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## ORIGINAL RESEARCH ARTICLE

# Evaluation methods of regional bank slope stability based on geographic information systems and integrated information model

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## ABSTRACT

Through the combination of the geographic information systems (GIS) and the integrated information model, the stability of regional bank slope was comprehensively evaluated. First, a regional bank slope stability evaluation index system was established through studying seven selected factors (slope grade, slope direction, mountain shadow, elevation, stratigraphic lithology, geological structure and river action) that have an impact on the stability of the slope. Then, each factor was rasterized by GIS. According to the integrated information model, the evaluation index distribution map based on rasterized factors was obtained to evaluate the stability of the regional bank slope. Through the analysis of an actual project, it was concluded that the geological structure and stratigraphic lithology have a significant impact on the evaluation results. Most of the research areas were in the relatively low stable areas. The low and the relatively low stable areas accounted for 15.2% and 51.5% of the total study area respectively. The accuracy of slope evaluation results in the study area reached 95.41%.

***Keywords:*** Regional Bank Slope; Stability Evaluation; Integrated Information Model; GIS

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## 1. Introduction

After the completion of the reservoir, the change of the water level will change the state of the reservoir bank slope, and will have adverse impact on the stability of the slope, leading to the occurrence of landslide. Once landslide occurs, it will have a serious impact on the normal operation of the reservoir. In order to reduce the impact of slope instability on the operation safety of the reservoir, it is necessary to timely evaluate the stability of the regional slope, so as to provide scientific decision-making basis for project construction and management[1]. At present, the stability evaluation of single slope has achieved in-depth research results, and deterministic analysis methods are mostly used. For example, Hungr[2], Xie *et al*.[3], and Zhou *et al*.[4] used the limit equilibrium method and finite element method to analyze the possibility of landslide of single slope. This deterministic analysis method can accurately evaluate the stability of single slope, but for the regional bank slope, due to the large number of slopes, the workload of calculating the stability of each slope is very heavy.

At present, many scholars have studied the stability evaluation of regional bank slope. Generally, multivariable analysis and mathematical models are used to analyze, and the weights of various factors affecting slope stability (such as slope grade, geological structure, stratigraphic lithology) are superimposed to obtain the comprehensive index distribution map in the region. For example, He *et al.*[5] combined GIS and analytic hierarchy process to evaluate the susceptibility of landslide disaster in Zada area, Tibet; Yang *et al.*[6] predicted landslide displacement based on the PSO-RBF model of the chaos theory; Sun[7] predicted the sliding force based on the ARMA model; Liu *et al.*[8] predicted and divided regional landslide hazards based on logical regression and the artificial neural network model; Li *et al.*[9] evaluated the stability of rock slope by using the method of combining fuzzy logic and neural network; Xue *et al.*[10] evaluated the stability of slope based on the fuzzy neural network model of genetic algorithm. However, when classifying the factor state, the above method largely depends on the engineer's engineering experience and has no reasonable theoretical support, which will affect the accuracy of the model results. The integrated information model is based on the statistical analysis of the real situation of the known broken area. This method classifies the factor state according to quantitative indicators, which can well overcome the above problems. Because the model has more theoretical basis, it has been widely used in the stability evaluation of regional bank slope[11–13].

Geographic information systems (GIS) has unique application advantages for regional problems. In GIS, vector data can be transformed into GIS grid dataset. And its compatibility and openness make it possible to be used to deal with very complex professional problems[14].

Based on the integrated information model of statistical analysis and the GIS platform, this article establishes an index evaluation system and obtains the evaluation index distribution map based on grid unit, so as to evaluate the stability of regional bank slope. The integrated information model is a kind of statistical analysis model, which not only overcomes the influence of relying on experience on the accuracy of results, but also gives the evaluation value quantitatively.

## 2. Integrated information model

The theoretical basis of the integrated information model is the information theory, which reflects the importance of various influencing factors through the actual situation of the known broken area, and uses the information value to reflect the possibility of landslide events. The greater the information value, the lower the safety factor of the slope, the greater the possibility of landslide[15].

When evaluating the regional slope based on GIS and the integrated information model, it is assumed that the study area is divided into $M$ grid units, of which $M_1$ is the number of grid units that have landslide. For a single factor, there are K grid units in single factor $x_i$, where $k_1$ is the number of grid units that have landslide, and the amount of information $Lx_i$ of single factor $x_i$ is:

$$Lx_i = log_2 \frac{K_1/K}{M_1/M} \quad (1)$$

If the number of rasterized units is converted to area, equation (1) can be expressed as:

$$Lx_i = log_2 \frac{B_1/B}{D_1/D} \quad (2)$$

In formula (2): $D$ is the total area of the study area; $D_1$ is the total area of landslide; $B$ is the total grid area of single factor $x_i$; $B_1$ is the total area of landslide in single factor $x_i$[16].

