Journal of Engineering Innovations & Technology

journal homepage: www.journal-eit.online

Paper Type: Original Article

The Debris Flow Risk Zoning Assessment in the Parlung Zangbo River Basin of Tibet Based on GIS and AHP

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Abstract

The Parlung Zangbo River Basin, located in the Tibet region, is a typical area prone to frequent debris flows. As a highly destructive geological hazard, debris flows pose a serious threat to the ecological environment and human activities in this basin. This paper aims to comprehensively assess the risk factors of debris flow in the Parlung Zangbo River Basin by integrating Geographic Information System (GIS) and Analytic Hierarchy Process (AHP), and to generate a debris flow risk zoning map. Firstly, the paper analyzes the main factors influencing the occurrence of debris flows in the basin, including topographic features (such as slope aspect, slope gradient, and Melton ratio), precipitation intensity, vegetation cover, and the nearest distance to faults. Based on this analysis, the AHP model is employed to assign weights to these factors and conduct consistency checks to ensure the scientific validity and reliability of the assessment results. The study results indicate that the Melton ratio, precipitation index, and slope aspect and gradient are the primary factors affecting the occurrence of debris flows, with varying degrees of influence across different areas. By applying the weights of these factors to the GIS platform, this study generates a debris flow risk zoning map for the Parlung Zangbo River Basin, providing a scientific basis for disaster prevention and planning in the region. The findings of this study not only hold significant implications for disaster control in the Parlung Zangbo River Basin but also offer valuable insights for debris flow risk assessment in similar geological environments.

Keywords: Parlung Zangbo River Basin, Debris Flow, Risk Zoning, Geographic Information System (GIS), Analytic Hierarchy Process (AHP)

1 | Introduction

Globally, debris flows are a common and highly destructive geological hazard, posing serious threats to the ecological environment, infrastructure, and human life and property in mountainous and basin regions. Particularly under the influence of climate change and intensified human activities, the frequency and intensity of debris flows have increased. The Parlung Zangbo River Basin in Tibet, with its unique geological structure, complex terrain, and variable climatic conditions, has become a high-risk area for debris flow disasters. Therefore, accurately assessing the debris flow risk in this region and implementing effective risk zoning methods have become crucial topics for disaster prevention and sustainable regional development.

In recent years, with the widespread application of Geographic Information System (GIS) technology and the Analytic Hierarchy Process (AHP) in geological hazard research, researchers have been able to more comprehensively consider multiple factors influencing debris flow occurrences, such as topographic features, precipitation patterns, vegetation cover, and fault activity. By evaluating the relative importance of these factors, they have constructed debris flow risk assessment models. The integration of these technologies provides a scientific and efficient tool for assessing debris flow susceptibility, enabling more precise and timely disaster warning and control.

This paper focuses on the Parlung Zangbo River Basin in Tibet, integrating the AHP model and GIS technology to comprehensively assess the various factors influencing debris flow occurrences and generate a debris flow risk zoning map. This provides a scientific basis for disaster prevention and planning within the region. Additionally, the research methods and findings presented in this paper offer valuable references for debris flow risk assessment in similar geological environments.

2 | Related Work

International research on debris flows is being actively pursued worldwide, with numerous countries and regions engaged in scientific studies and the development of countermeasures. Many internationally renowned institutions and academic communities are dedicated to the study of debris flows, such as the United States Geological Survey (USGS), the Swiss Federal Institute of Technology (ETH Zurich), and the National Institute for Environmental Studies in Japan (NIESP). These institutions conduct in-depth studies on the formation mechanisms, movement patterns, and influencing factors of debris flows through field surveys, experimental simulations, and numerical modeling. Building on this foundation, international researchers are committed to developing advanced debris flow monitoring technologies and early warning systems. For example, countries like the United States and Switzerland have made significant progress in terrain radar, remote sensing, and seismic monitoring, enhancing real-time monitoring and early warning capabilities for debris flows.

