**ORIGINAL PAPER**

# Landslide risk evaluation based on slope unit:a case on the Western Hubei area, China

Zhenxia Liu[1] · Lingling Sun[1] · Yue Zhang[1] · Zhaoyuan Yu[1,2]

## Abstract

The traditional landslide risk research mostly focuses on the spatial distribution of landslide occurrence probability, but the research on the time distribution of landslide occurrence probability is not in-depth, and there is no effective professional management advice for specific risk areas, so it has great limitations. This paper takes the landslide-prone area along the Qingjiang River in Jianshi County, Hubei Province as the research area, takes the slope as the unit, and uses the information value method to complete the landslide geological disaster risk assessment in the study area. Through the characteristics of landslide risk in time and space, the dynamic management measures of landslide risk in different periods of the study area are formulated. The map of landslide prevention and control planning measures in different periods in the study area can be obtained, which provides a basis for realizing the balance between safety and economy of landslide prevention and control planning. This has obvious guiding significance for landslide prevention and control planning in other regions.

**Keywords** Landslide · Slope unit · The information value method · Risk management

## 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 is located 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 was 4.23 billion CNY (Guo et al. 2014). 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 and Reghunath 2017; Guo et al. 2014; Hou et al. 2006; Pourghasemi et al. 2012), the frequency ratio method(Lee and 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; Farooq and Akram 2021; Guo-Liang et al. 2017), and the artificial neural networks(Lucchese et al. 2021; Lucchese et al. 2020; Soma et al. 2019). 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, in the traditional sense, the landslide risk distribution map mostly focuses on the spatial distribution of landslide probability, but the research on the time distribution of landslide probability is not in-depth, and it does not put forward effective professional management opinions for specific risk areas. It lacks guidance on urban construction, land use, and

---

Responsible Editor: Zeynal Abiddin Erguler

✉ Zhaoyuan Yu
  yuzhaoyuan@njnu.edu.cn

1   School of Geography, Nanjing Normal University,
    Nanjing 210023, China

2   Key Laboratory of Virtual Geographic Environment (Nanjing
    Normal University), Ministry of Education, Nanjing 210023,
    China

regional development planning. Therefore, it has significant limitations in providing effective and direct support to non-specialist policy makers and local administrations.

In this paper, taking the landslide-prone area along the Qingjiang River in Jianshi County, Hubei Province as the study area, according to the temporal and spatial distribution law of landslide disaster points and based on slope unit, the susceptibility, and hazard of landslide geological disasters in the study area is evaluated and analyzed by using the information value method, and the risk assessment of landslide geological disasters in the study area is completed by combining the vulnerability of buildings and population in the study area. The landslide prevention and control planning measures map based on the slope unit in the study area is put forward. The purpose of this paper is to propose a set of evaluation methods of landslide risk concentration area based on slope unit, describe the temporal and spatial variation characteristics of landslide risk, and apply it to landslide prevention and control planning measures. The innovation of this method is to combine the temporal and spatial variation characteristics of landslide risk in different return periods with landslide dynamic management, and to provide intuitive suggestions for non-professionals such as policymakers and local administrations to achieve the balance between safety and economy of landslide management.

## Study area and data sources

The research area is located along the Qingjiang River in Jianshi County, Hubei Province, China (Fig. 1). It is located in the folded mountain area of western Hubei Province, and the trend of the mountain is consistent with the direction of the fold tectonic line. The strata exposed in the study area are mainly the Badong Formation of the Middle Triassic($T_2b$), Longtan Formation of the Upper Permian($P_3l$), Maokou Formation of the Middle Permian($P_2m$), and Qixia Formation of the Middle Permian($P_2m$). The geological structure is relatively simple without large fault structures, and the main lithology is limestone and mudstone.

There are 19 geological disasters in the study area, mainly landslide deformation, and the data of 19 landslide sites were obtained from field survey. The formation and development of geological disasters are influenced by topography, formation and lithology, geological structure, rainfall, and human engineering activities. The law of geological hazards in the study area mainly includes four aspects: topographic and geomorphological control law, stratigraphic and lithologic control law, geological structure control law, and inducement control law.

Thirteen landslide geological hazards in the study area are concentrated in the 500–1000 m elevation section. The two sides of the landslide geological hazards in the area are

**Fig. 1** Location map of the study area
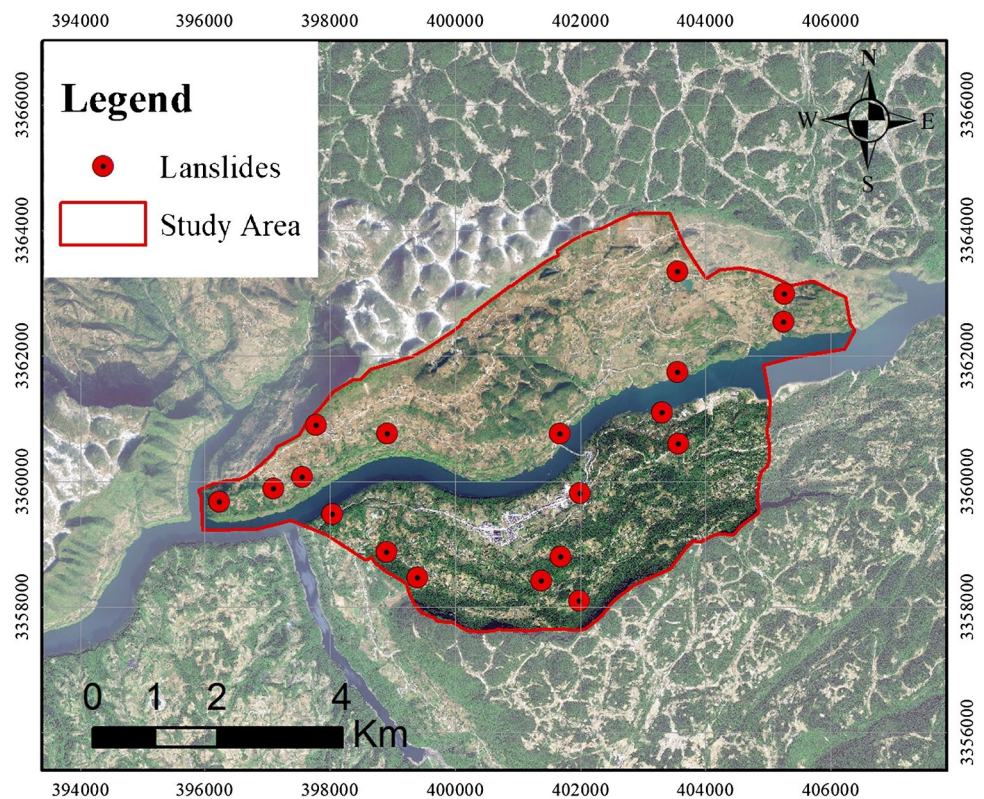
mainly based on the bedrock convex beam landform. The back edge of the landslide is mostly an armchair catchment terrain with three sides high and low in the middle, and the front edge is mostly a high and steep open surface formed by cross-cutting gully or engineering cut slope. Geological hazards of landslides mostly occur on the steep slope of 25°–40°, while the distribution of landslide disaster points is less in the slope of less than 25° or more than 40°. The former is not easy to slide due to the small slope and gentle terrain. The latter, however, is not easy to form landslide geological disasters because of its large slope and hard rock.

