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Evaluation of landslide disaster susceptibility based on the susceptibility index method--Taking Zhenxiong County as an example

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Abstract Taking Zhenxiong County as the research area and Zhenxiong County in Yunnan Province as the study area, this study systematically evaluated the susceptibility of landslide disasters using the susceptibility index method. By collecting and analyzing multi-source data such as geology, topography, meteorology, and human activities in the research area, a landslide susceptibility evaluation index system was constructed based on the determination of key factors affecting landslide susceptibility. ArcGIS technology was used to extract relevant evaluation factors and determine the weights of each index. Based on this, the susceptibility index method was used to quantitatively evaluate the susceptibility of landslide disasters in Zhenxiong County. The study area was divided into extremely high susceptibility areas, high susceptibility areas, medium susceptibility areas, low susceptibility areas, and non susceptibility areas. The results showed that the high susceptibility areas of landslide disasters in Zhenxiong County exhibited a clear band like distribution. In response to the above results, this article proposes corresponding prevention and control measures, aiming to provide scientific basis for preventing and reducing the risk of landslide disasters and ensuring the safety of people's lives and property.

Index Terms Landslide, Vulnerability Assessment, Vulnerability Degree Index Method, Zhenxiong County

I. Introduction

In recent years, the frequency and intensity of extreme weather events around the globe have gradually increased, which in turn has led to the increasing threat of their induced secondary disasters, especially geologic disasters, to human beings [1], [2]. As a common geological disaster, landslides, especially in mountainous and hilly areas, have a serious impact on human life and property and the ecological environment [3]. Zhenxiong County has become one of the most serious areas of geologic hazards due to its complex geological structure, steep topography, and high precipitation, as well as the fact that the county is a large county for coal resource extraction, with strong human engineering activities such as mining and the increasing scale of market town construction, and the geologic environment has been damaged to varying degrees [4]. Therefore, landslide susceptibility assessment in Zhenxiong County can guide the local government to take preventive and control measures against potential landslides in advance, so as to safeguard people's lives and reduce the property loss of local residents [5], [6].

Landslide susceptibility refers to the spatial probability of landslide occurrence in a certain area under the current conditions of topography, hydrometeorology, and geological environment [7]. Landslide susceptibility evaluation is to calculate the probability of landslide occurrence in a specific area by scientifically analyzing the nonlinear relationship between landslide and its intrinsic and extrinsic factors [8]. With the rapid rise of geographic information systems and artificial intelligence technologies, the research on landslide susceptibility evaluation has been promoted by efficiently fitting the nonlinear relationship between landslides and landslide evaluation factors, thus promoting the active development of landslide susceptibility evaluation research [9]-[11]. The proposed landslide susceptibility evaluation model provides a good basis for effective disaster prevention ideas [12]. However, the performance of the prediction model is usually affected by the evaluation unit and evaluation factors, and the evaluation results are not persuasive enough due to the existence of the “black box model” [13], [14]. Therefore, it is of great significance to study the optimization of evaluation units, the optimization of factor screening methods, and the construction of interpretable models to improve the accuracy and interpretability of models for disaster management and prevention [15], [16].

Zhenxiong County is located in the southwest region of China, which has high mountains and steep slopes, complex geological conditions, frequent seismic activities, fragile ecological environment, concentrated rainfall, and frequent occurrence of various geologic hazards, among which landslide disasters are extremely developed.

Landslide disasters seriously threaten the life and property safety of local residents, and also affect the social and economic development. In view of this, assessing the possibility of landslide disasters in Zhenxiong County has far-reaching theoretical and practical significance for disaster prevention and mitigation. In this study, the susceptibility index method was adopted to extract the relevant evaluation factors with the help of ArcGIS technology, determine the weights of each factor, and carry out the division of susceptibility areas, so as to effectively assess and predict the potential risk of landslide disasters, and provide a key scientific basis for the sustainable development of Zhenxiong County.

