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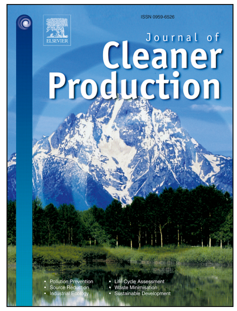

Risk assessment and its influencing factors analysis of geological hazards in typical mountain environment

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Credit author statement

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Risk assessment and its influencing factors analysis of geological hazards in typical mountain environment

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Risk assessment and its influencing factors analysis of geological hazards in typical mountain environment

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ABSTRACT: Fujian Province is a typical mountainous environment, where regional geological disasters occur frequently, posing serious threats to the safety of local residents' lives and property and regional ecological security. Accurately revealing the risk of geological disasters in Fujian Province have important guiding significance for the local government to develop targeted prevention strategies. This study selects 8 indicators including elevation, slope, normalized difference vegetation index (NDVI), lithology, land use type, average annual precipitation, distance from rivers and distance from faults to construct an evaluation index system, and reveal the spatial pattern and influencing factors of the risk of geological disasters in Fujian Province based on the information quantity model and geodetector method. The results showed that the geological hazard risk of mountainous areas in Fujian Province have an overall trend of high in the southeast and low in the northwest, and a characteristic of significant spatial agglomeration. The proportion of different levels of geological hazard risk is showed as that medium risk > medium-high risk > medium-low risk > high risk > low risk, among which, the combined area with medium and medium-high risk accounts for 76.06%. The occurrence of geological hazards in

Fujian Province is the result of the combined effects of the natural environment and human activities, and the night light intensity, elevation, slope, and distance from rivers are the main influencing factors causing geological hazards. In addition, The combination of dominant factors conducive to inducing geological hazards are found, which can provide scientific basis for the formulation of regional geological disaster prevention strategies.

Keywords: Geological hazards; Risk assessment; Information quantity model; Geodetector; Mountain environment; Fujian Province

1. Introduction

Mountainous geological hazards are one of the most common natural disasters, causing huge human casualties and economic losses each year. Their formation is closely related to the regional topography, landforms, lithology, vegetation, geological conditions and meteorological conditions (Bekteshi et al., 2017; He et al., 2017; Yilmaz et al., 2012). The risk assessment of geological hazards is to study the occurrence and distribution of regional geological disasters under the conditions of regional geological structural unit characteristics and topography (Deng et al., 2014; He et al., 2017). Since the 21st century, as the key step to predicting geological hazards, formulating policies for disaster prevention and mitigation (Alexakis et al., 2014; Cigna et al., 2018), and effectively reducing disaster losses, the risk assessment of geological hazards has become an intensive research topic for scholars and an important part of international disaster prevention and reduction strategies (Lee, 2004; Pan, 2016; Pavlova et al., 2017; Su et al., 2017), playing an extremely important role in disaster management. Fujian Province is one of the provinces with rapid economic development in China. It has a typical mountainous environment with mountainous and hilly areas accounting for more than 80% of the total areas. Under the

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special geological and ecological environment of manifold rainstorms, high mountains and multiple faults, created good conditions for geological disasters in the region, and various geological hazards such as landslide, debris flow, collapse, and the like frequently hit the areas, which has become an important limiting factor for sustainable socio-economic development in the region (Lu et al., 2010), there is an urgent need to accurately reveal the spatial and temporal patterns of geological disasters in Fujian Province. However, few studies have been conducted on the risk assessment of mountainous geological hazards in Fujian Province and on the systematic analysis of their influencing factors. Therefore, it is of great theoretical value and practical significance carrying out both the risk assessment and influencing factors analysis of mountainous geological hazards in Fujian Province.

At present, with the rapid development of geographic information system (GIS) technology, many studies have been carried out on the risk assessment of geological hazards, and fruitful results have been achieved (Lee, 2004; Niu et al., 2012; Su et al., 2017). From the perspective of research content, the current geological hazard risk assessment mainly focuses on the analysis of the spatial pattern characteristics of the geological hazard risk, while the analysis of the best combination of key factors and main influencing factors formed by the geological hazard is relatively insufficient. From the perspective of research methods, the risk assessment methods for geological hazards have been gradually transformed from qualitative analysis to quantitative measurement (Su et al., 2017; Weinmeister, 2007). The most common ones include analytic hierarchy process (AHP) assessment system (Jena et al., 2020; Mandal and Mandal, 2018; Kayastha et al., 2013), expert scoring method (Wang et al., 2016), fuzzy comprehensive evaluation method (Chalkias et al., 2014; Wang et al., 2012), artificial neural network method (Conforti et al.,

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2014; Dieu et al., 2012; Sdao et al., 2013), principal component analysis method (Yu et al., 2015), and information quantity model (Chen et al., 2013; Deng et al., 2014; Du et al., 2016). Among these quantitative assessment methods, the former three are characteristics of simple operation and easy to implement. However, their index weight assignment during index system construction is greatly impacted by human subjectivity (Liao et al., 2011). The artificial neural network method is highly accurate in prediction, but the process of modeling and evaluation is more complicated, a large number of accurate basic data are needed for modeling, and it is difficult to obtain large-scale and accurate data in reality, which making it difficult to promotion in large-scale(Tan et al., 2015). The principal component analysis method can aggregate many impact factors into a comprehensive indicator so as to reduce the co-linearity among evaluation indicators, but its evaluation process ignores the spatial attributes of the indicators. All of the above evaluation methods have certain limitations and cannot accurately reveal the spatial pattern of geological hazards and their influencing factors in this special mountain environment of Fujian Province. However, the information quantity model can find the best combination of key factors with greater contributions for geological hazards (Du et al., 2016), so as to achieve an effective risk evaluation for mountainous geological hazards (Deng et al., 2014).

In view of this, this study takes the typical mountain environment of Fujian Province as the research object, based on the information quantity model and the geodetector method, to accurately reveal the spatial pattern and its influencing factors of geological hazards in Fujian Province. Firstly, we established an evaluation index system using the information quantity model based on 8 carefully-selected geological hazards-related factors, including the elevation, slope, NDVI, lithology, land use type, average annual precipitation, distance from rivers, and distance

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from faults. Then, we comprehensively evaluated the geological hazards risk in Fujian Province from the aspects of overall characteristics, spatial distribution and main influencing factors of the geological hazards. At last, we verified the accuracy of the final evaluation results utilizing the receiver operating characteristic (ROC) curve, trying to accurately reveal the overall characteristics of the mountainous geological hazards in Fujian Province and provide the scientific basis for the local governments to formulate effective disasters prevention strategies and ensure regional ecological security.

