 404100, Chongqing, China

Correspondence should be addressed to Shao Hong Li; 164492100@qq.com

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Risk assessment of debris flow is conducted by multicriteria decisions. Based on the shortcomings of the existing methods in determining the weight of assessment factors, this paper proposes a new approach to conduct a risk assessment of debris flow. This new approach regards the weight of factors as a uniform random variable, whose bounds could be determined by the equal weight method, maximal deviation method, and entropy method. The results of this new approach are obtained by Monte Carlo simulation. According to the risk of 72 debris flows collected in Beichuan, Sichuan, China, this new approach proves convergent. It is suggested that the minimum sample amount of Monte Carlo simulation should be 63095. The result also demonstrates that sorted results with different weights of factors vary a lot, so it is not convincing to sort samples with a specific weight.

1. Introduction

The debris flow is a common geological hazard in rural areas [1], and debris flows are usually caused by intense rainfall [2]. The risk assessment of debris flow could provide pivotal references for policymakers to make prevention measures that achieve unity and economic and safety [3].

There are so many factors that can determine the risk of economic efficiency and safety. Therefore, the risk assessment should be regarded as a multicriteria problem [4]. People have conducted systematic researches on risk assessment of debris flow for the long term. A neural network model for the risk assessment of debris flow was established by Chong and Chao [5], which regarded the length of the creek, the average slope, the effective watershed area, the shape coefficient, the median size of soil grain, the effective cumulative rainfall, and the effective rainfall intensity as significant factors. Zhang et al. [6] established an extension model considering the impact of loose material volume per square kilometer, loose material supply length ratio, average gradient of the main channel, average hill slope, drainage density, curvature of the main channel, and poor vegetation area ratio for the risk assessment of debris flow. A professional debris flows early warning system considered the effective watershed, the length of the effective channel, the slope of the effective channel, the rocks in the effective watershed, the collapsed area within the effective watershed, the effective accumulated precipitation, the effective rainfall intensity, and the impact of the vegetation index proposed by Kung et al. [7]. The genetic algorithm was adopted to predict debris flow due to the excellent capacity of the global search [8]. The risk assessment of debris flow method based on a cloud model was developed by Cao et al. [9], and it was applied to the risk assessment of 29 debris flow gullies in Zhirui (Inner Mongolia, China). The Bayesian network model for debris flow prediction was proposed by Banihabib et al. [10], and this research indicated that average basin elevation, watershed area, current rainfall, and discharge of 1 day ago are the effective predictors in forecasting debris flows. The application of the fuzzy C-means algorithm in the risk assessment of debris flow has also achieved more reliable results [11]. The aforementioned studies provided many available approaches to conduct a risk assessment of debris flow. However, they failed to discuss the weight definition of assessment factors further.

As for multicriteria decision problems, weight calculation is one of the most critical problems. When the weight is clear in a continuous number multicriteria decision problem (assessment factors contain no interval number), decision schemes can quickly be ranked by the matrix multiplication formula. There are standard weight determination methods, including equal weight method, analytic hierarchy process [12], maximum deviation method [13], entropy method [14], and projection pursuit method [15]. There are subjective and objective methods, the equal weight method and analytic hierarchy process are subjective methods, while the maximum deviation method, entropy method, and projection pursuit method are objective methods. Different weight definition methods could lead to weights of comparatively large variance. As a result, it has long been focused on multicriteria decisions on adopting different methods to get the weight reasonably [16–18]. Some methods combining subjective and objective approaches (e.g., [17, 19]) are prompted and applied in real circumstances. However, these methods lack sufficient underpinnings.

This is in contrast to other engineering problems, such as the global sensitivity analysis of explicit equations [20] which usually have analytical expressions. There are no theoretically precise answers to multicriteria decision problems. This is where the complexity of the multicriteria decision problem lies. As a result, weights calculated through any weight definition methods could not be deemed precise. Therefore, it only can be a reference for policymakers to take measures. To settle the multicriteria decision, the weight was regarded as a variable, which is uniformly distributed and whose bounds could be determined by getting results based on different weight definition methods in this paper.

This paper proposed a new method to conduct the risk assessment of debris flow, which is a probabilistic method. In Section 2, 6 influencing factors selected in this paper and the calculation steps of the proposed method are introduced. In Section 3, the detailed justification of the proposed method's feasibility and rationality is demonstrated. In Section 4, the engineering geological conditions of the study area are introduced, and the risk assessment results are analyzed. The final section is the conclusions.

2. Study Area

Beichuan County lies in Sichuan province, China. After the 5.12 Wenchuan earthquake, the geological environment in Beichuan County is very fragile. There are many regional debris flows that were induced after a long period of rainfall. Therefore, this paper takes 72 debris flows in Beichuan County as the cases (Figure 1).

Mountains dominate the terrain in Beichuan County, and the maximum relative elevation difference can reach 1000 m. The overall trend is higher in the northwest and lowers in the southeast. The debris flow slope is generally greater than 25°, and the steeper gully slope even exceeds 50°. The high-mountain area accounts for 46.5% of Beichuan

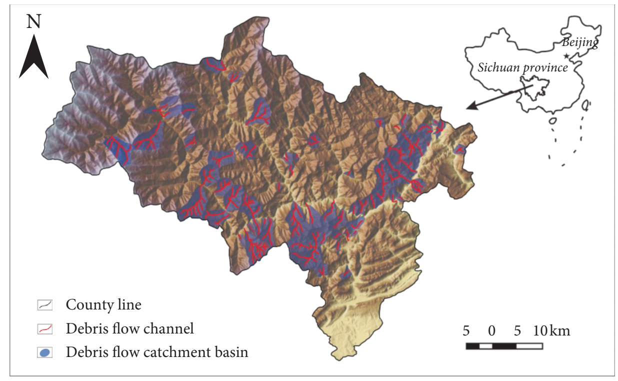

Figure 1: Distribution of debris flow in Beichuan County.

