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Landslide Hazard Assessment in the Northern Mountainous Areas of Tianshan Mountains Based on GIS

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Abstract

China is a country prone to geological disasters, especially in the northern mountainous areas of the Tianshan Mountains in Xinjiang, where the surface vegetation is sparse and the rainfall is concentrated, which is prone to landslides and brings a lot of losses to the local people. Based on the field investigation, this paper evaluates the landslide susceptibility in the northern mountainous area of Tianshan Mountains. The frequency ratio method is used to calculate the landslide probability, and the landslide index (LSI) is formed to represent the landslide susceptibility. The slope unit method is used to determine the landslide units, which values were calculated by the average of the landslide index. According to the calculated LSI range of 4.53 - 20.60. It is divided into 4 grades, LSI = 4.53 - 9, which is an area that is not prone to landslides, with an area of 891.69 km^2. LSI = 9 - 11 indicates an area where landslides are more likely to occur, with an area of 1252.31 km^2. LSI = 11 - 13 indicates the area is more prone to landslides, with an area of 714.86 km^2. LSI > 13 indicates the most prone area for landslides, with an area of 924.60 km^2.

Keywords

Landslide Susceptibility, Tianshan, Frequency Ratio, Slope Unit

1. Introduction

China is one of the countries with fragile geological environment and frequent geological disasters in the world. In 2021, a total of 4772 geological disasters occurred in China, including 2335 landslides, 1746 collapses, 374 debris flows, 285

ground subsidences, 21 ground fissures, and 11 ground sinks. A total of 80 people were killed and 11 were missing, resulting in a direct economic loss of 3.2 billion Yuan (RMB).
(http://www.mnr.gov.cn/dt/ywbb/202201/t20220113_2717375.html, 2022.6). Geological disaster susceptibility evaluation is an important part of geological disaster investigation and evaluation, which plays an important role in geological disaster prevention and control, and can provide scientific basis for regional geological disaster prevention and urban planning and construction. At present, the quantitative evaluation methods of geological hazards mainly include logistic regression analysis method [1], weight of evidence method [2], information quantity method [3], frequency ratio method [4], deep learning method [5], etc., as well as coupling analysis of various analysis methods. Because the frequency ratio method is simpler to operate than the algorithm, it can reflect the evaluation results more objectively. Many scholars use this method to evaluate the susceptibility of regional geological disasters in practical work. In the evaluation of landslide susceptibility, it is particularly critical to select a reasonable evaluation unit. Slopes are the basic topographical unit of landslide occurrence. Compared with the traditional grid evaluation unit, the landslide susceptibility evaluation using the slope as a unit can improve the consistency with the actual topography and landforms, and can better reflect the actual development of landslides in the region. situation [6]. In the northern mountainous area of the Tianshan Mountains, there are developed valleys, large fluctuations in terrain, and frequent geological disasters. In order to find out the occurrence of geological disasters, a large number of geological disaster investigations have been carried out.

In 2002, Xinjiang Uygur Autonomous Region Geological Environment Monitoring Institute (XUARGEMI) completed the "Report on Geological Hazard Investigation and Zoning in Changji City, Xinjiang". In 2004, XUARGEMI completed the "Report on Geological Hazard Investigation and Zoning in Hutubi County, Xinjiang". In 2005, XUARGEMI completed the "Report on Geological Hazard Investigation and Zoning in Manas County, Xinjiang", and the "Report on Geological Hazard Investigation and Zoning in Shawan County-Shihezi City, Xinjiang". In 2014, XUARGEMI completed the "Detailed Investigation of Geological Hazards in Changji City, Xinjiang". In 2016, Xinjiang Geological Engineering Exploration Institute "Basic Survey of Geological Environment in Wusu City, Xinjiang".

In the early stage, a lot of geological survey work was done, and the disaster assessment work was relatively small, in order to effectively divide the landslide-prone areas in this area.

In the study, the frequency ratio index [7] [8] [9] based on slope unit zone was used to evaluate the landslide susceptibility in the northern of the Tianshan Mountains. The frequency ratio (FR) index is a well accepted and popular quantitative approach for the preparation of landslide susceptibility maps [4] [10]. Most of the work was completed using ArcGIS Desktop, including building spatial model and mapping. Python with ArcPy module and Hydrological tools intergraded in ArcGIS finished data batching process and Watershed Hydrological Analysis.