II. Overview of the study area and data sources

II. A. Overview of the study area

Zhenxiong County, belongs to Zhaotong City, Yunnan Province. Located in the northern part of the Wumeng Mountains, it spans the area from 104°18′ to 105°19′ east longitude and 27°17′ to 27°50′ north latitude, bordering Xuyong County in Luzhou City, Sichuan Province in the east, Qixingguan District and Hezhang County in Bijie City, Guizhou Province in the south, neighboring Yiliang County in the west, and connecting with Weixin County in the north. Most of the county belongs to the warm temperate monsoon mountain climate, a few river valley areas belong to the north subtropical climate, the four seasons are distinct, late spring, short summer, early fall, long winter. The overall terrain in the territory of the northwest high, southeast low, the terrain is mainly mountainous, Zhenxiong County, there are 32 large and small rivers in the territory of Zhenxiong County, belonging to the Hengjiang River system, the Chishui River system, the Wujiang River system.

II. B. Data sources

The key information of this study includes: (1) Digital Elevation Model (DEM) with a resolution of 30m×30m, which is used to obtain relevant information such as slope gradient, slope direction, etc.; (2) Geological maps with a scale of 1:2.5 million, which is mainly applied to obtain data on the nature of stratigraphic rocks; (3) 1km rainfall data in NC format is used to NC format data of 1km rainfall is used to convert raster data to calculate the annual average rainfall; (4) vector data such as landslide disaster and Normalized Difference Vegetation Index (NDVI) in Zhenxiong County.

III. Evaluation factor analysis and indexation

According to the collection and analysis of the disaster-bearing conditions of landslides in Zhenxiong County and their influencing factors, it is known that there are seven factors that have a greater influence on landslide geohazards in the area: elevation, slope, slope direction, stratigraphic lithology, rainfall, disaster density, and NDVI.These seven factors are the first-level evaluation factors, and then combined with the specific disaster-bearing geologic conditions in the study area, the second-level evaluation factors are classified.

III. A. Selection and grading of evaluation factors

III. A. 1) Elevation

Elevation is one of the important influencing factors leading to the occurrence of landslides, and the slope will increase with the increase of the slope height, which in turn affects the stability of the slope body, thus exacerbating the possibility and probability of geologic disasters to a certain extent. Elevation data is the basis of terrain analysis, accurate elevation data is crucial for the accurate drawing of maps, elevation data can help assess disaster risk and design disaster prevention facilities. In this paper, the spatial analysis function of ArcGIS is used to reclassify the existing DEM elevation data into six levels, which are 626~1119m, 1120~1365m, 1366~1553m, 1554~1727m, 1728~1919m, and 1920~2395m respectively.As can be seen in Fig. 1, the elevation spans a wide range of elevations, with the highest point in Zhenxiong County The highest point of Zhenxiong County is located at 2395m in Jiamao Mountain of Maiche Village, Aner Township, while the lowest point is located at 626m in Datan, Tongping Village, Luokan Township.The elevation of Zhenxiong County is roughly between 626~2395m, and the probability of geologic hazards concentrates on 1366~1727m, whose area of the elevation value accounts for 64% of the whole area, and the disasters are concentrated in the hillside as seen from the figure.

III. A. 2) Slope

Slope gradient, is the key to controlling slope-based geologic hazards. Slope gradient affects the rate and direction of surface water flow. Water on steep slopes is usually faster and prone to surface runoff, while gentle slopes favor water infiltration and storage. Topographic slope affects the layout of the water system in a watershed and the intensity of stream erosion. In areas with steeper slopes, river erosion is more intense, often producing canyons and turbulent water flows. The slope was extracted from the DEM elevation map using the ArcGIS3D analysis tool and reclassified into five classes: 0°~10°, 10°~20°, 20°~30°, 30°~40°, and 40°~80°. See Fig. 2, it can be determined through the analysis that the landslide disasters occur most between 0°-30°, accounting for about 87% of the total disaster sites, and its area is about 2983km², while the landslide disaster sites in the area >30° are relatively less distributed, accounting for about 13% of the total disaster sites, and its area is about 714km².