Because there are many factors affecting slope stability, the information value is calculated by superimposing the information contributed by various factors, and the expression is:

$$I(y, x_1 x_2 \cdots x_n) = I(y, x_1) + I_{x_1}(y, x_2) + \cdots + I_{x_1 x_2 \cdots x_{n-1}}(y, x_n) \quad (3)$$

In formula (3): $L(y, x_1, x_2 \ldots x_n)$ is the information amount of the combination of each factor $x_1$, $x_2 \ldots x_n$.

## 3. Project overview

Benzilan water-source reservoir area of the central Yunnan water-diversion project is the landform of alpine deep erosion denudation canyon, with developed folds and faults, and most of the bedrock on the bank slope is exposed. It is mainly composed of Carboniferous, Permian and Devonian strata. The lithology is mainly composed of metamorphic basic volcanic rock (schistosity), slate, schist, limestone and marble. The overall trend of the rock stratum is nearly SN. Most of them are oblique to the bank slope at a small angle, and the dip angle is generally 45°–70°. The quaternary overburden is mainly alluvial proluvial sand gravel, which is distributed in the riverbed and floodplain, and less on both banks of the main stream of Jinsha River.

The unfavorable geological body developed in the reservoir area is mainly landslide, which may affect the stability of the reservoir bank slope under the extreme conditions of rainstorm and rapid change of water level.

# 4. Stability evaluation of regional bank slope

## 4.1 Division of grid units

In order to evaluate the slope stability in the study area, it is necessary to divide the study area into grid units. Based on the collation of spatial data (mainly including the 1:10,000 topographic map and 1:50,000 engineering geological map of the reservoir area), the CAD graphic data in the study area were transformed into vector data in ArcGIS environment. The relevant vector data such as terrain, stratum and geological structure were transformed into grid data through the spatial analysis function in ArcGIS. Then each grid unit was given an information value, that is, the value of each grid unit represented the influence of this factor on slope stability.

In the Jinsha River basin where the reservoir area is located, each 1.5 km along the left and right banks was taken as the study area. The study area was 65 km from North to South and 1.5 km from East to West. Take 10 m × 10 m as a grid unit and divide the study area into 8,136 rows and 3,084 columns. There were total 2,713,335 grid units.

## 4.2 Establishment of the index system

67 landslide data samples in the study area were selected to carry out the evaluation and research on slope stability. The factors with great correlation with slope stability were selected to construct the index system, among which the 7 selected factors included slope direction, slope grade, mountain shadow, elevation, stratigraphic lithology, geological structure and river action[11]. The establishment of the index system included index factor state classification and factor state correlation analysis.

### 4.2.1. Establishment of the index system

Because a single factor will have different effects on the results in different states, it is necessary to classify the state of the index. The standard of state classification is to find out the mutation point as the basis for classification according to the ratio curve and information curve of landslide obtained by the integrated information model. The data types can be divided into continuous data and discrete data.

#### 4.2.1.1 Topographic conditions

It mainly includes slope direction, slope grade, mountain shadow and elevation, which are continuous data. The grid data of these factors were extracted in GIS, and the information value and grid ratio of landslide in different states were counted, as shown in **Figure 1**. It can be seen that the slope in the study area can be divided into 0°–3 °, 3°–25°, 25°–40°, 40°–50° and 50°–90°, in which the slope grade of landslide was mainly in the range of 3°–40°. The slope direction can be divided into –1°–100°, 100°–180°, 180°–330°, 330°–360°, in which the slope direction of landslide was mainly in the range of 180°–330°. The mountain shadow can be divided into 0°–40°, 40°–120°, 120°–200°, 200°–254°, in which the direction of the mountain shadow of landslide was mainly in the range of 200°–254°. The elevation can be divided into 2,005–2,155 m, 2,155–2,505 m, 2,505–2,755 m and 2,755–3,500 m. The elevation of landslide is mainly in the range of 2,155–2,505 m. **Figure 2** shows the state classification diagram of continuous factors.

