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Landslide Risk Evaluation in Typical Karst Mountainous Areas: A Case on the Western Hubei Area, China

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Abstract: The challenging geological conditions in hilly mountainous areas, combined with intensive human engineering activities, have led to a high frequency of landslide disasters. This is particularly true in karst mountainous areas where the geology is complex and characterized by distinct karst phenomena influenced by stratigraphy and severe terrain cutting. Therefore, it is crucial to initiate the evaluation of landslide risk in typical karst mountainous areas and establish a sound evaluation system. In this study, the landslide risk in the Jianshi County was evaluated using the Information value method with the county as the evaluation scale , and the eight categories of elevation, slope, aspect, distance from road, distance from river, distance from structure, vegetation cover and engineering rock group are established as the main causative factors to evaluate the landslide susceptibility, and the two categories of land use and rainfall as the main predisposing factors to evaluate the landslide hazard. Meanwhile, the study highlights the important finding that in typical karst areas, high susceptibility areas and high vulnerability areas tend to overlap, resulting in a concentration of high-risk landslide areas. The evaluation factors identified in this study can serve as typical factors for evaluating landslide risk in similar karst mountainous areas. Furthermore, the risk distribution characteristics observed in this study can guide landslide risk assessments in other comparable regions. These insights can aid in the development of effective landslide risk management strategies in karst mountainous areas.

Keyword: Landslides; Risk Evaluation; Karst Mountain Area; Information Value Method

1.0 Introduction

Landslide, collapse, debris flow, and other geological disasters are widely distributed worldwide. They are not only important obstacles to human social and economic development but also potential threats that are difficult to eliminate. In China, 70% of the land locate in mountainous areas, and the frequency of landslides is higher than the world average. The loss caused by landslides reached 10.4 billion CNY, and the average loss is 4.23 billion CNY. Landslide disasters have caused huge losses to human beings. Scholars from all over the world study the formation and development of landslide disasters through various research means, explore the laws of landslide disasters, realize the risk assessment, early warning, and forecast of landslide disasters, to reduce the losses caused by landslide disasters as much as possible.

In recent years, with the development of remote sensing and GIS technology, researchers all over the world have widely applied remote sensing and GIS technology to the field of landslide risk research, including the analytic hierarchy process (Achu & Reghunath, 2017; Est et al., 2022; Pourghasemi et al., 2012), the frequency ratio method (Lee & Sambath, 2006; Yilmaz, 2009), the weight of evidence method (Cao et al., 2021; Hong et al., 2017; Kayastha et al., 2012), the information value method (Che et al., 2012; Liu et al., 2022), and the artificial neural networks (Lucchese et al., 2021; Soma et al., 2019) and so on. These spatio-temporal analysis methods allow us to analyse the probability of landslides qualitatively or quantitatively and to produce maps of landslide risk distribution (Tong et al., 2021). The landslide risk distribution map can be used to guide urban construction, land use, and regional development planning. However, no matter which evaluation method is used, the key lies in the selection of evaluation factors, and a suitable evaluation factor selection system is especially important to build a high precision landslide risk. Therefore, the construction of landslide risk evaluation system according to local conditions is the key work at this stage of research.

This study aims at landslide risk evaluation in karst mountainous areas, takes Jianshi County in Hubei Province as a research case, and constructs a landslide analysis and evaluation factor selection system suitable for karst mountainous areas according to the spatial and temporal distribution pattern of landslide hazard sites. The information value method is used to evaluate and analyze the susceptibility and hazard of landslide geological hazards in the study area, and the risk assessment of landslide in the study area is completed by combining the susceptibility of buildings and population in the study area, and the landslide risk characteristics of karst areas are summarized.

2.0 Study Area

The study area is located in the Qingjiang River basin of Jianshi County, Hubei Province, China (Figure 1), at the northern edge of the Wuling Mountains and the southern edge of the Daba Mountains. The main direction of the mountain range in the study area is nearly east-west, and the main geomorphological type is tectonic dissolution and erosion of low and middle mountain landscapes, which is a typical karst area.

