Application Research on Geological Hazard Risk Zonation Evaluation Based on GIS Information Fusion:A Case Study of Bama County

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Abstract: Given frequent landslide hazards and insufficient collaborative analysis of multi-source data in the carbonaceous mudstone mountainous areas of Bama County, this study uses GIS information fusion technology as the core to construct a three-level fusion framework. It is a "Data Layer-Feature Layer-Decision-making Layer" framework for geological hazard risk zonation evaluation. By integrating multi-source data including terrain (DEM), geology (structure, lithology), meteorology (rainfall), vegetation (NDVI) and historical hazards, the study area is divided into 5 risk levels, and the model accuracy is verified by 107 historical landslide points. The results show that: (1) GIS information fusion effectively integrates multi-source heterogeneous data, which solves the limitations of single data, and the model's recognition accuracy for high-risk areas reaches 89.7%; (2) the high-risk areas (Level 4-5) in Bama County account for 28.8%, concentrated in the area within < 0.5km around the northwestern Bama Fault Zone, the carbonaceous mudstone distribution area with slope > 25° and annual average rainfall > 1400mm; (3) the low-risk areas (Level 1-2) account for 46.6%, mainly distributed in the gentle areas with vegetation coverage > 60% in the southwest. Moreover, this study can serve as a reference for geological hazard prevention and control, as well as for risk management, in Bama County.

Keywords: GIS; Information Fusion; Geological Hazards; Risk Zonation; Carbonaceous Mudstone

1. Introduction

Bama County is located in northwestern Guangxi, belonging to the concentrated distribution area of carbonaceous mudstone on the southeastern margin of the Yunnan-Guizhou Plateau, with carbonaceous mudstone accounting for 38% of the county's total area. Due to the high carbon content (TOC 6%-40%) of the lithology in this area, the rock stratum is highly water-sensitive, prone to softening and swelling when encountering water, resulting in a 50%-70% reduction in shear strength. Coupled with the active regional fault structure, this can lead to significant reductions in shear strength. Geologically, the Bama Fault Zone runs through the county, and the area has a large annual average rainfall of 1200-1600mm. During 2014-2023, a total of 112 landslide hazards occurred, causing direct economic losses exceeding 210 million RMB, of which 87% of the landslides were related to the water-induced instability of carbonaceous mudstone.

The traditional geological hazard risk evaluation mostly relies on single geological data, ignoring the coupling effect of multi-source data, which leads to insufficient accuracy of risk zonation. The use of GIS information fusion technology can complement and integrate multi-source data to reduce data uncertainty; in addition, data layer fusion realizes the standardization of original data, feature layer fusion extracts key influencing factors, and decision-making layer fusion completes multi-index coupling evaluation. The collaboration of the three can significantly improve the scientificity of risk zonation [1-2]. Therefore, carrying out the research on geological hazard risk zonation in Bama County based on GIS information fusion has important practical value for disaster prevention and control in carbonaceous mudstone mountainous areas in Southwest China.

Internationally, Shiono et al. [3] completed the landslide zonation of the Kii Peninsula in Japan by superimposing terrain and lithology data based on GIS, but did not involve the special properties of carbonaceous mudstone and multi-source data fusion. Moreover, domestic research focuses on the combination of carbonaceous mudstone characteristics and GIS. Wang et al. [4] obtained through triaxial tests that the shear strength of carbonaceous mudstone in Bama County is only 35% of that in the dry state when the water content is 15%, providing a mechanical basis for the selection of fusion indexes. Zhang et al. [5] evaluated landslides in carbonaceous mudstone mountainous areas in Guizhou by combining GIS and random forest models, but did not systematically divide the fusion levels, and the weights of the decision-making layer were highly subjective. Similarly, Rivera et al. [6] applied the Analytic Hierarchy Process (AHP) combined with GIS to map landslide risk in Peru's Utcubamba River Basin, demonstrating AHP's effectiveness in quantifying subjective factor weights (e.g., terrain, rainfall) for regional-scale risk zoning. Moreover, Demirel et al. [7] integrated AHP with Failure Mode and Effects Analysis (FMEA) and Pareto analysis in Türkiye's Yalova region, enhancing risk assessment by incorporating failure probability and impact severity—addressing AHP's limitations in uncertainty analysis. Chaabane et al. [8] further advanced multicriteria analysis in landslide risk assessments, highlighting its flexibility in integrating ecological, geological, and socioeconomic factors to support decision-making.