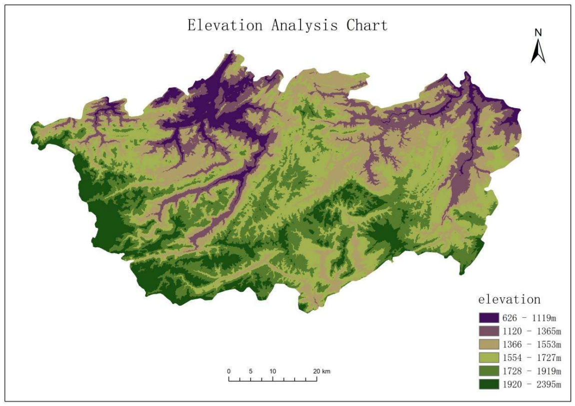

Figure 1: Elevation analysis diagram

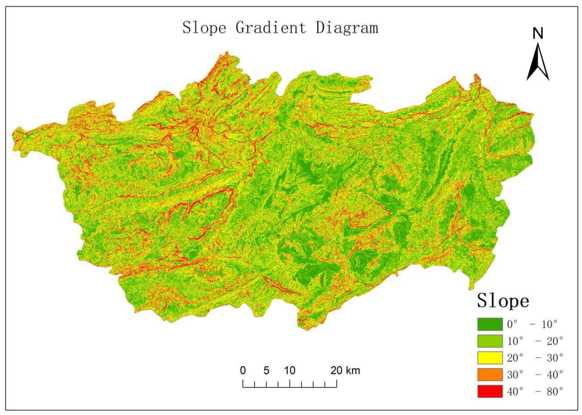

Figure 2: Slope analysis

III. A. 3) Slope orientation

Slope orientation determines how much sunlight a hillside receives. In general, southern (northern hemisphere) or northern (southern hemisphere) slopes receive more sunlight, while eastern and western slopes have better light in the morning and afternoon, respectively. Due to the difference in light, temperatures can vary from one slope orientation to another. Southern slopes (Northern Hemisphere) are usually warmer than northern slopes. Slope orientation may have an effect on the distribution of rainfall. In a given region, the direction of winds and the relative position of mountain ranges may cause one slope to receive more rainfall than others. Soil texture and plant species may also show differences in different slope orientations due to differences in light, temperature and rainfall. As shown in Figure 3, slope orientation was classified into 10 categories using ArcGIS: horizontal, north, northeast, east, southeast, south, southwest, west, northwest, and north. Further analysis revealing the differences shows that: the number of hazard sites distributed between sunny and semi- sunny slopes is higher than that distributed on shady and semi-shady slopes, accounting for about 52% of the total number of hazard sites; slope orientation affects the development and texture of the soil, with the soil on south slopes being drier and that on north slopes being wetter; the slope orientation likewise plays a role in the distribution and types of vegetation, with different slope orientations leading to the growth of different plant groups; the slope orientation influences precipitation, which in turn affects soil moisture content, with different slope orientations leading to different plant groups; and slope orientation influences precipitation, which in turn influences soil moisture content. The direction of the slope also affects the distribution and type of vegetation, and different slope directions lead to the growth of different plant groups. Thus, sunny slopes are more prone to disasters.

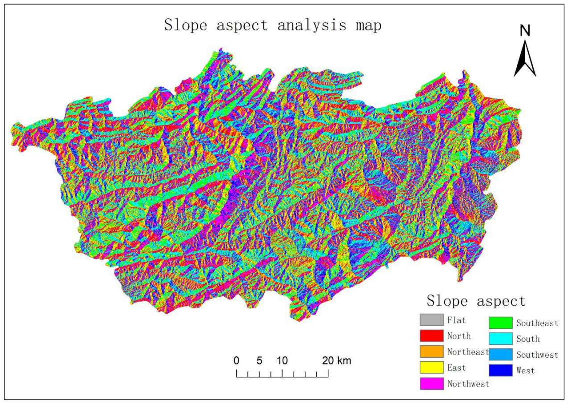

Figure 3: Slope orientation analysis

III. A. 4) Stratigraphic lithology

Rock properties are one of the key factors triggering geologic hazards such as landslides, landslides, and debris flows. Rock properties affect the occurrence and distribution of geohazards, and understanding rock properties can help assess the risk of geohazards. The stability of rock formations with different hardness and structural surfaces varies greatly. The stratigraphic rock data of Zhenxiong County were extracted from the geologic map by ArcGIS software, and a total of six different stratigraphic rock types can be seen in Fig. 4, including: marl and other mixed sediments, basalt, limestone and other carbonate rocks, sandstone, complex compositional sandstone, feldspathic sandstone, siltstone, mudstone, claystone, granite, and shale. By analyzing these stratigraphic rock types, it was found that the landslides in Zhenxiong County mainly occurred in the strata where siltstone, mudstone, claystone, and shale were developed, which accounted for about 86.69% of the total number of disaster sites, and the landslides occurring in the marl and other mixed strata had almost no distribution of disaster sites, and very few landslides occurred, which accounted for about 3.51% of the total number of disaster sites.