County's area, due to its high altitude, harsh climate, sparsely populated areas, and being mostly covered by virgin forests. The area of low mountain area accounts for 16.0%, but geological disasters are less due to the slow terrain. The middle mountain, which accounts for 37.5% of the area, is an area prone to geological disasters. Because residents are concentrated on the banks of the Baicaohe River, the Sushuihe River, and the Bainigou River, it is also the area where most of the debris flows studied in this paper are located.

In Beichuan County, there are Paleozoic Sinian, Cambrian, Silurian, Devonian, Carboniferous strata, and Quaternary loose source materials of Mesozoic and Cenozoic. Debris flows mainly occur in the loose accumulation layers of the Quaternary system in the east and south. Alluvial deposits and flood alluvial deposits are widely distributed on both sides of the river and consist of gravel-clay and clay layers. Residual overburden is distributed in high, deep, and gentle areas on slopes and gullies and is mainly composed of clayey sand and gravel soil.

Beichuan County is located in the subtropical humid monsoon climatic zone. Simultaneously, because the rainfall is mostly concentrated in summer, July–September are also months with a high incidence of debris flow disasters. The rainfall is affected by the topography of the mountain area and shows a decreasing tendency in space from the southeast to the northwest.

3. Methods

3.1. Material. The debris flow is a major geological hazard in Beichuan County. Sorting levels of severity of debris flow could provide policymakers references when they tackle disasters. Many factors should be taken into consideration to assess the risk of debris flow. Referring to current researches, the assessment factors are simplified to 6. This paper takes the following aspects as assessment factors based on the development characteristics of debris flow in Beichuan County after the earthquake: the loose source material reserves, the basin area, the drainage density, the basin relative relief, the shifting bed proportion, and the main channel length. The term named "the loose source material reserves" is defined as the volume of the source of loose solids that form debris flows, which is composed of colluvium deposits, eluvium deposits, and channel deposits. It is one of the most direct indicators that affect the risk of debris flow. The term named “basin area” is defined as the catchment area surrounded by the drainage divide. The term named “drainage density” is defined as the ratio of the total length of a gully to the basin area. The term named “basin relative relief” is defined as the difference between the highest and the lowest points in the basin area. The term named “main channel length” is defined as the plane projection length of the main channel head to the channel end, and the term named “shifting bed proportion” is defined as the ratio of unstable channel length to the main channel length. Table 1 lists the survey data of the loose source material reserves, the basin area, the drainage density, the basin relative relief, the shifting bed proportion, and the main channel length of 72 debris flows located in Beichuan County. These data are from Wang [21].

3.2. Assessment Method. In this section, a method of sorting the risk of debris flow is given. Prior to this, two definitions are introduced.

Decision matrix: the matrix in the form of Table 1 is called the decision matrix Z, where $Z=\{Z_{ij}\}_{i=1,2,\ldots,m;\, j=1,2,n}$, m represents the number of samples (in this paper, the number of debris flows, that is 72), and n is the number of assessment factors (in this paper, $n=6$).

Weights: the vector $w=[w_1, w_2, \ldots, w_n]^T$ that satisfies $\sum_{i=1}^{n} w_j = 1, w_j \geq 0$ is called the weight.

In order to eliminate the influence between the dimensions of the assessment factors, the decision matrix should be normalized first, i.e.,

$$\tilde{z}_{ij} = \frac{z_{ij} - \min\left(z_{1:\, m,j}\right)}{\max\left(z_{1:\, m,j}\right) - \min\left(z_{1:\, m,j}\right)}, \tag{1}$$

where max( ) means taking the maximum function and min( ) means taking the minimum function. Because the larger the value of the six assessment factors in this paper, the higher the risk grade, it is only necessary to use equation (1) to normalize the decision matrix. A positive relationship exists between the normalized value and the risk grade.

Multiply the normalized decision matrix $\tilde{Z}=\left\{\tilde{z}_{ij}\right\}_{i=1,2,\ldots,m;\, j=1,2,\ldots,n}$ by the weight w to get the score vector u.

$$\mathbf{u} = \tilde{Z}\mathbf{w}, \tag{2}$$

where $\mathbf{u}=[u_1, u_2, \ldots, u_m]^T$. The larger the score value $\mathbf{u}_i$, the higher the risk grade of the i-th debris flow. Determining the weight w is the core problem of risk assessment of debris flow.

Several more commonly used methods of weight determination are described hereinafter.

3.2.1. Equal Weight Method. The equal weight method is the most widely used in practice. For some problems where it is often difficult for people to judge the importance of assessment factors, the equal weight method is needed. The equal weight method can be expressed as

$$w_j = \frac{1}{n}. \tag{3}$$

The equal weight method can be regarded as a special case of the analytic hierarchy process. If the importance of the assessment factors is considered the same in the analytic hierarchy process, the equal weight method results can be obtained.

3.2.2. Maximum Deviation Method. The maximum deviation method determines weights based on a decision matrix [13].

Calculate the deviation v according to the following equation:

$$v_{ij} = \sum_{k=1}^{m}\left|w_j\tilde{z}_{ij} - w_j\tilde{z}_{kj}\right|. \tag{4}$$

The total deviation is defined as

$$V_j = \sum_{i=1}^{m} v_{ij} = \sum_{i=1}^{m}\sum_{k=1}^{m}\left|w_j\tilde{z}_{ij} - w_j\tilde{z}_{kj}\right|. \tag{5}$$

In the maximum deviation method, it is considered that the weights should maximize the deviation of all assessment factors. That is,

$$\max\sum_{j=1}^{n} V_j = \sum_{j=1}^{n}\sum_{i=1}^{m}\sum_{k=1}^{m}\left|w_j\tilde{z}_{ij} - w_j\tilde{z}_{kj}\right|. \tag{6}$$

