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Ecological risks of geological disasters and the patterns of the urban agglomeration in the Fujian Delta region

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ABSTRACT

Geological disasters not only hinder the ecological security guarantee in urban agglomerations, but also pose serious threat to the life and property of residents in the areas. The study establishes a "hazard-vulnerability-exposure" three-dimensional ecological risk assessment model, adopts an information value model to assess hazard, use landscape indices to analyze vulnerability and nighttime light data to indicate population exposure, and then quantitatively assesses the watershed-scale ecological risks of geological disasters and their patterns. The results show that ecological risks of geological disasters are mainly medium risks, presenting the trend of weakening from southeastern coastal areas to northwestern inland areas. The ecological risks exist in eight patterns in combination of the three dimensions of hazard, vulnerability and exposure. The elevation of 600–800 m, slope of 5 ~ 15°, aspect as southwest, NDVI of 0.4–0.6, lithology of metamorphic rocks, land use type as farmland, multi-year average precipitation of >1600 mm, distance to river of less than 200 m and distance to fault of less than 1000 m are the combination of greater likelihood of inducing geological disasters. The study finds that ecological risks of geological disasters show the trend of high in the southeast and low in the northwest and are the highest under combination of the high vulnerability and high exposure pattern out of the eight patterns that are predominated by high population exposure. In addition, the study discovers the combination of greater likelihood of inducing geological disasters, and puts forward the prevention and control measures against geological disasters in the future.

1. Introduction

The study on ecological risk assessment started in the 1970s (Calow, 1998). In 1992, the U.S. Environmental Protection Agency defined the ecological risk assessment and laid out the theoretical foundation and analysis framework for related study (Kang et al., 2016; U.S. Environmental Protection Agency, 1992; Zhang et al., 2014). Assessment of ecological risk mainly covers hazard assessment, exposure assessment, receptor analysis and risk characterization (Du et al., 2012, 2016; Jin et al., 2019; Zhang et al., 2019). As the human society paid increasingly greater attention to the natural ecosystem, domestic and foreign scholars conducted extensive research on ecological risk assessment and related theories and methods were constantly developed and improved (Chen et al., 2013a, 2013b; Hope, 2006; Liu et al., 2014; Xu et al., 2016). Typical of mountain environment, the urban agglomeration in the Fujian Delta region suffers frequent geological disasters due to its particular topographic conditions and climatic features, causing tremendous casualties and economic losses every year. This has become a major obstacle to the sustainable development of the urban agglomeration (Lin et al., 2018; Lu et al., 2010). Therefore, ecological risk assessment over geological disasters in the urban agglomeration in the Fujian Delta region provides support for decision-making on local ecological protection and administration more effectively.

Today, as GIS and RS technologies advance rapidly, ecological risk assessment has become a popular subject of research for domestic and foreign scholars and also an important part in the international disaster prevention and mitigation strategy (Lee, 2004; Niu et al., 2012; Peng et al., 2015; Su et al., 2017). As one of its important branches, ecological

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risk assessment over geological disasters has attracted wide attention and achieved fruitful results (Muceku et al., 2016; Kuriqi et al., 2016; Kuriqi and Mehmet, 2018). Regarding object of study, the scholars mainly focus on the ecological risks in pollutant dispersion, flood, drought, typhoon, land use, ecological degradation, landscape ecology and ecosystem services (Alexakis et al., 2014; Lei et al., 2014; Liu et al., 2017a, 2017b; Kingwell and John, 2007), while identification and study on ecological risk of geological disasters are insufficient. In terms of content of study, the studies are concentrated on spatial distribution, temporal change, quantitative characteristics, spatial differentiation and region division of ecological risks (Hong et al., 2016; Lin et al., 2019; Maanan et al., 2015; Xu et al., 2012), but the risks' spatial aggregation and combination patterns are seldom covered. With respect to methods, scholars today mostly start from disaster breeding environment, disaster-causing factors and value of disaster-bearing bodies to establish assessment indicator models (Du et al., 2016; Kang et al., 2016), among which probability-loss two-dimensional model, relative risk model (RRM), procedure for ecological tiered assessment of risks (PETAR) and pressure-state-response model are commonly adopted (Echeverría et al., 2012; Gong et al., 2012a, 2012b; Landis and Wiegers, 2007; Obery and Landis, 2002). However, these methods mainly highlight hazard and vulnerability of the natural ecosystem and give little thought to population exposure of the human society, the most important disaster-bearing body. Therefore, though domestic and foreign scholars have conducted numerous researches on regional ecological risk, their object of assessment and scale of research differ, and the assessment indicator systems still need a unified framework (Kang et al., 2016) for further improvement. Assessment indicator systems need be constructed correspondingly according to particular geographical characteristics in different areas.

In view of this, the study takes the urban agglomeration in the Fujian Delta region in a mountainous environment as study area and geological disasters as object of study, and starts from disaster breeding environment, disaster-bearing body and exposure response to establish a three-dimensional ecological risk assessment model. It adopts an information value model to assess hazard of geological disasters, uses landscape indices to analyze vulnerability and selects nighttime light data to indicate population exposure, comprehensively assessing the ecological risks of geological disasters in the region from the perspectives of spatial distribution, spatial aggregation and combination patterns. Based on the watershed-scale ecological risk combination patterns, the study attempts to enrich the theories and indicator systems on ecological risk assessment of geological disasters, discuss prevention strategies against ecological risks of geological disasters in the future development of the urban agglomeration, and provide a theoretical foundation for the control of natural disaster risk, construction of ecological civilization and guarantee of ecological security in the urban agglomeration in the Fujian Delta region.

2. Material and method

2.1. Overview of the study area

The urban agglomeration in the Fujian Delta region (23°33′20″N-25°56′45″N, 116°53′21″E-119°01′38″E) consists of three cities with subordinate districts, namely Xiamen, Quanzhou and Zhangzhou. It is located in the southeastern coast in Fujian Province and faces Taiwan across the sea (Fig. 1(a)), covering a total area of 25,000 km^2 (excluding Jinmen). The area lies in the typical subtropical monsoon climate zone and is covered by mountainous areas and hills over 80% of its land, featuring rolling and fragmented terrains, sharp slopes, widely distributed geological faults and thus a fragile ecological environment. For this reason, the area is frequently hit by geological disasters that bring serious damage in large scope, and especially susceptible to the disasters in the summer rainy season (Lu et al., 2010). So far, the number of geological disasters in the study area is recorded at 2,030, including 1339 landslides, 668 collapses, 15 mudslides and 8 cases of ground subsidence (Fig. 1(b)).