2. Materials and methods

2.1. Study area

Fujian Province with a total area of about 121,400 km^2 is located on the southeast coast of China, bordering Zhejiang Province in the north, Jiangxi province in the west, Guangdong Province in the south, and Taiwan Province cross the sea (Fig. 1). It is a typical mountainous environment where surrounded by mountains with the terrain being high in the northwest and low in the southeast. The region has a typical subtropical monsoon climate, being hot and rainy in the summer and mild and lack of rain in the winter, accompanied by short-term heavy rainfall. Due to its undulating terrain, large slopes, and widespread geological faults, the mountainous environment is relatively fragile, resulting in frequent occurrence of large scale, highly harmful geological hazards during the summer rainy season (Alexakis et al., 2014). So far, there are 6,672 sites with historical geological hazards documented in the relevant government websites. These sites are widely distributed and characterized as contiguous clusters in the area. The core density analysis of the geological hazards reveals that Dehua County, Yongchun County, Anxi County, Jianning County and Fuan City are the core areas of geological hazards (Fig. 2) , posing a serious threat to the safety of local people's lives and property and to the regional ecological security.

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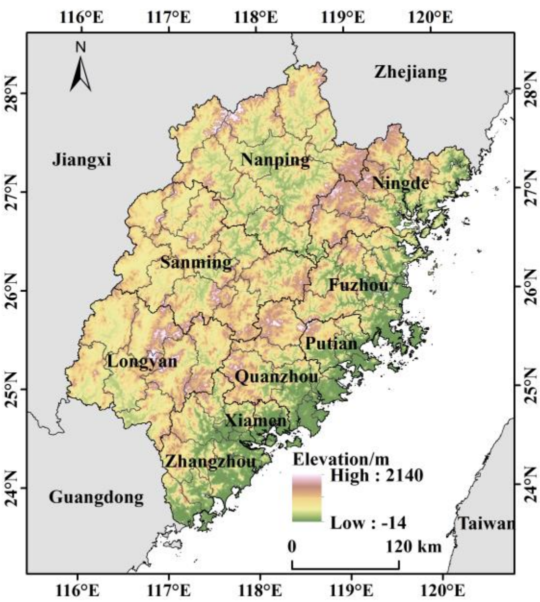

Fig. 1. Geographical location of the study area.

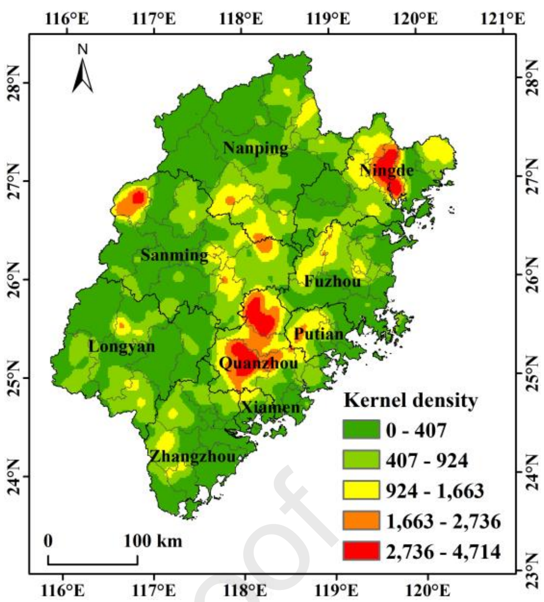

Fig. 2. Geological hazard points and its Kernel density.

2.2. Data acquisition and preprocessing

Table 1 shows the data type and source. These data are used to generate multi-source spatial data that can be used for spatial superposition and model operations after unified in the projected WGS1984 coordinate system and formatted as unified 30m resolution raster data.

Table 1 Data sources.

Data type	Method for data acquisition	Data format	Data source
Geological hazard points	Spatialization of geological hazard points	Vector point data	Related government statistical reports
Elevation	Extracted using DEM	Raster data	Geospatial data cloud
Slope	Calculated using DEM	Raster data	Digital elevation model
NDVI	(NIR-RED)/(NIR+RED)	Raster data	Data Center of Resources and Environmental Sciences, Chinese Academy of Sciences
Lithology	Vectorization from geological maps	Vector data	Geological map of Fujian Province
Land use type	Interpreted by Landsat image remote sensing	Raster data	Data Center of Resources and Environmental Sciences, Chinese Academy of Sciences
Night light intensity	Pixel value of night light image	Raster data	NPP-VIIRS night light data
Average annual Precipitation	Kriging interpolation from multiyear mean precipitation	Raster data	Fujian Meteorological Bureau
Distance from river	First extracting water system using DEM and then calculating Euclidean distance	Raster data	Digital elevation model
Distance from fault	Calculating Euclidean distance from vectorized fault data	Raster data	Fault map of Fujian Province

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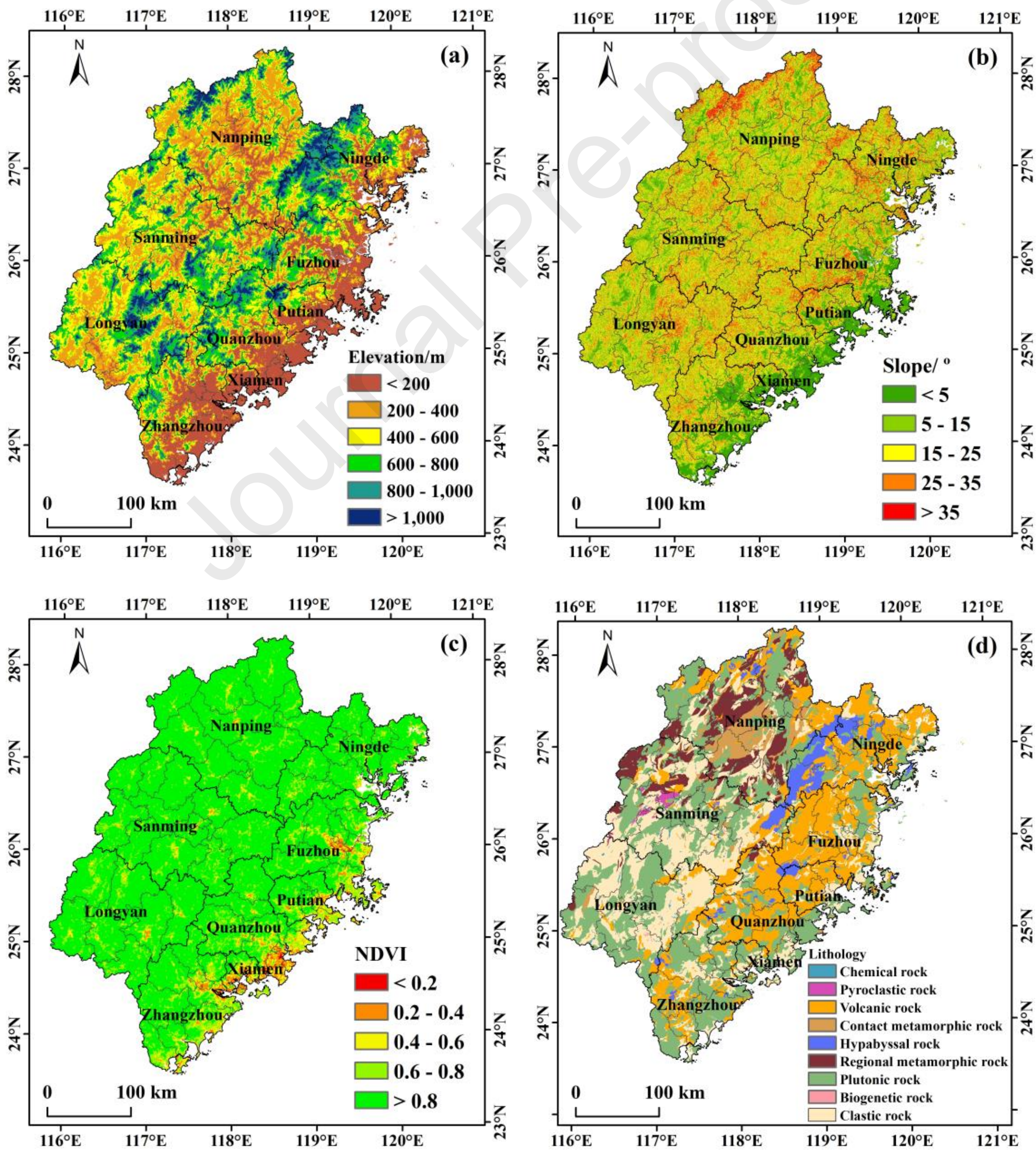
2.3. Risk assessment model construction