Using the Lagrangian method, the solution yields weights of

$$w_j = \frac{\sum_{i=1}^{m}\sum_{k=1}^{m}\left|\tilde{z}_{ij} - \tilde{z}_{kj}\right|}{\sum_{j=1}^{n}\sum_{i=1}^{n}\sum_{k=1}^{m}\left|\tilde{z}_{ij} - \tilde{z}_{kj}\right|}. \tag{7}$$

3.2.3. Entropy Method. The entropy method is also a method to determine the weight based on the decision matrix [14].

The entropy vector H of the evaluation factor is defined as

$$H_j = -\frac{1}{\ln m}\sum_{i=1}^{m}\frac{\tilde{z}_{ij}}{\sum_{i=1}^{m}\tilde{z}_{ij}}\ln\frac{\tilde{z}_{ij}}{\sum_{i=1}^{m}\tilde{z}_{ij}}. \tag{8}$$

According to equation (8), the entropy weight of the assessment factor is

$$w_j = \frac{1 - H_j}{n - \sum_{j=1}^{n} H_j}. \tag{9}$$

It can be seen from equations (8) and (9) that there is a negative relationship between the entropy value and the entropy weight, which indicates that the more effective the information of the assessment factor, the more significant the assessment factor. Conversely, the larger the entropy value is, the smaller the entropy weight is, and the less important the assessment factor is. The entropy weight reflects that the function of the assessment factor in objective information is the objective weight.

Table 1: Basic data statistics table of 72 debris flows [21].

Samples	Loose source material reserves (10^3 m^3)	Basin area (km^2)	Drainage density (km^{-1})	Basin relative relief (km)	Shifting bed proportion (%)	Main channel length (km)
#1	0.04	2.5	19.32	1.6	0.48	2.06
#2	39.04	13.9	21.85	1.4	0.5	4.03
#3	43.65	10.3	20.21	1.4	0.72	3.89
#4	728.2	7.8	25.17	1.46	0.85	4.1
#5	79.5	4.5	15.89	0.98	0.64	3.35
#6	385.95	12.2	24.5	1.36	0.85	5.88
#7	104.5	1.8	28.17	1.04	0.86	1.38
#8	240.45	10	22.71	1.56	0.76	5.39
#9	50.2	1.9	25.68	1.1	0.48	1.36
#10	2.4	2.4	18.63	1.14	0.23	1.78
#11	1500	1.6	44.06	1.12	0.61	3.32
#12	242	0.5	18.6	0.46	0.84	0.73
#13	160.7	0.8	17.38	0.66	0.72	1.09
#14	6.6	7.5	22.55	1.38	0.39	2.86
#15	4.8	4.6	21.33	0.86	0.54	1.99
#16	73.2	21.8	21.67	2.04	0.42	7.82
#17	2.85	5.7	20.47	1.92	0.37	3.05
#18	14.7	6.8	21.79	1.8	0.4	2.55
#19	109.3	23.2	23.24	2.3	0.61	7.49
#20	35	10.6	19.05	1.68	0.47	4.25
#21	160.34	16	23.43	1.04	0.51	5.89
#22	60	3.5	22.94	1.24	0.65	2.25
#23	70.6	0.7	16.29	0.96	0.61	1.43
#24	40.53	0.7	19.86	1	0.81	1.36
#25	163.32	18.7	22.6	1.68	0.76	5.91
#26	0.89	0.9	27.56	0.72	0.43	1.36
#27	60	1.2	22.5	0.86	0.41	1.45
#28	26.2	1	19.5	0.6	0.62	1.32
#29	1016.4	0.8	21.5	0.88	0.86	1.15
#30	1967.9	15.7	20.89	1.22	0.84	5.97
#31	378.24	21.4	24.7	1.5	0.76	7.42
#32	199	8.7	27.37	1.36	0.6	2.83
#33	101.63	9.9	25.09	1.7	0.58	4.59
#34	40.2	1.2	27.58	0.82	0.81	1.45
#35	74	1.1	26.18	0.75	0.69	1.05
#36	119.3	17.6	20.65	1.66	0.56	7.62
#37	15.55	2.7	23.33	1.22	0.45	2.89
#38	54	2.6	27.12	1.26	0.41	3.13
#39	67.44	0.8	19.38	0.82	0.82	1.22
#40	107.3	0.6	16.67	0.67	0.73	0.99
#41	33.54	2.2	25.45	0.74	0.57	2.09
#42	106.5	0.3	10.67	0.52	0.76	0.66
#43	3.36	0.7	27.86	0.55	0.47	2.09
#44	4.13	2.8	18.79	1	0.47	2.35
#45	51.8	1.1	28.09	0.59	0.46	0.99
#46	12.14	0.5	18.4	0.92	0.52	1.15
#47	10.8	1.4	21.43	0.98	0.47	1.06
#48	507	1.1	24.91	0.58	0.79	1.15
#49	120.08	1.8	19.56	1.04	0.89	1.35
#50	15.98	3.1	20.1	0.84	0.51	2.54
#51	30	3.5	21.74	0.82	0.75	1.8
#52	114	24.6	20.84	1.22	0.64	8.1
#53	14.26	2.8	20.82	1.12	0.7	1.56
#54	33	4.1	19.63	1.09	0.46	3.64
#55	900.03	22.2	22.05	1.7	0.44	11.36
#56	210	3.6	21.25	1.2	0.96	3.12
#57	1000.1	7	21.8	1.22	0.87	4.02
#58	485	2.5	21.8	1	0.81	1.97
#59	931.24	23.1	21.34	1.2	0.66	9.88

Table 1: Continued.