2. Materials and Method

2.1. Data and Source

The factors that cause landslides are complex, including elevation, slope, aspect, and relief, and geological factors include lithology, faults, vegetation coverage, and human activities. In this paper, we collect data related to landslides (**Table 1**).

The landslide hazard point data comes from the document data of the field survey. Terrain data from ALOS DEM. Slope, aspect, drainage system and relief maps were derived from ALOS DEM. Lithology and fault map were from Regional Geological Survey Map of 1:50,000. Road map is from Gaode digital Map (2020). Land use map is from database of China 2nd National Land and Resources Survey (2018). Fractional vegetation coverage (FVC) is calculated from Sentinel-2 data of 2020.

2.2. Data Preprocess

The following factors are formed: slope, Aspect, relief, Distance to drainage, Drainage density, lithology, Distance to fault, Vegetation coverage, Land use, Distance to road. All the data were processed in ArcGIS Desktop 10.3. Slope, Aspect, Relief are derived from DEM data, the format is 12.5 m raster data. Line buffer analysis is used to generate buffer distance maps for water systems, roads

Table 1. Spatial data of study area.

Classification	scale	Data type	Data source
landslide hazard	1:10,000	Point	Field Survey
Topological map	12.5 m	TIFF	ALOS DEM
Slope map	12.5 m	TIFF	ALOS DEM
Aspect map	12.5 m	TIFF	ALOS DEM
Terrain relief	12.5 m	TIFF	ALOS DEM
Drainage		Line	ALOS DEM
Fault map	1:50,000	Line	Geological survey map
Lithology	1:50,000	Polygon	Geological survey map
Land use map	1:10,000	Polygon	China 2nd National Land and Resources Survey(2018)
Road map	1:50,000	Line	Gaode Digital Map（2020）
FVC	10 m	GRID	Sentinel-2 NDVI(2020)

and fractures, which are then converted into 12.5 m raster maps. The Lithology layer is coded according to lithology and converted into 12.5 m raster data, and the Land use map layer is coded according to land use types and converted to 12.5 m raster data. The FVC is obtained from the annual average NDVI data set of sentinel-2 satellite in 2020, and is calculated on the GEE platform.

2.3. Correlation Analysis

In order to judge the correlation between the disaster-pregnant factors, the correlation coefficient ($Corr_{ij}$) can be used to represent the correlation between the two. The formula is as follows:

$$Corr_{ij} = \frac{Cov_{ij}}{\delta_i \delta_j} \tag{1}$$

$$Cov_{ij} = \frac{\sum_{k=1}^{N} \left(Z_{ik} - u_i\right)\left(Z_{jk} - u_j\right)}{N - 1} \tag{2}$$

where, Cov_{ij}, covariance matrix, are the covariance between all pairs of factors. Z is the value of a cell. I, j are factors, μ is the mean of factors; N is the number of cells, k denotes a particular cell. δ is standard deviation of factors i and j.

The value of C ranges from −1 to 1. C = 1 means that the two factors *are* completely correlated, and C = 0 means that the two factors have no correlation. C = −1 means that the two factors are negatively correlated.

2.4. Frequency Ratio Method

The formation of landslide is affected by a variety of factors, such as Topography, geology, soil, land cover, rivers, human activities, etc. The frequency ratio method reflects the combination of the most hazard-prone factors and their subdivisions in a certain geological environment; specifically, the frequency and region of landslide under the action of a certain factor in a specific evaluation unit. The frequency of landslide can be compared. Corresponding to a certain factor, the information quantity formula of geological disasters under a specific state can be expressed as:

$$\text{FRi} = \frac{N_i / N}{S_i / S} \tag{3}$$

where, FRi is the frequency ratio index of landslide corresponding to a specific factor in i internal N_i is the number of landslides corresponding to specific factor in i internal, N is the total number of landslide in the study area, S_i is the area corresponding to a specific factor in i internal, S is the total area of the study area.

Since each evaluation unit is affected by many factors, and each factor has several states (internal), the total frequency of landslide under the combined conditions of each state factor can be determined by the following formula:

$$\text{LSI} = \sum \text{FRi} = \sum_i^n \frac{N_i / N}{S_i / S} \tag{4}$$

LSI is the total frequency ratio index of landslide under various factors in a specific unit, indicating the possibility of collapse, which can be used as a landslide susceptibility index.

According to the calculated LSI value interval and the actual situation of the landslide, the landslide susceptibility of the study area is divided into four grades: extremely high, high, medium and low.