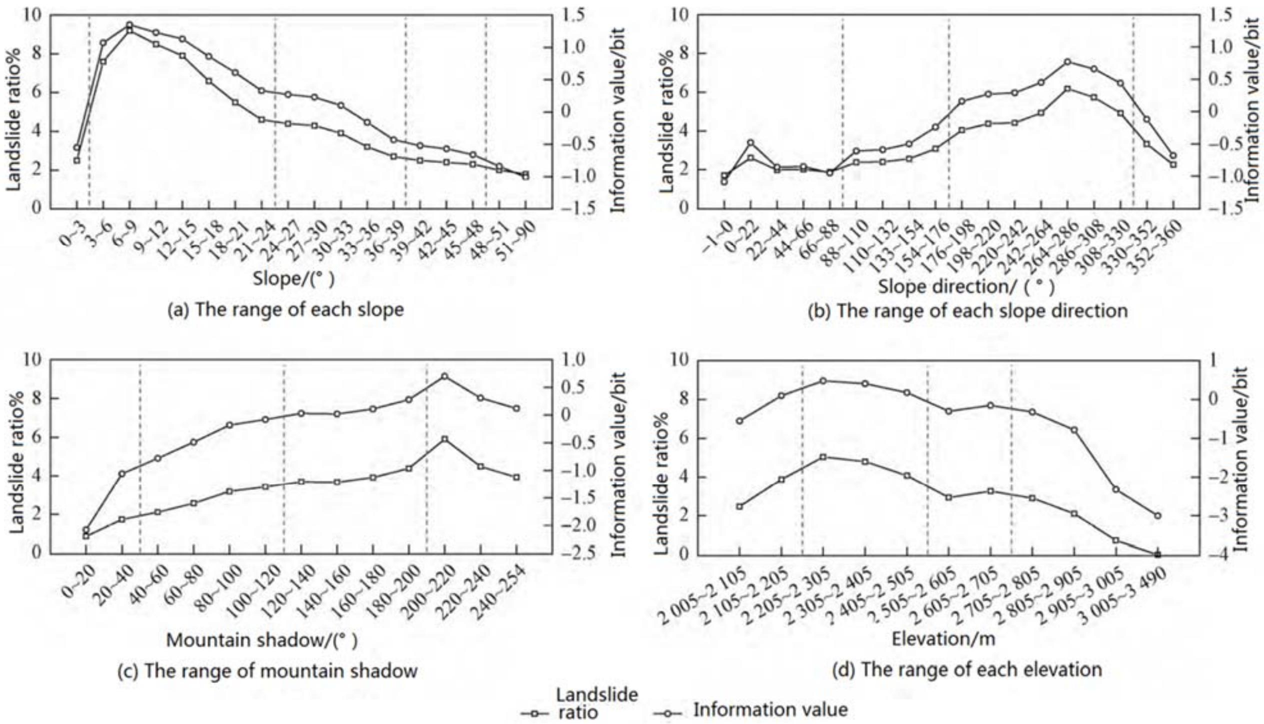


**Figure 1.** Distribution curves of landslide ratio and weighted information value.

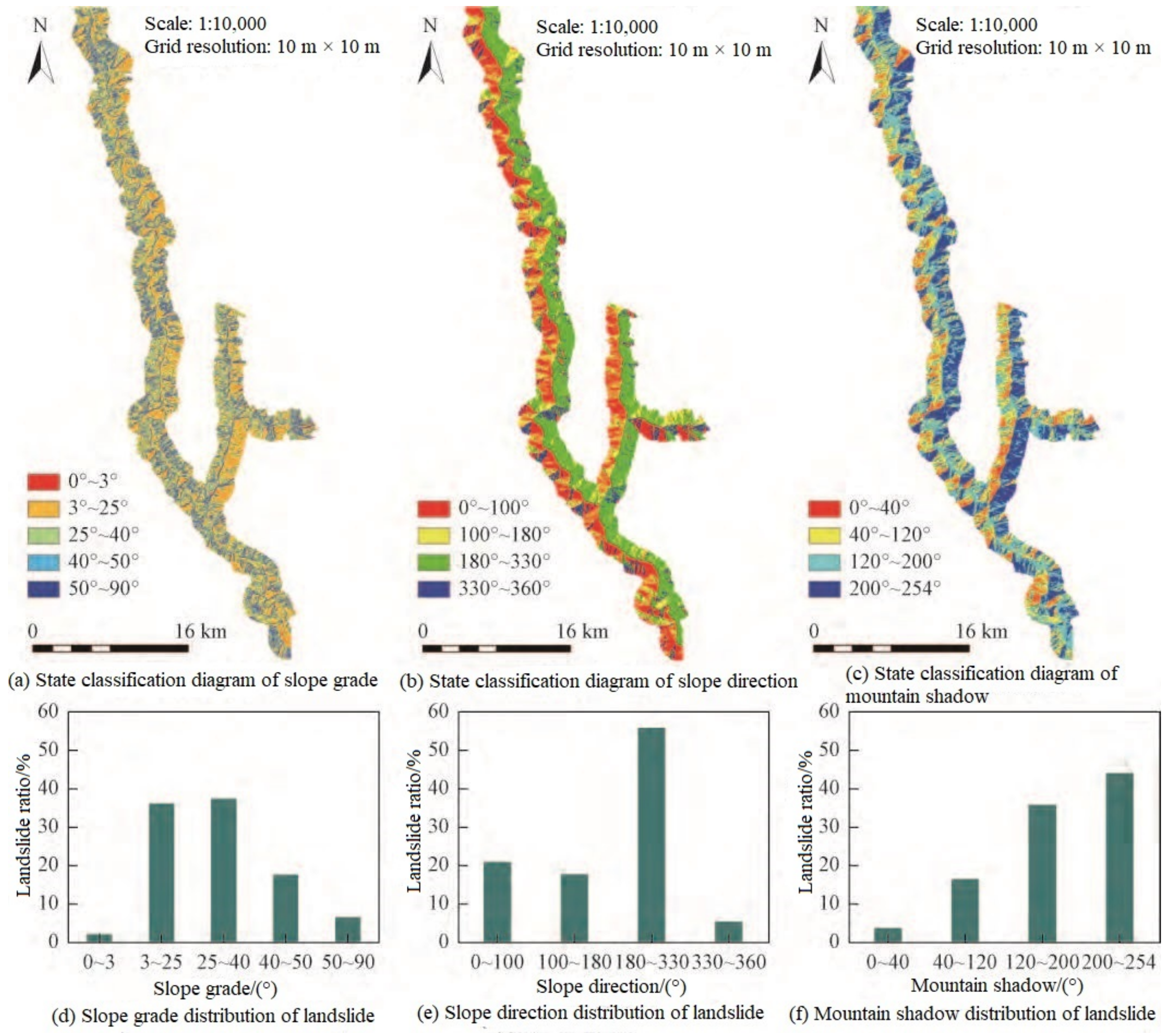


**Figure 2.** The state classification of continuous factors.

#### 4.2.1.2 Stratigraphic lithology

There are mainly sedimentary rocks, magmatic rocks and metamorphic rocks in the study area. There are strong folds and faults in this area, accompanied by magmatic activity dominated by plutonic intrusion. According to the lithology of each stratum and the distribution of unstable slope, the information value in different stratigraphic lithology and the grid ratio of landslide were counted, as shown in **Figure 3(a)**. The results show that the stratigraphic lithology in the study area can be divided into six groups: DTJ, $D_2^a$, $P_1^b$, $Pt_2x^3$, $P_2g$, $P_1^r$, $C_3$, $P_1^a$, $D_2q$, $T_2q^1$, $T_3j$, $T_2q^2$, $Pt_2x^1$ and $D_1g$. The stratigraphic lithology of landslide is mainly in DTJ and $D_2^a$ strata.