Samples	Loose source material reserves (10^3 m^3)	Basin area (km^2)	Drainage density (km^{-1})	Basin relative relief (km)	Shifting bed proportion (%)	Main channel length (km)
#60	12.21	4	18.98	1.03	0.53	2.56
#61	34.08	16	20.99	1.28	0.39	5.91
#62	0.08	11.7	22.03	1.08	0.21	4.74
#63	16.8	5.4	19.57	1.46	0.4	3.02
#64	98.5	22.7	26.04	1.86	0.76	7.66
#65	67.2	2.5	18.12	1.02	0.83	1.32
#66	17.5	1.5	20.93	1.24	0.9	1.75
#67	93.3	2.8	21.36	1.3	0.78	2.75
#68	50.8	7.3	20.68	1.2	0.84	3.91
#69	135.57	26.4	21.93	1.8	0.67	8.46
#70	14.66	2.8	29.96	1.34	0.82	2.29
#71	8.95	10.9	20.11	1.5	0.57	4.12
#72	97.82	17.1	19.64	1.28	0.7	6.43

The weights calculated by different methods are entirely different. How to combine the weights obtained by different methods is a classic problem. A common approach is to average the weights from different methods. However, this approach is too simple and lacking insufficient evidence. Hereinafter, we will propose a new method to synthesize the weights obtained by different methods.

3.2.4. Proposed Method. According to the definition of weight, any vector $w = [w_1, w_2, \ldots, w_n]^T$ satisfying $\sum_{i=1}^{n} w_j = 1, w_j \geq 0$. can be used as a weight. The weights of assessment factors are obtained from different data analysis perspectives, including the equal weight method, the maximum deviation method, and the entropy method. Through the three methods, the upper and lower limits of weights of assessment factors can be obtained. The proposed method drew on the probability analysis idea to obtain weights, which regarded the weight as a random variable with uniform distribution within the boundary. To sum up, a method combining the weights of different methods through probability analysis and calculating the score vector is proposed in this paper. Its implementation steps (Figure 2) are as follows.

Step 1: The weights of assessment factors are calculated using the equal weight method, the maximum deviation method, and the entropy method.

Step 2: Calculate the upper and lower limits of weights of the assessment factor.

Step 3: Calculate the normalized decision matrix.

Step 4: Generate the random variable sample $W = \{w_{ij}\}$ $i = 1, 2, \ldots, l$; $j = 1, 2, \ldots, n$ that satisfies the uniform distribution of weight within the boundary, where l represents the number of samples.

Step 5: Calculate the scoring matrix of each random weight sample according to equation (2). It should be noted that since the random sample of each weight does not meet the definition of weight, it is necessary to normalize each random sample.

Step 6: Take the average value of l scoring matrices to obtain the final scoring matrix.

Steps 3–6 above are often referred to as the Monte Carlo simulation strategy. It is worth noting that the Monte Carlo simulation strategy is only used to generate random weights within the boundary, while the debris flow decision matrix uses field statistics. There are two essential questions that need to be answered about the proposed approach. One is whether the method converges, and the other is how much l should be taken. These two issues will be discussed below.

4. Results

4.1. Calculation Results of the Three Methods. Figure 3 is the calculation results of the equal weight method, the maximum deviation method, and the entropy method. The maximum deviation method and the entropy method are calculated by Matlab [22]. As shown in Figure 2, there is a large difference between the calculations of the three methods. The entropy method considers that loose source material reserves are much more important than other assessment factors, while the maximum deviation method considers that the importance of the basin area is more significant than other assessment factors. The results obtained by several methods are consistent with only one evaluation factor (i.e., the main channel length).

Because the essence of the entropy method is to reflect the degree of disorganization, the greater the randomness and degree of disorganization, the more critical the assessment factor. The loose source material reserves have a large difference among the 72 debris flows in this paper. The maximum is 1967.9×10^3 m^3, and the minimum is only 0.04×10^3 m^3. Therefore, the weight of the loose source material reserves in the entropy method is as high as 0.44. However, this result overemphasizes the importance of loose source material reserves.

The maximum deviation method considers the deviation between the basic data and its average value. Although the sample range of loose source material reserves is huge, the deviation is smaller than that of the basin area. Moreover, the weight of the basin area is assigned 0.21 in the maximum deviation method. However, of the 72 debris flows in Beichuan County, the main ones are small- and medium-sized debris flows. The deviation of each debris flow assessment