2.5. Slope Unit Division

The slope unit is the basic unit of landslide occurring, so the division of the unit is particularly important in the evaluation of landslide susceptibility. We use the basin hydrology method to divide the unit, and the minimum unit area is 1 km^2.

2.6. Landslide Susceptibility Evaluation Process

1) First, each landslide-pregnant factor was standardized, and generated raster data with a unit size of 12.5 meter Factor correlation was analyzed, in order to remove the factors with strong correlation, and ensure the independence of each factor. 2) The landslide frequency of each factor was calculated. 3) The slope units were divided to generate vector slope units by DEM. 4) The LSI of each slope unit was obtained by zonal statistics. 5) According to the natural the breakpoint method divides LSI into 4 levels, indicating the difficulty of landslide occurrence.

3. Description of Study Area

The study area is located in the northern part of the Tianshan Mountains, including Changji City, Hutubi County, Manas County, and Wusu City. The geographic coordinates are between 84˚18' - 87˚18' longitude and 43˚18' - 44˚12' latitude (**Figure 1**), and the study area covers 3660.9 km^2.

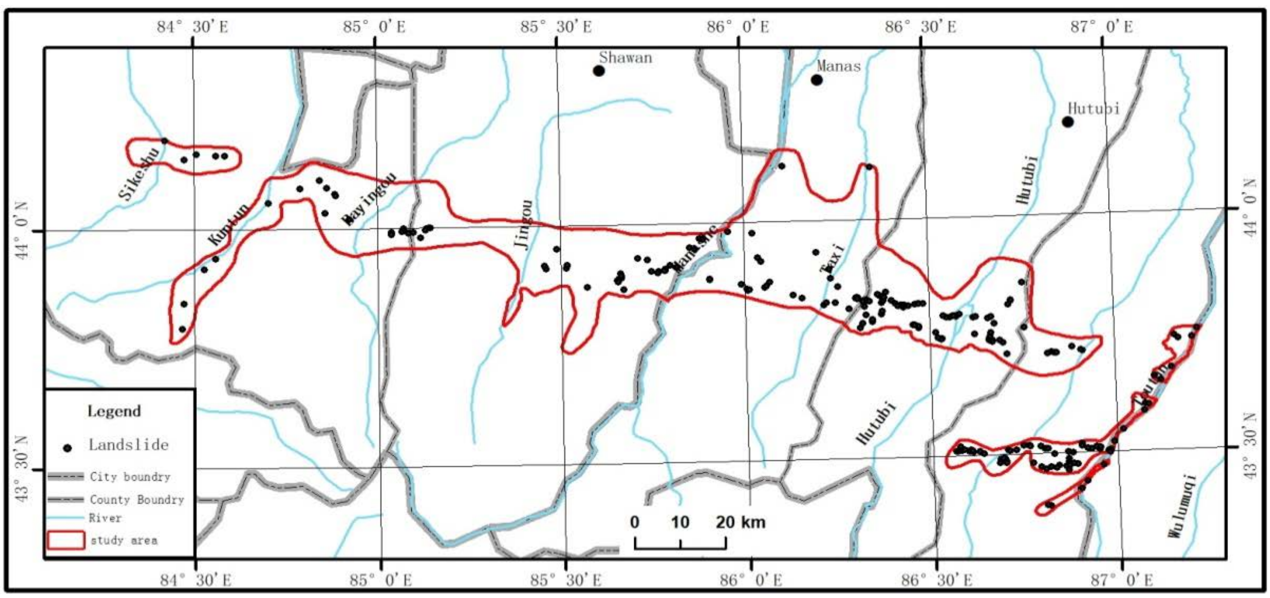

Figure 1. Location of study area.

The study area is located in northern mountains of Xinjiang and the southern margin of the Junggar Basin. TThe altitude of high mountains is 4000 - 5000 m, and the highest peak, Heyuan Peak, is 5289 m. It is a typical continental arid and semi-arid climate, with an average annual temperature of 6.8˚C. The average temperature in July is 24˚C - 28˚C, and the average temperature in January is −10˚C - 20˚C. The average annual precipitation is 167.2 - 220 mm, and the average annual evaporation is about 400 - 1088.2 mm.

The types of geological disasters developed in the northern mountainous areas of the Tianshan Mountains in Xinjiang mainly include collapse, landslide, debris flow, and ground subsidence. Collapses, landslides and debris flows are distributed in the study area, and there are 255 landslide points, which mainly threatens the surrounding township residents, livestock, township roads, provincial highway 101, water conservancy facilities, etc. (**Figure 1**).