#### 4.2.1.3 Geological structure

The geological structures affecting slope stability in the study area are mainly fault structures. The study area is located in the northwest boundary of the Sichuan-Yunnan rhombic block, where the compression phenomenon is serious. According to the distribution of each fault structure and landslide, considering the activity of fault structures, the influence density of fault structures was calculated, and the information value in each density interval and the grid ratio of landslide were counted, as shown in **Figure 3(b)**. The results show that the density of fault structures can be divided into 0–0.8, 0.8–1.6, 1.6–2.4, 2.4–3.2, 3.2–4.73, in which the landslide mainly occurs when the density value is 1.6–2.4.

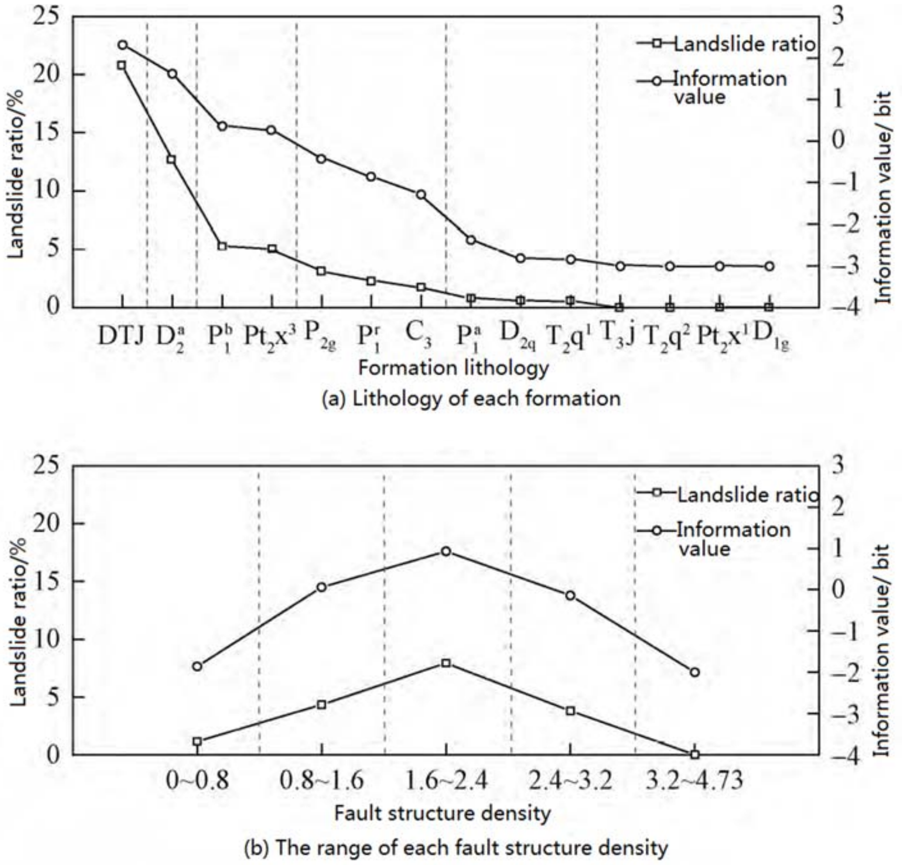


**Figure 3.** Distribution curves of landslide ratio and weighted information value in each stratigraphic and density of fracture structure range.