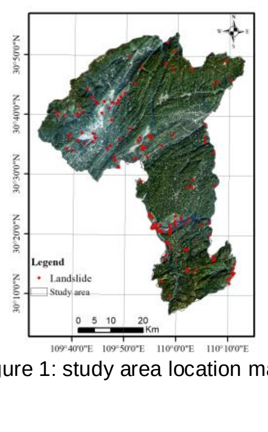

Figure 1: study area location map.

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3.0 Data and Methodology

3.1 Data

The data in this study are mainly divided into three categories: one is the actual landslide measurement data obtained through the actual field surface survey. The second is various thematic data collected from Jianshi County Natural Resources and Planning Bureau, including rainfall, geology, roads, rivers, etc. The third is various remote sensing data, including remote sensing images gathered from ASTER GDEM 30M and DEM gathered from a Landsat ETM+ satellite image.

3.2 Methodology

Landslide geological disaster risk includes the danger of landslide geological disaster and the hazard to the disaster-bearing body, which is the collection of the possibility size and severity of the hazard to life and property safety when landslide geological disaster occurs. Due to the different conditions of topography and geological structure, the probability of occurrence of geological hazards is different and the intensity of occurrence is also different; due to the different types and values of damaged objects, the losses caused by geological hazards of the same intensity are also different, so the risk of geological hazards is the uncertainty of occurrence of geological hazards and the uncertainty of losses caused. Therefore, it is necessary to consider the susceptibility of the slope body, the hazard of the risk source and the vulnerability of the disaster-bearing body when conducting landslide risk, and it is necessary to evaluate separately from these three perspectives and integrate the results.

In the evaluation of landslide risk, firstly, the spatial probability of landslide occurrence should be evaluated based on the causative factors to get the distribution of landslide geological hazard susceptibility. Then, the spatial probability of landslide induced exogenous factors should be evaluated based on the inducing factors, and the distribution of landslide geological hazard should be obtained. Then, based on the spatial distribution of the hazard-bearing body and the spatial distribution of the susceptibility, the distribution of the vulnerability of landslide geological hazards is obtained. Finally, the probability of induced is multiplied by the size of the possible loss caused by the bearing body, i.e., the hazard is multiplied by the susceptibility, and the risk evaluation of the study area is obtained.

3.2.1 *Landslide susceptibility*

The vulnerability assessment of landslide geological hazards is the basis of risk assessment. It provides the key intermediate data for the spatial probability of landslide occurrence. Based on the theory of Information value method, this study quantitatively evaluates the susceptibility of landslide geological hazards in the study area. The occurrence of landslide geological hazards is related to the quantity and quality of information obtained in the prediction process, which can be measured by the amount of information. The greater the amount of information, the greater the likelihood of geological hazards. There are many evaluation factors acting on landslide geological hazards, so a simplified single-factor information content model can be used for step-by-step calculations, followed by a comprehensive superposition analysis. The corresponding calculation formula is shown below:

$$I = \sum_{i=0}^{n} I_i = \sum_{i=1}^{n} lg\frac{S_0^i/S^i}{A_0/A} \quad (1)$$

Where $\boldsymbol{I}$ is the predicted value of information content of a unit in the prediction area; I_i is the predicted value of information content of a unit in the prediction area by factor *i*. S^i is the total area of the unit occupied by factor *i*; S_0^i is the sum of the unit areas of landslide geological disasters in factor $\boldsymbol{I}$ unit; A is the total area of units within the region; A_0 is the sum of the unit areas of landslide geological hazards.

The value of $\boldsymbol{I}$ directly indicates the possibility of landslide in this unit and is an important index of landslide geological hazard susceptibility zoning. The larger the $\boldsymbol{I}$ value is, the more likely landslide will occur. When $I_i > 0$, it indicates that factor $\boldsymbol{I}$ is favorable for landslide occurrence. When $I_i < 0$, it indicates that factor $\boldsymbol{I}$ is not conducive to landslide. When $I_i = 0$, it means that factor $\boldsymbol{I}$ does not provide any information about whether a landslide occurs.