4. Result Analysis

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4.1. Correlation Coefficient

In ArcGIS, the landslide-pregnant factor layers are grouped into stacks, and then the correlation coefficient matrix between layers is obtained. The data shows that the correlation between slope and terrain relief is very high, and the correlation coefficient (c) is 0.8858. Therefore, one of the two should be eliminated, and we will eliminate the relief factor. The correlation between the remaining factors is very low, and the largest correlation coefficient (c) is the distance between the road and the drainage, c = 0.02438.

Through correlation analysis, the landslide-pregnant factors are determined as 9 factors including slope, aspect, fault distance, engineering rock formation, drainage distance, drainage density, fractional vegetation coverage, land use type, and road distance.

4.2. Slope Unit

The slope units in this study area were divided by the watershed division method, ALOS DEM data with an accuracy of 12.5 m was used, and the minimum watershed unit was set to 1 km^2. Finally, 7743 slope units were obtained (**Figure 2**).

4.3. Calculating the Landslide Frequency Ratio

After all the factors were converted into raster data, they are reclassified according to the data characteristics, and the landslide frequency ratio of each type is calculated (**Table 2**). Landslides mainly occurred at slopes between 8˚ - 15˚ and

Table 2. Landslide frequency ratio.

Factors	Class	No of pixels in internal	% of in internal	No of landslide	% of landslide	Frequency ratio
slope	0˚ - 7˚	1,073,694	0.26	30	0.12	0.46
	8˚ - 15˚	1,198,318	0.29	82	0.32	1.13
	16˚ - 25˚	1,003,784	0.24	92	0.36	1.51
	26˚ - 35˚	584,827	0.14	39	0.15	1.10
	>35˚	342,995	0.08	12	0.05	0.58
aspect	flat	32,864	0.01	2	0.01	1.00
	N	642,061	0.15	58	0.23	1.49
	NE	692,749	0.16	62	0.24	1.48
	E	622,765	0.15	27	0.11	0.71
	SE	420,820	0.10	22	0.09	0.86
	S	291,271	0.07	12	0.05	0.68
	SW	343,124	0.08	11	0.04	0.53
	W	496,224	0.12	26	0.10	0.86
	NW	661,740	0.16	35	0.14	0.87
Rock formation	γ	6634	0.00	0	0.00	0.00
	P	148,296	0.04	9	0.04	1.00
	D	125,565	0.03	3	0.01	0.39
	C	525,210	0.13	14	0.05	0.44
	T	37,799	0.01	5	0.02	2.18
	J	1,437,547	0.34	190	0.75	2.18
	K	337,329	0.08	9	0.04	0.44
	E-N	407,086	0.10	10	0.04	0.40
	Q_3pl-Q1	944,902	0.22	3	0.01	0.05
	Q4	229,284	0.05	12	0.05	0.86
Distance to fault	0 - 1500 m	1,706,709	0.41	82	0.32	0.79
	1500 - 3000 m	969,180	0.23	68	0.27	1.16
	3000 - 4500 m	576,475	0.14	49	0.19	1.40
	4500 - 6000 m	314,189	0.07	34	0.13	1.78
	>6000 m	637,065	0.15	22	0.09	0.57
Distance to drainage	0 - 400 m	1,348,084	0.32	165	0.65	2.02
	400 - 800 m	1,057,756	0.25	32	0.13	0.50