#### 4.2.2.4 River action

The Jinsha River runs through the whole study area in a north-south direction and flows from north to south. The impact of the river on the stability of the slope mainly includes softening, reducing the viscous force of rock mass, and scouring and liquefaction[17]. After these actions, the rock and soil will gradually soften and the strength will decrease, resulting in instability.

**Figure 4** shows the state classification diagram of discrete index factors. According to the fact that the farther away from the river, the less affected by the river, the distance of the river was divided into six grades, namely 0–300 m, 300–600 m, 600–900 m, 900–1200 m and 1,200–1,500 m. The ratio of landslide in each section was counted. It can be seen from **Figure 4(f)** that the closer the distance to the river, the greater the possibility of landslide.

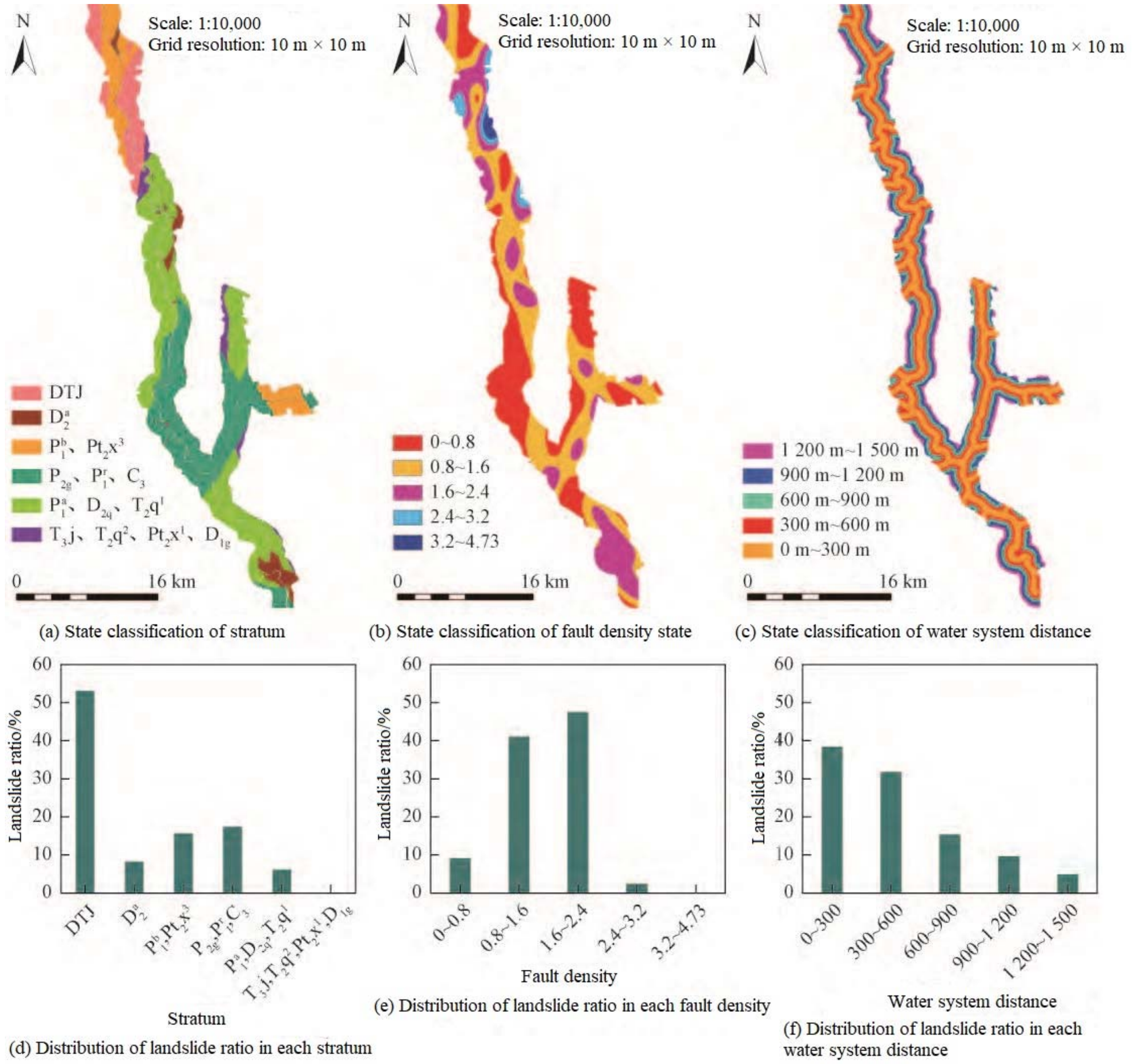


**Figure 4.** The state classification of discrete factors.

### 4.2.2 Analysis of factor state correlation

There are various factors affecting slope stability, but there may be some correlation between these factors. The amount of information of each factor will be superimposed, which will affect the accuracy of the model. Therefore, it is necessary to eliminate the index factors with large repeatability, and apply the calculation covariance and correlation matrix module in Arc-GIS for correlation analysis to get the correlation coefficients between the factors with a significance of 0.01 (**Table 1**).

**Table 1.** The correlation coefficients of each factor

| Index factors | Slope grade | Slope direction | Mountain shadow | Slope height | Stratigraphic lithology | Geology structure |
|---|---|---|---|---|---|---|
| Slope grade | 1.00 | | | | | |
| Slope direction | 0.04 | 1.00 | | | | |
| Mountain shadow | 0.02 | 0.02 | 1.00 | | | |
| Slope height | 0.31 | 0.03 | 0.03 | 1.00 | | |
| Stratigraphic lithology | 0.07 | 0.08 | 0. 04 | 0.28 | 1.00 | |
| Geology structure | 0.03 | 0.01 | 0.01 | 0.02 | 0.07 | 1.00 |
| River action | 0.05 | 0.04 | 0.04 | 0.20 | 0.04 | 0.04 |