2.3.1. Selection of evaluation indexes

The scientific selection of evaluation index system is the key to the risk assessment of regional geological disasters. Aiming at the special topographic and geomorphological characteristics of the study area, this study select relevant evaluation indicators based on the cause-effect model, and from the perspective of the influencing factors of geological disasters, taking into account the availability, operability and scientific nature of the data, eight factors including elevation, slope, NDVI, lithology, land use type, average annual precipitation, distance from rivers, and distance from faults were selected as geological hazard risk evaluation indexes in Fujian Province, to reflect the regional topographic geomorphologic characteristics, vegetation, geologic conditions, land use, river system, and weather conditions. Fig. 3 shows the spatial distribution characteristics of each index.

Among these 8 indexes, elevation and slope are selected to characterize the effects of topographic and geomorphologic characteristics, which affect the occurrence of geological hazards by impacting the stability of regional rocks and soils (Grant et al., 2016; Pan, 2016; Wu and Hu, 2019). NDVI are used to characterize the different vegetation conditions, which have significantly different effects on water and soil conservation, water source conservation, and ecosystem stability on regional geological hazards (Arabameri et al., 2019; Mind'je et al., 2019). Geological lithology and distance from faults are used to reflect the effects of the degree of rock fragility and geological conditions in the area, respectively, both of which could further affect the occurrence and development of geological hazards (Hadji et al., 2013; Wu and Hu, 2019). Land use type is used to reflect the degree of interference of human activities in the region on the natural environment (Raghuvanshi et al., 2014). In particular, construction lands will cause huge damage to regional rock and soil stability, which will lead to geological hazards. The distance from rivers is used to characterize the status of river system, which can scour and erode rocks and soils in the area through the confluence process of surface runoff, thereby affecting the stability of geological conditions and further impacting the occurrence and development of geological hazards in the region. Average annual precipitation is used to characterize the meteorological conditions. Intensity of rainfall in the region is an important factor inducing the formation and development of regional geological disasters (Liu et al., 2018).



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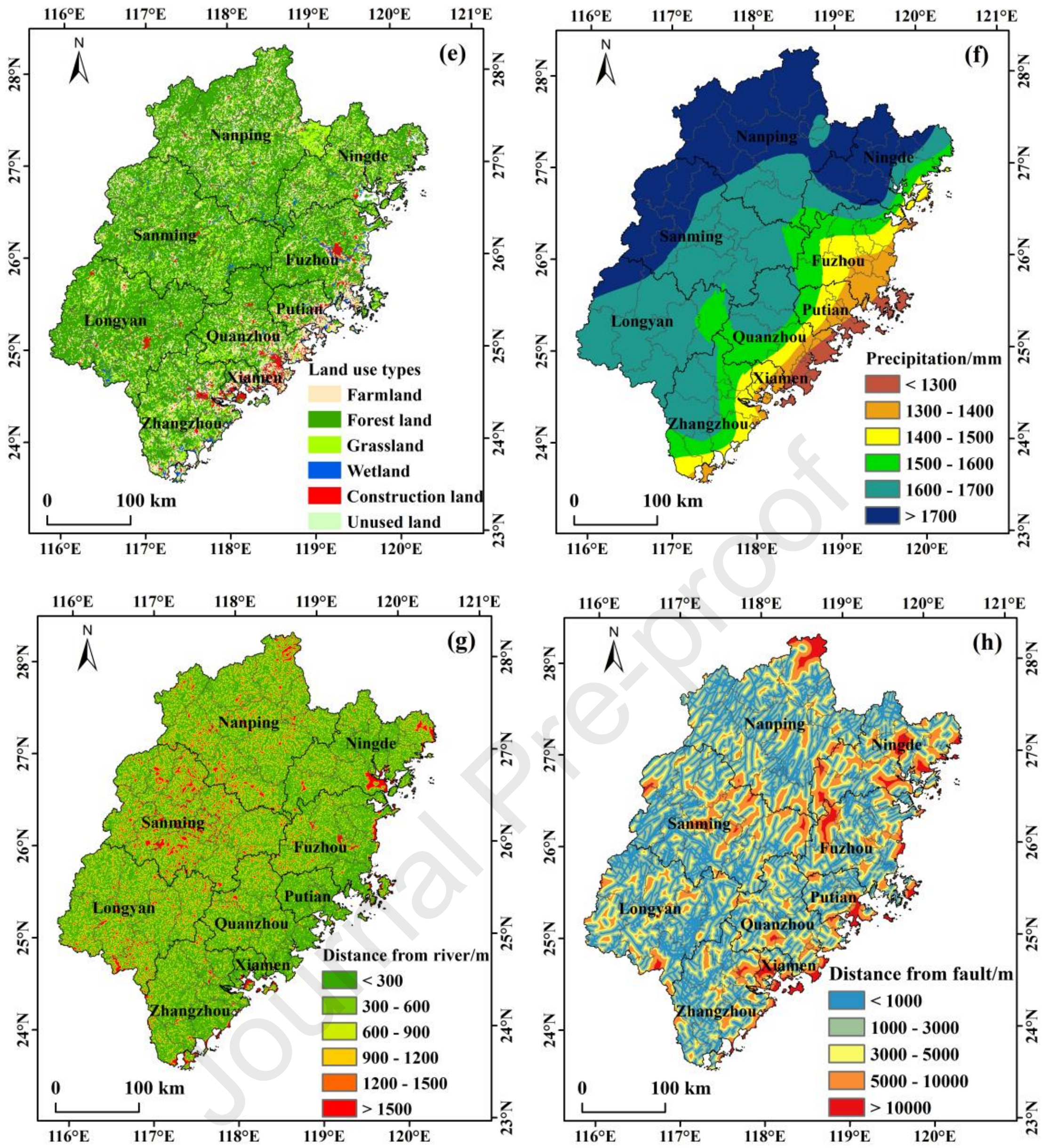

Fig. 3. Spatial distribution of geological hazard risk assessment indexes.(a. Elevation, b. Slope, c. NDVI, d. Lithology, e. Land use, f. Average annual precipitation, g. Distance from river, h. Distance from fault.)