Remote sensing and IoT technologies are driving innovations in monitoring and early warning. Enkela et al. [9] utilized GIS and remote sensing to assess landslide risk in Albanian settlements, leveraging satellite imagery for terrain and land-use analysis to identify high-risk residential areas. Ambika et al. [10] took a step further by integrating geotechnical data, remote sensing, IoT, and sensor networks for real-time unstable slope monitoring, enabling landslide early warning through continuous data transmission on slope deformation and environmental conditions—filling the gap between static risk mapping and dynamic hazard response.

As geospatial tools have enhanced spatial analysis and modeling capabilities, the risk zonation map production can be produced in GIS. In this research, the risk zonation delineation is realized by constructing a three-level fusion framework of Data Layer - Feature Layer - Decision-making Layer and using the data of GIS information fusion levels.

2. Theoretical Basis and Overview of the Study Area

2.1 Core Concepts of Geological Hazard Risk Evaluation

According to the terminology of disaster risk reduction by UNISDR, risk is the coupling result of "hazard" and "vulnerability", and its calculation according to the formula (1).

$$\text{Risk (R)} = \text{Hazard (H)} \times \text{Vulnerability (V)} \quad (1)$$

where, hazard refers to the possibility and intensity of geological hazards occurring in a specific area, controlled by natural factors such as terrain, geology and meteorology; vulnerability refers to the ability of hazard-bearing bodies (population, buildings, infrastructure, etc.) in the area to withstand hazards, affected by social and economic factors.

2.2 GIS Information Fusion Technology Framework

GIS information fusion is divided into three levels according to the hierarchy. The core is to gradually integrate through "data - feature - decision-making" to realize the refinement of risk evaluation, as shown in Figure 1.

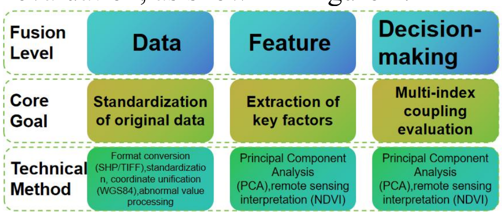


Figure 1. Three-level GIS Information Fusion Framework

2.3 Characteristics of Landslide Risk Factors

The instability mechanisms of landslides mainly include water-induced softening, structural disturbance, gravity triggering, etc. Among them, rainwater seeps through fractures, and montmorillonite absorbs water and swells (interlayer distance expands 3-5 times), resulting in a sharp drop in its shear strength; secondly, the activity of the Bama Fault Zone leads to the development of fractures in the rock mass (density 5-8 fractures/m), providing channels for water infiltration; in addition, when the slope is > 25°, the gravity component exceeds the shear strength of the rock and soil mass, triggering shallow landslides (sliding surface depth 1-3m) [6].

Combined with the actual situation of Bama County, this study identifies 6 core risk factors: terrain factors, geological factors, meteorological factors, ecological factors, and historical factors. The details are as follows:

(1) Terrain factor: slope (controlling the gravity component);

(2) Geological factors: geological structure (distance from fault zone), lithology (distribution of carbonaceous mudstone);

(3) Meteorological factor: annual average rainfall (controlling the degree of water-induced softening);

(4) Ecological factor: vegetation coverage (root system consolidates soil and reduces erosion);

(5) Historical factor: historical landslide events (reflecting the instability probability of the region).

3. Data Layer Fusion

3.1 Collection of Multi-source Data

Six types of risk factor data are collected to construct the geological hazard database of Bama County, as shown in Table 1.

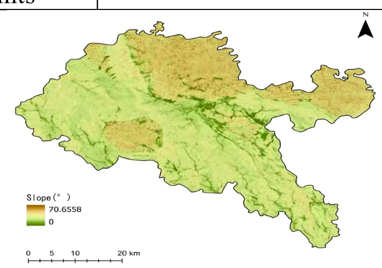
3.2 Data Layer Fusion Processing

The core of data layer fusion is to eliminate the differences of multi-source data and realize the unification of format, coordinate, and accuracy. The flow chart is shown in Figure 2.