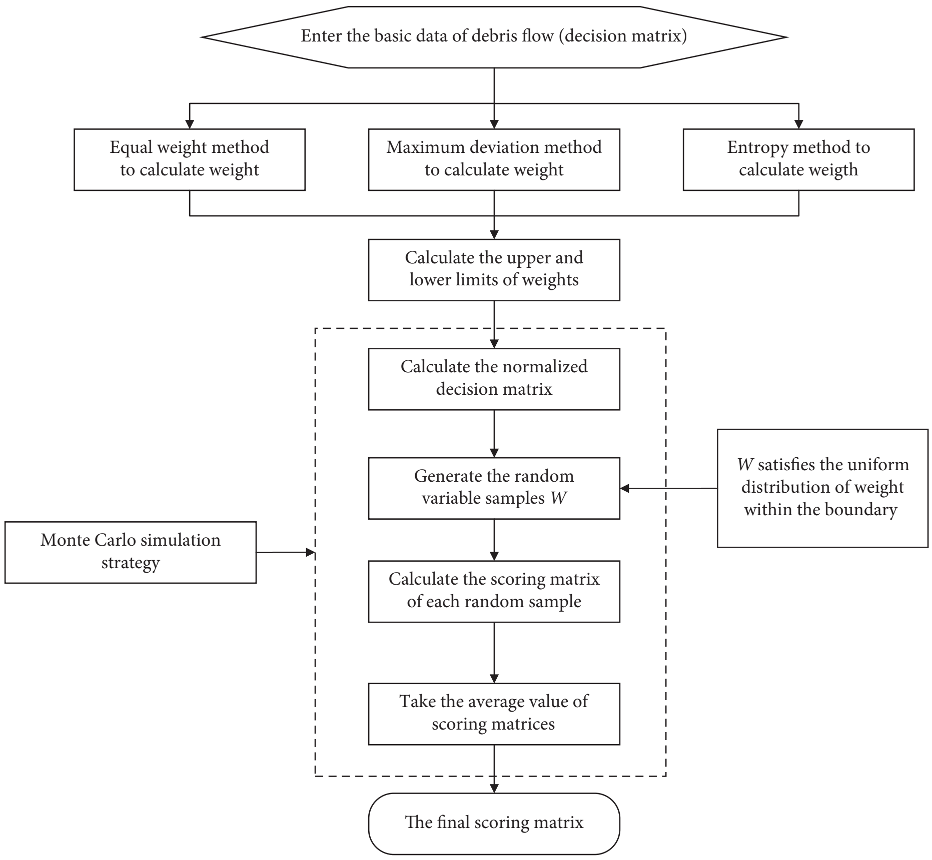

Figure 2: Combination weight of probability analysis flow chart.

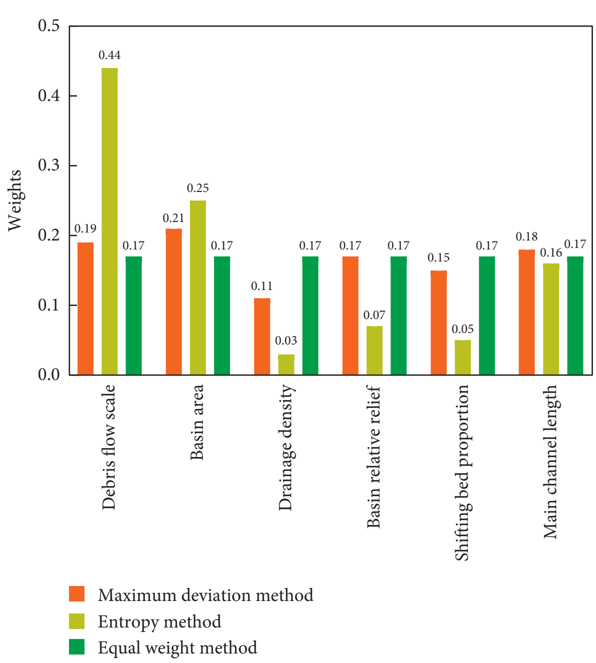

Figure 3: Weight calculation results of different methods.

factor is small, and the calculated weights have little difference, which fails to reflect the characteristics of assessment factors. Because of the advantages and disadvantages of the two methods, the proposed method within the boundary conditions considers the characteristics of assessment factors and avoids overemphasizing the importance of a specific factor.

4.2. Convergence Analysis. The value range of 6 assessment factors, respectively, obtained from Figure 3 is

$$\begin{aligned} w_1 &\in [0.17, 0.44],\\ w_2 &\in [0.17, 0.25],\\ w_3 &\in [0.03, 0.17],\\ w_4 &\in [0.07, 0.17],\\ w_5 &\in [0.05, 0.17],\\ w_6 &\in [0.16, 0.18]. \end{aligned} \tag{10}$$

Random samples of different l(31, 63, 125, 251, 501, 1000, 1995, 3981, 7943, 15848, 31622, 63095, 125892, 251188, 501187, 1000000, 1995262) were generated in Matlab 2018a. Figure 4 shows the change curve of the score values of some debris flows with the number of samples l. As shown in Figure 4, with the increase of l, the scoring value gradually tends to be stable, indicating that the proposed method is convergent.

There was some fluctuation in the sorting of the 5th and 63rd debris flow samples in the calculations (Figure 5). However, with the increase of l to 63095, the sorting of the risk level has been entirely stable. The limit for l seems to be