Extensive research has also been conducted on disaster prevention measures and engineering responses to debris flows. Various protective structures, dams, and retaining walls have been developed to mitigate the damage and risks associated with debris flows. Additionally, numerical simulations and predictive models are used to simulate and forecast the behavior and spread of debris flows. Researchers have established physics-based mathematical models and integrated data on terrain, rainfall, and soil to conduct numerical simulations and predictions, assisting decision-makers in making informed disaster prevention decisions. Furthermore, international researchers have delved into the impact of climate change on debris flows. By analyzing the effects of climate change on rainfall patterns and glacier melt, they assess potential changes in the frequency and magnitude of debris flows. These studies not only advance the understanding of debris flows but also provide valuable experience and technical support for monitoring, early warning, disaster prevention, and mitigation measures worldwide. The findings are of great significance for global debris flow risk management and disaster reduction.

Wang et al. (2022) classified and estimated sedimentation in the debris flow-prone areas within the Parlung Zangbo River Basin, revealing the spatial distribution characteristics and potential impacts of debris flows in this region[1]. Deng et al. (2018) further studied the rainfall characteristics and triggering thresholds of debris flows in the Parlung Zangbo River Basin, providing quantitative indicators for the relationship between rainfall and debris flows and exploring the critical role of rainfall in debris flow formation[2]. Meanwhile, Zhang et al. (2022) investigated the impact of glaciers and geomorphology on the differences in debris flow mechanisms between the northern and southern banks of the Parlung Zangbo River Basin, highlighting the importance of glacier retreat and terrain conditions in influencing debris flow activities[3]. Zhang et al. (2018) further elucidated the conditions and mechanisms of glacial debris flow formation, emphasizing the dominant role of glacial meltwater and terrain in debris flow formation[4]. Wang et al. (2021) analyzed the characteristics of glacial debris flow activities in the Parlung Zangbo River Basin, revealing the frequency of debris flows in the region and their potential threat to the regional environment[5]. Additionally, Lin et al. (2023) proposed a damage model and analyzed the effectiveness of disaster reduction engineering in the region by studying the impact factors of mitigation engineering on glacial debris flows[6]. Kunzhong et al. (2021) used numerical models to simulate the dynamics of ice avalanche-debris flows along the Yarlung Zangbo River in Tibet, providing predictions and prevention strategies for potential debris flow disasters[7]. Bao et al. (2023) studied the interaction between debris flows and engineering structures and proposed an integrated approach considering structural damage to enhance debris flow disaster prevention capabilities[8]. Finally, Zhang et al. (2023) characterized and dynamically predicted the Lebai Gully debris flow along the Yarlung Zangbo River, exploring the causes and potential risks of debris flows in this area[9]. Lv et al. (2024) analyzed the group movement evolution characteristics of two adjacent debris flow gullies at the Great Bend of the Yarlung Zangbo River, further deepening the understanding of debris flow activities in this region[10].

3 | Related Model Theories

3.1 Main Research Methods and Technical Route

In previous research, by integrating fundamental regional geological survey data, meteorological information from relevant weather stations in the Parlung Zangbo River Basin, and meteorological data from NASA's Earth Science Data and Information Services Center, software such as ArcGIS and Origin was used to statistically analyze the distribution of elevation, topography, geomorphology, tectonics, lithology, aspect, slope, and precipitation in relation to debris flows. Additionally, correlation analysis and other statistical methods were employed to summarize the distribution patterns of different types of debris flows in the Parlung Zangbo River Basin.

3.2 Feasibility Analysis of Using the AHP Model

AHP (Analytic Hierarchy Process) model decomposes complex decision-making problems into multiple factors through a hierarchical structure. It uses expert scoring or empirical data to quantitatively analyze the relative importance of each factor, providing a scientifically sound and rational method for weight assignment in debris flow risk assessment. In the context of the Parlung Zangbo River Basin in Tibet, where the factors influencing debris flow occurrence are diverse and complex, the AHP model can comprehensively consider the impacts of terrain, precipitation, geological conditions, and other factors, making the risk prediction results more aligned with reality.