2.3.2 Indexes weight assignment

This research is based on the cause-effect model, starting from the influencing factors of the occurrence of geological disasters, constructs an evaluation index system for the risk of geological disasters in Fujian Province. In terms of the assignment of index weights, the information quantity model is selected to calculate the weight of each index, which convert the measured values of multiple impact factors into information values. Then the information of each influencing factor is

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weighted and superimposed to obtain the comprehensive information of each grid unit, which is used to characterize the risk of geological disasters.

The information quantity model is constructed based on the information theory by using the reduction of entropy during the occurrence of geological hazards to characterize the possibility of geological hazardous events. It has advantages of able to comprehensively study the "best combination of factors" contributing the most to geological hazards, rather than a single factor (Chen et al., 2013). The greater the quantity of information about its factors is, the greater the possibility of geological hazards occurring (Niu et al., 2011). The formula for calculating the information quantity (Deng et al., 2014) is showed in Eq. (1).

$$I(Y, X_1, X_2, ..., X_n) = \frac{\ln P(Y, X_1, X_2, ..., X_n)}{P(Y)} \quad (1)$$

where n is the number of selected evaluation factors, $I(Y, X_1, X_2, X_3, \cdots, X_n)$ is the combination of information quantity of specific factors $X_1, X_2, X_3, ..., X_n$ affecting the occurrence of geological hazards, and $P(Y)$ is the probability of geological hazards occurrence. The information quantity $I(Y, X_1, X_2, X_3, ..., X_n)$ could be either positive or negative. The larger the value of the information quantity is, the higher the risk of geological hazards. When the value of $I(Y, X_1, X_2, X_3, ..., X_n)$ is greater than 0, it means that the risk of geological hazards in the unit is greater than the average value of the overall regional risk. By contrast, when the value of $I(Y, X_1, X_2, X_3, ... X_n)$ is less than 0, it means that the risk of geological hazards in the unit is less than the average value of the overall regional risk.

2.4. Geographic detector method

Geodetector method is a new type of statistical analysis method, it mainly includes 4 aspects of Geodetector analysis, including factor detection, interaction detection, risk detection and ecological detection (Wang and Xu, 2017). The method can effectively identify the spatial differentiation characteristics of a certain natural geographic element, reveal the influence degree of the factor and the related natural and human factors in the region, and further determine its internal driving force. As it can effectively overcome the limitations of various assumptions and constraints of traditional statistical analysis methods (Bai et al., 2019).

In recent years, the analysis of the driving force of geographic elements using geodetector method has been widely used in the academic field, such as ecological service value, NDVI, economic development and ecological vulnerability in the region (Peng et al., 2019; Qiao et al., 2019). Among them, the application of factor detection module is the most common to reveal the main influencing factors of a certain geographic phenomenon. We used a factor detection module to explored the influencing factors of geological hazards in Fujian Province, which mainly uses the value of q for measurement. The larger the value of q, the greater the impact of the impact factor on the geographic feature, and vice versa (Zhou et al., 2018). The formula for calculating the value of q is showed in Eq. (2).

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$$q = 1 - \frac{1}{N\sigma^2}\sum_{n=1}^{L} N_h \sigma_h^2 \tag{2}$$

where $h = 1, 2, \ldots, L$ is the stratification (classification or partition) of the variable Y or factor X; N_h and N are the number of units in the layer h and the whole region, σ_h^2 and σ^2 are the variance of the layer h and Y value in the whole region.

3. Results

3.1. Overall characteristics of risks for geological hazards

The index data of eight influencing factors were evaluated using the information quantity model. The generated information quantity index and its ranking are obtained (Table 2). The first amount of information for each index is the elevation of 200-400 m, slope of 5-15°, NDVI of 0.6-0.8, biogenetic rocks, construction lands, average annual precipitation of 1500-1600 mm, distance from rivers being < 300 m, and distance from faults being 5000-10000 m, which is the combination of the dominant influencing factors that can easily induce mountainous geological hazards in Fujian Province.

Table 2 Index system of geological disaster risk assessment.

Index	Segmentation standard	Information quantity	Order of information quantity	Index	Segmentation standard	Information quantity	Order of information quantity
Elevation (m)	<200	0.088	18	Land use	Arable land	0.453	3
	200–400	0.184	12		Woodland	-0.244	32
	400–600	-0.016	22		Grassland	0.18	13
	600–800	0.03	19		Wetland	-0.095	26
	800–1000	-0.313	34		Construction land	0.469	2
	>1000	-1.45	47		Unused land	-0.43	38
Slope (°)	<5	-0.145	29	Average annual precipitation	<1300	-0.547	41
	5–15	0.317	6		1300–1400	-0.802	44
	15–25	0.12	16		1400–1500	-0.278	33
	25–35	-0.457	39		1500–1600	0.202	9
	>35	-1.371	46		1600–1700	0.163	14
NDVI	<0.2	-2.547	48		>1700	-0.151	30
	0.2–0.4	-0.557	42	Distance from river	<300	0.355	5
	0.4–0.6	-0.023	23		300–600	-0.157	31
	0.6–0.8	0.4	4		600–900	-0.417	36
	>0.8	-0.068	25		900–1200	-0.419	37
Lithology	Chemical rock	0.234	8		1200–1500	-0.722	43
	Pyroclastic rock	-1.313	45		>1500	-0.521	40
	Volcanic rock	0.299	7	Distance from fault	<1000	-0.047	24
	Contact metamorphic rock	0.113	17		1000–3000	-0.007	20
	Hypabyssal rock	0.196	10		3000–5000	-0.009	21
	Regional metamorphic rock	0.189	11		5000–10000	0.144	15
	Plutonic rock	-0.131	27		>10000	-0.132	28
	Biogenetic rock	1.543	1				
	Clastic rock	-0.382	35				

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Based on the information quantity model, the comprehensive information quantity is calculated to obtain the assessment results of risks for geological hazards in Fujian Province. The results are divided into five grades using the natural break method, namely low risk, medium-low risk, medium risk, medium-high risk, and high risk. The higher the grade is, the greater the risk. Table 3 shows the overall characteristics of risks for geological hazards at different grade levels.

Table 3 Overall characteristics of risks for geological hazards at different grade levels.