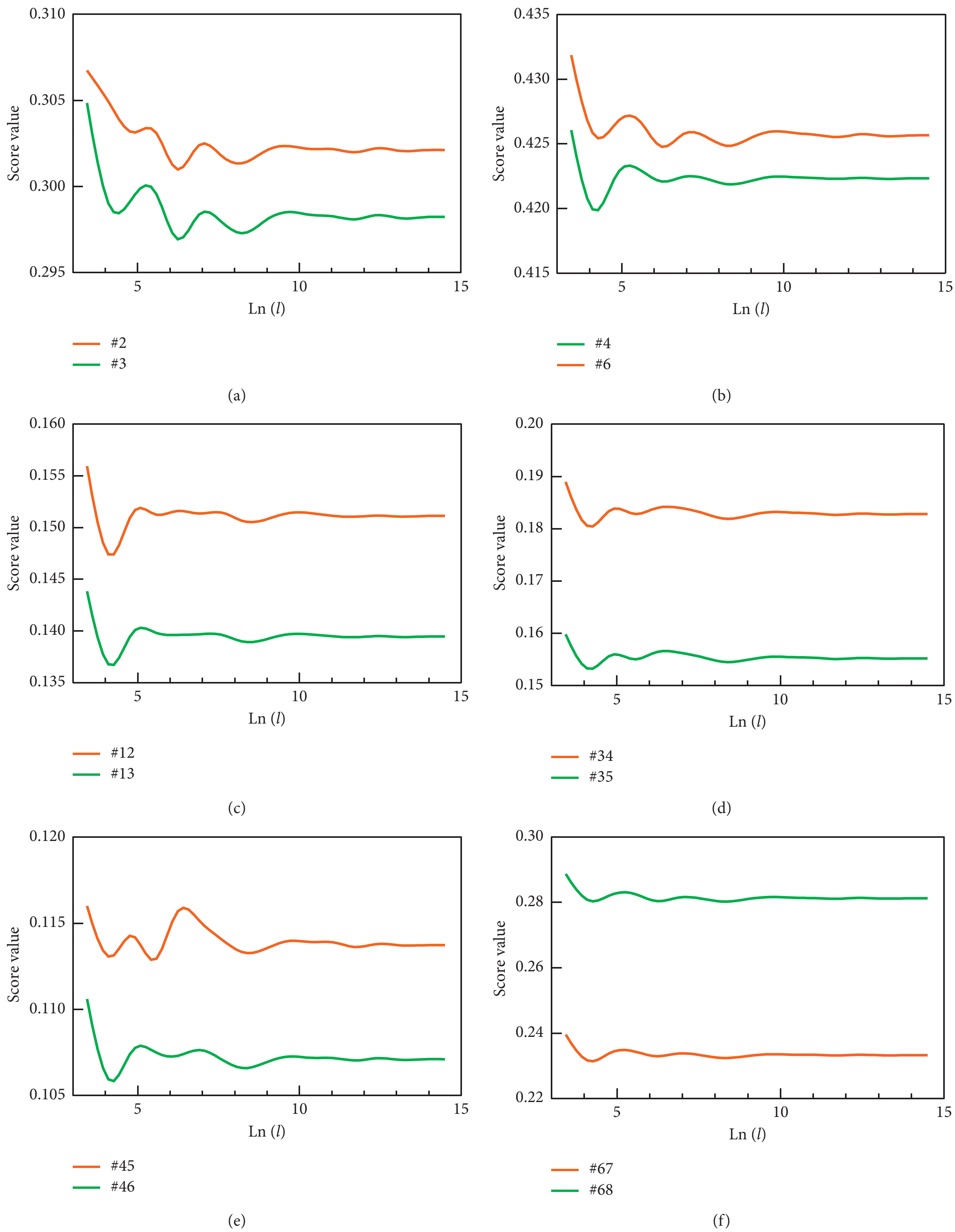

Figure 4: Iteration curve of some samples.

reduced to a certain range between 31622 and 63095. However, even if 63095 is taken, the calculation time is only 0.3510 seconds, and 63095 is completely feasible.

4.3. Comparison of Results. The weights calculated by equal weight method, maximum deviation method, entropy method, and average method are substituted into equation (2) to sort the debris flow risk. Table 2 shows the detailed

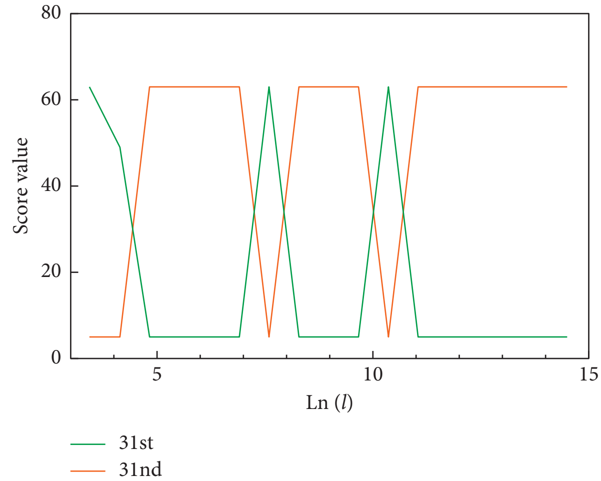

FIGURE 5: Iteration curve of partial sorting results.

TABLE 2: Sorting results by different methods.

Sorting	Equal weight method	Maximum deviation method	Entropy method	Average method	Proposed method
1	#30	#30	#30	#30	#30
2	#55	#55	#55	#55	#55
3	#59	#59	#59	#59	#59
4	#11	#69	#11	#11	#69
5	#69	#31	#57	#69	#19
6	#31	#19	#31	#31	#31
7	#19	#64	#4	#19	#64
8	#64	#11	#29	#64	#11
9	#52	#52	#69	#52	#52
10	#16	#16	#52	#16	#16
11	#57	#57	#19	#57	#25
12	#25	#25	#64	#25	#57
13	#4	#36	#6	#4	#6
14	#6	#4	#16	#6	#36
15	#36	#6	#25	#36	#4
16	#72	#72	#36	#72	#72
17	#8	#8	#72	#8	#8
18	#21	#21	#21	#21	#21
19	#29	#29	#8	#29	#33
20	#33	#61	#58	#33	#61
21	#61	#33	#61	#61	#29
22	#2	#2	#48	#2	#2
23	#32	#3	#33	#32	#3
24	#3	#32	#32	#3	#32
25	#20	#20	#2	#20	#71
26	#71	#71	#20	#71	#20
27	#56	#68	#3	#56	#56
28	#68	#56	#56	#68	#68
29	#58	#58	#71	#58	#58
30	#70	#62	#62	#70	#70
31	#62	#18	#68	#62	#67
32	#48	#17	#5	#48	#18
33	#67	#48	#18	#67	#62
34	#18	#67	#67	#18	#17
35	#17	#70	#14	#17	#48
36	#7	#14	#17	#7	#7
37	#14	#63	#12	#14	#14
38	#22	#5	#63	#22	#22

Table 2: Continued.