The main data include the data of landslide damage points, the digital elevation model (DEM), the normalized difference vegetation index (NVDI), land use type, rainfall, population, and buildings. The data of landslide damage points are from field measurements. The DEM was gathered from ASTER GDEM 30 M. The NDVI map and the land use type were produced from a Landsat ETM + satellite image using red (R; band 3) and near-infrared (NIR; band 4) bands by rationing the reflectance values of the related bands (NDVI = (NIR − R) / (NIR + R)). The rainfall, population, and building data were gathered from Jianshi County Natural Resources and Planning Bureau.

## Methodology

### Slope unit division

The different unit division has a great influence on the evaluation results of landslide risk evaluation at different research scales (Schlogel et al. 2018; Xie et al. 2003; Yuan et al. 2010). Raster-based evaluation is often applied to large-scale regional evaluation, and its evaluation results reflect the variation trend of regional disaster risk. Slope-based unit evaluation is often applied to the evaluation of key areas in a small range, and its evaluation results are mostly used to guide the prevention and control of local disasters in key areas. Therefore, the first step of regional landslide geological hazard susceptibility evaluation is to determine the division method and type of evaluation unit.

In the risk management of landslide geological hazards, disaster prevention should be carried out based on slope. To improve the usability of evaluation results, it should be expressed in the form of the vulnerability of slope elements (Liu et al. 2018; Wu et al. 2013). Considering that the area studied in this study is a small area with a high incidence of land disasters, the slope unit is selected as the basic evaluation unit. Slope units are divided by DEM hydrological analysis model. In this method, the ridgelines and valley lines of the catchment basin were extracted by positive and anti-topographic methods. Then, the generated catchment and reverse catchment basin are fused to get slope units. Finally,

according to topographic factors such as mountain shadow, slope body shape, and stratigraphic lithology factors, the slope units are artificially modified. For example, the slope unit with too large an area and shape does not conform to the actual situation is modified to obtain the slope unit with a large size and shape consistent with the actual terrain.

### Landslide susceptibility

The vulnerability assessment of landslide geological hazards is the basis of risk assessment. In particular, it provides the key intermediate data for the spatial probability of landslides. Landslide geological hazards are a natural geological phenomenon with obvious temporal and spatial attributes that occur on the surface. Its influencing factors have relatively fixed ground and space information in the process of natural geological and geographical evolution.

Based on the theory of the information volume model, this paper quantitatively evaluates the susceptibility of landslide geological hazards in the study area. The information volume model theory holds that the generation of geological disasters is related to the quantity and quality of information obtained in the forecasting process, which can be measured by the amount of information. The greater the amount of information, the greater the possibility of geological disasters.

There are many factors that act on landslide geological hazards, and the corresponding factor combination states are particularly numerous, but the number of sample statistics is often limited. So the simplified single-factor information content model can be used for step-by-step calculation, followed by comprehensive superposition analysis. The corresponding information content model is as follows:

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

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

Using the information volume model, and considered the contribution of various factors to geological disasters such as landslides, the predicted information value of the research area was obtained by taking the raster as the unit. Then, the predicted information value of the slope unit was obtained by the weighted average calculation based on the result of taking the raster as the unit. The weighted average calculation model is as follows:

$$I = \frac{\sum_{i=0}^{n} I_i * S_i}{S} \quad (2)$$

where $I$ is the predicted information value of the slope unit; $I_i$ is the predicted information value of the raster unit; $S_i$ is the total area of an area with a predicted information value of $I_i$; $S$ is the total area of the slope unit.

## Landslide hazard

The landslide hazard is the probability of a landslide disaster of a certain scale and type occurring in a certain area and a certain period under the action of certain inducing factors. In the study of small key areas, the landslide hazard($H_L$) is determined by the time probability and scale probability of disaster occurrence. Its calculation formula is as follows:

$$H_L = P(N_L) \times P(s) \quad (3)$$

where $P(N_L)$ is the time probability of landslide occurrence, that is, the surpassing probability of landslide occurrence in different return periods; $P(s)$ is the spatial probability of landslide occurrence.

The time probability of landslide occurrence $P(N_L)$: Time probability of landslide occurrence is determined by the surpassing probability of landslide occurring at least one disaster in different recurrence periods in the survey area. This time probability is subject to the Poisson distribution (Jiang 2021; Zhang et al. 2005)) and is calculated by the following formula:

$$\begin{cases} P(N_L) = 1 - e^{-\frac{t}{RI}} \\ RI = \frac{T}{N} \end{cases} \quad (4)$$

where $t$ is the regression period, which can be 1a,10a, 20a,50a, representing the changes on the time scale; $T$ is the difference between the occurrence year of the latest historical landslide and the oldest historical landslide in the research area, which are 2020 and 1983 respectively, so $T = 37$; $N$ is the number of landslides in the slope unit when the regression period is 1a, if the regression period is 10a and 20a, then $N$ is equal to the number of historical landslides plus the number of slopes in the very high-risk areas; if the regression period is 50a, then $N$ is equal to the number of historical landslides plus the number of slopes in very high-risk areas and high-risk areas.