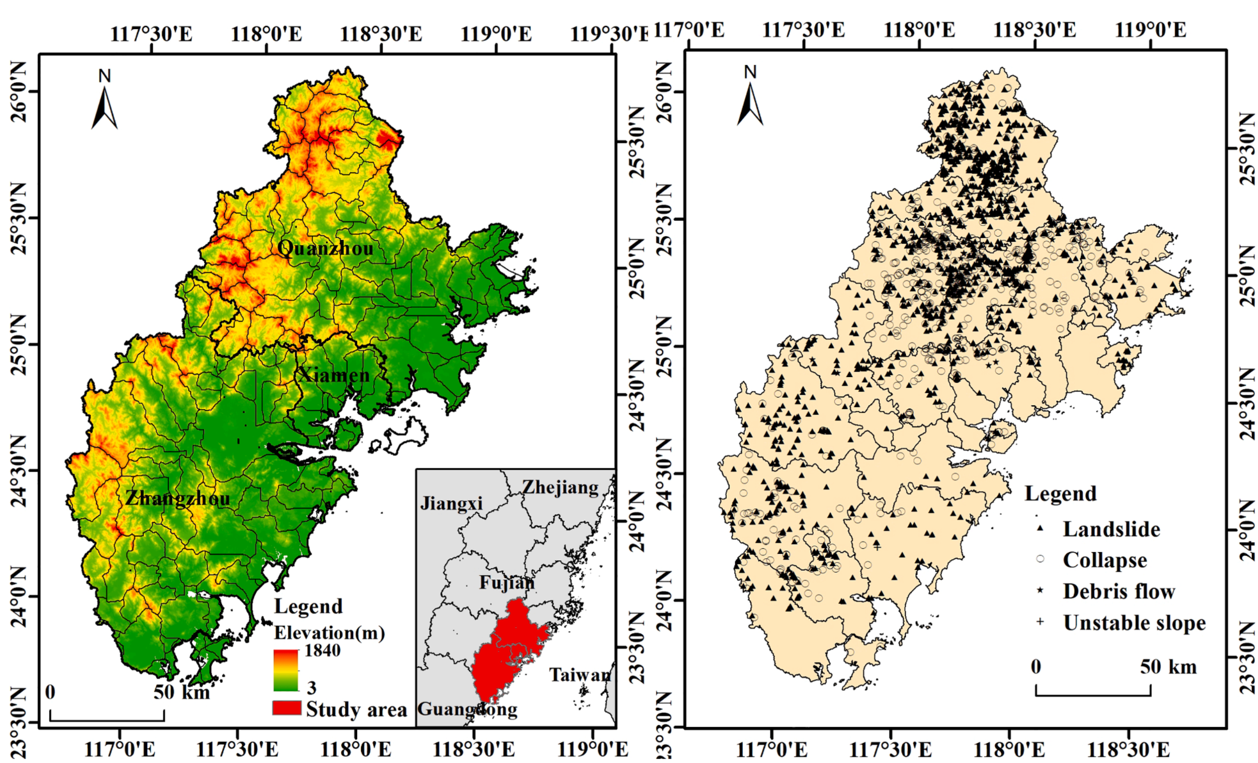

Fig. 1. Geographical location of the study area (a) and distribution of geological disaster points (b).

2.2. Methodology and data source

2.2.1. Conceptual framework

Ecological risk refers to the adverse impact that uncertain accidents or disasters may pose on the ecosystem or its components within an area (Yan et al., 2010). On the basis of previous studies, this paper starts from the disaster breeding environment, disaster-bearing body and exposure response to construct a three-dimensional framework on ecological risk assessment. As the conceptual framework shows in Fig. 2, ecological risk of geological disasters is composed of three dimensions including hazard, vulnerability and exposure. Among them, hazard represents probability of landslide disasters and it is based on various factors such as geographic and geomorphic conditions, vegetation, geology and human activities as well as their combinations; vulnerability is susceptibility of structural components of natural landscape to disaster stress and also anti-interference ability in response to disaster threat; exposure is the "ecological end point" in the risk causal chain model and the direct response of risk receptors in exposure to risk sources. Based on this, the spatial pattern of geological disaster ecological risk is obtained, and then the combination mode is analyzed from the three dimensions of risk, vulnerability and exposure

2.2.2. Ecological risk assessment model of geological disasters

By referring to previous researches and the above-mentioned conceptual framework, this study start from the basic characteristics of regional geological disasters, combined with the natural ecological environment of the region, and constructed a geological disaster ecological risk assessment model from the three dimensions of hazard, vulnerability and exposure. The ecological risk is a natural geographical feature, but the traditional statistical analysis based on administrative divisions will unreasonably split its features, causing mismatch in scale and failure to well reflect its actual spatial pattern features. Therefore, the hazard, vulnerability, exposure and ecological risk of 169 tier-2 sub-watersheds in the whole region are calculated respectively, and the watershed data is extracted with DEM. Based on this, the quantitative characteristics, spatial distribution, spatial agglomeration and combination of great likelihood in hazard of ecological risks are obtained, and then the combination patterns are analyzed from the perspective of the internal structure of the three dimensions. The ecological risk of geological disasters is calculated as formula (1).

$$R = H \times V \times E \tag{1}$$

Where, R represents the ecological risk of geological disasters, H the hazard of geological disasters, V the vulnerability of geological disasters, and E the exposure of geological disasters.

The calculation of the ecological risk of geological disasters is realized from the three dimensions of hazard, vulnerability and exposure. The technical flow is shown in Fig. 3. Among them, selects nine indicators to build the evaluation index system of hazard, with an information value model adopted to identify the optimal combination of hazards, determine weight according to their information value and complete assessment; vulnerability is represented by the watershed-scale landscape pattern characteristics; exposure is represented by the nighttime light, with intensity of nighttime light used to reflect density of exposed receptors and exposure intensity. Then calculate the ecological risk of geological disasters on the basis of hazard, vulnerability and exposure.

(1) Hazard assessment of geological disasters

This study selects factors closely related to the occurrence and development of regional geological disasters to construct a risk assessment index system, and calculates the weight of each factor based on the information value model. According to the particular geographic and geomorphic features in the study area, the paper starts from impact factors of geological disasters and takes into consideration availability of data, operability and scientificalness to select nine impact factors, namely elevation, slope, aspect, NDVI, lithology, land use type, multi-year average precipitation, distance to river and distance to fault, as assessment indicators for hazard of geological disasters in the urban agglomeration in the Fujian Delta region. Geographic and geomorphic conditions reflect stability characteristics of rock mass in an area, for which the study selects three factors of elevation, slope and aspect (Fig. 4(a)–(c)). Vegetation growth status on ground affects conservation of water and soil and balance of the ecosystem, and the study reflects the vegetation coverage in the region with NDVI (Fig. 4(d)). Geological conditions are the major prerequisite of occurrence and development of geological disasters and the study selects two factors of lithology and distance to fault (Fig. 4(e) and (i)). Different land use types indicate the intensity of human development and utilization of the ecological environment within an area, which influences stability and interference immunity of local geological conditions, and the study selects the factor of land use types (Fig. 4(f)). Meteorological conditions are one of the major inducing factors for occurrence of regional geological disasters and the study uses multi-year average precipitation to represent its influence over occurrence of geological disasters (Fig. 4(g)). Rivers wash out and erode soil-rock mass in an area in the converging process of surface runoffs and consequently induce geological disasters and this study selects distance to river to reflect the impact of rivers (Fig. 4(h)).