This method breaks down complex decision problems into a hierarchical structure, allowing for a clearer understanding of the components and interrelationships of the problem. It quantifies the weights of various influencing factors and derives comprehensive decision-making results. Additionally, AHP employs Consistency Index (CI) and Consistency Ratio (CR) to check the decision-maker's consistency, helping to assess the rationality and reliability of the decision. Therefore, this method allows for determining the weights of different influencing factors and performing consistency checks.

3.3 Methods for Estimating Different Influencing Factors

In this study, I will conduct a detailed estimation of multiple influencing factors related to debris flow risk. First, I will extract the Melton ratio of the basin using ArcGIS to assess the impact of steep terrain on debris flow development. Next, historical rainfall data will be used to calculate the precipitation index, quantifying the correlation between rainfall intensity and duration with debris flow occurrence. Then, DEM data will be analyzed to determine slope aspect and gradient factors, evaluating the influence of topographic features on the kinetic energy of debris flows. Additionally, by combining actual vegetation coverage with the C value from the USLE, I will calculate the vegetation cover and management factor to assess the regulatory effect of vegetation on debris flow risk. Finally, the nearest neighbor distance method will be employed to calculate the distance from each pixel in the basin to the nearest fault, in order to analyze the influence of geological conditions on debris flow susceptibility.

3.2.1|Melton Ratio (R):

The Melton Ratio (R) is an indicator used to describe the steepness of the terrain in a watershed. It quantifies the steepness of the landscape by considering the area and elevation difference of the basin, and is commonly used to assess the impact of topography on debris flow occurrence. Specifically, the higher the Melton Ratio, the steeper the terrain and the greater the slope within the basin; conversely, a lower R value indicates a more gentle terrain.

The Melton Ratio directly influences the occurrence and development of debris flows. Steep terrain implies greater potential energy, which provides stronger driving forces for the material transport in debris flows. In watersheds with high R values, debris flows are more likely to gain sufficient kinetic energy, allowing them to carry larger amounts of sediment and boulders, thereby increasing their destructive power. However, if the R value is too high, it may also lead to the rapid accumulation and deposition of debris flow materials. Therefore, while the Melton Ratio within a certain range can facilitate the formation and development of debris flows, extremely high or low R values may hinder the sustained development of debris flows. The formula for calculating the Melton Ratio is as follows:

$$\mathrm{R} = \frac{\mathrm{dH}}{\sqrt{\mathrm{A}}}$$

Where dH represents the elevation difference of the basin (the difference between the maximum and minimum elevation), usually measured in meters (m), and A represents the area of the basin, typically measured in square kilometers (km^2). First, we obtain the Digital Elevation Model (DEM) data of the basin to extract the elevation information and boundaries of the basin. Next, using the DEM data, we calculate the elevation difference (dH) within the basin, which is the height difference between the highest and lowest points in the basin. Then, we determine the area (A) of the basin. Finally we divide the elevation difference (dH) by the square root of the area (A) to obtain the Melton Ratio (R) of the basin. Through these steps, the steepness of the terrain in the basin can be quantified.

Table 1 shows the statistical relationship between the average Melton Ratio in the basin and the development of debris flows

Average Melton Ratio in the Basin	<0.3	0.3-0.4	0.4-0.5	0.5-0.7	>0.7
Frequency/Count	15	57	73	25	11
Percentage (%)	8.28%	31.5%	40.3%	13.8%	6.1%
Percentage (%)	0.12	1.1	1.41	1.17	3.42

The statistical data (as shown in Table 1) indicates that as the average Melton Ratio within the basin increases, the development of debris flows initially rises and then declines. The most significant development of debris flows occurs within the Melton Ratio range of 0.4 to 0.5, suggesting that the topographical conditions within this range are most conducive to the formation and progression of debris flows.

3.2.2 | Estimation of the Precipitation Index (A):

Debris flows often occur after heavy or torrential rain because rainfall saturates the soil, increases the mobility of loose materials on slopes, and thereby heightens the risk of debris flows. Thus, there is a clear correlation between rainfall and debris flows. The precipitation index is a method used to quantify rainfall events, typically considering factors such as rainfall amount and duration.