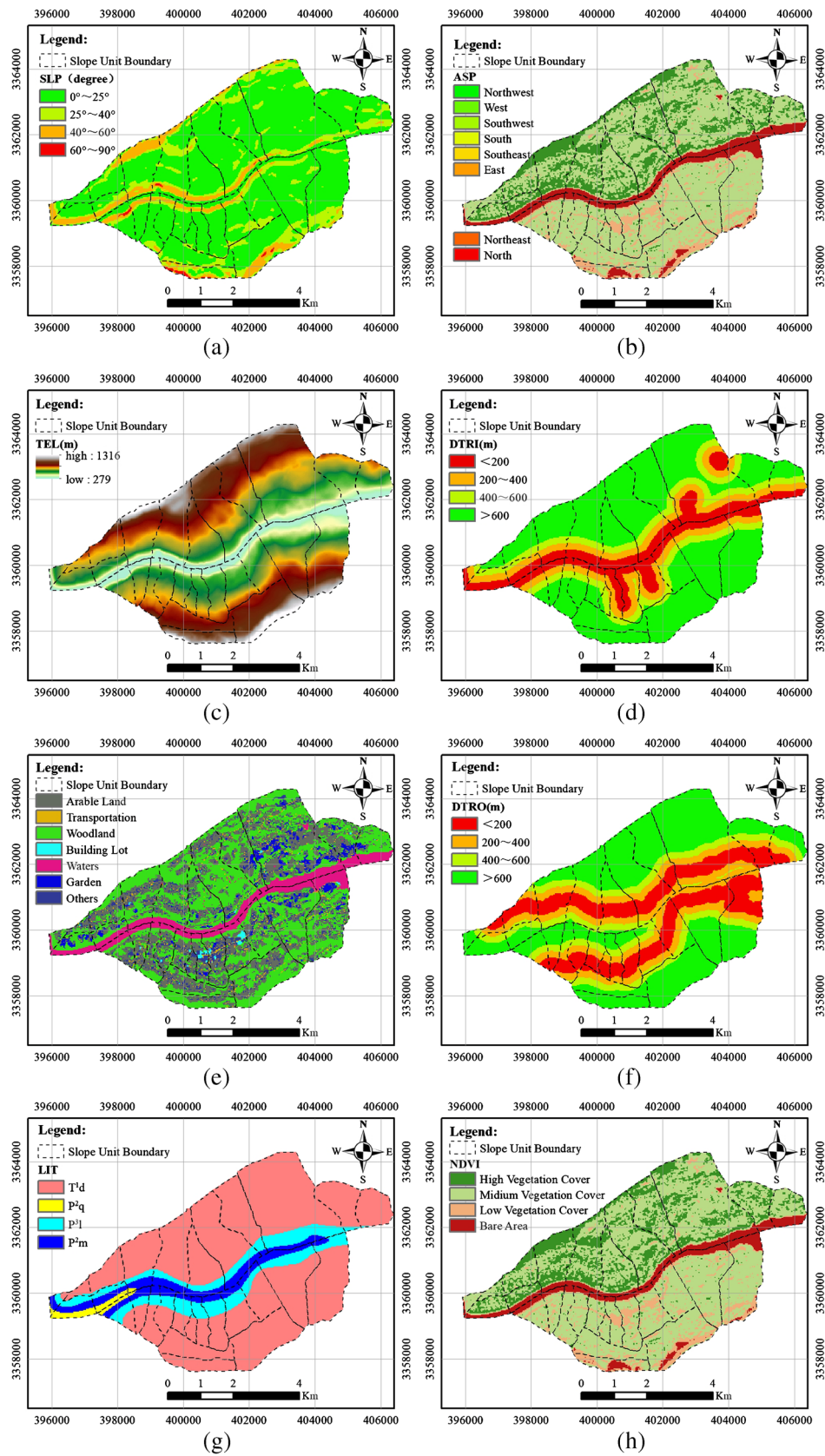**Fig. 2** Division map of slope units in the study area
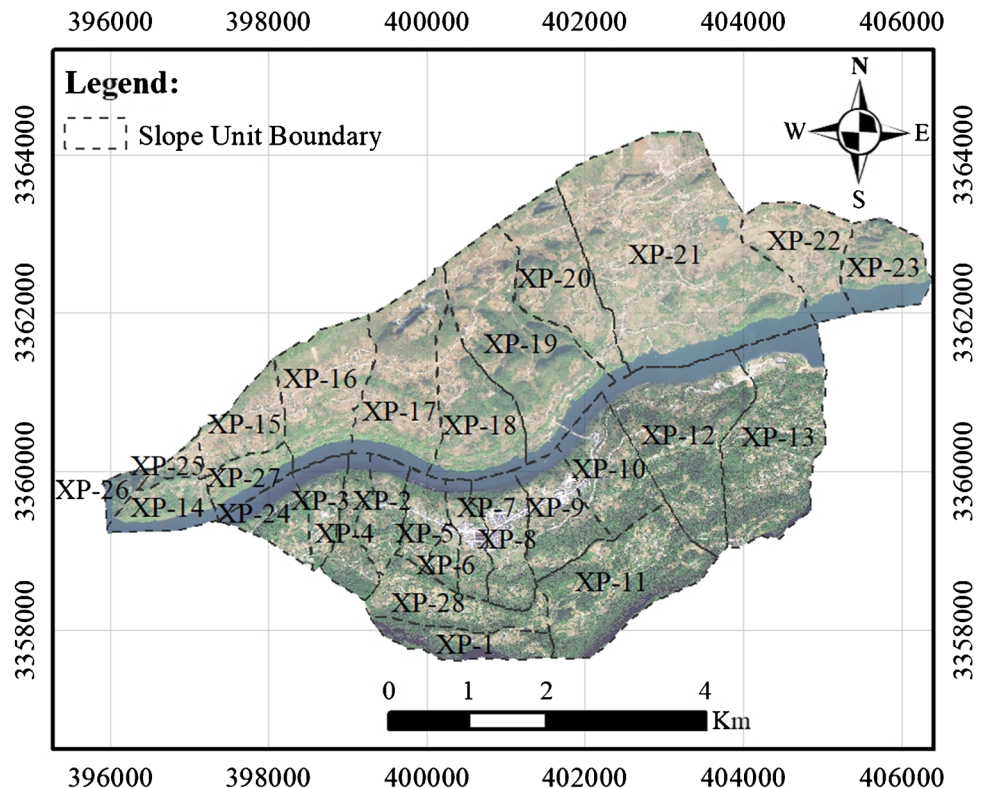
**Fig. 3** Distribution map of landslide risk assessment factors in the study area

Spatial probability of landslide occurrence $P(s)$: The spatial probability of landslide occurrence refers to the probability of historical landslide occurrence in the evaluation unit, and the value is between 0 and 1. The spatial probability can be reflected by the evaluation results of landslide susceptibility after normalization processing(Afungang et al. 2017; Chen 2005; Sujatha et al. 2013)).

## Vulnerability

Vulnerability is a measure of the disaster-resisting ability of the disaster-bearing body in the face of a specific disaster intensity and a function of disaster intensity and bearing capacity. The definition of vulnerability indicates that the vulnerability is mainly manifested in the disaster-causing intensity and the disaster-resisting ability of the disaster-bearing body. This study mainly evaluated the vulnerability of landslide geological disasters of buildings and population(Bourenane and Bouhadad 2021; Das et al. 2011; Kumar et al. 2021), with data from Jianshi County Natural Resources and Planning Bureau.

The population vulnerability ($V_p$): the population vulnerability is assumed to be the probability of death and loss caused by geological disasters. The vulnerability of people can be considered from the aspects of people's age, people's education level, the degree of publicity of geological disasters, and the perfection of the geological disaster forecast system. The population vulnerability value is calculated by the following formula (4):

$$V_p = E \times (W_a \times C_a + W_q \times C_q + W_g \times C_g) \tag{5}$$

where $E$ is the probability of building damage, which can be reflected by the evaluation results of landslide susceptibility after normalization processing; $W_a$ is the weight of population age evaluation factors, and 0.5 is taken here; $C_a$ is the population age coefficient; $W_q$ is the weight of educational level evaluation factors, and 0.1 is taken here; $C_q$ is the literacy coefficient; $W_g$ is the weight of factors in the evaluation of local prevention and control efforts, and 0.4 is taken here; $C_g$ is the local prevention and control intensity coefficient. Put the collected population data into the formula (4) and get the population vulnerability distribution map of the study area.