The information value model uses reduction of entropy during occurrence of geological disasters to represent probability of geological disasters and can comprehensively study the "optimal factor

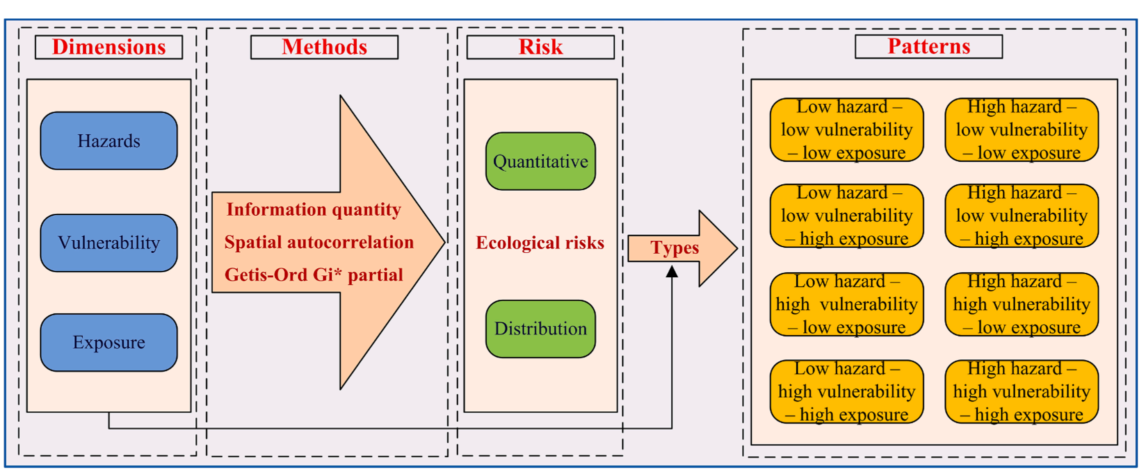

Fig. 2. Conceptual framework.

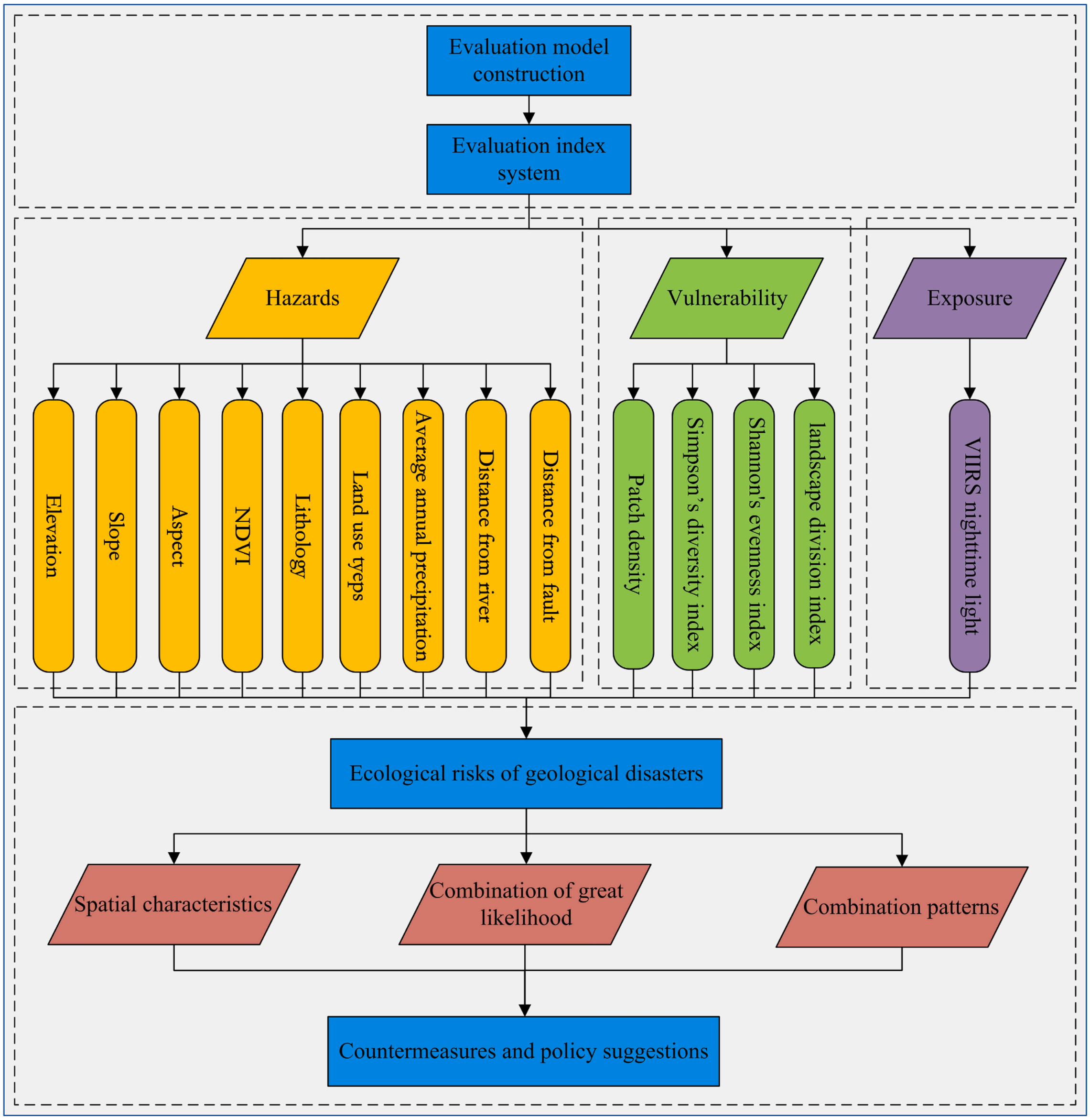

Fig. 3. Technical flow chart.

combination" with the greatest contribution to occurrence of landslides (Chen et al., 2013a, 2013b; Meng et al., 2009). The model translates measured value of various factors affecting regional stability into information value, the greater information value indicates higher probability of geological disasters (Niu et al., 2011). Formula of the information value model (Deng et al., 2014) is as follow:

$$I(Y, X_1, X_2, ..., X_n) = \frac{lnP(Y, X_1, X_2, ..., X_n)}{P(Y)} \tag{2}$$

Where, $I(Y, X_1, X_2, X_3,\ldots,X_n)$ is information value that factor combination $X_1, X_2, X_3,\ldots,X_n$ provides for geological disasters; $P(Y, X_1, X_2, X_3,\ldots,X_n)$ is probability of geological disasters under the combination conditions of factor $X_1, X_2, X_3,\ldots,X_n$ and $P(Y)$ is probability of occurrence of geological disasters.