**Table 2.** The weighted information values of each factor state

| Index types | Types | State | Information value | Sort | Variable | Index types | Types | State | Information value | Sort | Variable |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Slope grade/(°) | Continuity | 0~3 | –0.55 | 15 | $X_{01}$ | Stratigraphic lithology | Discrete type | DTJ | 2.3 | 1 | $X_{14}$ |
| | | | | | | | | $D_2^a$ | 1.6 | 2 | $X_{15}$ |
| | | 3~25 | 0.63 | 4 | $X_{02}$ | | | $P_1^b$, $Pt_2x^3$ | 0.29 | 6 | $X_{16}$ |
| | | 25~40 | –0.22 | 12 | $X_{03}$ | | | $P_2g$, $P_1^r$, $C_3$ | –0.77 | 16 | $X_{17}$ |
| | | 40~50 | –0.82 | 17 | $X_{04}$ | | | $P_1^a$, $D_2q$, $T_2q^1$ | –2.61 | 26 | $X_{18}$ |
| | | 50~90 | –1.01 | 19 | $X_{05}$ | | | $T_3j$, $T_2q^2$, $Pt_2x^1$, $D_1g$ | –4 | 29 | $X_{19}$ |
| Slope direction/(°) | Continuity | 0~100 | –0.96 | 18 | $X_{06}$ | Geological structure | Discrete type | 0~0.8 | –1.86 | 23 | $X_{20}$ |
| | | 100~180 | –0.41 | 13 | $X_{07}$ | | | 0.8~1.6 | 0.06 | 9 | $X_{21}$ |
| | | 180~330 | 0.32 | 5 | $X_{08}$ | | | 1.6~2.4 | 0.93 | 3 | $X_{22}$ |
| | | | | | | | | 2.4~3.2 | –0.14 | 11 | $X_{23}$ |
| | | 330~360 | –0.46 | 14 | $X_{09}$ | | | 3.2~4.73 | –2 | 25 | $X_{24}$ |
| Mountain shadow/(°) | Continuity | 0~40 | –1.89 | 24 | $X_{10}$ | River action/m | Discrete type | 0~300 | –1.43 | 20 | $X_{25}$ |
| | | 40~120 | –0.55 | 15 | $X_{11}$ | | | 300~600 | –1.65 | 22 | $X_{26}$ |
| | | 120~200 | –0.06 | 10 | $X_{12}$ | | | 600~900 | –2.63 | 27 | $X_{27}$ |
| | | 200~254 | 0.22 | 7 | $X_{13}$ | | | 900~1,200 | –3.21 | 28 | $X_{28}$ |
| | | | | | | | | 1,200~1,500 | –4.05 | 30 | $X_{29}$ |

It can be seen from **Table 1** that the combination of the correlation coefficient >0.10 includes the elevation and the slope grade, the elevation and the stratigraphic lithology, and the elevation and the river action. It can be seen that elevation is highly correlated with slope grade, stratigraphic lithology and river, and the amount of information may overlap each other, so the factor of elevation was eliminated.