The building vulnerability ($V_b$): for building vulnerability, the economic vulnerability of housing construction, other projects, and land is mainly considered. The vulnerability of housing construction mainly refers to the housing construction of residents. Other projects mainly include public facilities, road projects, lifeline projects, water conservancy projects, and mining projects, which are summarized as other projects here.

Land mainly refers to the relevant types of land. The building vulnerability value is calculated by the following formula:

$$V_b = E \times S \times W \tag{6}$$

where $E$ is the probability of building damage, which can be reflected by the evaluation results of landslide susceptibility after normalization processing; $S$ is the elements at risk area; $W$ is the cost per square meter of hazard-affected body.

**Table1** Information quantity of the considered parameters and their subgroups

| Considered parameters | Subgroups | Information |
|---|---|---|
| TEL | <500 m | 0.142362 |
| | 500~1000 m | −0.01641 |
| | >1000 m | −0.43695 |
| SLP | 0°~25° | −0.0853 |
| | 25°~40° | 0.265437 |
| | 40°~60° | 0.132711 |
| | 60°~90° | 0 |
| ASP | North | −0.286011 |
| | Northeast | 0.529118 |
| | East | 1.00727 |
| | Southeast | −0.50782 |
| | South | 0.159349 |
| | Southwest | 0 |
| | West | 0.610815 |
| | Northwest | 0.192549 |
| LIT | T$^1$d | −0.1212 |
| | P$^2$q | 0 |
| | P$^3$l | 0.89423 |
| | P$^2$m | 0 |
| DTRO | <200 m | 0.20576 |
| | 200 m~400 m | −0.03351 |
| | 400~600 m | 0.221477 |
| | >600 m | −0.2003 |
| DTRI | <200 m | −0.56202 |
| | 200 m~400 m | 0.238343 |
| | 400~600 m | 0.687174 |
| | >600 m | −0.20879 |
| NVDI | Bare Area | 0 |
| | Low vegetation cover | −0.06548 |
| | Medium vegetation cover | 0.231147 |
| | High vegetation cover | −0.36896 |
| LUS | Arable Land | 0.394096 |
| | Garden | 0.279177 |
| | Woodland | −0.36744 |
| | Transportation | 0 |
| | Waters | 0 |
| | Building Lot | 0 |
| | Others | 0.938177 |

After the population vulnerability and building group vulnerability are obtained, the vulnerability of the whole region can be obtained by the following formula:

$$V = V_p + V_b \tag{7}$$

## 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:

$$R = H \times V \tag{8}$$

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.

## Results and discussion

Considering the scope of the study area, according to the 30 m resolution digital elevation model, based on DEM hydrological analysis model and combined with field investigation, a total of 27 natural slope units in the study area were divided (Fig. 2).

Based on the preliminary analysis of the development law of geological hazards in the study area, the considered parameters related to landslides in the region were slope (SLP), aspect (ASP), topographical elevation (TEL), lithology (LIT), distance to rivers (DTR), land use (LUS), distance to roads (DTRO), and normalized difference vegetation index (NDVI). All files are stored in the GIS platform, which is presented in Fig. 3.

The information volume model is adopted, and the contribution of various factors to geological disasters such as landslides was considered (Table 1). The predicted information value of the research area is obtained. The predicted information value of the slope unit is obtained by the weighted average calculation based on the result of taking the raster as the unit. Then, the information volume model is established by using Formula (1) to obtain the predicted information value by taking the raster as the unit (Fig. 4a). The predicted information value of the research area is obtained. Then, the predicted information value of the slope unit is obtained by the weighted average calculation based on the result of taking the raster as the unit (Fig. 4b) by using Formula (2). The predicted information of each slope unit in the study area is divided into relative grades, which can be used to guide the qualitative evaluation and decision-making of geological hazards. 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 ($I \geq 1.18$), high susceptibility area ($0.16 \leq I < 1.18$), medium susceptibility area ($-0.74 \leq I < 0.16$), and low susceptibility area ($I \leq -0.74$).
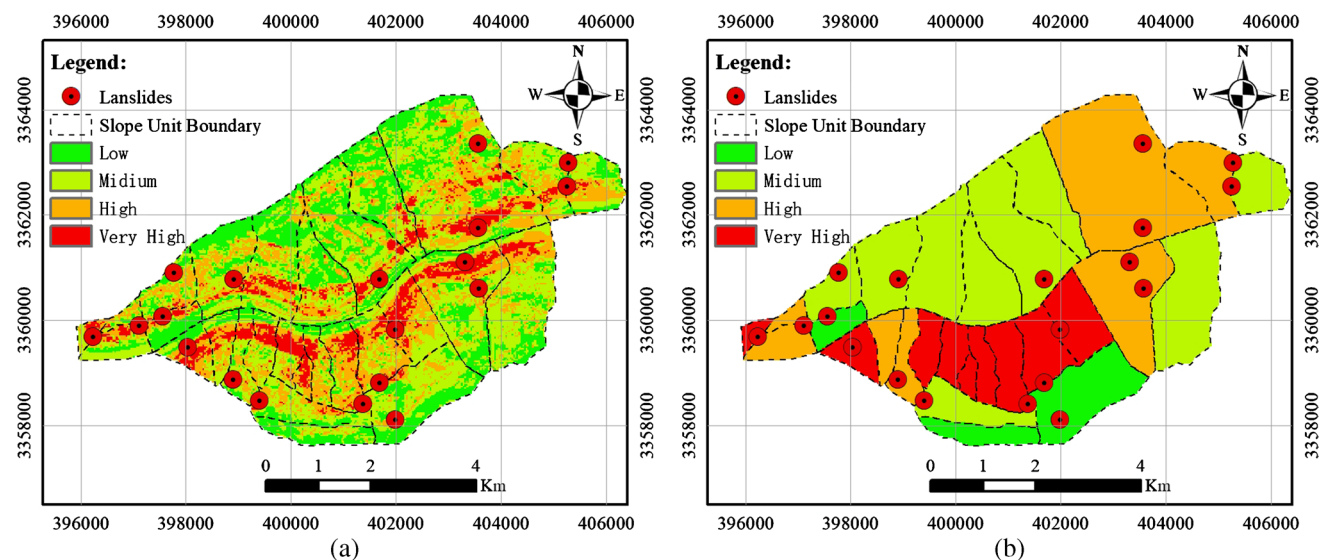


**Fig. 4** Landslide susceptibility analysis results: **a** based on raster unit, **b** based on slope unit

The landslide susceptibility in the study area is mainly controlled by landform, stratigraphic lithology, and related inducements. The landslide susceptibility in the study area mainly occurs on the steep slope of 25° ~ 40° slope. The interbedded layers of argillaceous siltstone and mudstone are widely developed in the study area, and it provides material conditions for the occurrence of landslides. The regional tectonics not only formes the slope, but also makes the rock break seriously and weather easily, which creates favorable conditions for the occurrence of geological disasters. The influence of water and human engineering activities on landslide geological hazards is obvious, and the development of landslide geological hazards is more obvious in the areas with obvious human engineering activities such as urban construction and slope toe excavation in the rainy season.