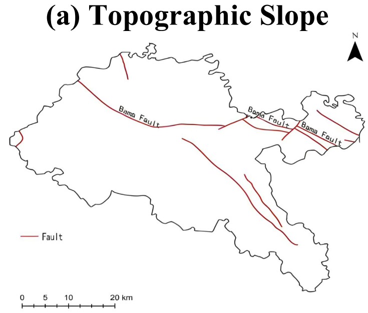
The specific steps are as follows. Firstly, In the data cleaning link, to eliminate the differences of multi-source data, for the daily rainfall of 300mm at the Natiao Township Meteorological Station in 2018 (exceeding the annual average by 20%), the Kriging interpolation method (based on data from 5 surrounding meteorological stations) is used to correct it to 152mm; in addition, duplicate historical landslide points are removed (5 duplicate records are deleted), and 107 valid points are retained. For the missing areas of vegetation coverage (NDVI) (cloud coverage), the band replacement method (based on adjacent monthly images) is used to supplement. Secondly, to unify the format and coordinate, DEM and NDVI are converted from HDF format to GIS-compatible TIFF format, and geological structures and historical landslide points are converted to SHP vector format; at the same time, the geographic coordinate system WGS84 (EPSG:4326) and the projected coordinate system UTM Zone 48N (EPSG:32648) are adopted to eliminate spatial offset. Thirdly, to realize accuracy standardization, rainfall (1km) and population distribution (1:250,000) are resampled into 30m×30m grids by the bilinear interpolation method, consistent with the resolution of DEM and NDVI; in addition, the 6 factors are divided into 5 levels by the natural break method.

Table 1. Multi-source Data for Geological Hazard Risk Evaluation

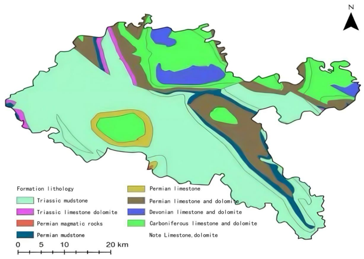
Data Type	Source	Scope
Topographic Slope	Geological Cloud of China Geological Survey	Entire territory of Bama County
Geological Structure	Geological Cloud of China Geological Survey	
Lithology	Geological Cloud of China Geological Survey	
Rainfall	National Meteorological Information Center	
Vegetation Coverage	Geological Cloud of China Geological Survey	
Historical Landslide Points	Institute of Geographic Sciences and Natural Resources Research, CAS	
Population Residential Distribution Points	1:250,000 National Fundamental Geographic Database	



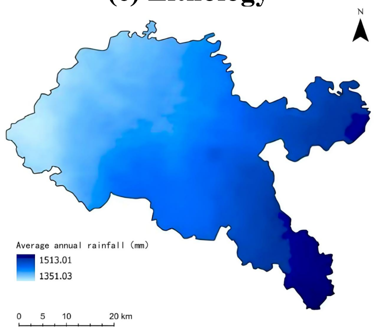
(a) Topographic Slope



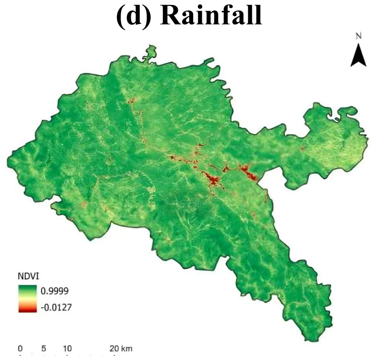
(b) Geological Structure



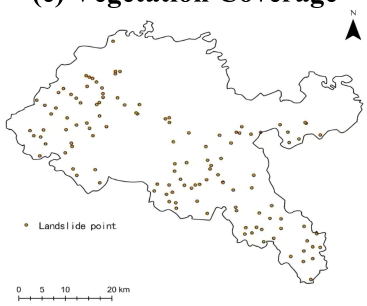
(c) Lithology



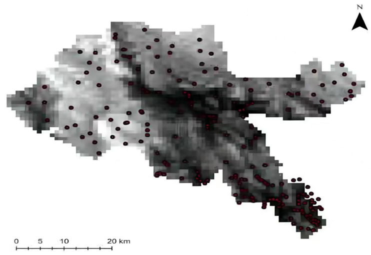
(d) Rainfall



(e) Vegetation Coverage



(f) Historical Landslide Points



(g) Population Residential Distribution Points

Figure 2. Layer Data

4. Feature Layer and Decision-making Layer Fusion

4.1 Feature Layer Fusion

Principal Component Analysis (PCA) is used to extract features from the 6 standardized factors to reduce data redundancy. The details are as follows:

(1) Construct a factor matrix: convert the 6 factor grids into a sample matrix;

(2) Calculate the covariance matrix: eliminate the dimensional difference of factors, and extract 3 principal components according to the principle of eigenvalue > 1, with a cumulative contribution rate of 89.2% (Table 2), covering the core information of the 6 factors.

It can be seen from the table that slope, distance from fault zone, rainfall and distribution of carbonaceous mudstone are the core characteristic factors affecting landslides in Bama County, which are consistent with the landslide instability mechanism

4.2 Decision-Making Layer Fusion

The decision-making layer fusion determines the factor weights through AHP, combines GIS weighted overlay to realize multi-index coupling, and outputs the risk level.