Sorting	Equal weight method	Maximum deviation method	Entropy method	Average method	Proposed method
39	#38	#22	#54	#38	#66
40	#63	#7	#22	#63	#49
41	#66	#38	#38	#66	#63
42	#5	#54	#49	#5	#5
43	#49	#49	#7	#49	#38
44	#54	#66	#13	#54	#54
45	#37	#37	#70	#37	#65
46	#34	#1	#60	#34	#34
47	#65	#65	#65	#65	#51
48	#51	#51	#37	#51	#53
49	#1	#60	#51	#1	#37
50	#53	#53	#15	#53	#1
51	#60	#34	#50	#60	#60
52	#24	#15	#1	#24	#24
53	#15	#24	#41	#15	#15
54	#9	#50	#66	#9	#39
55	#41	#9	#53	#41	#35
56	#35	#41	#9	#35	#41
57	#39	#12	#40	#39	#9
58	#12	#44	#44	#12	#12
59	#50	#39	#35	#50	#50
60	#44	#35	#39	#44	#44
61	#13	#13	#34	#13	#13
62	#23	#23	#23	#23	#23
63	#43	#40	#27	#43	#40
64	#40	#27	#24	#40	#43
65	#27	#10	#42	#27	#47
66	#45	#47	#10	#45	#27
67	#47	#43	#45	#47	#45
68	#26	#45	#28	#26	#26
69	#28	#28	#47	#28	#28
70	#10	#26	#43	#10	#46
71	#46	#46	#46	#46	#10
72	#42	#42	#26	#42	#42

sorting results of the 4 methods. It can be seen that the sorting results of these methods are vastly divergent. Figure 6 more intuitively shows the differences in the sorting of debris flow risk by different methods, which is calculated from Table 2. It reflects the compliance degree of the five methods on the same debris flow's sorting result (for example, #30 debris flow sorts first among all methods in terms of risk, so its compliance degree is 100%; #25 debris flow only ranks 11th in this method, so its compliance degree is 0%). The results of several methods on the top three dangerous debris flows (i.e., #30, #55, #59) are exactly the same. From the field survey data (Table 1), these three debris flows are highly developed and potentially dangerous.

The correlation matrix is defined as the ratio of the same number of sorting to the total debris flows. Table 3 is calculated from Table 2 and shows the correlation matrix of the 5 methods. As shown in Table 2, the correlation coefficients of the equal weight method, the maximum deviation method, and the entropy method are all very small due to the difference in weights. Although the average method of the weight obtained by the 3 methods also considers the differences between different methods, it is only a special case of the proposed method. Take the highest dangerous debris flow (i.e., #30) as an example. The loose source material reserves are $1967.9 \times 10^3\,m^3$, and the loose source materials in the channel are abundant. Simultaneously, the basin area is $15.7\,km^2$, and the water source in the basin is sufficient. The considerable basin relative relief and shifting bed proportion reflect the high erosion degree of the channel, and the sediment and loose source materials along the way are adequately recharged. Therefore, from the perspective of hydrological and topographical conditions, #30 is more dangerous.

5. Discussions

5.1. Risk Sorting Results. As can be seen from Table 2, the equal weight method and entropy method consider #11 to be more dangerous than #69. However, the 50-year debris flow scale in #11 is only $16.2 \times 10^3\,m^3$, and the debris flow scale in #69 is $184.61 \times 10^3\,m^3$. This result is not credible. Although the loose source material reserves of #11 have reached 1500 × 103m3, there are not enough water sources in the basin to provide conditions for the development of debris flows, and low basin relative relief is not conducive to the occurrence of large-scale debris flows. This error is due to the excessive consideration of #11 loose source reserves when using the single weight method. In the proposed method, this error is avoided.

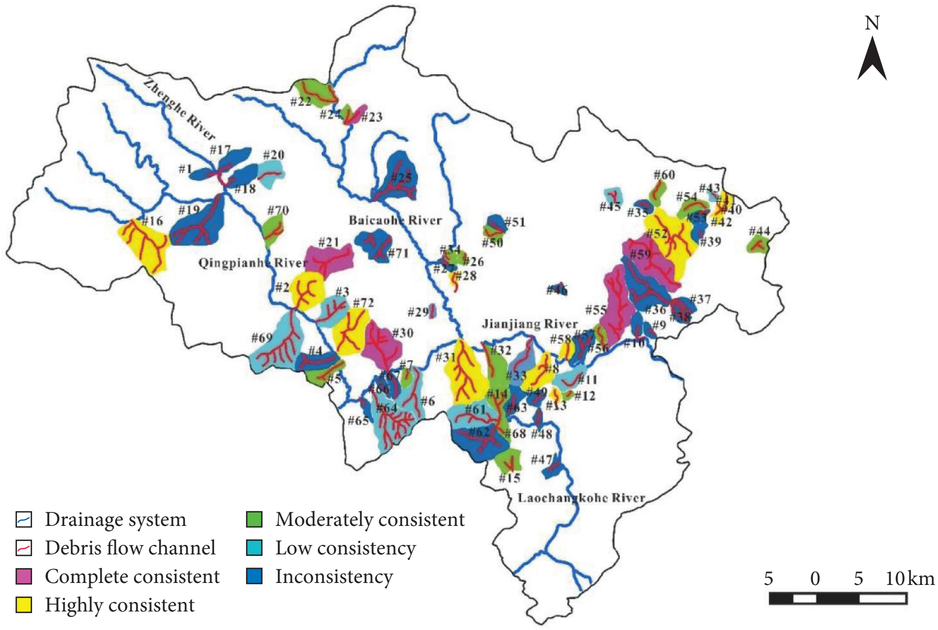

Figure 6: The coincidence degree of the sorting results.

Table 3: Correlation coefficient of sorting results by different methods.

	Equal weight method	Maximum deviation method	Entropy method	Average method	Proposed method
Equal weight method	1	0.152778	0.208333	0.402778	0.25
Maximum deviation method	0.152778	1	0.166667	0.166667	0.180556
Entropy method	0.208333	0.166667	1	0.263889	0.25
Average method	0.402778	0.166667	0.263889	1	0.513889
Proposed method	0.25	0.180556	0.25	0.513889	1

Since there are 72 debris flows in this paper, typical debris flows #30 and #42 are taken as examples in discussing the assessment results. Figure 7 shows the activity of the #30 and #42 debris flows. The formation of debris flow is determined by topographic, geomorphic, and water source sources and loose source materials. The #30 is the debris flow with the highest risk score in the proposed method. It can be seen from Table 1 that the loose source material reserves of #30 are $1967.9 \times 10^3\,m^3$, while the average value is only $191.3 \times 10^3\,m^3$. Water source conditions are the driving factors that induce debris flow determined by the basin area. The basin area of #30 reaches $15.7\,km^2$, while the average basin area is only $6.2\,km^2$. Therefore, for #30, the loose source materials are extensive, the water source in the basin is sufficient, and the necessary conditions for debris flow are available. The basin relative relief exceeds 1.8 km, and the larger drainage density and shifting bed proportion reflect the high erosion degree of the channel and sufficient sediment replenishment along the way. Therefore, the proposed method which regards #30 as the most dangerous debris flow is reasonable.