Grade of risks for geological hazards	Information classification standard	Grade area (km^2)	Proportion of grade area (%)	Number of disaster point within the classification grade	Proportion of disaster location (%)
Low risk	-5.92– -1.85	5934.93	4.96	41	0.61
Medium low risk	-1.85– -0.91	20038.33	16.74	338	5.07
Medium risk	-0.91– -0.17	38156.93	31.87	1286	19.27
Medium high risk	-0.17–0.53	35371.79	29.54	2354	35.28
High risk	0.53–3.39	20220.97	16.89	2653	39.76

The order of the areas of geological hazards at different grade levels in Fujian Province is medium risk hazards> medium-high risk hazards> medium-low risk hazards> high risk hazards> low risk hazards, and their corresponding area proportions are 42.69%, 33.37%, 14.39%, 5.49% and 4.05%, respectively. It is not difficult to find out that the geological hazard risks in Fujian Province are mainly concentrated in three grade levels: medium risk, medium-high risk and medium-low risk, and their area accounts for more than 90% of the total. Especially, the area of the medium risk and medium-high risk geological hazards accounts for 76.06% of the total. By comparison, the distribution of high and low risk geological hazards is scattered, indicating that the risk of geological hazards in the study area is generally high. From the distribution of the number of geological hazard points under different grade levels, it can be known that the geological hazard points are mainly distributed in two grades: high risk as well as medium-high risk, and the proportion of geological hazard points at these two grades exceeds 70%, especially

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those at high risk level. Although the proportion of high-risk areas accounts for only 16.89%, the proportion of high-risk geological hazards in the area is 39.76%. It can be seen that geological hazards are highly concentrated in the high-risk areas, which also reflects that the geological hazard risk assessment in Fujian Province based on information quantity model from are scientific and reasonable, and can better reflect the distribution of geological hazard risks in the region.

3.2. Spatial distribution characteristics of risks for geological hazards

Fig. 4 shows the spatial distribution characteristics of risks for geological hazards in Fujian Province. Spatially, the risk of geological hazards is high/medium-high for the southeast coastal area and medium-low/low for the northwest inland area. In addition, the distribution of risks for geological hazards in Fujian Province shows an obvious “strip-like” characteristic. For example, the high-risk areas in the southeast coastal area show a strip-shaped distribution and is basically parallel to the coastal zone; and the low risk areas are mainly distributed in the northwestern inland area and is basically consistent with the high-risk strips. Moreover, the evaluation results of geological hazard risks at the county level, as shown in Fig. 5, clearly indicate that the risks for geological hazards in Fujian Province have obvious spatial clustering characteristics. In other words, the contiguous effect of risks of geological hazards is obvious. The high-risk areas are mainly distributed in the county units of Zhangzhou, Quanzhou, Fuzhou, and Ningde on the southeast coast, while the low risk areas are mainly concentrated in county units of Nanping, Longyan and Sanming in the northwest as well as Xiamen on the southeast Coast.

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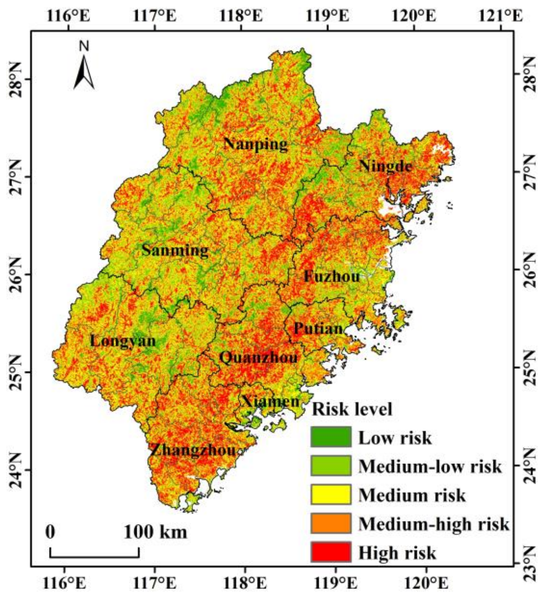

Fig. 4. Geological hazards risk on grid scale.

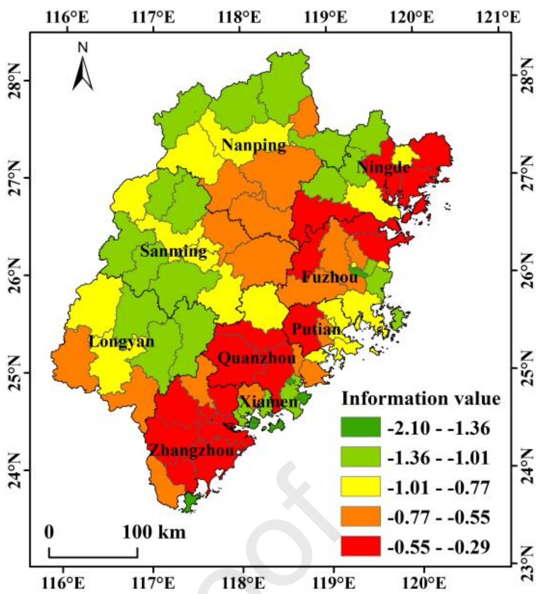

Fig. 5. Geological hazards risk on county scale.

3.3. Analysis of factors influencing the occurrence of geological hazards

From the two aspects of natural environment and human activities, this study take the risk value of geological hazards as a dependent variable and factors of lithology, elevation, land use, NDVI, slope, distance from faults, average annual precipitation night light intensity and distance from rivers as independent variables, we analyzed the impacting degree of these geographical factors on the occurrence of geological hazards in Fujian Province using the Geodetector method. Among them, the impact of human activities is mainly reflected by two indicators of night light intensity and land use type. Because the land use and lithology in the evaluation index system constructed by this research are type data and cannot be used as statistical units in traditional administrative units, in this study, they were analyzed by randomly extracting 5000 sites generated by using ArcGIS to extract the value of each impact factor.

Table 4 shows the geographical factors affecting the risks of geological hazards. The influence magnitude q of these factors is in the order of night light intensity < distance from faults < average annual precipitation < lithology < NDVI < land use < slope < distance from rivers <

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elevation, indicating that night light intensity, elevation, distance from faults and slope are the main factors inducing geological hazards in Fujian Province, while the distance from rivers, average annual precipitation and lithology have relatively less impact on the occurrence of geological hazards. It can be seen that the risk of geological disasters in the study area is the result of the combined effects of the natural environment and human activities. The fragility of the regional geological environment provides a good disaster-pregnant environment for the occurrence and development of geological disasters, but human activities have an impact on the regional ecology. in addition, the human activities using land use as a carrier have caused certain disturbance to the rock and soil mass, and destroyed the stability of the regional ecosystem, which is an important factor in inducing geological disasters. Therefore, the occurrence frequency of geological disasters is intensified to a certain extent, and the induced effect of human activities on geological disasters should not be underestimated.

Table 4 Geographical exploration results of evaluation indicators.

Index	Lithology	Elevation	Land use type	NDVI	Slope	Distance from fault	Average annual precipitation	Night light intensity	Distance from river
Q value	0.077	0.282	0.171	0.137	0.212	0.008	0.058	0.311	0.231

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4 .Discussion

4.1. Accuracy verification of geological hazard evaluation

Receiver operating characteristic (ROC) curve is a simple, intuitive and comprehensive index reflecting the sensitivity and specificity of continuous variables. Plotting ROC curve does not require selection of classification thresholds, thus avoiding interference of excessive human factors to the accuracy verification and resulting in good objectivity (Martens et al., 2016; Baker et al., 2018). The method has been widely used to verify the accuracy of geological hazards risk assessment in recent years. Based on the spatial distribution of the risks and locations of geological hazards in the study area, a 5-km grid is used as the evaluation unit, and the prediction value of geological hazard risks and the presence/absence of geological hazards in each evaluation unit are used as the input data to plot the ROC curve using the SPSS software to assess the accuracy of geological hazards evaluation in Fujian Province. As shown in Fig. 6, the area under the ROC curve in Fujian Province is 0.683, indicating that the result of geological hazard risk assessment in this area is accurate and reliable.