Landslides can often result from a combination of natural and man-made factors. In specific areas, certain factors tend to have a major influence on landslides and there are often clear correlations between these factors. When selecting causative factors for landslides, it is important to prioritize those that are easily accessible and have a wide range of impact.

Elevation, as the most basic geographical environment feature, can fundamentally affect all kinds of geological environment features, so DEM data can be used as the susceptibility evaluation factor. Slope is the steepness of surface unit, which can be extracted from DEM data. The size of slope is positively related to the occurrence of landslide, i.e., the larger the slope, the higher the probability of landslide, because the slope can induce the deformation of slope body by affecting the potential energy inside the slope body. Therefore, slope is chosen as the evaluation factor of susceptibility. The relationship between aspect and stratigraphic properties can greatly affect the stability of slope body. When the aspect is consistent with the stratigraphic yield, the slope body is easily destabilized along the stratigraphic level, so the aspect is chosen as the susceptibility evaluation factor. Geological structures represent the intensity of stratigraphic activity and the degree of stratigraphic fragmentation. The closer the area is to the tectonic zone, the more likely it is that the slope will be destabilized, and landslides will occur, so the distance from the structure (DFS) is included as an evaluation factor in the study. The river present in various water systems will erode the slope of the water body by scouring, which will lead to slope instability. At the same time, the river often serves as the end point of groundwater or surface water discharge and carries out the formation of stable subsurface seepage field or broken surface flow, which will also have an impact on the slope stability, so the distance from river (DFRI) is included in the evaluation factor in this study. The road represents a typical human engineering activity, and the slope excavation during road construction leads to slope instability, which is the main landslide geological hazard human induced influence factor, so the distance from the road (DFRO) is included in the evaluation factor in this study. Surface vegetation cover reduces the rate of flow production after rainfall as well as the rate of rainfall infiltration after rainfall, i.e., it reduces the delayed response to rainfall. Meanwhile, the root system of surface vegetation has the effect of preventing soil erosion. Therefore, vegetation cover was included as an evaluation factor in this study. The physical structure properties of rocks are landslide-induced. The geological conditions in the study area are complex, the stratigraphic ages span a wide range, and the stratigraphic lithologies are diverse. To reduce the complexity of stratigraphic lithology in the study area, the stratigraphic lithology in the study area is divided into five categories of engineering rock groups according to the category of rock formations and the degree of hardness, and the engineering rock groups (ERG) are selected as evaluation factors. According to the above analysis, the considered parameters related to landslides in the study area are elevation, slope, aspect, distance from road (DFRO), distance from river (DFRI), distance from structure (DFS), vegetation cover and engineering rock group (ERG).

3.2.2 *Landslide hazard*

Landslide hazard refers to the probability of landslide geological hazard occurring in a certain area within a certain period under the action of some specific predisposing factors. Predisposing factors are the internal and external driving forces for the evolution of unstable slope bodies toward the occurrence of landslides as a hazard. The hazard is obtained in a similar way as the susceptibility. After determining the predisposing factors, the information value of different predisposing factors is obtained by using the Information value method and weighting them to obtain the hazard distribution of the study area. The change of land use will inevitably have an irreversible impact on the stability of slope bodies within a certain range, so land use is one of the most important predisposing factors of landslide hazards. According to the analysis of the main causes of landslides in the study area, post-rainfall runoff is also one of the most important predisposing factors for landslide hazards. Based on the above analysis, in the evaluation of regional hazards, the main inducing factors for the occurrence of hazards in the study area can be determined by comprehensive analysis as rainfall and land use. Combining the information quantity values of these two types of predisposing evaluation factors, the information value model is used to evaluate the landslide hazard of the study area with a 1:1 weighting.