Precipitation is a key trigger for debris flows. Intense rainfall rapidly increases surface water flow, causing loose materials like mud, sand, and rocks on slopes to be washed away and slide down, forming debris flows. The precipitation index, by integrating rainfall amount and duration, reflects the potential for debris flow occurrence in a given area during specific rainfall events. A high precipitation index indicates a stronger rainfall impact and a greater risk of debris flows. The calculation of the precipitation index typically follows this formula:

$$A = P \times R$$

Here, P represents the rainfall intensity per unit time (usually measured in millimeters per hour), and R represents the duration of the rainfall event (usually measured in hours).

First, collect historical rainfall data for the study area to determine the average rainfall intensity per unit time (P) and the total duration of the rainfall event (R). Then, multiply the rainfall intensity (P) by the rainfall duration (R) to calculate the precipitation index (A). This index quantifies the intensity of the rainfall event and its potential impact on debris flow risk

3.2.3 | Estimation of the Precipitation Index (A):

The Slope Length and Steepness factor (LS) is a key indicator used to describe terrain features, where both slope aspect (the direction the slope faces) and slope gradient (the angle between the slope and the horizontal plane) significantly influence the occurrence of debris flows. A steeper slope provides greater gravitational potential energy, allowing debris flows to gain higher kinetic energy as they slide down, increasing their coverage and enhancing their destructive power. Additionally, slope aspect determines the amount of precipitation the slope receives and the direction of water flow accumulation, thereby affecting the frequency and scale of debris flows. For example, slopes facing directions with more precipitation are more likely to experience debris flows, as moisture accumulates more easily and triggers the sliding of surface materials.

Specific steps are as follows:

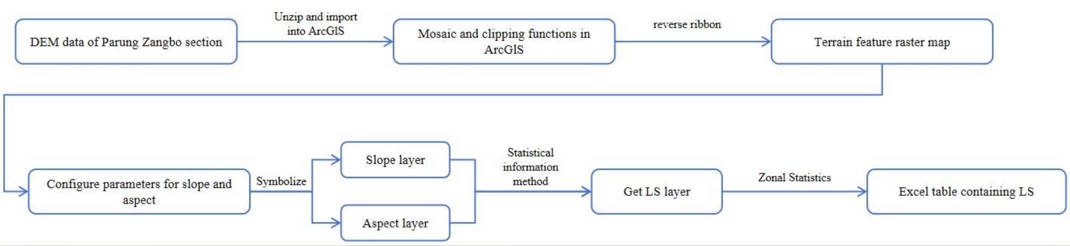

Figure 1 The specific steps to estimate the aspect slope factor

Among them, DEM data can be obtained from the Geographic Data Space Cloud. Adjusting the reverse color ramp and symbolization in ArcGIS is done to make the map clearer and more visually understandable. Finally, the LS layer is obtained, and the Zonal Statistics tool is used to extract data into an Excel file, which can be directly used in the subsequent AHP model application.

3.2.4 | Estimation of Vegetation Cover and Management Factor C:

The vegetation cover and management factor C involves the impact of vegetation on surface stability and rainfall runoff and is assessed from four aspects: maintaining soil stability, reducing soil erosion, absorbing rainfall moisture, and improving soil structure. The vegetation cover and management factor C can effectively and convincingly demonstrate the influence of this factor on the susceptibility to debris flows, further illustrating that the vegetation cover and management factor C is significantly feasible in assessing debris flow susceptibility.