According to the landslide distribution information in the study area and the evaluation results of the landslide susceptibility after normalization treatment, the zoning results of the landslide hazards in the study area with different return periods (Fig. 5) can be calculated by using Formula (3) and Formula (4). Due to spatial control factors, different slopes exhibit different hazards at the same time. Landslide hazards on some sloped may become more dangerous over time, but some remain the same. It means that the landslide hazard has obvious spatial–temporal variation characteristics.

Put the collected population data into the Formula (5) and get the population vulnerability distribution map of the study area (Fig. 6a). And put the collected Building data into the formula(6) and get the building vulnerability distribution map of the study area(Fig. 6b).
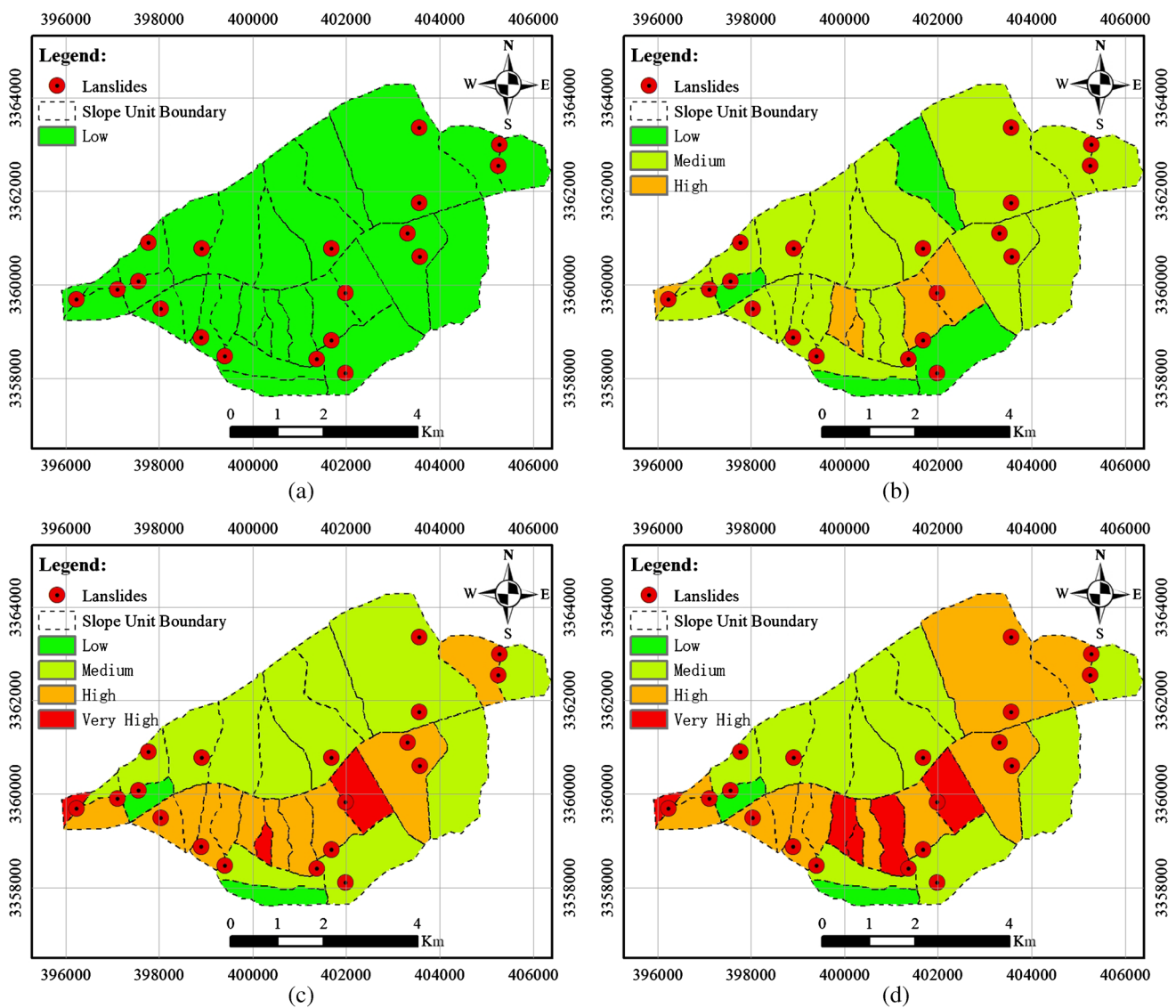


**Fig. 5** Landslide hazard analysis results in 1a,10a,20a, and 50a return periods. **a** In 1a return periods, **b** in 10a return periods, **c** in 20a return periods, **d** in 50a return periods
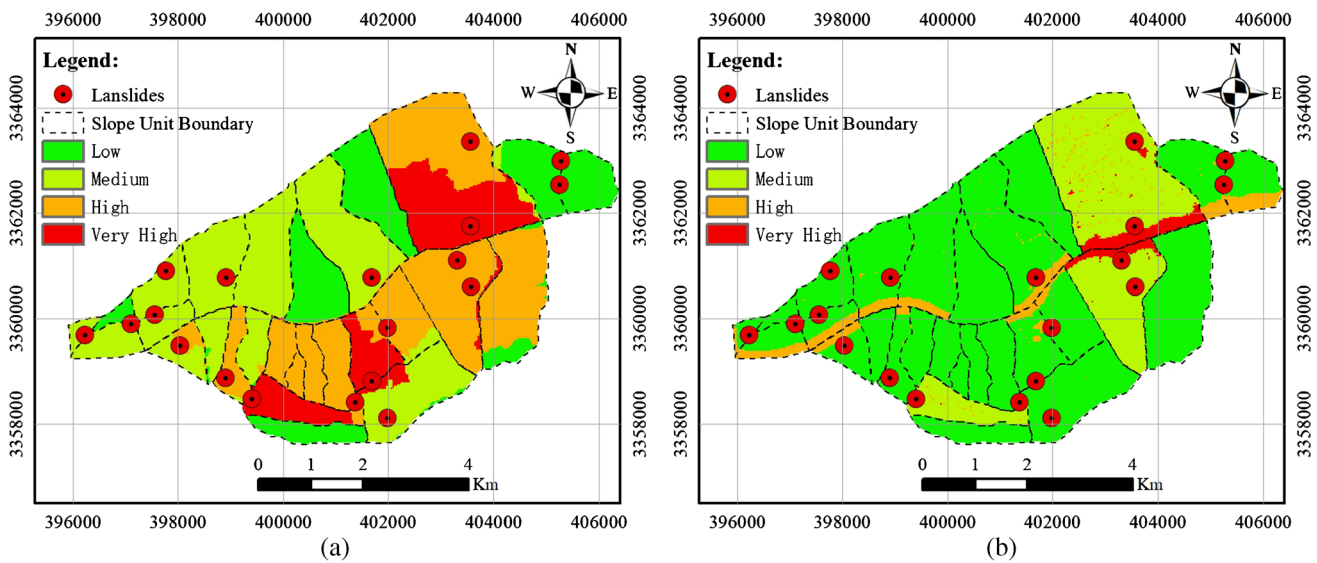
**Fig. 6** Landslide vulnerability analysis results: **a** based on the population vulnerability, **b** based on the building vulnerability

The population vulnerability ($V_p$) and the building vulnerability ($V_b$) are superimposed to obtain the vulnerability distribution map of the study area (Fig. 7a). The vulnerability of the research area was obtained by taking the raster as the unit. Then, through the distribution map of slope elements, raster information value in the slope was extracted to realize the vulnerability zoning based on slope elements in the study area (Fig. 7b).