Under normal circumstances, overlay of single-factor information value results in comprehensive information value under the combined effect of multiple factors. Therefore, the calculation model of information value can be expressed as:

$$I(Y, X_1, X_2, ..., X_n) = \sum_{i=1}^{n} I_i = \sum_{i=1}^{n} ln\frac{N_i/N}{S_i/S} \tag{3}$$

Where, n represents the number of assessment factors that are selected; N_i is the area of geological disaster unit within the certain assessment factor type X_i; N is the total area of all the geological disaster units within the entire study area; S_i is the unit area including a certain assessment factor type X_i; S is the total area of the entire study area.

(2) Vulnerability assessment of geological disasters

Currently, landscape pattern analysis with landscape indicators can reasonably reveal the structural components and spatial configuration of the ecosystem in an area and quantitatively express the spatial correlation between landscape patterns and ecological processes (Du et al., 2016). The study focuses on the four aspects of landscape fragmentation, landscape diversity, landscape heterogeneity and landscape aggregation and selects the four landscape indicators including Patch density (PD), Simpson's diversity index (SHDI), Shannon's evenness index (SHEI) and landscape division index (DIVISION) to represent vulnerability characteristics of geological disasters in the urban agglomeration in the Fujian Delta region.

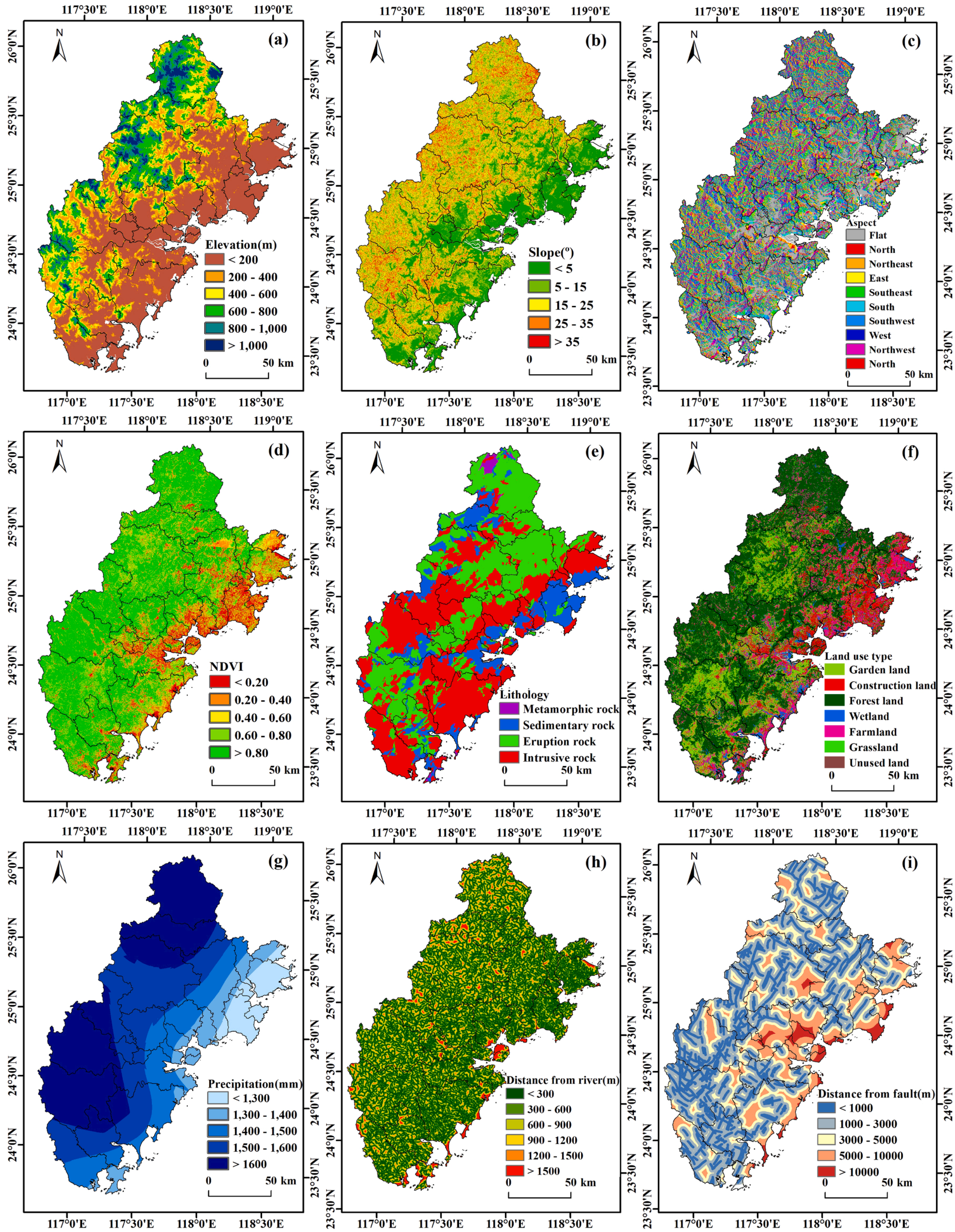

Fig. 4. Spatial distribution of assessment indicators for hazard of geological disasters in the urban agglomeration in the Fujian Delta (a. Elevation, b. Slope, c. Aspect, d. NDVI, e. Lithology, f. Land use types, g. Multi-year average precipitation, h. Distance from river, i. Distance from fault.)

$$VI = \left(\frac{1}{SHDI} + PD + DIVISION + \frac{1}{SHEI}\right) \Big/ 4 \tag{4}$$

Where, SHDI represents the diversity of landscape units or ecosystem in structure and functions, and higher SHDI indicates richer types of landscape. PD expresses the number of patches in the unit area and indicates the fragmentation degree of landscape. Higher PD indicates more patches and further fragmented landscape. DIVISION represents the degree of division of different types of ecosystems and higher degree of division means lower stability. SHEI describes the degree of distribution evenness of various components in the landscape and higher SHEI value represents more evenly distributed landscape patch types (Liu et al., 2014; Pan et al., 2012; Zhang et al., 2012).

(3) Population exposure assessment of geological disasters

The paper uses exposed population as risk receptor after occurrence of geological disasters. Traditional exposed population is analyzed on the basis of census data in administrative units, but census data is less precise on the one hand and not up to date on the other. Besides, for ecological risk assessment for geological disasters, administrative units as assessment units are not reasonably divided to some extent and do not entirely match in scale with natural geographical units in reality, thus unable to accurately reveal the characteristics of spatial patterns. As the remote sensing technology rapidly develops today, nighttime light data has been widely applied in economic development, traffic network building and analysis of population distribution characteristics. Given so, the study selects the VIIRS nighttime light image data in 2017 to represent the spatial distribution characteristics of population. The data is derived from monthly light data downloaded from NOAA official website (https://ngdc.noaa.gov/eog/viirs/index.html) and then consolidated and calculated to get the light value throughout the year.