### 4.3 Slope stability zoning based on the information model

After analyzing the correlation, the factors of the slope direction, slope grade, mountain shadow, geological structure, stratigraphic lithology and river action were selected to form the evaluation index system. The information value can be calculated by using the integrated information model, and the results are shown in **Table 2**; the distribution of slope stability evaluation was obtained. The statistical results show that the information weight of stratigraphic lithology is the largest. In addition, the information value of influencing factors from large to small is: stratigraphic lithology, geological structure, slope grade, slope direction, mountain shadow and river action.

The distribution of slope stability evaluation was divided into five levels according to information value: high stability area (–14.5, –11.7); relatively high stability area (–11.7, –9.6), medium stability area (–9.6, –6.1), relatively low stability area (–6.1, –1.9) and low stability area (–1.9, 3.1). The classification is mainly based on the standard[18–20] shown in **Figure 5**. The zoning of reservoir bank slope stability evaluation is shown in **Figure 6**.

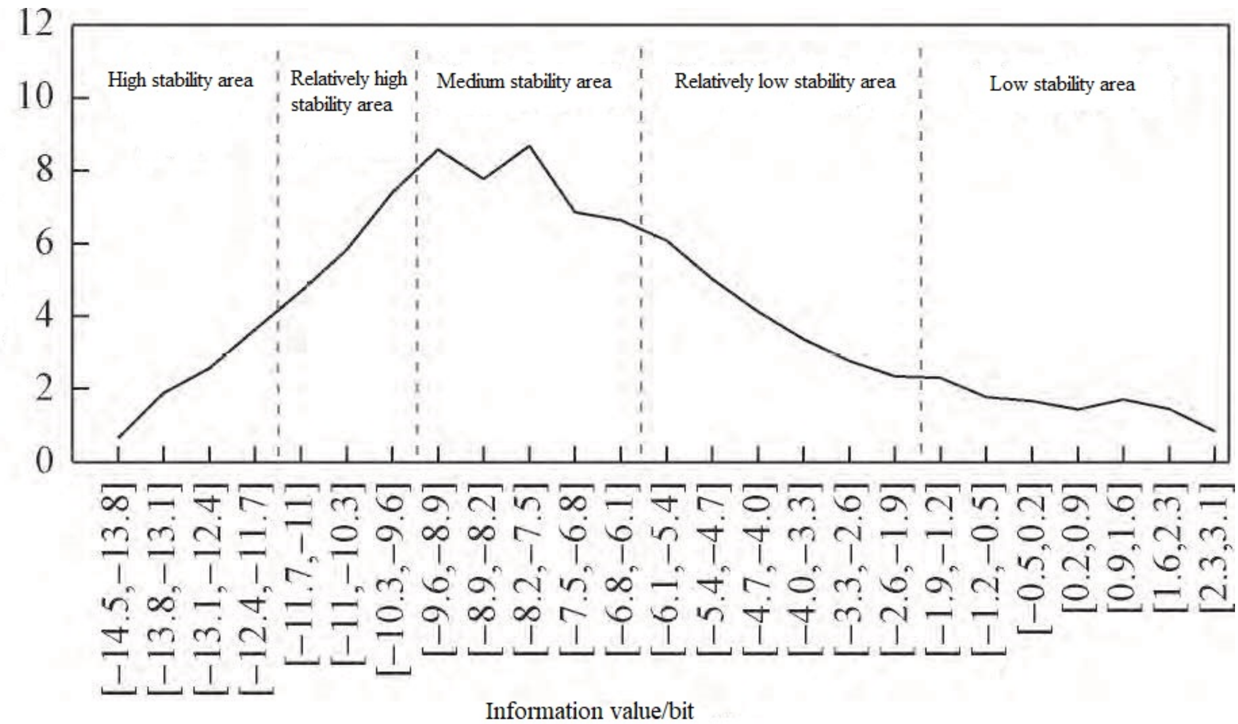


**Figure 5.** The classification standard of slope stability.

## 5. Analysis of results and accuracy

### 5.1 Analysis of evaluation results

As shown in **Figure 6**, according to the zoning results of reservoir bank slope stability evaluation in the study area, the areas with relatively low stability and low stability have the following characteristics.

1) The areas with relatively low and low stability are mainly distributed in the Paleozoic Devonian Jinsha River ophiolite group DTJ and the middle Qiongcuo group $D_2^a$. The rock mass fissures of DTJ stratum are relatively developed, and the stratum is prone to landslide; The Paleozoic Middle Devonian Qiongcuo group $D_2^a$ is characterized by dissolution along the structural plane and easy to form secondary fillings, which is likely to produce sliding fracture surface. It belongs to the stratum with low slope stability.

2) Areas with relatively low and low stability are mainly distributed in areas with concentrated distribution of fault structures. Fault structures are developed in the study area, including 19 faults, mainly with steep dip angle, and some are active faults. The integrity of rock mass is poor, which is

low slope stability.