At the final stage of the study, landslide risk is produced by considering the landslide hazard and vulnerability. Landslide risk is achieved by Formula (8), expressing the specific risk throughout the study area in different return periods (Fig. 8). The landslide risk of 27 slopes in the study area is

divided into very high-risk areas, high-risk areas, medium-risk areas, and low-risk areas (Fig. 8).

The temporal and spatial variation of landslide risk in the study area was obtained. When the return period is 1a, the whole study area is a low-risk area, indicating a low risk of landslide in the short term. With the increase of the regression periods, the landslide risk in the study area increases, and gradually expands from the built-up areas along the river to other areas. This indicates that the evaluation of landslide risk is related to human society. For areas where human activities are not active, even if the probability of landslide occurrence is high, they cannot be evaluated as high-risk areas. In particular, for XP-11, the investigation found that
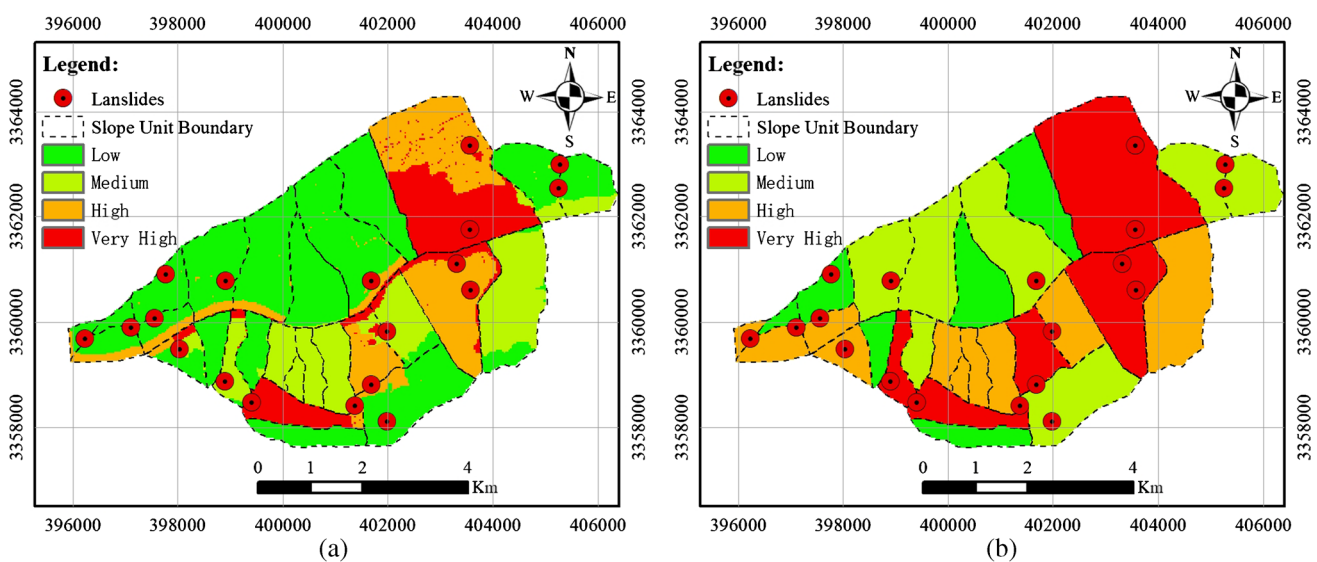