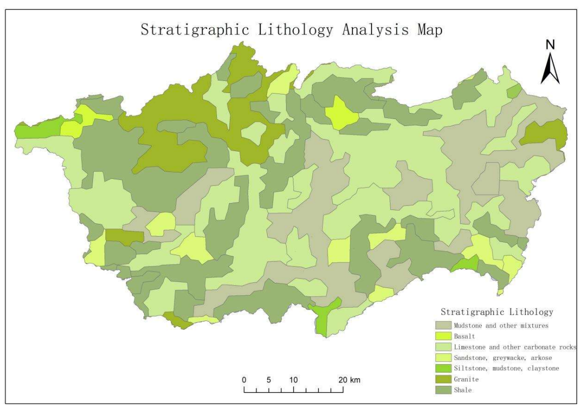

Figure 4: Stratigraphic lithology analysis

III. A. 5) Rainfall

Continuous rainy weather plus heavy rainfall or regional rainstorms are most likely to induce landslide and avalanche disasters. After a long period of rainfall, the surface soil water content is saturated, at which time heavy rainfall of short calendar time has a close relationship with the outbreak of landslides. The average annual rainfall from 2020 to 2023 was calculated in ArcGIS (see Figure 5). Its rainy season is mainly concentrated in May to September every year. According to the data of 2023, the rainfall in May is 54 mm, while it increases sharply to 241.3 mm in July and 463.5 mm in August, which is the highest rainfall month of the year. Subsequently, the rainfall decreased in September, but remained at 229.8 mm. entering October, the rainfall further decreased to 65.9 mm. it is evident that the rainy season in Zhenxiong County starts from May and reaches its peak in September, followed by a gradual decrease. Therefore, this is the most concentrated period of rainfall in the area, and is also the period of frequent landslide disasters. In addition, winter is also a concentrated and frequent period of landslide disasters in Zhenxiong County. After earthquakes or rainstorms during the rainy season, the continuous infiltration of precipitation in the previous period softens the soft surface within the rock body, coupled with the rain and snow prior to the occurrence of landslides leads to the enrichment of groundwater, which reaches its critical point, and then induces the occurrence of landslides.

On January 22, 2024, the landslide that occurred in Liangshui Village, Tangfang Town, Zhenxiong County, Yunnan Province, was affected by the steep topography and geomorphology, the layered fractured structural rock, and the continuous infiltration of precipitation in the previous period, especially the continuous infiltration of precipitation, which softened the soft and weak surfaces within the rock, coupled with the rain and snow that led to the enrichment of the groundwater, which reached its threshold, and then induced the landslide. Thus, continuous precipitation during the rainy season is an important external trigger for areas with fragile geologic structures and can exacerbate the occurrence of landslides.