2.2.3. Spatial autocorrelation

Currently, ecological risk analysis for geological disasters is mostly limited to the spatial distribution characteristics, but seldom discusses spatial aggregation of the ecological risk. Therefore, on the basis of assessment result of ecological risk of geological disasters, the paper takes the 169 tier-2 sub-watershed natural units in the urban agglomeration in the Fujian Delta region as assessment units to calculate mean value of the ecological risk in each watershed, calculate the overall Moran's I index and analyze the overall spatial autocorrelation. Based on the hotspot analysis tool Getis-Ord Gi*, it discusses spatial aggregation characteristics of the ecological risk in the urban agglomeration and reveals spatial distribution characteristics of coldspot areas and hotspot areas of the ecological risk.

The overall Moran's I index is calculated as follows (Li et al., 2011):

$$I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\sum_{i=1}^{n}(x_i - \overline{x})^2} \tag{5}$$

Getis-Ord Gi* partial statistics are calculated as follows (Liu et al., 2017a, 2017b):

$$G_i{}^* = \frac{\sum_{j=1}^{n} w_{i,j}x_j - \frac{\sum_{j=1}^{n} x_j}{n}\sum_{j=1}^{n} w_{i,j}}{\sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - \left(\frac{\sum_{j=1}^{n} x_j}{n}\right)^2}\sqrt{\frac{\left[n\sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2\right]}{n-1}}} \tag{6}$$

Where, I represents Moran's I index; Gi^* means the score of z; x_i and x_j indicate the ecological risk value of geological disasters in the *ith* and *jth* assessment unit; n means the total number of elements; $\overline{X}$ refers to the average ecological risk value of all the assessment units; W_{ij} means spatial weight matrix; S represents the sum of all the elements in the spatial weight matrix.

2.2.4. Data sources

The study has constructed an evaluation index system of ecological risk based on the three dimensions of hazard, vulnerability and exposure. The elevation, slope, aspect, NDVI, lithology, land use type, multi-year average precipitation, distance to river, distance to fault, four landscape indexes and 169 tier-2 sub-watershed data are selected. Among them, elevation is the result of rasterization of 1: 100,000 digital line graphics, and slope and aspect are extracted from DEM statistics, with a resolution of 30 m; NDVI is extracted from Landsat8 OLI images in the year of 2017, and resolution is 30 m; lithology is the digitalized 1: 200,000 geologic map of 2010 in Fujian Province and categorized into four groups: intrusive rock, extrusive rock, sedimentary rock and metamorphic rock; land use types are acquired from the first national geoinformation survey statistics in the year of 2015, which covers seven types including farmland, garden land, grassland, forest land, construction land, wetland and unused land; multi-year average precipitation is acquired from long-term monitoring data at monitoring stations using Kriging interpolation, and resolution is 30 m; distance to river and distance to fault are acquired from river vector data and geological fault vectors with ArcGIS-based Euclidean distance tools, and resolution is 30 m; landscape indexes are calculated based on land use types data and Fragstats software. The 169 tier-2 sub-watershed vector data is extracted with DEM. The projection coordinate system of all the data is unified into WGS1984.

3. Result analysis

3.1. Spatial distribution features of hazard, vulnerability and exposure

Based on the conceptual framework in ecological risk of geological disasters and its patterns analysis, this study constructs the evaluation index system of hazard, vulnerability and exposure respectively, and then obtains the spatial distribution pattern of hazard, vulnerability, exposure and ecological risk of geological disasters, with their calculation results shown in Table 1.

3.1.1. Spatial distribution features of hazard

Comprehensive information value of each assessment unit is calculated based on the information value model to get the hazard assessment result of geological disasters in the urban agglomeration. Sequence of different hazard levels by area is medium hazard > medium–high hazard > medium–low hazard > high hazard > low hazard, covering the area of 38.08%, 24.73%, 17.06%, 15.54% and 4.59% respectively. It's not difficult to find that hazard of geological disasters is concentrated in the three levels of medium, medium high and medium low, with the sum of their area accounting for >80% of the total, which indicates that the hazard of geological disasters in the study area is generally high. Table 2 shows that there are 877, 563 and 432 geological disaster points respectively in areas with high hazard, medium–high hazard and medium hazard, accounting for 85.32% of all the points. General distribution of both disaster point/area ratio and density of disaster points reflects the same trend that geological disasters are mainly concentrated in areas with high hazard levels and seldom break out in areas with low hazard levels. The distribution of disaster points and levels of disaster hazard highly match.

Comprehensive information value in each assessment unit is calculated based on the information value model and hazard of geological

Table 1
The data statistics of ecological and its three dimensions.

Dimension	Minimum	Maximun	Mean	Standard deviation
Hazard	0	1	0.5263	0.2244
Vulnerability	0.0001	13.6400	6.7270	3.4438
Exposure	0	36.5940	3.1883	5.2387
Ecological risk	0	45.2834	6.7925	8.9364

Table 2
Levels of disaster hazard and distribution of geological disaster points.

Level of hazard	Area (km^2)	Share of area (%) (a)	Number of disaster points	Share of disaster points (%)(b)	Disaster point/ area ratio(b/a)	Density of disaster points (number/ 100 km^2)
Low hazard	1137.24	4.59	14	0.71	0.16	1.23
Medium-low hazard	4227.02	17.06	78	3.97	0.23	1.85
Medium hazard	9436.34	38.08	432	22.00	0.58	4.58
Medium-high hazard	6128.47	24.73	563	28.67	1.16	9.19
High hazard	3850.22	15.54	877	44.65	2.87	22.78

disasters is categorized into five levels according to size of the information value. The spatial distribution characteristics are shown in Fig. 5 (a). Hazard of geological disasters in the urban agglomeration in the Fujian Delta region spatially displays the trend of growing higher from southeastern coastal areas to northwestern inland areas. Besides, intensity of the hazard and distribution of the disaster points enjoy strong spatial correlation and density of the disaster points in the areas with high hazard is far higher than that in the areas with low hazard. In the watershed scale, regional statistical tools are used to calculate the average hazard value of geological disasters in each watershed and then get spatial distribution characteristics of the hazard in the watershed scale (Fig. 5(b)). It can be seen that areas with high hazard are concentrated in the northwest and southwest of the study area, such as Dehua County, Yongchun County and Anxi County in the northwest and Nanjing County and Pinghe County in the southwest. Areas with low hazard are concentrated in eastern and southeastern coastal areas in the study area, such as Quangang District, Hui'an District, Fengze District, Jinjiang City, Shishi City, Jimei District, Haicang District, Xiang'an District, Siming District, Huli District and Dongshan County.