Continued

	800 - 1200 m	770,123	0.18	15	0.06	0.32
	1200 - 1600 m	493,016	0.12	16	0.06	0.53
	1600 - 2000 m	298,034	0.07	13	0.05	0.72
	2000 - 2400 m	152,044	0.04	9	0.04	0.98
	>2400 m	84,561	0.02	5	0.02	0.97
Drainage density	<0.9/km	340,397	0.08	25	0.10	1.21
	0.9 - 1.1/km	1,467,887	0.35	143	0.56	1.61
	1.1 - 1.3/km	1,622,329	0.39	73	0.29	0.74
	1.3 - 1.5 km	536,025	0.13	13	0.05	0.40
	>1.5/km	236,980	0.06	1	0.00	0.07
FVC	0% - 10%	52,120	0.01	4	0.02	1.27
	10% - 20%	204,596	0.05	19	0.07	1.53
	20% - 50%	1,342,311	0.32	72	0.28	0.88
	50% - 75%	1,256,670	0.30	66	0.26	0.87
	75% - 100%	1,347,921	0.32	94	0.37	1.15
landuse	farmland	76,033	0.02	1	0.00	0.22
	forest	465,573	0.11	25	0.10	0.89
	grass	715,873	0.17	86	0.34	2.00
	water	50,268	0.01	0	-	0.00
	reservoir	9289	0.00	0	-	0.00
	tidal flat	30,105	0.01	6	0.02	3.32
	snow	8361	0.00		-	0.00
	buildup	24,506	0.01	5	0.02	3.40
	bare soil	1,402,117	0.33	29	0.12	0.34
	gravel	138,967	0.03	8	0.03	0.96
	rock	1,278,564	0.30	91	0.36	1.19
Distance to road	0 - 500 m	1,244,405	0.30	178	0.70	2.36
	500 - 1000 m	993,757	0.24	27	0.11	0.45
	1000 - 1500 m	750,699	0.18	21	0.08	0.46
	1500 - 2000 m	511,902	0.12	14	0.05	0.45
	2000 - 2500 m	322,203	0.08	9	0.04	0.46
	>2500 m	380,652	0.09	6	0.02	0.26

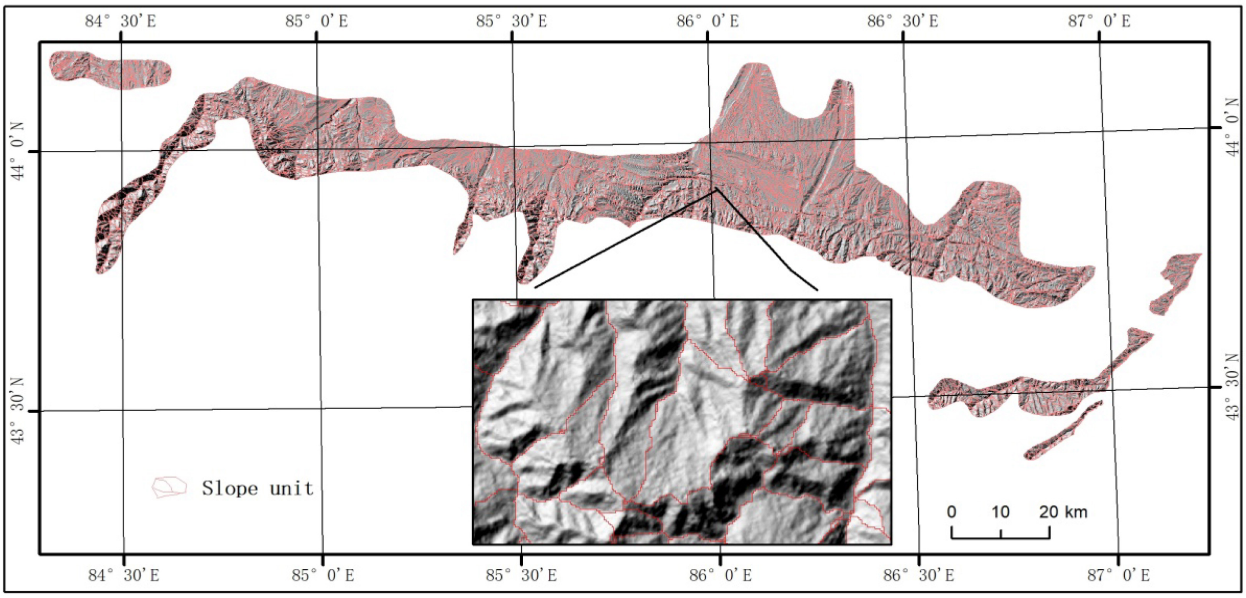

Figure 2. Slope units map.

15˚ - 25˚, accounting for 68.23% of the total number of landslides, with Fri of 1.13 and 1.51, respectively. For the aspect factor, landslides mainly occurred on the north and northeast slopes, with Fri of 1.49 and 1.48, respectively. In the Jurassic thick-layered hard conglomerate, sandstone, conglomerate and coal layers, landslides are more likely to occur, accounting for 74.51% of the total landslides, and the Fri reaches 2.18. Within the range of 3000 - 4500 meters and 4500 - 6000 meters from the fault. It is more prone to landslides, accounting for 32.55% of the total landslides, and the Fri is 1.4 and 1.78, respectively. Landslides were mainly developed within 400 m from the river, accounting for 64.71% of the total landslides, and the Fri was 2.02. Landslides are more likely to occur when the water system density is in the range of 0.9 - 1.1, accounting for 56.08% of the total landslides, and the Fri is 1.61. As the drainage density increases, the probability of landslides decreases gradually. The fractional vegetation coverage affects the development of landslides. The fractional vegetation coverage is between 10% - 20%, and the more prone to landslides, the Fri is 1.53. Among the land use types, grasslands, tidal flats and buildup land are more prone to landslides, with Fri of 2.0, 3.32, and 3.40, respectively. Within 500 m from the road, there is a high incidence of landslides, accounting for 69.80% of the total landslides, and Fri is 2.36.