By maintaining healthy vegetation cover and implementing effective management measures, the risk of debris flows triggered by rainfall can be significantly reduced. This project plans to use the different vegetation types and their average coverage obtained from surveys to look up the C value in the USLE (Universal Soil Loss Equation) table, thereby determining the C value for the Parlung Zangbo section. For areas without vegetation cover, the surface cover factor is not considered, and C is set to 1. Based on existing research results, reference values can be taken from the table below:

Table 2 Vegetation coverage and management factor C reference value

Tropical Coniferous Forest	C value	Tropical Coniferous Forest	C value
Protective Forest	0.09	Tropical Plantation and Economic Forest	0.11
Shrubland	0.14	Mountain Evergreen Broadleaf Forest	0.15
Mangrove Forest	0.085	Mountain Rainforest	0.06
Farmland	0.001	Mountain Summit Scrubland	0.02
Tropical Rainforest	0.06	Savanna	0.085
Valley Rainforest	0.004	Timber Forest	0.043
Grassland	0.001	Tropical Coniferous Forest	0.15

3.2.5 | Estimation of the Nearest Neighbor Distance to Fault B:

The nearest neighbor distance to a fault refers to the shortest distance from a point within the watershed to the nearest fault. Faults are fractures or zones of rupture in the Earth's crust, and their surrounding areas are often geologically fragile and more susceptible to geological hazards. The closer the distance to a fault, the more unstable the geological conditions in the area may be, increasing the risk of debris flows.

Geological conditions near faults are usually fragmented and loose, with unstable rock and soil structures that are prone to landslides and debris flows under external forces such as rainfall or earthquakes. Areas closer to faults are more likely to be high-risk zones for debris flows due to their fragile geological structure. Fault activity can also directly trigger earthquakes, further increasing the likelihood of debris flows. Therefore, the nearest neighbor distance to faults is an important indicator for assessing debris flow risk.

First, obtain Digital Elevation Model (DEM) data and fault distribution data for the study area. Then, load the fault data into GIS software and generate a fault line layer. Next, use GIS tools to calculate the distance from each pixel or specific location to the nearest fault line, which represents the nearest neighbor distance. Finally, classify the area into different distance categories based on these distance values to identify high-risk zones close to the fault.

3.4 AHP Model Theoretical Analysis

When establishing an AHP model to assess debris flow risk, the following steps are essential:

1. Determine the Evaluation Objective:

Clearly define that the goal of the AHP model is to assess the risk of debris flows within the study area. This objective will guide the entire model development and analysis process.

2. Construct the Hierarchical Structure:

Based on the factors influencing debris flow risk, build the hierarchical structure of the AHP model. This typically includes three levels:

Goal Level: Debris flow risk assessment.

Criteria Level: Major influencing factors such as the Melton ratio, precipitation index, slope aspect and gradient factor, vegetation cover and management factor, and the nearest neighbor distance to faults.

Alternative Level: Specific regions or locations to be assessed according to these influencing factors.

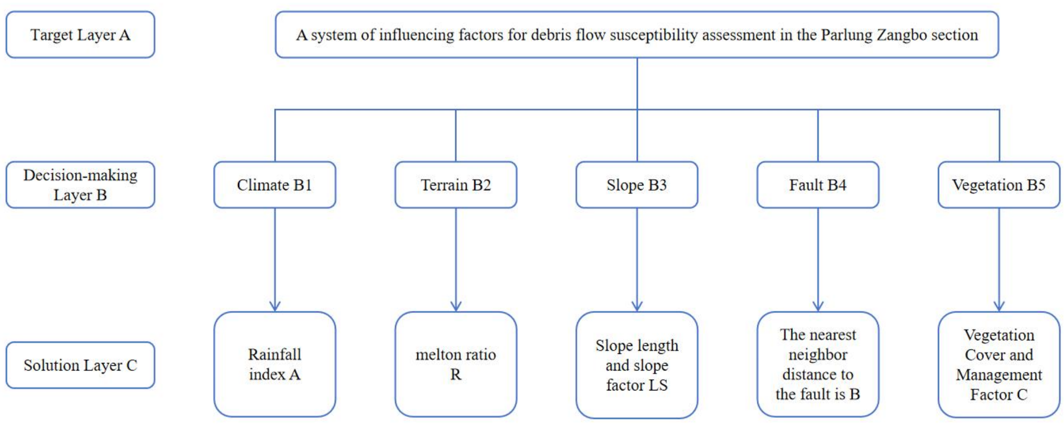

Figure 2 AHP model hierarchy diagram

3. Construct the Judgment Matrices:

For each factor in the criteria level, construct pairwise comparison judgment matrices to determine the relative importance of each factor. The values in the judgment matrices are determined based on experience, expert opinions, or existing research results, typically using a scale of 1 to 9.