3.1.2. Spatial distribution features of vulnerability

On the basis of land use data in the urban agglomeration in the Fujian Delta region, the study selects watershed unit as assessment unit and constructs a vulnerability assessment model of geological disasters based on Patch density (PD), Simpson's diversity index (SHDI), Shannon's evenness index (SHEI) and landscape division index (DIVISION). The vulnerability score in the watershed scale is calculated and the vulnerability is categorized into five levels (low, medium–low, medium, medium–high, high) with the natural breakpoint method. The spatial distribution characteristics are shown in Fig. 6. Vulnerability of geological disasters in the urban agglomeration displays the general trend of weakening from southeastern coastal areas to northwestern inland areas. The watershed with high vulnerability is concentrated in economically developed southeastern coastal areas in the study area, where land utilization is intensive, landscape is highly fragmented, stability of the ecosystem is threatened and the ecology is highly fragile. The watershed with low vulnerability is concentrated in the northwestern inland areas with a low level of economic development, where land development is less intensive, human interference is low, landscape fragmentation is limited, the ecology is less fragile and the ecosystem is relatively stable.

3.1.3. Spatial distribution features of population exposure

The study uses the nighttime light remote-sensing image data in the urban agglomeration in 2017 as basis and in order to avoid unreasonable division of natural units by traditional administrative units and improve precision, selects watershed unit as assessment unit. It calculates and extracts the average light value in the 169 tier-two sub-watersheds in the study area and categorizes population exposure into five levels (low, medium–low, medium, medium–high, high) with the natural break point method. The spatial distribution characteristics are shown in Fig. 7. Population exposure in the urban agglomeration shows the general trend of being reduced from southeastern coastal areas to northwestern inland areas. Especially in the watershed near downtown

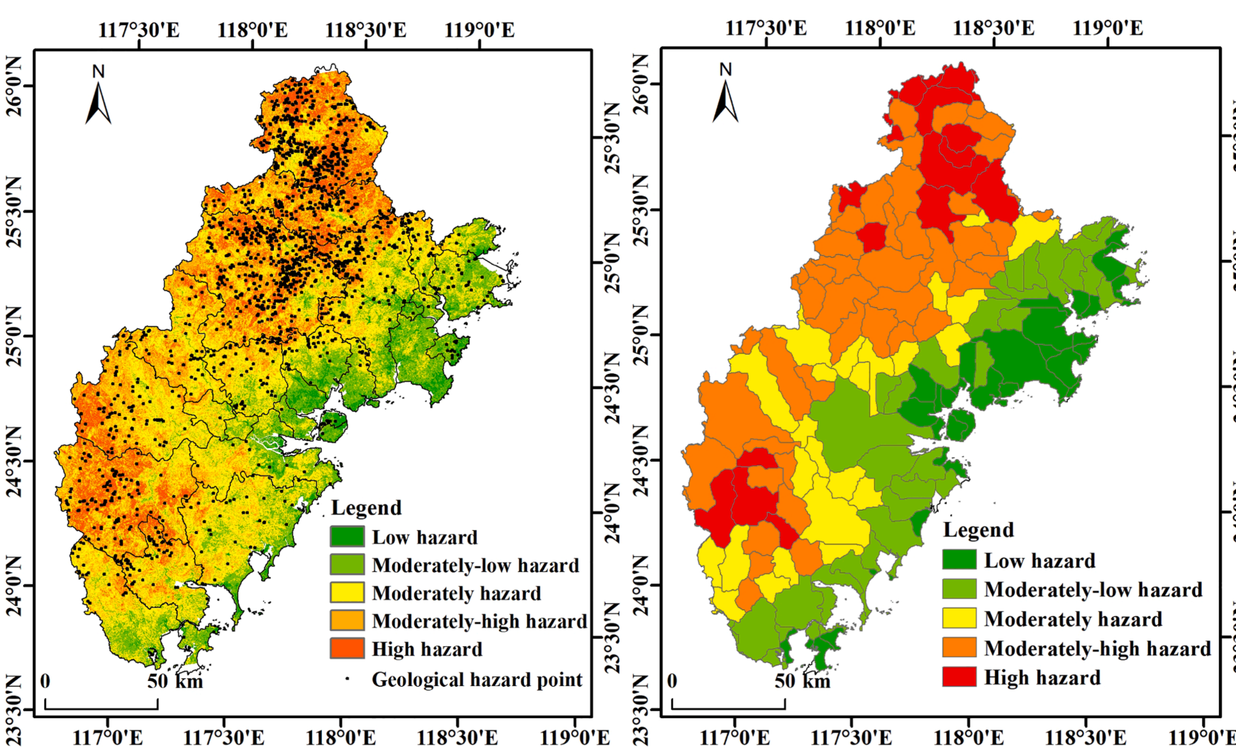

Fig. 5. Spatial distribution of hazard of geological disaster in grid scale (a) and in watershed scale (b).

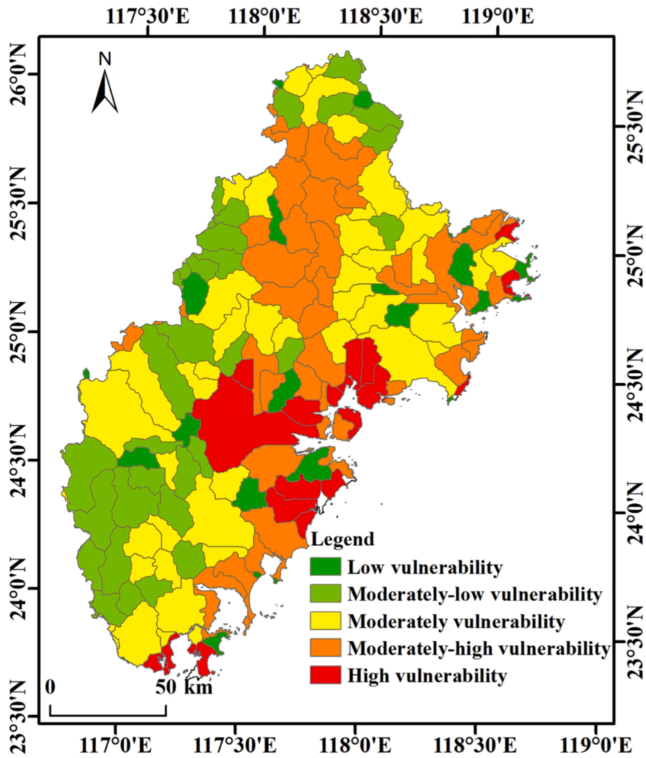

Fig. 6. Spatial distribution of vulnerability of geological disasters.