**Fig. 7** Landslide vulnerability analysis results: **a** based on raster unit, **b** based on slope unit
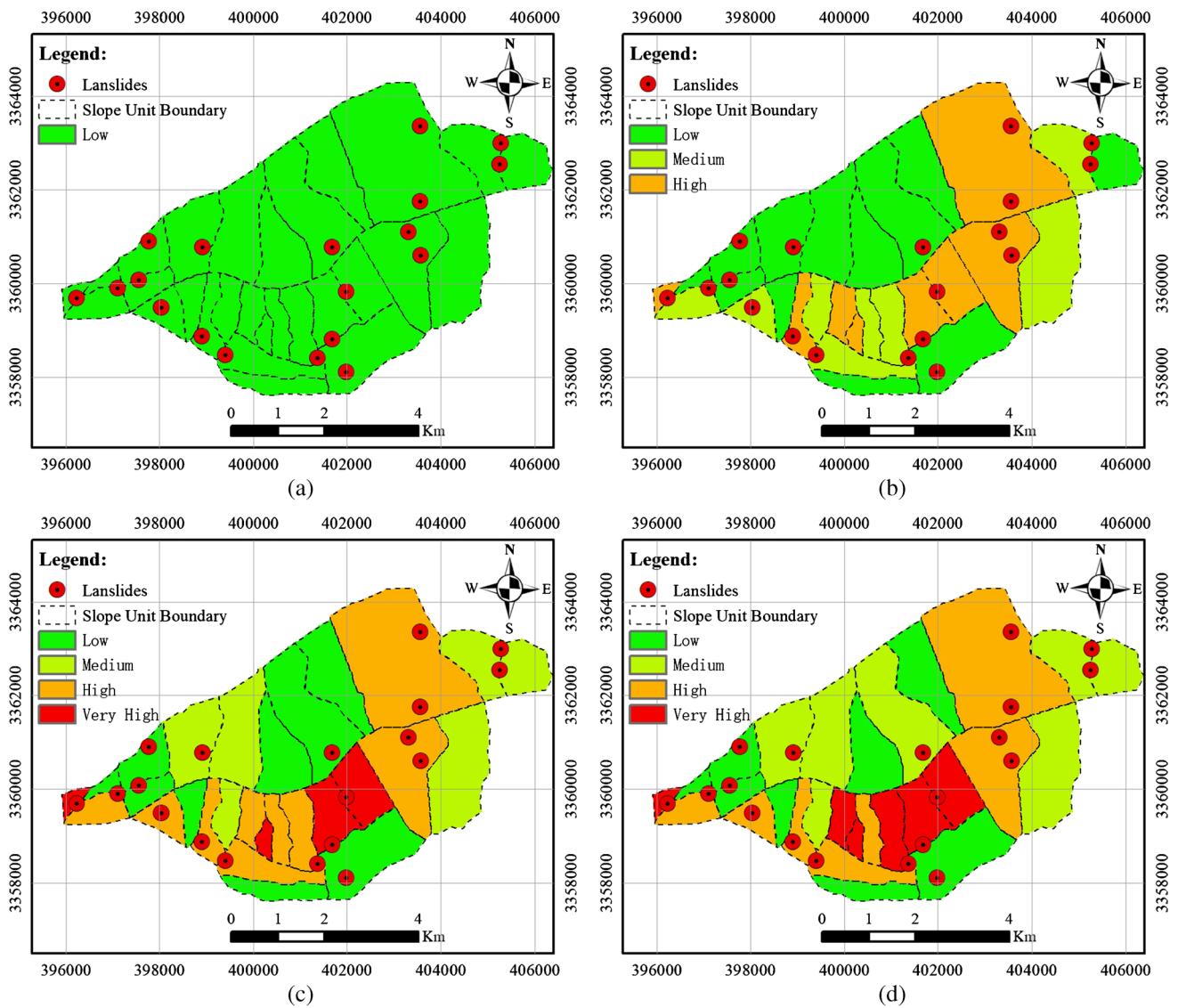
**Fig. 8** Landslide risk zoning map of the study area in different return periods. **a** In 1a return periods, **b** in 10a return periods, **c** in 20a return periods, **d** in 50a return periods
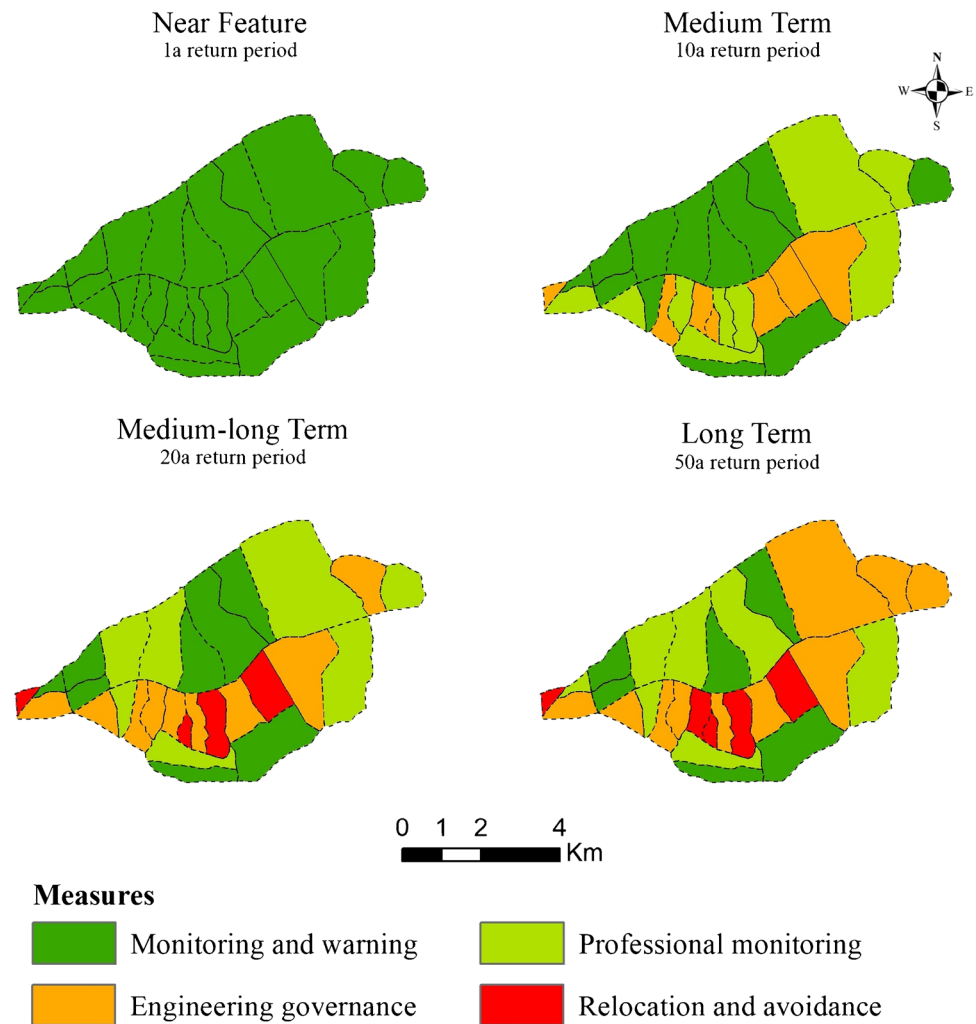
the landslides that had occurred inside it were induced by human reclamation, and its stratigraphic structure and other characteristics were different from those of other landslide areas, indicating that the occurrence of the landslide was accidental. Therefore, the probability of risk in the slope

unit did not increase with the increase of the return period. This phenomenon provides an important idea for landslide risk management, that is, not only the results of the systematic evaluation should be considered, but also the evaluation should be combined with the actual investigation. For

**Table 2** Principle of geological landslide risk prevention and control measures in the study area

| Hazard | Risk | | | |
|---|---|---|---|---|
| | Very High | High | Medium | Low |
| Very high | Relocation and avoidance | Engineering governance | Engineering governance | Professional monitoring |
| High | Engineering governance | Engineering governance | Engineering governance | Professional monitoring |
| Medium | Engineering governance | Professional monitoring | Professional monitoring | Monitoring and warning |
| Low | Monitoring and warning | Monitoring and warning | Monitoring and warning | Monitoring and warning |

**Fig. 9** Landslide prevention and control planning measures map at different time



Near Feature
1a return period

Medium Term
10a return period

Medium-long Term
20a return period

Long Term
50a return period

0 1 2 4 Km

**Measures**

Monitoring and warning

Professional monitoring

Engineering governance

Relocation and avoidance

this kind of areas, human activities are extremely obvious to induce landslides. Therefore, reducing human activities is of great significance to risk management of landslide-prone areas.

For the slopes with different risk grades in the study area, the matrix superposition method is adopted to comprehensively put forward the risk prevention and control principles of landslide geological disasters. The governance measures under different risk situations include relocation and avoidance, engineering governance, professional monitoring, monitoring, and warning, as shown in Table 2.

As the regression periods increase, the risk of most slope units increases. Therefore, landslide risk prevention and control should be dynamic work, and its prevention and control measures should be adjusted with the change of time to achieve a balance between economic benefits and safety. According to the temporal and spatial changes of disaster and risk of landslide and the principle of geological landslide risk prevention and control measures, the landslide prevention and control planning map of the study area was drawn (Fig. 9). In this map, the data of 1a regression period is used to represent the near future, 10a regression periods for the medium term, 20a regression periods for the medium-long term, and 50a regression periods for the long term. The results showed that the control measures in some slope units in the study area were gradually upgraded over time. For example, the landslide prevention and control planning measures of XP-10 is *Mnitoring and warning*, *Egineering governance*, *Eineering governance*, and *Relocation and avoidance* in 1a, 10a, 20a, and 50a return period, respectively. This means that from the perspective of long-term planning, it is very necessary to choose appropriate management measures because some redundant measures will lead to unnecessary economic waste. The map visually shows the prevention and control measures in different areas and different periods of the study area. This plays an important role for

policy makers and local administrations in minimizing the damage caused by landslides and making long-term plans for the region.