Table 3 The relative importance between the factors

Relative Importance	Definition
1	Equally important
3	Slightly important
5	It is quite important
7	Obviously important
9	Absolutely important
2,4,6,8	The intermediate value of two adjacent judgments
1/3	Slightly unimportant
1/5	Quite unimportant
1/7	Obviously not important
1/9	Absolutely not important
1/2,1/4,1/6,1/8	The intermediate value of two adjacent judgments

4.Calculate the weight : use the judgment matrix to calculate the weight of each factor. This step can be achieved by eigenvalue method or geometric average method. The weight reflects the relative importance of each factor in debris flow risk assessment.

Firstly, the sum of each column of the judgment matrix is calculated, and a vector S is obtained by summing each column of the judgment matrix A.

$$S_j = \sum_{i=1}^{n} a_{ij}, \quad j = 1,2,\ldots,n$$

Secondly, the judgment matrix is normalized. Each element of the judgment matrix is normalized, and each element is divided by the sum of its columns to obtain the normalized judgment matrix A'.

$$a_{ij}' = \frac{a_{ij}}{S_j}, \quad i,j = 1,2,\ldots,n$$

Finally, the row average of the normalized judgment matrix A' is calculated, and the average value of each row of the normalized judgment matrix is calculated to obtain the weight vector of each factor.

$$w_i = \frac{1}{n}\sum_{j=1}^{n} a_{ij}{'} \quad , \quad i = 1,2,\ldots,n$$

Among them, w_i is the weight of the factor C_i.

4. Consistency test : Consistency test is performed on the judgment matrix, and the consistency ratio (CR) is calculated. If the CR value is less than 0.1, the consistency of the judgment matrix is acceptable ; otherwise, the judgment matrix needs to be adjusted until a reasonable level of consistency is reached.

Firstly, the maximum eigenvalue λ_{max} is calculated, and the maximum eigenvalue λ_{max} of the judgment matrix is calculated.

$$\lambda_{max} = \sum_{i=1}^{n} \frac{(AW)_i}{w_i}$$

Among them, AW is the vector obtained by multiplying the judgment matrix A with the weight vector W.

Secondly, the consistency index (CI) is calculated, and the consistency index λ_{max} is calculated according to the maximum eigenvalue.

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

Finally, the consistency ratio (CR) is calculated, and the consistency index is compared with the random consistency index (Rl) to calculate the consistency ratio.

$$CR = \frac{CI}{RI}$$

Among them, it is a random consistency index determined according to the order of the matrix, and its common values are as follows :

Table 4 Common value table of random consistency index

n	1	2	3	4	5	6	7	8	9
CR	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.46

6.Comprehensive score : The weight of each influencing factor is multiplied by the score of each region or location under these factors, and the comprehensive score of each region is calculated. The higher the comprehensive score, the greater the risk of debris flow in the region.

7.Risk zoning : According to the results of the comprehensive score, the study area is divided into different risk levels, such as high-risk, medium-risk and low-risk areas. This step can be done by setting the threshold or grading standard of the score.

3.4 Drawing debris flow susceptibility map by ArcGIS

We draw the degree of debris flow susceptibility through ArcGIS.

Firstly, the main factors affecting debris flow (such as precipitation index A, Melton ratio R, aspect slope factor LS, vegetation cover and management factor C, nearest neighbor distance from fault B, etc.) are projected into the corresponding raster data, and these raster data are classified. Then, the weight (Wi) of each factor calculated by the AHP model is imported into the table containing these attributes.

On this basis, the debris flow susceptibility distribution map of each region is generated by weighted sum and grid calculation. The reclassification of the Shange data is to divide the continuous data values into different discrete categories to make them more accurate and more optimized. After the classification, the symbolization can make the debris flow susceptibility map clearer and more intuitive, and then extract the data for the kappa model consistency test to analyze the consistency with the real data. This process also includes the natural breakpoint symbolization of the calculation results in order to clearly show the debris flow risk levels in different regions.