Table 2. Results of Principal Component Analysis

Principal Component	Eigenvalue	Contribution Rate (%)	Cumulative Contribution Rate (%)	Main Loading Factors
PC1	3.2	54.2	54.2	Slope, Distance from Fault Zone
PC2	1.56	26.0	80.2	Rainfall, Lithology
PC3	1.14	19.0	89.2	Vegetation Coverage, Historical Landslides

4.2.1 AHP weight calculation

Firstly, the 1-9 scale method is used to construct a judgment matrix (Table 3), the weight is calculated by the sum-product method, and consistency test is performed; secondly, based on the core factors extracted from the feature layer, the relative importance of the factors is determined (for example, the slope has a stronger impact on landslides than vegetation coverage, with a scale of 2-3), and the judgment matrix is constructed; then, the weight is calculated by formulas (2)-(3) and the weight value is obtained (Table 3).

$$b_{ij}=\frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad (2)$$

$$w_i=\frac{1}{n}\sum_{j=1}^{n} b_{ij} \quad (3)$$

where, a_{ij} presents the element of the judgment matrix; b_{ij} notes as the normalized element ;w_i refers to the weight of the i-th factor.

Table 3. Judgment Matrix, Weights and Ranking of Risk Factors

Factor	Slope	Geological Structure	Lithology	Rainfall	Vegetation Coverage	Historical Landslides	Weight	Ranking
Slope	1.0	1.25	1.538	1.25	2.5	2.5	0.2581	1
Geological Structure	0.8	1.0	1.0	1.0	1.0	1.0	0.1562	2
Lithology	0.65	1.0	1.0	1.0	1.0	1.0	0.1501	3
Rainfall	0.8	1.0	1.0	1.0	1.0	1.0	0.1562	2
Vegetation Coverage	0.4	1.0	1.0	1.0	1.0	1.0	0.1397	4
Historical Landslides	0.4	1.0	1.0	1.0	1.0	1.0	0.1397	4

4.2.2 GIS weighted overlay

Based on the AHP weights, the decision-making layer fusion is realized through GIS "Spatial Analyst Tools - Weighted Overlay", and the formula is as follows:

$$R=\sum_{i=1}^{6} w_i \times F_i \quad (4)$$

where, R represents the risk index (ranging from 1 to 5); w_i notes as the weight of the i-th factor; F_i is the graded score of the i-th factor (ranging from 1 to 5).

The weighted overlay fusion process includes the flowing steps:

(1) Import 6 factor grid layers and input the weights of the corresponding layers in Table 3;

(2) Set the risk index classification thresholds, namely 1.00-1.80 (Level 1), 1.81-2.60 (Level 2), 2.61-3.40 (Level 3), 3.41-4.20 (Level 4), 4.21-5.00 (Level 5);

(3) Output the geological hazard risk zonation map of Bama County (Figure 3) to complete the decision-making layer fusion.

5. Risk Zonation Results and Accuracy Verification

5.1 Risk Zonation Results

Through the three-level GIS fusion, the geological hazard risk in Bama County is divided into 5 levels. The area, proportion, and spatial distribution of each level are shown in Table 4 and Figure 3.

As shown in the Figure 3, the high-risk areas (Level 4-5) are distributed in a "northeast-southwest strip shape", consistent with the strike of the Bama Fault Zone, and the proportion of carbonaceous mudstone exceeds 78%, reflecting the "structure + lithology + rainfall" coupling effect; the very low-risk areas (Level 1) are concentrated in the southwest, with high vegetation coverage and far from the risk sources, and the ecological protection effect is significant; the central medium-risk areas (Level 3) are the "low-high" transition zone, affected by human activities, and the potential risks need to be focused on.

5.2 Accuracy Verification

Based on the "historical landslide point matching degree", the accuracy of the GIS information fusion model is verified, and the core is to test the consistency between the high-risk areas and the actual disaster distribution. Moreover, the 107 historical landslide points are superimposed with the risk zonation map, and the proportion of landslide points in each level is counted, as the table 4 listed.