## Conclusions

Based on the landslide control factors in the study area, the spatial distribution of landslide susceptibility based on slope units in the study area was determined by the information value method, and the spatial and temporal distribution rules of the landslide hazard of each slope unit were calculated based on different return periods. Then, the vulnerability of each slope unit was obtained by taking population and buildings as the evaluation objects. Finally, the spatial and temporal distribution of landslide risk in the study area was obtained. The spatial and temporal distribution of landslide risk well reflects the spatial and temporal variation of landslide risk in the study area. According to the risk prevention and control principles of landslide geological disasters, combined with the spatial and temporal variation of landslide risk, it provides a great reference for policymakers and local administrative departments in landslide prevention and control, and puts forward reasonable prevention and control opinions according to the time variation of risk and prevention principle, to achieve the balance between safety and economy of landslide prevention and control.

## Declarations

**Conflict of interest** The authors declare no competing interests.

## References

Achu AL, Reghunath R (2017) Application of analytical hierarchy process (AHP) for Landslide Susceptibility Mapping: a study from southern Western Ghats, Kerala, India. Paper presented at the Disaster, Risk and Vulnerability Conference (DRVC2017)

Afungang RN, Valdir D, Nkwemoh CA (2017) Assessing the spatial probability of landslides using GIS and informative value model in the Bamenda highlands. Arab J Geosci 10(17):384

Bourenane H, Bouhadad Y (2021) Impact of land use changes on landslides occurrence in urban area: the case of the Constantine City (NE Algeria). Geotech Geol Eng 1–21

Cao Y, Wei X, Fan W, Nan Y, Xiong W, Zhang S (2021) Landslide susceptibility assessment using the Weight of Evidence method: a case study in Xunyang area, China. PLoS One 16

Che VB, Kervyn M, Suh CE, Fontijn K, Ernst G, Marmol M, . . . Jacobs P (2012) Landslide susceptibility assessment in Limbe (SW Cameroon): a field calibrated seed cell and information value method. Catena 92(none) 83–98

Chen S (2005) Spatial risk analysis of Li-shan landslide in Taiwan. Eng Geol

Das I, Kumar G, Stein A, Bagchi A, Dadhwal VK (2011) Stochastic landslide vulnerability modeling in space and time in a part of the northern Himalayas, India. Environ Monit Assess 178(1–4):25–37

Farooq S, Akram MS (2021) Landslide susceptibility mapping using information value method in Jhelum Valley of the Himalayas. Arab J Geosci 14(10):1–16

Guo-Liang DU, Zhang YS, Javed I, Yang ZH, Yao X (2017) Landslide susceptibility mapping using an integrated model of information value method and logistic regression in the Bailongjiang watershed, Gansu Province, China. J Mt Sci (14):249–268

Guo R, Bulag UE, Crang MA, Heberer T, Hwang E-G, Millward A, . . . Tapp N (2014) Multicultural China: a statistical yearbook (2014): Springer

Hong H, Ilia I, Tsangaratos P, Chen W, Xu C (2017) A hybrid fuzzy weight of evidence method in landslide susceptibility analysis on the Wuyuan area, China. Geomorphology 290(aug.1):1–16

Hou M, Jia SH, Guo ZC (2006) Using RS,GIS and AHP technologies for landslide Hazard Assessment:taking Tiantai Landslide in Xuanhan County,Sichuan Province as an Example. Geoscience

Jiang S (2021) Study of landslide geological hazard prediction method based on probability migration. Nat Hazards 1–10

Kayastha P, Dhital MR, Smedt FD (2012) Landslide susceptibility mapping using the weight of evidence method in the Tinau watershed, Nepal. Nat Hazards 63(2):479–498

Kumar M, Krishnaveni V, Muthukumar S (2021) Geotechnical investigation and numerical analysis of slope failure: a case study of landslide vulnerability zone in Kolli Hills, Tamil Nadu. J Geol Soc India 97(5):513–519

Lee S, Sambath T (2006) Landslide susceptibility mapping in the Damrei Romel area, Cambodia using frequency ratio and logistic regression models. Environ Geol 50(6):847–855

Liu Y, Niu R, Yu X, Zhang K (2018) Application of the rotation forest model in landslide susceptibility assessment. Wuhan Daxue Xuebao (Xinxi Kexue Ban)/Geomatics and Information Science of Wuhan University 43(6):959–964

Lucchese LV, Oliveira G, Pedrollo OC (2021) Mamdani fuzzy inference systems and artificial neural networks for landslide susceptibility mapping. Nat Hazards(6) 1–25

Lucchese LV, Oliveira GD, Pedrollo OC (2020) Attribute selection using correlations and principal components for artificial neural networks employment for landslide susceptibility assessment. Environ Monit Assess 192(2), 129.121–129.122

Pourghasemi HR, Pradhan B, Gokceoglu C (2012) Application of fuzzy logic and analytical hierarchy process (AHP) to landslide susceptibility mapping at Haraz watershed, Iran. Nat Hazards 63(2):965–996

Schlogel R, Marchesini I, Alvioli M, Reichenbach P, Rossi M, Malet JP (2018) Optimizing landslide susceptibility zonation: effects of DEM spatial resolution and slope unit delineation on logistic regression models. Geomorphology 301(jan.15):10–20

Soma AS, Kubota T, Mizuno H (2019) Optimization of causative factors using logistic regression and artificial neural network models for landslide susceptibility assessment in Ujung Loe Watershed, South Sulawesi Indonesia. J Mt Sci 16(02):144–162

Sujatha ER, Rajamanickam V, Kumaravel P, Saranathan E (2013) Landslide susceptibility analysis using probabilistic likelihood ratio model—a geospatial-based study. Arab J Geosci

Tong D, Tan F, Su A, Song H, Lu Z, Yu J (2021) Deformation mechanism and stability evaluation of Tanjiawan landslide based on multi-source data. Bull Geol Sci Technol 40(4):162–170

Wu X, Ren F, Niu R, Peng L (2013) Landslide spatial prediction based on slope units and support vector machines. Wuhan Daxue

Xuebao (Xinxi Kexue Ban)/Geomatics and Information Science of Wuhan University 38(12):1499–1503

Xie M, Tetsuro E, Zhou G (2003) GIS method for slope-unit-based 3D landslide hazard evaluation. Chin J Rock Mech Eng

Yilmaz I (2009) Landslide susceptibility mapping using frequency ratio, logistic regression, artificial neural networks and their comparison: a case study from Kat landslides (Tokat—Turkey). Comput Geosci 35(6):1125–1138

Yuan T, Xiao C, Lun W (2010) Slope unit-based landslide susceptibility zonation. Paper presented at the International Conference on Geoinformatics

Zhang Z, Shi-Hai LI, Li MA (2005) Probability analysis of relationship between landslide and rainfall in Chongqing area. Chin J Rock Mech Eng 24(17):3185–3191