Finally, the Zonal Statistics tool is used to extract and count the result data, and the Excel table containing the prone level is output to provide the basis for further analysis and risk assessment.

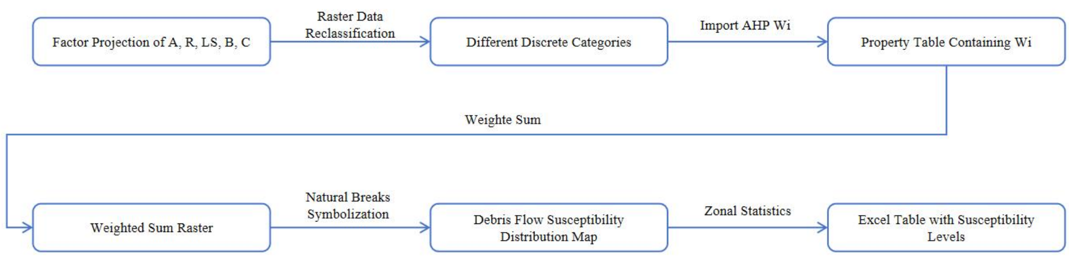

Figure 3 The Zonal Statistics tool was used to extract and count the result data.

Then, using the data classification method of the natural discontinuity point classification method in GIS, the debris flow susceptibility index is divided into four grades : not easy to occur, mildly prone, moderately prone, and highly prone, and the debris flow susceptibility evaluation index is calculated. According to the classification of the size of the evaluation index, the debris flow susceptibility area of the Palongzangbu section of Sichuan and Tibet is divided.

3.5 Consistency test

In order to test whether the model algorithm method can be used to predict the degree of debris flow susceptibility, and to optimize the method of the model, we used the Kappa consistency test.

The Kappa coefficient is calculated by comparing the consistency and random consistency of actual observations. The Kappa coefficient is calculated based on the confusion matrix, which includes true positive (TP), true negative (TN), false positive (FP) and false negative (FN).

Kappa coefficient is an index to measure the classification accuracy. It is obtained by multiplying the total number of pixels (N) in all real surface classifications by the sum of the diagonals of the confusion matrix (Xkk), and then subtracting the sum of the product of the total number of real pixels in a certain type of surface and the total number of classified pixels in the class, and finally dividing by the square of the total number of pixels minus the sum of the product of the total number of real pixels in a certain type of surface and the total number of classified pixels in the class.

The calculation formula of Kappa coefficient is as follows :

$$k = \frac{p_o - p_e}{1 - p_e}$$

Among them, P_0 is the sum of the number of samples for each type of correct classification divided by the total number of samples, that is, the overall classification accuracy.

Suppose that the number of real samples for each class is a1, a2,..., aC, respectively, and the number of predicted samples for each class is b1, b2,..., bC, respectively, and the total number of samples is n, then :

$$p_e = \frac{a1 \times b1 + a2 \times b2 + \ldots + aC \times bC}{n \times n}$$

Based on the consistency analysis and evaluation between the actual observation value and the predicted value of the simulated debris flow susceptibility, the following results are obtained :