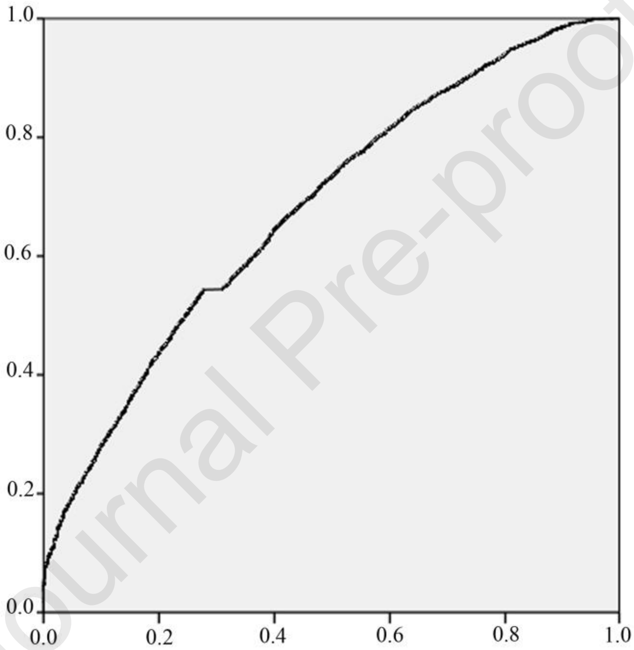

Fig. 6. Receiver operating characteristic curve of risks for geological hazards.

4.2. Comparison of evaluation results using different models

At present, the risk assessment of geological hazards has become an intensive research topic and play an extremely important role in disaster management. With the deepening of the research, many assessment methods have been put forward for the risk assessment of geological hazards, which are gradually mature in the process of practice. Among them, the AHP method, expert scoring method, fuzzy comprehensive evaluation method, artificial neural network method, spatial principal components analysis method and information quantity model are most widely used. Different scholars have choosed the corresponding evaluation model according to the

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characteristics of their own research area, and then evaluate the risk of geological disaster in this region. However, the application scope of different evaluation models are different, there are two main challenges in the current, on the one hand, the weighting process of evaluation indicators is greatly impacted by human subjectivity, which can not truly reflect the objective impact of different indicators on geological disasters (for example, AHP and expert scoring method); on the other hand, the modeling process is too complex, which requires too many precise parameters that is difficult to obtain (for example, artificial neural network method). The information quantity model can comprehensively study the "best combination of factors" contributing the most to geological hazards, rather than a single factor (Chen et al., 2013), which is fully considers the objective impact of evaluation indexes on geological hazards compared with other evaluation models, avoids the subjective randomness of human weighting, and its evaluation results are more scientific and reasonable.

Fujian Province as a typical mountainous environment in China, in recent decades, the geological disasters occur frequently, and bring serious threat to local social economy, life and property safety. Therefore, there are relevant scholars have carried out risk assessment of geological hazards based on different evaluation models in this region. For example, Liu et al. (2010) constructed an index system with elevation, lithology, slope and aspect as the influencing factors based on the logistic regression model, and evaluated the risk of landslide disaster in Putian City, this study provides an important scientific basis for local landslide disaster prediction; Yang et al. (2016) selected the DEM data and its eight derived factors, including altitude, slope, aspect, topographic relief, curva ture, stream power index (SPI), sediment transport index (STI) and topographic wetness index (TWI) , to assess the landslide susceptibility based on the logistic

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regression model in Fujian Province, the results show that the accuracy of landslide susceptibility evaluation using DEM derived factors can reach 73%. Lin et al. (2018) selected eight indicators including slope, elevation, soil types, NDVI, lithology, average annual precipitation, the distance from the main road and the geological hazards points in 5km grids, for comprehensively assessing the sensitivity of geological hazards based on spatial principal components analysis, and revealing the spatial pattern characteristics of geological hazard risk in urban agglomeration of Fujian Delta Region. Compared with previous studies, this study selected eight factors related to geological disasters to construct and evaluation index system for comprehensively evaluate the risk of geological disasters in Fujian Province, which not only effectively avoids the subjective randomness of human weighting, but also reveals the best combination of factors contributing the most to geological hazards and main influencing factors in this area. Therefore, we believed that the research has certain innovation, it not only enrich the theoretical methods of geological disaster risk management, but also provide scientific reference for the effective prevention and control of geological disasters in Fujian Province.

4.3. Development strategy in key areas of geological hazards

The hierarchical data of the 8 evaluation indexes and the geological hazard points were superimposed, analyzed and ranked based on the information quantity of each factor. Table 2 lists their ranking. It is clear from the table that the combination of the dominant influencing factors that can easily induce mountainous geological hazards in Fujian Province includes elevation of 200-400 m, slope of 5-15°, NDVI of 0.6-0.8, biogenetic rocks, construction lands, average annual precipitation of 1500-1600 mm, distance from rivers being < 300 m, and distance from faults being 5000-10000 m. Based on this, it can effectively identify the degree of geological hazards in

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the region, and provide scientific basis for the formulation of regional geological disaster prevention strategies. For example, when the specific evaluation unit in the region meets the above-mentioned multiple dominant conditions, the probability of occurring mountainous geological hazards is the highest, and the unit has a high risk of geological hazards. Thus, the relevant departments can strengthen the construction of geological hazards prevention facilities in the region and implement measures to prevent and mitigate geological hazards, making geological hazards prevention more targeted, so as to improve the effectiveness of regional geological hazards prediction and prevention.

The results of geographical exploration based on geographical detector method for influencing factors show that the occurrence of regional geological hazards is the result of the combined effects of the natural environment and human activities. such as night light intensity, elevation, distance from rivers and slope, and the disturbance of human activities using land use as a carrier to the stability of the ecosystem could also induce regional geological hazards to certain degrees. Therefore, the impact of human activities on regional geological hazards should not be underestimated. In the future process of urban construction, ecological protection should be taken as the guiding principle to minimize the damage to the original ecosystem stability. At the same time to maintain rapid socioeconomic development, we must adhere to the development strategy of equal emphasis on development and protection. Land development and use should avoid as far as possible the areas with high ecological vulnerability and high risk of geological hazards. For regions satisfying multiple combination conditions, prohibited development zones should be established to protect ecological environment, avoid exacerbating regional environmental degradation and induction of geological disasters. Necessary ecological restorations can also be

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appropriately implemented in the areas with high risk of geological hazards so as to restore and rebuild regional ecosystem stability.