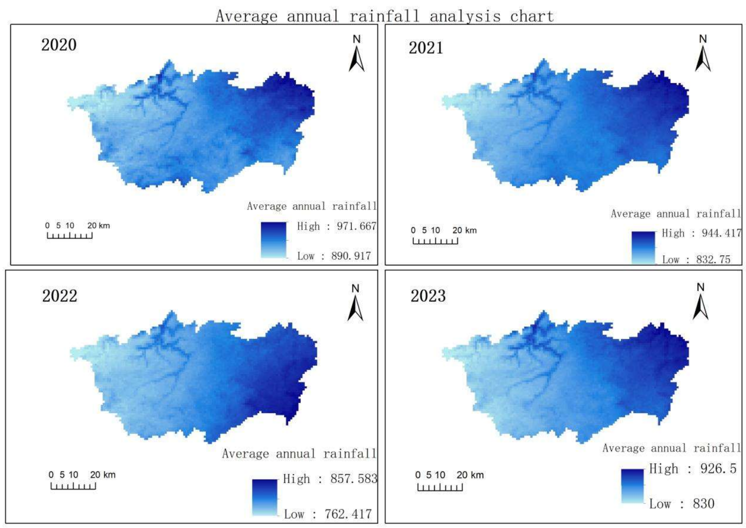

Figure 5: Rainfall analysis from 2020 to 2023

III. A. 6) Disaster density

Disaster density refers to the number of distribution of disaster sites in a certain area, which can reflect the risk level of disaster in that area. By analyzing landslide density, it is possible to identify which areas are more prone to landslides, thus providing a basis for land use planning, building design, etc. In the event of a disaster, rescue organizations can decide on the allocation of rescue resources based on landslide density, and prioritize the areas that are severely affected. By analyzing the density of landslides in different areas, the mechanism of landslide occurrence can be studied, providing scientific basis for prediction and prevention. In the study of geologic disasters, the greater the density of disaster sites, the greater the possibility of disasters. On the contrary, the smaller it is. The evaluation grid of this paper is 50m×50m, and the number of geohazards occurring in this grid scale is used as the secondary judgment factor, which is divided into 4 levels: 0, 1, 2, and ≥3.

Figure 6 presents the distribution of disaster density points. The areas of high landslide disaster mainly include: Cedar Township, Bowl Factory Township, Luokan Township, Niuchang Township, Wude Township, Huashan Township, Pingshang Township, Baiba Township, Zhongtun Township, Piaoqi Township, Tangfang Township, Linkou Yi Miao Township, and Potou Township. It can be seen that Zhenxiong County is prone to landslide disasters, and most townships are subject to landslide disasters, with large landslides and small landslides intermingling with each other.

III. A. 7) NDVI vegetation normalization index

NDVI can be used to monitor the cover and density of surface vegetation, which is of great significance in areas such as agriculture, forest management and ecological research. Vegetation plays a vital role in trapping precipitation, retaining soil and water, and maintaining slope stability. The amount of vegetation cover has an effect on the occurrence of geohazards, and usually areas with higher vegetation cover have a lower likelihood of geohazards because higher vegetation cover usually means less human engineering activities in the area, and correspondingly less modification and destruction of the geological environment. On the other hand, the root system of vegetation can increase the cohesion of the soil, reduce the scouring of the soil by rainfall, as well as regulate the surface moisture through transpiration, reduce the formation of surface runoff, and reduce the risk of geohazards. According to the development of vegetation in the study area, the normalized vegetation index (NDVI) ranges from

0.0066 to 0.8056, and it is found that the NDVI is lower in the southern, northeastern, and part of the northern part of Zhenxiong County, which has a higher potential for disasters (see Figure 7).