The loose source material reserves of #42 are $106.5 \times 10^3\,m^3$, and the basin area is only $0.3\,km^2$, which are both much smaller than the average. The terrain of #42 is relatively flat, with the basin relative relief of 0.52 km. The drainage density and shifting bed proportion are far below the average. Consequently, #42 is relatively safe in terms of terrain, hydrological, and provenance conditions.

5.2. Further Discussion of the Proposed Method. The proposed method is to sort the risk grade of debris flow from the perspective of probability. The purpose of this method is to avoid the problem of determining weights. Weight determination has always been an essential issue in decision science. Although many weight determination methods have been put forward, there is no absolute criterion to judge the rationality of the obtained weight. It is because there will always be some deviation existing when using a certain weight to sort the risk grade of debris flow. In contrast, the sorting method in this paper can be regarded as a reasonable way considering all possible weights.

It is worth noticing that the proposed method is different from the study of Zhang et al. [6]. The proposed method just sorted the risk grade of debris flow and did not categorize the debris flow. In the study of Zhang et al. [6], a classification standard was artificially given, and a series of calculations were made to determine the risk grade of debris flow, which should be more appropriately called a classification issue. Such an approach is reasonable, but the classification

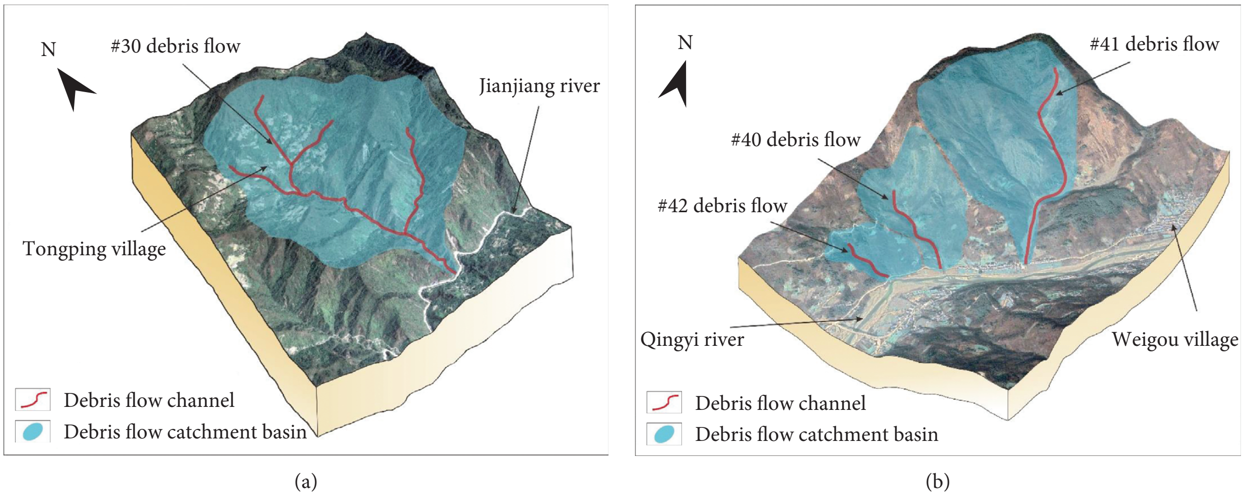

Figure 7: 3D topographic map of partial debris flows. (a) The #30 debris flow. (b) The #40, #41, and #42 debris flows.

standard needs to be subjectively given which often will be unconvincing. The study of classification standards is beyond the scope of this paper.

It should also be noted that this paper only uses the equal weight method, the maximum deviation method, and the entropy method to determine weights. Using more methods will be more beneficial in determining the value range of weight in practical application.

In a recent study, Alireza [23] reviewed the development of fuzzy multicriteria decision problems in the past decade. The sorting of fuzzy numbers is still a big challenge, but the sorting of real numbers has been well solved. In other words, it is obvious that the difficulty of debris flow risk assessment lies only on the determination of weight. However, different sorting models, such as the grey target model [24] or the fuzzy assessment model [25], have little difference in terms of their essence with equations (1) and (2). For classification problems, after the classification standard is given, the classification boundary can be substituted into equations (1) and (2) to obtain the boundary score value. And the sample grade can be determined by comparing the size of the sample score value and the boundary score value.

Although some studies (such as Wang et al., [17]) claim that classification standards also have fuzziness, the fuzziness of the assessment factor should be the main factor. Therefore, in future research, we will use fuzzy number operation rules to consider debris flow risk assessment under a fuzzy environment.

6. Conclusion

A new method for sorting the risk grade of debris flow is proposed. The new method regards weight as a variable, which is uniformly distributed and whose boundaries could be determined by the results calculated by the equal weight strategy, the maximal deviation method, and the entropy method.

(1) This new method is adopted to sort the risk grade of 72 debris flow gullies in Beichuan. Furthermore, the result proves that the proposed method is convergent and finds out the minimum sample volume needed by the proposed method.

(2) The new method considers the characteristics of the assessment factor and avoids the defects of the traditional weight method. Therefore, this method is more objective and accurate.

(3) The comparison between the assessment results of the new method and the actual results verifies the reliability of the new method.

Our suggestions for further study are to apply the proposed method to sort the risk grade of debris flow in fuzzy environments.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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