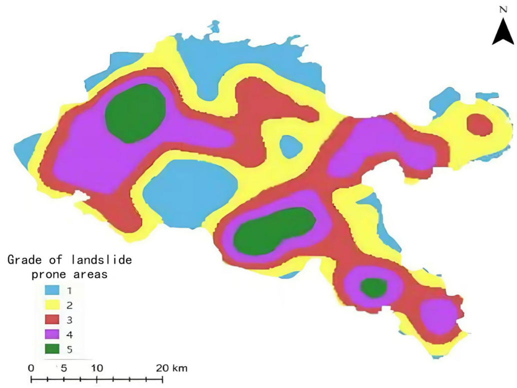


Figure 3. Map of Landslide Risk Zonation in Bama County

Table 4. Statistics of Geological Hazard Risk Zonation in Bama County

Risk Level	Risk Index Range	Area (km²)	Proportion (%)	Spatial Distribution Characteristics	Carbonaceous Mudstone Proportion (%)	Historical Landslide Points Proportion (%)
Level 1	1.00-	286.5	12.1	Suolue Township in the southwest, slope	5.2	1.9

(Very Low)	1.80			< 10°, vegetation coverage > 70%		
Level 2 (Low)	1.81-2.60	826.8	34.5	Nashe Township in the west, Natiao Township in the south, far from the fault zone (> 3km)	12.8	8.4
Level 3 (Medium)	2.61-3.40	684.2	28.6	Jiazhuan Township in the central part, Xishan Township in the east, slope 10-25°	42.5	29.0
Level 4 (High)	3.41-4.20	368.7	15.6	Yandong Township in the northwest, 1-3km from the fault zone, rainfall 1200-1400mm	78.3	31.8
Level 5 (Very High)	4.21-5.00	316.3	13.2	Bama Town in the north, Dongshan Township in the northeast, slope > 25°, rainfall > 1400mm	92.1	39.3

Taking Yandong Township as an example, Yandong Township is a Level 4 high-risk area with an area of 87.2km² and a carbonaceous mudstone proportion of 91.3%. A total of 23 landslides occurred during 2014-2023 (accounting for 21.5% of the county). The fusion model identifies this area as a high-risk area, which is completely consistent with the actual disaster distribution; among them, the slope of this area is mostly 25-40°, the annual average rainfall is 1450mm, and the distance from the fault zone is <0.8km, which meets the "three-factor coupling" condition for the instability of carbonaceous mudstone, verifying the rationality of the model.

6. Prevention and Control Measures and Emergency Management Based on Fusion Results

Combined with the risk zonation results of GIS information fusion, differentiated prevention and control measures are formulated for different level areas to realize "precision policy implementation". The details are as follows:

(1) High-risk areas (Level 4-5)

For high-risk areas, the prevention and control measures of combining engineering and monitoring are adopted. At the engineering construction level, "anchor rods + lattice beams" are arranged on the exposed slopes of carbonaceous mudstone; in addition, catchment ditches (longitudinal slope 3‰, width 1m) and blind ditches (diameter 100mm, spacing 5m) are built to reduce pore water pressure; at the safety monitoring level, GNSS monitoring stations (mm-level accuracy) are arranged to monitor slope displacement in real time.

(2) Medium-risk areas (Level 3)

For medium-risk areas, the prevention and control measures of combining ecology and management are adopted. In terms of ecological measures, native tree species (Pinus massoniana, Amorpha fruticosa) are planted to increase the vegetation coverage to more than 60% and consolidate the soil with root systems; in terms of management measures, the development of cultivated land in areas with slope > 25° is restricted, disturbing projects such as highway excavation are prohibited, and guardrails are set in developed areas.

(3) Low-risk areas (Level 1-2)

For low-risk areas, the prevention and control measures focusing on publicity and inspection are adopted. At the publicity and education level, popularize landslide identification knowledge (such as cracks, abnormal sounds) through village radio and publicity boards; in terms of daily hidden danger investigation, conduct inspections once a month, focusing on local waterlogging areas in the rainy season (June-August) to prevent small-scale landslides.

7. Conclusions

By constructing a three-level GIS fusion risk zonation framework, the data layer fusion realizes the standardization of multi-source data, the feature layer fusion extracts core factors (contribution rate 89.2%), and the decision-making layer fusion completes multi-index coupling. The model's recognition accuracy for high-risk areas reaches 89.7%, realizing intelligent risk zonation of the study area. Among them, the high-risk areas (Level 4-5) account for 28.8%, concentrated in the carbonaceous mudstone areas around the Bama Fault Zone, controlled by the "slope + rainfall + structure" coupling; the low-risk areas (Level 1-2) account for 46.6%, with significant ecological protection effects. Finally, based on the risk zonation results, a hierarchical prevention and control strategy is proposed, that is, "engineering + monitoring" for high-risk areas, "ecology + management" for medium-risk areas, and "publicity + inspection" for low-risk areas. In summary, this study can serve as a reference for geological hazard prevention and control, as well as for risk management, in Bama County.

Acknowledgments

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