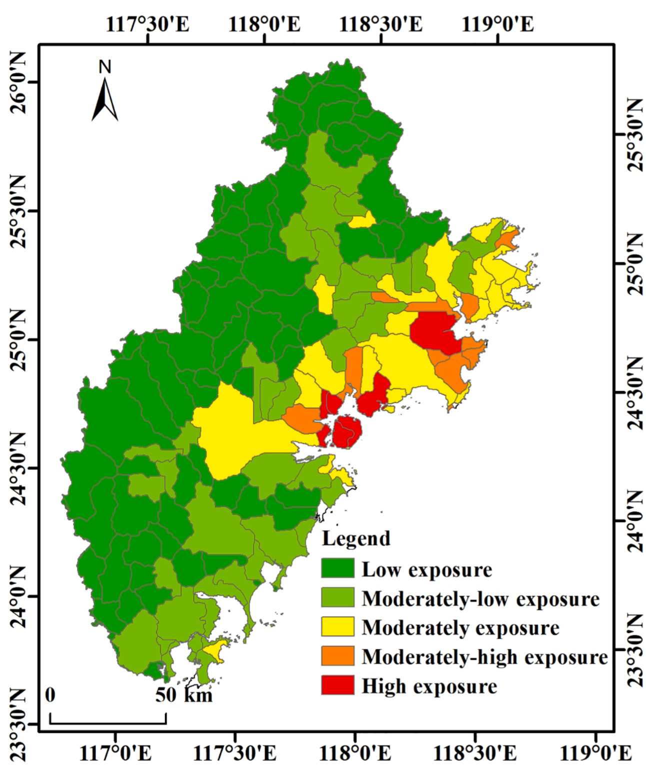

Fig. 7. Spatial distribution of population exposure of geological disaster.

Xiamen and Quanzhou, high exposure and medium–high exposure of population are dominant, indicating that these units are areas with highly concentrated population and that the population exposure risk brought by geological disasters will be higher.

3.2. Ecological risks of geological disasters and the combination patterns

The study focuses on hazard, vulnerability and population exposure of geological disasters to assess the ecological risk of the disasters in the urban agglomeration in the Fujian Delta region. The comprehensive risk assessment model is used to calculate the risk index and the natural break point method is adopted to categorize the ecological risk into three levels (low, medium, high). The spatial distribution characteristics show as Fig. 8. Ecological risk of geological disasters in the area displays the general trend of growing weaker from southeastern coastal areas to northwestern inland areas. High risk and medium risk are concentrated in the southeastern coastal area, especially the watershed around downtown areas. Despite the relatively low hazard of geological disasters, the area is high in vulnerability, fragile in the ecological environment, dense in population and thus high in the general ecological risk. Areas of low risk are scattered and cover a broad mountainous and hilly area in the northwest of the study area. The area suffers high disaster hazard, but due to the widely distributed mountains and hills and the consequent low utilization rate of land, the economic development is relatively weak and population density is low here, with the reduced artificial damage effectively protecting the ecosystem stability.

On the basis of the ecological risk, the study further highlights the hazard, vulnerability and population exposure of geological disasters in the watershed scale, defining their level 1–3 as low-value area and level 4–5 as high-value area, and then studies the combination patterns of hazard, vulnerability and exposure of the ecological risk. As shown in Fig. 8, the ecological risk in the urban agglomeration in the Fujian Delta region can be combined into eight different patterns, namely low hazard–low vulnerability–low exposure, low hazard–low vulnerability–high exposure, low hazard–high vulnerability–low exposure, low hazard–high vulnerability–high exposure, high hazard–low vulnerability–low exposure, high hazard–low vulnerability–high exposure, high hazard–high vulnerability–low exposure and high hazard–high vulnerability–high exposure.

As revealed by the overlapping result of the ecological risk and its combination patterns (Table 3), the combination patterns at different levels of ecological risk are heterogeneous to some extent. The number of watershed units in areas with low risk, medium risk and high risk is

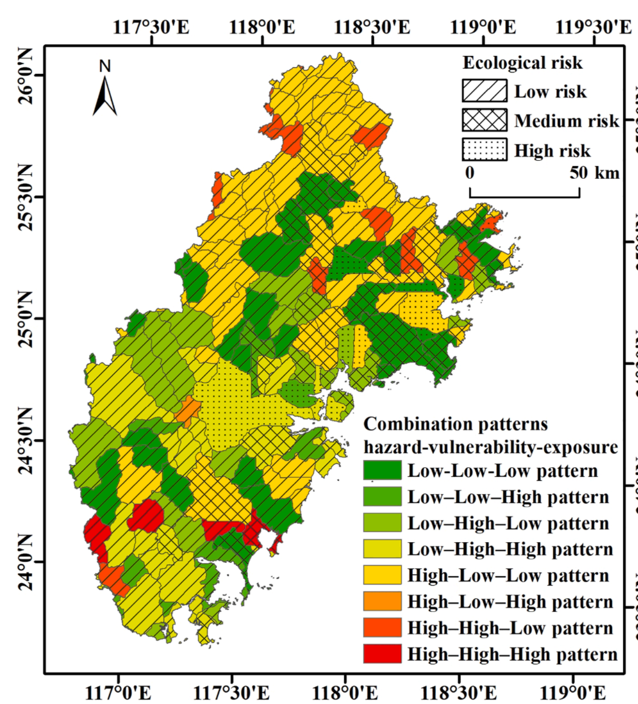

Fig. 8. Ecological risk of geological disasters and the combination patterns.

Table 3
Statistics on the ecological risk of geological disasters and the combination patterns.

Combination pattern	Low risk		Medium risk		High risk	
	Watershed unit/number	Share/%	Watershed unit/number	Share/%	Watershed unit/number	Share/%
Low hazard-low vulnerability-low exposure	39	34.51	2	5.71	0	0.00
Low hazard-low vulnerability-high exposure	0	0.00	5	14.29	3	27.27
Low hazard-high vulnerability-low exposure	11	9.73	7	20.00	0	0.00
Low hazard-high vulnerability-high exposure	0	0.00	15	42.86	7	63.64
High hazard-low vulnerability-low exposure	53	46.90	0	0.00	0	0.00
High hazard-low vulnerability-high exposure	0	0.00	0	0.00	1	9.09
High hazard-high vulnerability-low exposure	10	8.85	1	2.86	0	0.00
High hazard-high vulnerability-high exposure	0	0.00	5	14.29	0	0.00
Total	113	100.00	35	100.00	11	100.00

113, 35 and 11 respectively, indicating that the ecological risk of geological disasters in the area is mainly medium and low. Low risk covers four combination patterns, namely low hazard–low vulnerability–low exposure, low hazard–high vulnerability–low exposure, high hazard–low vulnerability–low exposure and high hazard–high vulnerability–low exposure, among which high hazard–low vulnerability–low exposure and low hazard–low vulnerability–low exposure are dominant, accounting for 46.90% and 34.51% respectively. Medium risk covers six combination patterns, namely low hazard–low vulnerability–low exposure, low hazard–low vulnerability–high exposure, low hazard–high vulnerability–low exposure, low hazard–high vulnerability–high exposure, high hazard–high vulnerability–low exposure and high hazard–high vulnerability–high exposure, among which low hazard–high vulnerability–high exposure is predominating, accounting for 42.86%. High risk covers three combination patterns, namely low hazard–low vulnerability–high exposure, low hazard–high vulnerability–high exposure and high hazard–low vulnerability–high exposure, among which low hazard–high vulnerability–high exposure is dominant, accounting for 63.64%. Therefore, the ecological risk of geological disasters in the area is predominated by high population exposure and the risk under the combination of high vulnerability and high exposure is the highest.