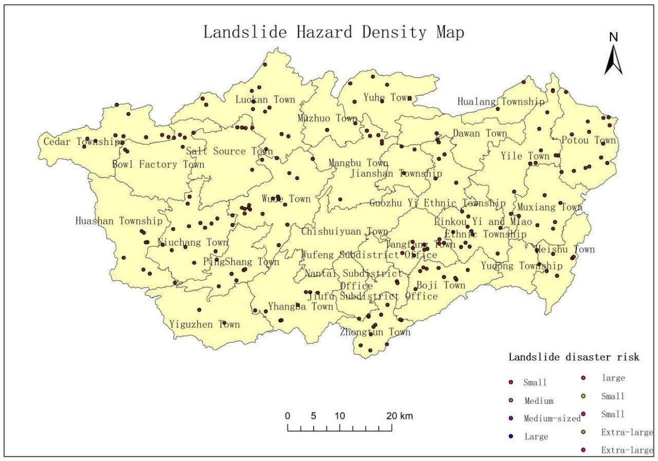

Figure 6: Density map of landslide disaster

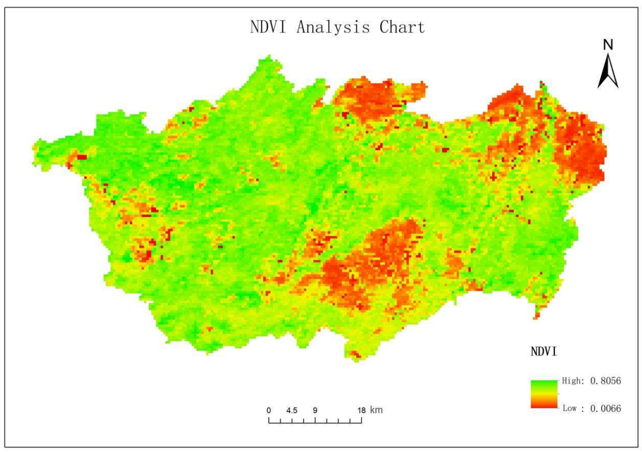

Figure 7: NDVI analysis diagram

III. B. Indexing of evaluation factors

III. B. 1) Graded assignment of evaluation factors

According to the Ministry of Natural Resources (MNR) Implementing Rules for Basic Requirements for Geological Hazard Survey and Zoning of Counties (Municipalities) (2006 Revision), the weights and grading assignments for each impact factor in this study area are shown in Table 1.

III. B. 2) Calculation of vulnerability indices for each factor of the evaluation grid

The vulnerability index for each impact factor was obtained by multiplying the secondary grading value for each category with the percentage of area within the grid of the cell in which it is located, using the formula:

$$N_1 = A_1 a + A_2 b + A_3 c + A_4 d \tag{1}$$

where N_1 represents the vulnerability index of the factors in the evaluation unit; A_1, A_2, A_3, A_4 are the rank assignments of each computational factor, respectively; and a, b, c, d denote the proportion of the area that is occupied by the second-level graded factors in the evaluation unit.

Table 1: Grading and assignment of landslide disaster evaluation factors

Level 1 evaluation factor	weight	Secondary evaluation factors	Graded assignment
Density of disaster points	0.10	The number of disaster points in the evaluation cell is greater than or equal to 3	9
		The number of disaster points in the evaluation cell is greater than or equal to 2	6
		The number of disaster points in the evaluation cell is greater than or equal to 1	3
		The number of disaster points in the evaluation cell is greater than or equal to 0	1
falling gradient	0.20	≥30°	9
		20°~30°	6
		10°~20°	3
		0°~10°	1
aspect	0.05	adret	3
		Schattenseite	1
rainfall	0.15	Annual rainfall is 948mm or daily maximum rainfall is 199.8 mm	3
altitude	0.20	<1366m	9
		1366~1727m	6
		>1727m	3
Stratigraphic lithology	0.25	Fragile rocks such as mudstone, shale and sandy rock	9
		Hard rock such as granite	1
NDVI vegetation normalized index	0.05	0.0066~0.4061	3
		0.4061~0.8056	1

III. B. 3) Calculation of the geohazard vulnerability index

The vulnerability index of each factor is obtained according to equation (1), assigned to each corresponding factor layer, and the cumulative index value of each factor is calculated in each cell grid, i.e., the vulnerability index of each grid cell.

$$Z = \sum_{i=1}^{n} N_i K_i \tag{2}$$

Where: Z is the index of geohazard susceptibility of the evaluation factor; N_i is the vulnerability index of the evaluation factor; K_i is the weight of each evaluation factor; and n is the number of factors.

III. C. Vulnerability Evaluation Subdivision

The geologic hazard susceptibility is divided into: high susceptibility zone (Z > 6), medium susceptibility zone (6 ≥ Z ≥ 3), low susceptibility zone (3 ≥ Z ≥ 1), and non-susceptibility zone (Z < 1). As can be seen from Figure 8, the disaster susceptibility of the study area is dominated by high susceptibility zone, medium susceptibility zone and low susceptibility zone. Among them are Lokan Township, Muzhuo Township, Yanyuan Township and Wude Township; low susceptibility areas include Chishuiyuan Township, Dawan Township and Yudong Township; and the rest of the townships are medium susceptibility areas. According to the results of the comprehensive evaluation of the susceptibility to geologic hazards, the adjacent grids with similar conditions are divided into the same zoning, and the susceptibility zoning map is drawn, and the results of the division are shown in Figure 9.