5. Conclusions and recommendations

5.1. Main conclusions

Based on the characteristics of the typical mountainous environment in Fujian Province, this study selected eight factors including elevation, slope, NDVI, lithology, land use type, average annual precipitation, distance from rivers, and distance from faults to construct an evaluation index system, and based on the information quantity model and geodetector method to evaluate the risk of geological hazards in Fujian Province in terms of overall characteristics, spatial distribution and influencing factors. The main conclusions are as follows.

(1) The overall risk of geological disasters in Fujian Province is relatively high, and are dominated by medium-risk and medium-high risks, accounting for 42.69% and 33.37% of the total area respectively, both high-risk and low-risk account for a small proportion.

(2) The risk of geological hazards in Fujian Province show an overall spatial trend of high in southeast and low in northwest, and there are significant "stripe" and spatial agglomeration characteristics. High risk and medium-high risk areas are mainly concentrated in the southeast coast while the low risk areas are mainly distributed in the northwest inland area.

(3) The occurrence of regional geological hazards is the result of the combined effects of the natural environment and human activities, and the night light intensity, elevation, distance from the river and slope are the main factors affecting the risk of geological disasters in Fujian Province, while the distance from the river, annual average rainfall and lithology are relatively small.

(4) The distribution of geological hazard points and the risk level have a good spatial match, and the result of ROC curve also indicates that the risk assessment result of geological disasters

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based on the information quantity model have a high reliability.

5.2. Recommendations

Fujian Province is a typical mountainous environment, coupled with its special geographical location, regional geological disasters occur frequently in recent years, which have seriously threatened for the production and life of residents who live in this region and the regional ecological safety. It is of great significance for local governments to formulate targeted geological disaster prevention measures. Based on the special topography and geomorphology of the area, this study constructs an evaluation model for the risk of geological disasters in Fujian Province, and reveals the spatial pattern and its main influencing factors of hazards in the region. This research can improve the scientificity of government geological disasters prevention strategy formulation, There are specific suggestions in the following areas. (1) The local government should focus on the core areas with greater geological hazards, and combine the advantageous combination and the main influencing factors of geological hazards in each area, to delineate key prevention and control areas, and formulate targeted regional development strategies. Adhere to both development and protection, while ensuring the rapid development of the regional economy, we must pay more attention to the ecological security issues to avoid the occurrence of geological disasters caused by excessive land development; (2) Increase the level of disasters prevention and control in high-risk areas, set up emergency shelters, strengthen publicity for residents in key risk areas, increase the frequency of emergency drills, and improve residents' awareness of geological disasters prevention and emergency response; (3) Making full use of the new technologies such as drones, big data and machine learning etc. Accelerate the deployment of real-time monitoring networks, improve the efficiency of remote sensing monitoring of geological disasters, realize the

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forecast and early warning of geological disasters, reduce the possible harm of geological disasters, and effectively protect the lives and property of local residents.

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Conflicts of interest

The authors declare no conflict of interest.

References

Alexakis, D.D., Agapiou, A., Tzouvaras, M., Themistocleous, K., Neocleous, K., Michaelides, S., Hadjimitsis, D.G., 2014. Integrated use of GIS and remote sensing for monitoring landslides in transportation pavements: the case study of Paphos area in Cyprus. Nat. Hazards 72,119-141.

Arabameri, A., Rezaei, K., Cerdà, A., Conoscenti, C., Kalantari, Z., 2019. A comparison of statistical methods and multi-criteria decision making to map flood hazard susceptibility in Northern Iran. Sci. Total Environ. 660, 443-458.

Bai, L., Jiang, L., Yang, D., Liu, Y., 2019. Quantifying the spatial heterogeneity influences of natural and socioeconomic factors and their interactions on air pollution using the geographical detector method: A case study of the Yangtze River Economic Belt, China. J. Clean Prod. 232, 692-704.

Baker, A.M., Hsu, F.C., Gayzik, F.S., 2018. A method to measure predictive ability of an injury risk curve using an observation-adjusted area under the receiver operating characteristic curve. J. Biomech. 72, 23-28.

Bekteshi, S., Kabashi, S., Ahmetaj, S., Xhafa, B., Hodolli, G., Kadiri, S., Alijaj, F., Abdullahu, B., 2017. Radon concentrations and

Journal Pre-proof

exposure levels in the Trepça underground mine: A comparative study. J. Clean Prod. 155, 198-203.

Chalkias, C., Ferentinou, M., Polykretis, C., 2014. GIS supported landslide susceptibility modeling at regional scale: an expert-based fuzzy weighting method. ISPRS Int. Geo-Inf. 3, 523-539.

Chen, Y., Guo, H.D., Wang, Q.J., 2013. Geological disaster susceptibility assessment of the Lushan earthquake based on RS and GIS (in Chinese). Chin. Sci. Bull. 58, 3859-3866.

Cigna, F., Tapete, D., Lee, K., 2018. Geological hazards in the UNESCO World Heritage sites of the UK: From the global to the local scale perspective. Earth-Sci. Rev. 176, 166-194.

Conforti, M., Pascale, S., Robustelli, G., Sdao, F., 2014. Evaluation of prediction capability of the artificial neural networks for mapping landslide susceptibility in the Turbolo River catchment (northern Calabria, Italy). Catena, 113, 236-250.

Deng, H., He, Z.W., Chen, Y., Cai, H., Li, X.Q., 2014. Application of information quality model to hazard evaluation of geological disaster in mountainous region environment: a case study of Luding County, Sichuan Province. Journal of Natural Disasters, 23, 67-76.

Du, Y.Y., Peng, J., Zhao, S.Q., Hu, Z.C., Wang, Y.L., 2016. Ecological risk assessment of landslide disasters in mountainous areas of Southwest China: A case study in Dali Bai Autonomous Prefecture. Acta Geographica Sinica, 7, 1544-1561.

Grant, A., Wartman, J., Abou-Jaoude, G., 2016. Multimodal method for coseismic landslide hazard assessment. Eng. Geol. 212, 146-160.

Hadji, R., Boumazbeur, A. errahmane, Limani, Y., Baghem, M., Chouabi, A. el M., Demdoum, A., 2013. Geologic, topographic and climatic controls in landslide hazard assessment using GIS modeling: A case study of Souk Ahras region, NE Algeria. Quat. Int. 302, 224–237.

He, F., Gu, L., Wang, T., Zhang, Z., 2017. The synthetic geo-ecological environmental evaluation of a coastal coal-mining city using spatiotemporal big data: A case study in Longkou, China. J. Clean Prod. 142, 854-866.

Jena, R., Pradhan, B., Beydoun, G., Nizamuddin, Ardiansyah, Sofyan, H., Affan, M., 2020. Integrated model for earthquake risk assessment using neural network and analytic hierarchy process: Aceh Province, Indonesia. Geosci. Front. 11, 613-634.

Journal Pre-proof

Kayastha, P., Dhital, M. R., De Smedt, F., 2013. Application of the analytical hierarchy process (AHP) for landslide susceptibility mapping: A case study from the Tinau watershed, west Nepal. Comput. Geosci. 52, 398-408.