3.2.3 *Landslide Vulnerability*

Landslide susceptibility represents the negative impact of landslide on human social and economic activities and is a prerequisite for geological risk evaluation. Landslide vulnerability evaluation focuses on the analysis of various disaster-bearing bodies, such as buildings, roads, and population. In this paper, population density and land use are used to represent social and economic activities respectively, and population distribution and the value of different land use types are used as disaster-bearing bodies for vulnerability evaluation to obtain population vulnerability and economic vulnerability respectively. By superimposing the population susceptibility and economic susceptibility together, the total landslide vulnerability evaluation results of the study area are obtained.

3.2.4 *Landslide Risk*

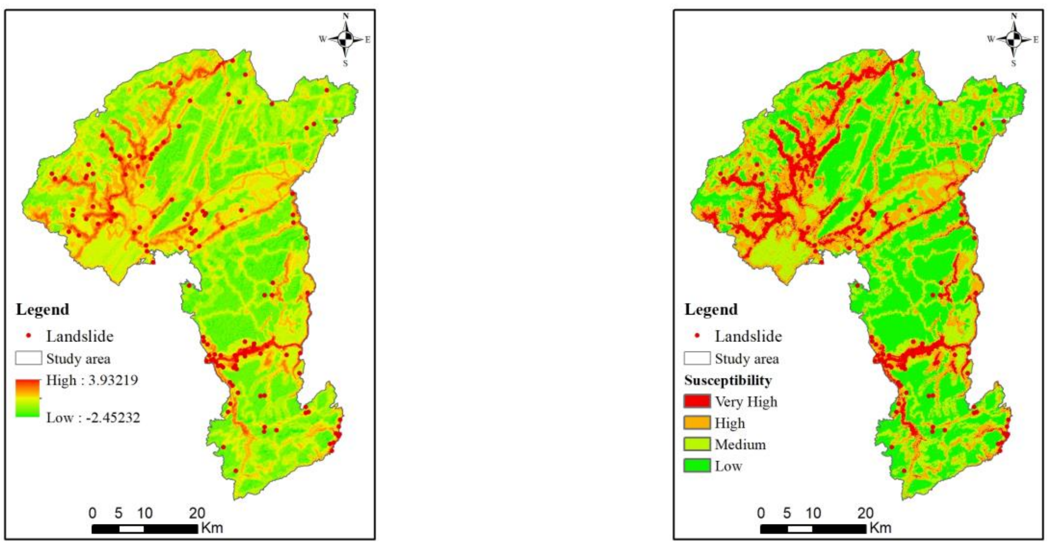
In 1992, the Department of Humanitarian Affairs of the United Nations proposed that risk is the possible loss of life, property, and economic activities that may be caused by a certain geological disaster in a specific region and a specific period and put forward the expression that risk degree equals the product of risk degree and vulnerability degree. The specific calculation formula is as follows:

$$R = H \times V \quad (2)$$

Where R is the economic and demographic risks of geological hazards; *H* is the probability of a potential geological disaster occurring in a certain area within a certain period; *V* is the vulnerability value of elements at risk.

4.0 Results

Based on the preliminary analysis of the development law of landslide in the study area, the considered parameters related to landslides in the study area are elevation, slope, aspect, distance from road (DFRO), distance from river (DFRI), distance from structure (DFS), vegetation cover and engineering rock group (ERG). The information value model is adopted, and the contribution of various factors to landslide is considered. The information value model is established by using Formula (1) to obtain the predicted information value of each factor, as shown in Table 1, and get the predicted information value of all factors, as shown in Figure 2a. According to the statistics of the distribution data of grid information in the whole area, the abrupt change point of the data is taken as the critical value of grade division, and the vulnerability of landslides in the whole area is divided into four grades: very high susceptibility area, high susceptibility area, medium susceptibility area, and low susceptibility area, as shown in Figure 2b.



(a) (b)

Figure 2: Landslide susceptibility analysis results: (a) susceptibility information value distribution, (b) Study area susceptibility classification.