III. D. Summary

According to the susceptibility evaluation and zoning, it can be found that the high susceptibility area of landslide disaster in Zhenxiong County is distributed in a belt shape, especially in the superposition area of the disaster point and NDVI, which is mainly concentrated in Wude Township, Niuchang Township, Zhongtun Township, Tangfang Township, Luokan Township, Potou Township, Wufeng Township, Piaoqi Township, Eile Township, Yuha Township, and Cedar Shue Township; the middle susceptibility area is concentrated in Mukheng Township, Pingshang Township, Bowl Factory Township, Yanyuan Township, and Mangbu Township, Heishu Township, Guozhu Yi Township, Muzhuo Township, Dawan Township, Jianshan Township, Yaba Township, and Linkou Yi and Miao

Township; and low susceptibility areas are mainly concentrated in Yudong Township, Huashan Township, Egu Township, and Chishuiyuan Township.

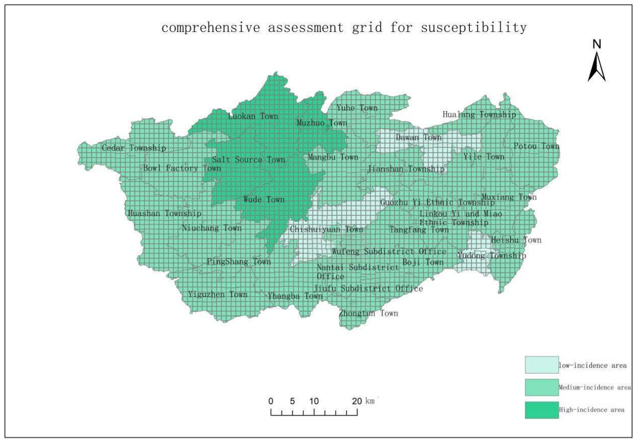

Figure 8: Comprehensive evaluation grid of prone areas

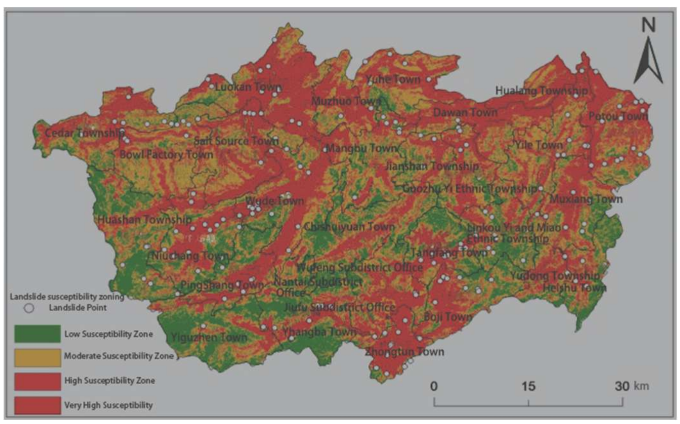

Figure 9: Map of prone areas

In view of the results of landslide disaster susceptibility evaluation and zoning in Zhenxiong County, it is recommended to strengthen the prevention and control in the following aspects: firstly, to comprehensively investigate the hidden geological hazards, and to focus on monitoring the mountainous areas of high susceptibility zones, gully mouths, and other sensitive areas, at the same time, the hidden danger points, construction projects underway, water conservancy facilities, major transportation routes, mines, reservoirs, etc. within the jurisdiction should be included in the investigation of the key objects; secondly, to build and optimize the prevention and control system of geological hazards and to enhance the emergency rescue effectiveness; third, through the social dissemination of the evaluation results, public awareness of landslide disaster risks has been raised, and community residents' awareness of disaster prevention has been enhanced; fourth, appropriate policies and regulations have been formulated to provide support for the prevention and control of geologic hazards. Through these measures, the aim is to safeguard people's lives and property and reduce the risk of landslide disasters.

IV. Conclusion

This study integrates multi-source data with the help of GIS technology, including remote sensing images, topography and geomorphology, geological structure, rainfall data, etc., which provides rich data information support for evaluation. Through the susceptibility index method, a systematic evaluation system of landslide disaster susceptibility was established, including elevation, slope, slope direction, rainfall and other factors, and based on the evaluation results, Zhenxiong County was divided into areas with different susceptibility grades, which provides a scientific basis for land-use planning and disaster prevention and control. The evaluation results are of great significance in guiding the local disaster prevention and mitigation work, helping to optimize resource allocation and improve disaster prevention capability.

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