The LSI range is 4.53 - 20.60 calculated by Fri. The LSI is divided into 4 grades according to the natural breakpoint method (**Figure 3**). LSI = 4.3 - 9 is the lowest grade, which represents an area that is not prone to landslides, with an area of 891.69 km^2 and 5 landslides in history. LSI = 9 - 11 indicates an area that is prone to landslides, with an area of 1252.31 km^2 and 30 landslides in history. LSI = 11 - 13 indicates an area more prone to landslides, with an area of 714.86 km^2 and 45 landslides in history. LSI > 13 indicates the most prone area for landslides. The area is 924.60 km^2, and 175 landslides have occurred in history.

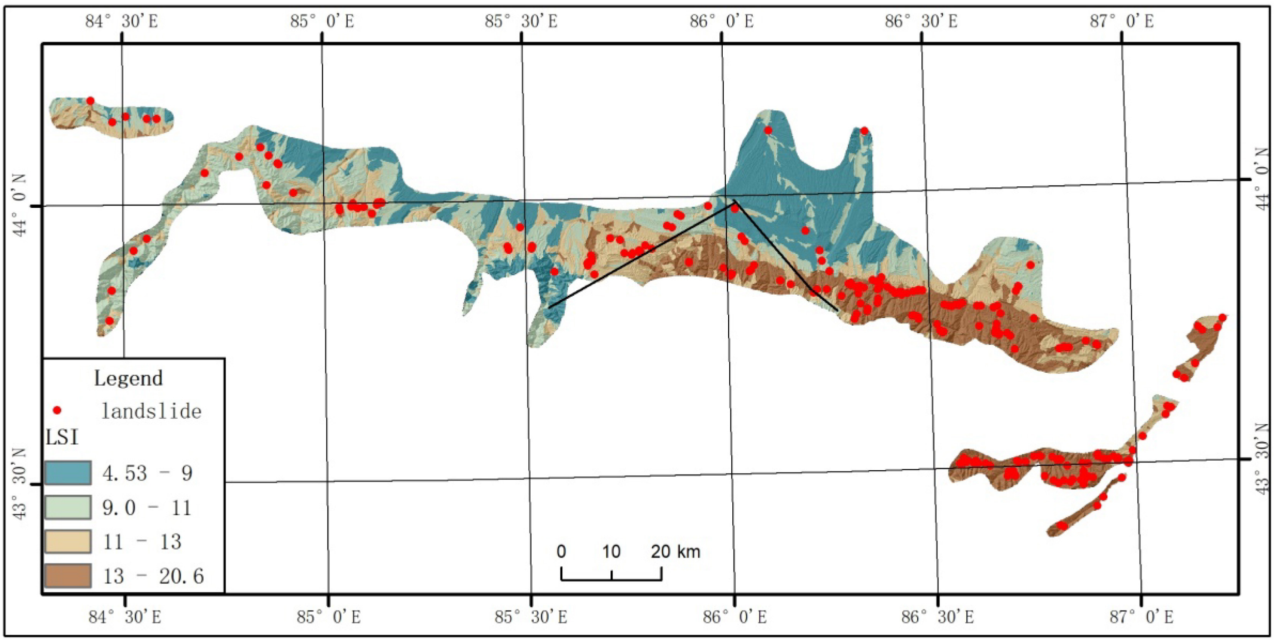

Figure 3. Landslide susceptibility map.

5. Conclusion

Through correlation analysis, 9 evaluation factors including slope, slope aspect, lithology, distance to fault, distance to river, drainage density, distance to road, fractional vegetation coverage and land use type were selected, and landslide susceptibility was calculated by frequency ratio method and landslide index. Landslide susceptibility evaluation method is simple in calculation and reliable in results, which is a method suitable for widespread adoption. A possible next step to consider is that the weight of each factor's impact on landslides is not equally important and may require further study.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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