Based on the preliminary analysis of above, land use and rainfall are considered as the main landslide predisposing factors to calculate landslide hazard. And the information value model is established by using Formula (1) to obtain the predicted information value of each factor, as shown in Table 2, and get the predicted information value of all factors, as shown in Figure 3a. According to the statistics of the distribution data of grid information in the whole area, the abrupt change point of the data is taken as the critical value of grade division, and the vulnerability of landslides in the whole area is divided into four grades: very high hazard area, high hazard area, medium hazard area, and low hazard area, as shown in Figure 3b.

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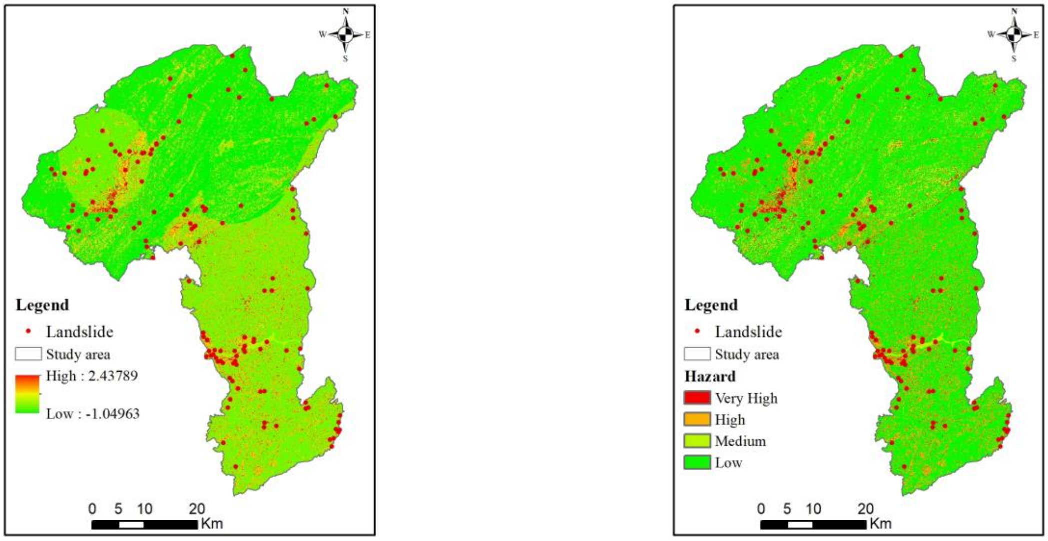
Table 1: The susceptibility information value of factors

Factor	Classification	Number of landslides	Area/ km^2	Information value
Elevation	＜873m	10	320.72	1.823167
Elevation	873-1190m	77	960.91	0.483426
Elevation	1190-1516m	31	1204.10	-0.63378
Elevation	＞1516m	12	451.26	-0.59332
Slope	0°~10°	92	1899.49	0.000821
Slope	10°~22°	26	613.20	-0.14619
Slope	22°~35°	12	130.07	0.517105
Slope	35°~90°	0	6.24	0
Aspect	North	22	453.40	-0.00335
Aspect	Northeast	12	248.80	0.002064
Aspect	East	16	330.78	-0.0108
Aspect	Southeast	23	415.98	0.116709
Aspect	South	12	299.41	-0.1831
Aspect	Southwest	16	270.93	0.188816
Aspect	West	14	298.39	-0.06188
Aspect	Northwest	15	331.31	-0.11247
ERG	A1	0	15.12	0
ERG	A2	2	23.43	0.285234
ERG	A3	54	670.89	0.226524
ERG	A4	81	1851.55	-0.10481
ERG	A5	5	88.01	0.214618
DFS	＜200m	21	386.00	0.086131
DFS	200m~400m	16	318.40	0.027356
DFS	400~600m	11	277.98	-0.24233
DFS	＞600m	82	1666.62	0.009715
DFRI	＜200m	28	398.84	0.341113
DFRI	200m~400m	28	373.34	0.43457
DFRI	400~600m	21	342.48	0.205753
DFRI	＞600m	53	1534.34	-0.34122
NDVI	High vegetation cover	14	463.10	-0.44737
NDVI	Medium vegetation cover	94	1917.64	-0.00053
NDVI	Low vegetation cover	20	250.90	0.479185
NDVI	Bare Area	2	17.36	0.585114
DFRO	＜200m	43	412.19	0.750007
DFRO	200m~400m	20	342.06	0.169253
DFRO	400~600m	12	297.06	-0.17521
DFRO	＞600m	55	1597.69	-0.35351