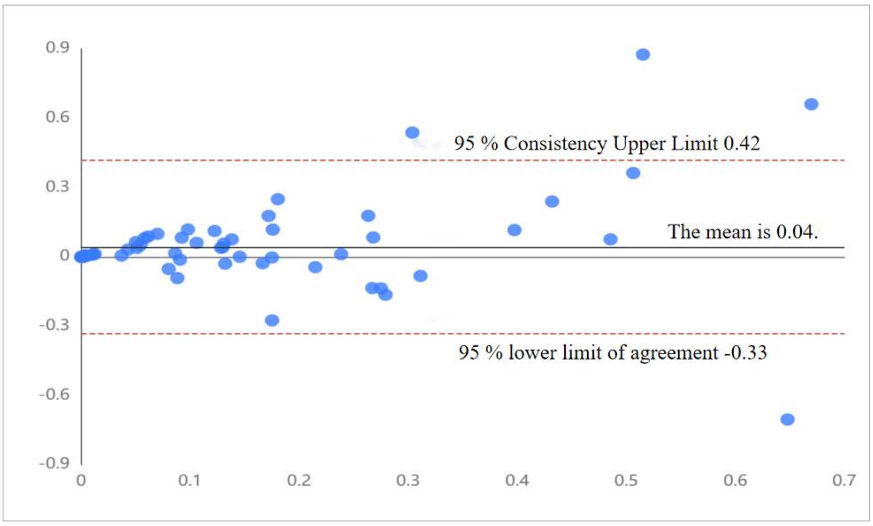

Figure 4 Consistency test results

Generally, the closer the value of the Kappa coefficient is to 1, the higher the consistency, and the closer the value is to 0 or negative, the lower the consistency. Usually, the Kappa coefficient between 0.6 and 0.8 is considered to be good consistency. The more points are within 95 % LoA (dotted line in the figure), the better the consistency is.

4 | Conclusion

Through the multi-factor weighted superposition method based on AHP model, this paper successfully generated the debris flow susceptibility distribution map of Palongzangbu basin.

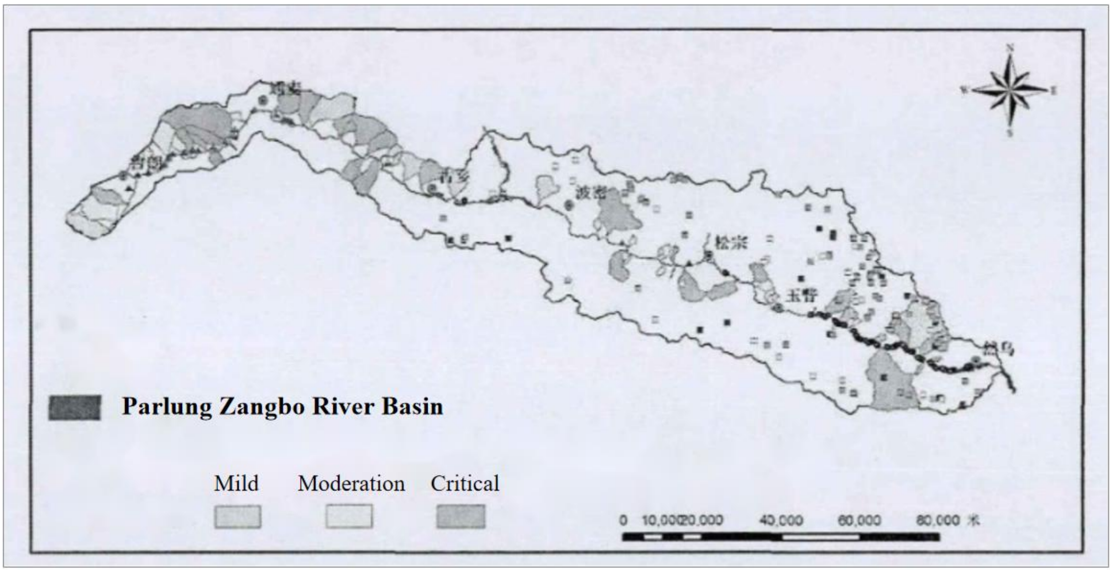

Figure 5 Distribution map of debris flow susceptibility in Palongzangbu basin

The distribution map clearly reflects the degree of debris flow susceptibility in different regions of the basin, and the areas with high susceptibility are closely related to the distribution of various influencing factors. Through the identification of these high-risk areas, it can provide an important basis for regional disaster warning, risk management and planning decision-making. In addition, the results also verify the role and relative importance of each influencing factor in debris flow risk assessment, which provides strong support for further research and practice.

Funding

This research was funded by National University Student Innovation and Entrepreneurship Project "Analysis of Inducing Factors and Susceptibility Assessment of Debris Flow in Palongzangbu Section by Mathematical Model and ArcGIS", grant number S202410694010.

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