Lee S., 2004. Application of likelihood ratio and logistic regression models to landslide susceptibility mapping using GIS. Environ. Manage. 34, 223-232.

Liao, W., Li, L., Wu, Y.J., Shi, Z.H., 2011. Land use change and eco-environmental vulnerability evaluation in the Danjiangkou Reservoir area . Journal of Natural Resource, 26, 1879-1889.

Lin, J.H., Zhang, A., Deng, C., Chen, W.H., Liang, C.Y., 2018. Sensitivity assessment of geological hazards in unban agglomeration of Fujian Delta Region. Journal of Geo-information Science, 20(9), 1286-1297.

Liu, K., Wang, M., Cao, Y., Zhu, W., Yang, G., 2018. Susceptibility of existing and planned Chinese railway system subjected to rainfall-induced multi-hazards. Transp. Res. Pt. A-Policy Pract. 117, 214–226.

Liu,W.Y., Wu, X.B., An, J., Liu, J.L., 2010. Research on information map of landslide hazard evaluation—A case study in putian of Fujian Province. Journal of Catastrophology, 25(2), 21-25.

Lu, S.J., Wang, Y., Wen, M.Z., 2010. Research on geological disasters caused by monsoon rainstorm and typhoon rainstorm in Fujian Province. Geology of Fujian, 29, 77-86.

Mandal, B., Mandal, S., 2018. Analytical hierarchy process (AHP) based landslide susceptibility mapping of Lish river basin of eastern Darjeeling Himalaya, India. Adv. Space Res. 62, 3114-3132.

Martens, F.K., Tonk, E.C.M., Kers, J.G., Janssens, A.C.J.W., 2016. Small improvement in the area under the receiver operating characteristic curve indicated small changes in predicted risks. J. Clin. Epidemiol. 79, 159-164.

Mind'je, R., Li, L., Amanambu, A.C., Nahayo, L., Nsengiyumva, J.B., Gasirabo, A., Mindje, M., 2019. Flood susceptibility modeling and hazard perception in Rwanda.Int. J. Disaster Risk Reduct. 38, 101211.

Niu, Q., Cheng, W., Liu, Y., Xie, Y., Lan, H., Cao, Y., 2012. Risk assessment of secondary geological disasters induced by the Yushu earthquake. J Mt. Sci. 9(2), 232-242.

Journal Pre-proof

Journal Pre-proof

Niu, Q.F., Cheng, W.M., Lan, H.X., Liu, Y., Jie, Y.W., 2011. Susceptibility assessment of secondary geological disaster based on information value methodology for Yushu earthquake region. J Mt. Sci. 9, 243-249.

Pan, A., 2016. Study on mobility-disadvantage group' risk perception and coping behaviors of abrupt geological hazards in coastal rural area of China. Environ. Res. 148, 574-581.

Pavlova, I., Makarigakis, A., Depret, T., Jomelli, V., 2017. Global overview of the geological hazard exposure and disaster risk awareness at world heritage sites. J. Cult. Herit. 28, 151-157.

Peng, W., Kuang, T., Tao, S., 2019. Quantifying influences of natural factors on vegetation NDVI changes based on geographical detector in Sichuan, western China. J. Clean Prod. 233, 353-367.

Qiao, P., Yang, S., Lei, M., Chen, T., Dong, N., 2019. Quantitative analysis of the factors influencing spatial distribution of soil heavy metals based on geographical detector. Sci. Total Environ. 664, 392-413.

Raghuvanshi, T.K., Ibrahim, J., Ayalew, D., 2014. Slope stability susceptibility evaluation parameter (SSEP) rating scheme–An approach for landslide hazard zonation. J. Afr. Earth Sci. 99, 595–612.

Su, Q., Zhang, J., Zhao, S., Wang, L., Liu, J., Guo, J., 2017. Comparative Assessment of Three Nonlinear Approaches for Landslide Susceptibility Mapping in a Coal Mine Area. ISPRS Int. Geo-Inf., 6(7), 228-244.

Tien Bui, D., Pradhan, B., Lofman, O., Revhaug, I., Dick, O.B., 2012. Landslide susceptibility assessment in the Hoa Binh province of Vietnam: A comparison of the Levenberg-Marquardt and Bayesian regularized neural networks. Geomorphology, 171, 12-29.

Wang J, Xu C. 2017. Geodetector: Principle and Prospective. Acta Geographica Sinica, 72, 116-134.

Wang, Y., Yang, W., Li, M., Liu, X., 2012. Risk assessment of floor water inrush in coal mines based on secondary fuzzy comprehensive evaluation. Int. J. Rock Mech. Min. Sci. 52, 50-55.

Wang, Z.F., Zhang, T.S., Wang, L., Tang Z.Y., 2016. The integrated assessment system of ecogeological environmental carrying capacity for Dujiangyan-Wenchuan Highway. Science of Surveying and Mapping, 41, 77-81.

Weinmeister H.W., 2007. Integrated debris flow disaster mitigation—A comprehensive method for debris flow disaster mitigation. J Mt.

Journal Pre-proof

Sci. 4, 293-308.

Wu, Z., Hu, M., 2019. Neotectonics, active tectonics and earthquake geology: terminology, applications and advances. J. Geodyn. 127, 1-15.

Sdao, F., Lioi, D.S., Pascale, S., Caniani, D., Mancini, I.M., 2013. Landslide susceptibility assessment by using a neuro-fuzzy model: A case study in the Rupestrian heritage rich area of Matera. Nat. Hazards Earth Syst. Sci. 13, 395-407.

Su, Q., Zhang, J., Zhao, S., Wang, L., Liu, J., Guo, J., 2017. Comparative assessment of three nonlinear approaches for landslide susceptibility mapping in a coal mine area. ISPRS Int. Geo-Inf. 6, 228-244.

Yang, C., Lin, G.F.,Zhang, M.F., Zhang, R.Y., Sun, X.G., 2016. Soil landslide susceptibility assessment based on DEM. Journal of Geo-information Science, 18(12), 1624-1633.

Yilmaz, C., Topal, T., Süzen, M.L., 2012. GIS-based landslide susceptibility mapping using bivariate statistical analysis in Devrek (Zonguldak-Turkey). Environ. Earth Sci. 65, 2161-2178.

Yu, F.H., Liu, Z.H., Xia, Y.Z. Zhang, D.Z., She, T.Y., 2015. Evaluation of the unexpected geological disasters distribution in coastal region of Zhejiang Province based on sensibility coefficient and principal component analysis. Journal of Catastrophology, 30, 64-68.

Zhou, C., Chen, J., Wang, S., 2018. Examining the effects of socioeconomic development on fine particulate matter (PM2.5) in China's cities using spatial regression and the geographical detector technique. Sci. Total Environ. 619, 436-445.

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Highlights

- Comprehensive evaluation system was constructed using information quantity model.
- Geodetector was conducted to reveal the influencing factors of geological hazards.
- Combination of dominant factors conducive to inducing geological hazards was found.
- Geological hazard risk show an trend of high in the southeast and low in the northwest.
- The geological disaster is affected by both natural environment and human activities.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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