A1: Quaternary loose rocks. A2: Soft blocky sandstone, mudstone, and shale. A3: Hard - softer shales, and sandstones. A4: Hard limestone with shale. A5: Hard and thick layered limestone, and dolomite.

Table 2: The hazard information value of factors

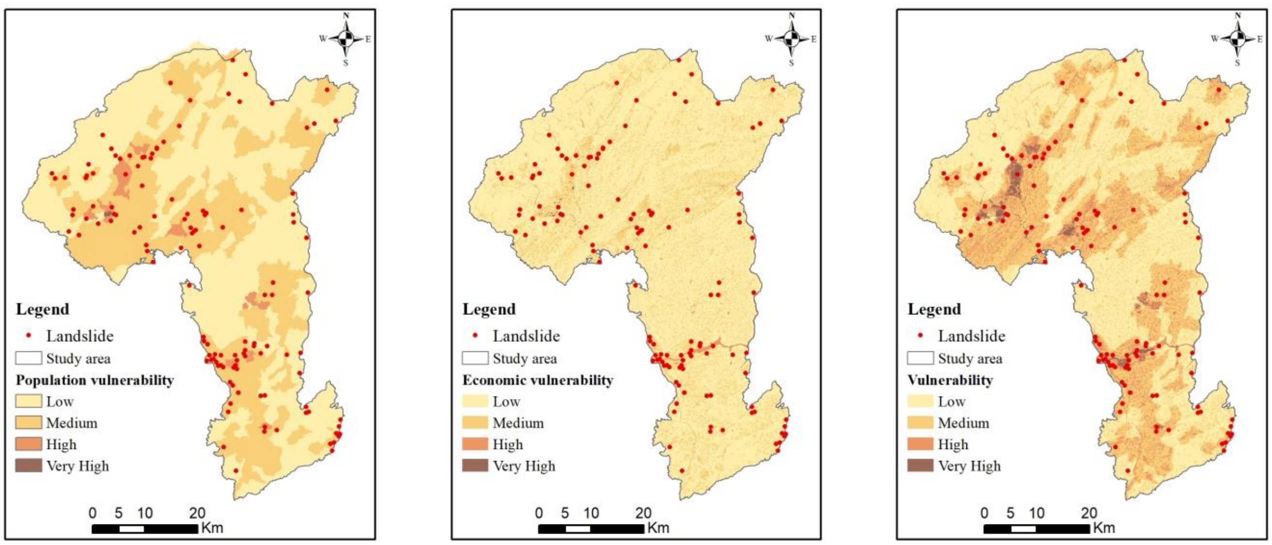
Factor	Classification	Number of landslides	Area/ km^2	Information value
Rainfall	＜973mm	70	1109.94	0.255865743
Rainfall	973~1010mm	20	666.05	-0.536353284
Rainfall	1010~1057mm	25	609.98	-0.170776337
Rainfall	＞1057mm	15	263.03	0.169607153
Land use	Arable Land	42	463.26	0.615191796
Land use	Garden	1	11.95	0.265652758
Land use	Woodland	58	2004.64	-0.513276068
Land use	Transportation	2	33.42	-0.069819043
Land use	Waters	3	41.78	0.112422228
Land use	Building Lot	2	3.52	2.182021548
Land use	Others	22	90.44	1.642598332



(a) (b)

Figure 3: Landslide hazard analysis results: (a) Hazard information value distribution, (b) Study area hazard classification.