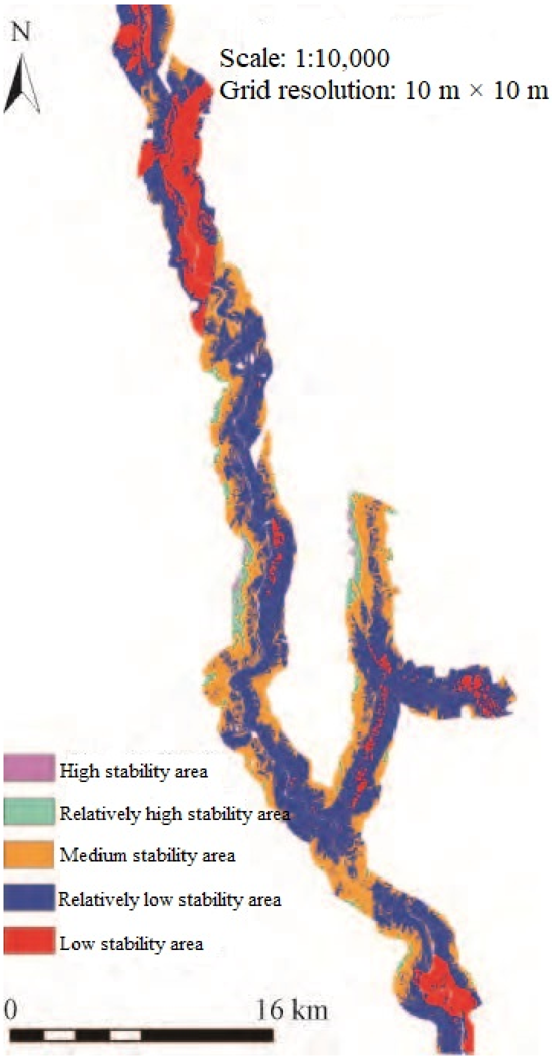

**Figure 6.** The distribution of slope stability evaluation.

prone to landslide, belonging to the stratum with

### 5.2 Analysis of accuracy

According to the stability evaluation results, the grid number *a*, total grid number *b*, landslide grid ratio *a/b*, the ratio of grid number at each level to total grid number *c*, and the ratio of grid number at each level to total landslide grid number *d* were counted (**Table 3**).

It can be seen from **Table 3** that there are 95.41% of landslides occur in areas with relatively low and low stability. The slope stability changes from high to low, and the ratio of landslides gradually increased from 0.2% to 18.15%. The area with relatively low stability accounts for the largest ratio of grids, up to 51.5%, indicating that most of the study area are in areas with relatively low stability. The largest ratio of landslides occurs in areas with low stability, reaching 71.85%.

In short, through the study, it is found that most areas are in the area with relatively low stability. According to the statistical analysis results of reservoir bank landslide database in the study area, it is found that the unstable slopes reaching 71.85% are in the low stability area. The unstable slopes reaching 23.56% are in the area with relatively low stability. If the evaluation accuracy is expressed by the ratio of actual landslide units in relatively low stability and low stability areas units, the evaluation accuracy can reach 95.41%.

**Table 3.** The statistical of grids

| Stability level | Number of landslides *a* | Total number of grids *b* | Landslide grid scale (*a*/*b*)/% | Ratio in total grid *c*/% | Ratio in total landslide grid *d*/% |
|---|---|---|---|---|---|
| High | 589 | 17,236 | 0.20 | 0.67 | 0.52 |
| Relatively High | 1,032 | 105,544 | 0.58 | 3.93 | 1.33 |
| Medium | 6,201 | 778,431 | 0.97 | 28.7 | 2.74 |
| Relatively low | 24,644 | 1,397,958 | 1.7 | 51.5 | 23.56 |
| Low | 75,163 | 414,156 | 18.15 | 15.2 | 71.85 |

## 6. Conclusion

1) Based on GIS and the integrated information model, seven factors including slope direction, slope grade, mountain shadow, elevation, geological structure, stratigraphic lithology and river action were selected to establish the reservoir bank slope stability evaluation system. The regional reservoir bank slope stability was evaluated, and a set of rapid evaluation methods for regional bank slope stability were established. The feasibility of this method is verified by practical engineering.

2) Compared with other variable analysis methods, the standard of state classification is to find out the sudden change point of curve distribution as the critical point of classification according to the curve of landslide ratio and information volume, which reduces the error caused by human experience.

3) The research results show that the geological structure and stratigraphic lithology have the most significant impact on the evaluation results. The areas with relatively low stability and low stability are mainly distributed in the strata of Jinsha River ophiolite group and middle Qiongcuo group of the Paleozoic Devonian system, as well as the areas with developed geological structures. And most of the study area are in relatively low stability areas. The ratio of low stability and relatively low stability areas in the total study area is 15.2% and 51.5% respectively, and the accuracy of stability evaluation results is up to 95.41%.

## Conflict of interest

The authors declare that they have no conflict of interest.


## Acknowledgements

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