Population density and land use type are used to represent social and economic activities respectively, and population distribution and the value of different land use types are used as disaster-bearing bodies for vulnerability evaluation to obtain population vulnerability and economic vulnerability respectively, as shown in Figure 4a and Figure 4b respectively. By superimposing the population susceptibility and economic susceptibility together, the total landslide vulnerability evaluation results of the study area are obtained, as shown in Figure 4c.



(a) (b) (c)

Figure 4: Landslide hazard analysis results: (a) Population vulnerability, (b) Economic vulnerability, (c) Study area vulnerability classification.

At the final stage of the study, landslide risk is produced by considering the landslide hazard and vulnerability. Landslide risk is achieved by formula (2), as shown in Figure 5.

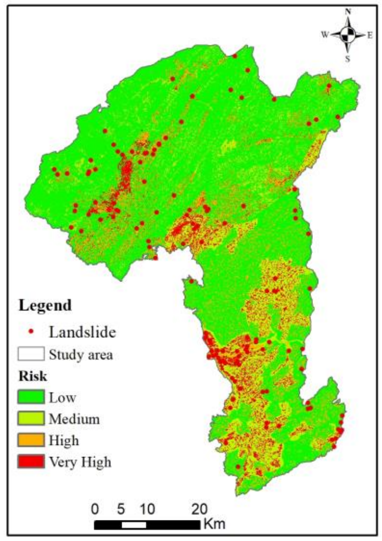


Figure 5: Landslide risk of study area

5.0 Discussion

From Figure 5, the very high-risk area of landslide is mainly distributed in the gully areas along the main streams of rivers and their tributaries where roads, buildings, geological formations are active and river erosion is strong, with an area of 182.73 km^2, accounting for 6.90% of the total area. At the edge of the very high-risk area, the intensity of its human engineering activities and the use of land are also stronger, and although the degree has been reduced, the overall impact is still strong. This area is a high-risk area for landslide, with an area of 291.40 km^2, accounting for 11.00% of the total area. In the southern and central areas of the study area, due to the dense vegetation, sparse population, less land development and utilization, land use type is mainly woodland, human activities are weak, the risk of landslide is a medium risk area, with an area of 476.56 km^2, accounting for 17.99% of the total area. In other areas of the study area, the landslide risk is particularly low, and the land use and human engineering activities are weak, and the area is a low-risk area, with an area of 1698.31 km^2, accounting for 64.11% of the total area.

According to the distribution characteristics of landslide in the study area, it can be found that in the typical karst area, due to the geological environment, the areas with high economic and population values that can be used for production are often located in the gully areas along the main streams of rivers and their tributaries where roads, buildings, geological structures are active and river erosion is strong, and such areas are also highly susceptible to landslide. This superposition makes the high-risk areas of landslide in typical karst areas more concentrated, so it is especially important to focus on the prevention and control of high susceptibility areas.

6.0 Conclusions

As a typical karst mountainous area, the landslide development in the study area has obvious regional characteristics. In this study, the eight categories of elevation, slope, slope direction, distance from road, distance from water system, distance from structure, vegetation cover, and engineering rock group are established as the main disaster-causing factors to evaluate the susceptibility, and the two categories of land use type and rainfall are used as the main triggering factors to evaluate the hazard. To a certain extent, the selection of this evaluation factor can be used as a typical evaluation factor for this type of karst mountainous area and used in the evaluation of landslide geological hazards in other similar areas

In terms of landslide risk distribution, the study area also has obvious regional characteristics, that is, due to the geological environment, the areas with high economic and population values that can be used for production are often located in the valley areas along the main streams of rivers and their tributaries where roads, buildings, geological structures are active and river erosion is strong, and such areas are also highly susceptible to landslide geological hazards. This superposition makes the high-risk areas of landslide geological hazards in typical karst areas more concentrated, in this case, the landslide prevention and control in typical karst mountainous areas should focus on the high-risk areas and adopt more relocation and avoidance, engineering treatment and other methods.

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Conflicts of Interest The authors declare no conflict of interest.

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