As shown by the overlapping result of the ecological risk and its combination patterns, in the future development of the urban agglomeration, prevention of the ecological risk of geological disasters requires sustainability measures in a customized way. Besides areas with high disaster hazard in the northwest, attention should also be paid to southeastern coastal plains with high population density, high economic development and intensive land development, because threats brought by the ecological risk lie not only in probability of occurrence of geological disasters, but also in consequent casualties and property losses. For some areas with high ecological risk, ways of land use can be moderately adjusted. Development strategies highlighting both development and conservation should be promoted and reserves or development-prohibited areas can even be established to reduce the ecological risk of local geological disasters and safeguard the efficient and sustainable development and the ecological civilization construction.

3.3. Spatial aggregation features of ecological risks of geological disasters

On the basis of comprehensive assessment result of the ecological risk of geological disasters, the study adopts the overall Moran's I index and the Getis-Ord Gi* partial statistical tool to analyze the spatial aggregation. As found out, the overall Moran's I index of the ecological risk in the study area is 0.3465 > 0 and the score of Z is 8.0111 > 1.96, meaning that the ecological risk in the area is significantly autocorrelated in space and the significant spatial correlation is positive. The Getis-Ord Gi* calculation result better reveals its regional spatial aggregation characteristics and the Gi* score is categorized into six levels (core coldspot, sub-core coldspot, peripheral coldspot, peripheral hotspot, sub-core hotspot, core hotspot). As shown in Fig. 9, the ecological risk in the urban agglomeration spatially displays the overall trend of gradual transition from core hotspots to core coldspots from southeastern coastal area to northwestern inland area. Core hotspots are mainly concentrated in the watershed units around downtown Xiamen and Quanzhou, indicating that these areas are high-value aggregation areas of the ecological risk of geological disasters. Core coldspots are concentrated in the watershed units in Dehua, Anxi and Pinghe in the northwest, meaning that these areas are low-value aggregation areas of the ecological risk.

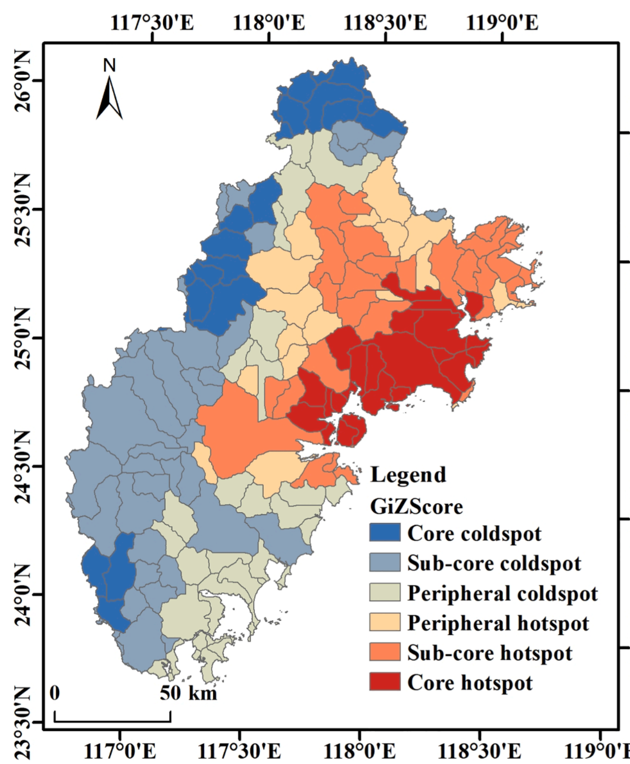

Fig. 9. Spatial aggregation of the ecological risk of geological disasters.

4. Discussion

4.1. Precision validation for hazard

Receiver Operating Characteristic curve (ROC) is a comprehensive indicator for continuous variables of sensitivity and specificity (Chen et al., 2013a, 2013b). It is widely applied in hazard assessment of geological disasters today. Larger Area Under the Curve (AUC), higher accuracy of diagnosis (Du et al., 2016). The study compares the geological disaster points with the hazard assessment result, defining the units with geological disasters as 1 and the units without geological disaster point as 0, and uses SPSS ROC curve to validate the accuracy of geological hazard assessment in combination with hazard value of geological disasters in the assessment units. As shown in Fig. 10, AUC value of the hazard assessment based on the information value model reaches 0.749, meaning the model generates a reliable result in the hazard assessment of geological disasters in the area.

As the ROC curve is simple and direct to observe, requires no choice of classification threshold, generates more objective assessment result and boasts higher test accuracy (Niu et al., 2011), this study selects it to assess the accuracy of hazards forecast. The research conclusion is consistent with the coupling relationship between the geological disaster points and the hazards. The geological disaster points are mainly distributed in the areas with high hazard, while the geological disaster points in the areas with low hazard are few. It can be found that the evaluation model can realize a high level of forecast accuracy in this area, which is similar to conclusions of related researches with the ROC curve in other areas. Therefore, the geological hazard hazard assessment model based on the information value model can better reflect the true probability of geological hazards in the region.

4.2. Comparison of different ecological risk assessments

Ecological risk refers to some uncertain accidents or disasters that may damage the structure and function of the ecosystem in a certain area, thus endangering the safety of the entire ecosystem, and it is an very important part of environmental risk assessment (Landis, 2003; Martin et al., 2003). The concept of sustainable development was put forward in 1972, the US Environmental Protection Agency defined ecological risk assessment and formed an ecological risk assessment framework (U.S. Environmental Protection Agency, 1992;). Since then, ecological risk assessment methods and theories have been continuously developed and improved (Wallack and Hope, 2002; Efroymson and Murphy, 2001; Du et al., 2016). Ecological risk assessment not only takes into account the uncertainty of environmental changes, but also adapts to the continuously changing natural and humane social environment (Wu et al., 2016). Ecological risk assessment as an important basis for regional ecological construction, resource management, environmental restoration and related decision-making, has attracted the attention of scholars, and has become the key to the current comprehensive assessment of ecosystems.

Currently, regional ecological risk assessment, as a branch of ecological risk assessment, has become a research hotspot at this stage and has achieved fruitful results (Su et al., 2017). Regional ecological risk research mainly includes disaster ecological risk, land ecological risk, watershed ecological risk, and urban ecological risk and so on (Landis and Wiegers, 1997; Wang et al., 2014; Du et al., 2016) (Table 4). It is not difficult to find that regional ecological risk assessment involves all aspects of natural and social economic systems. Different types of ecological risk assessment have their own rich research objects, and their ecological risk assessment connotations are also quite different. In addition, these research results for each object and each special area also effectively reveal the ecological risks of the region, and provide a solid scientific basis for formulating targeted regional disaster prevention strategies.

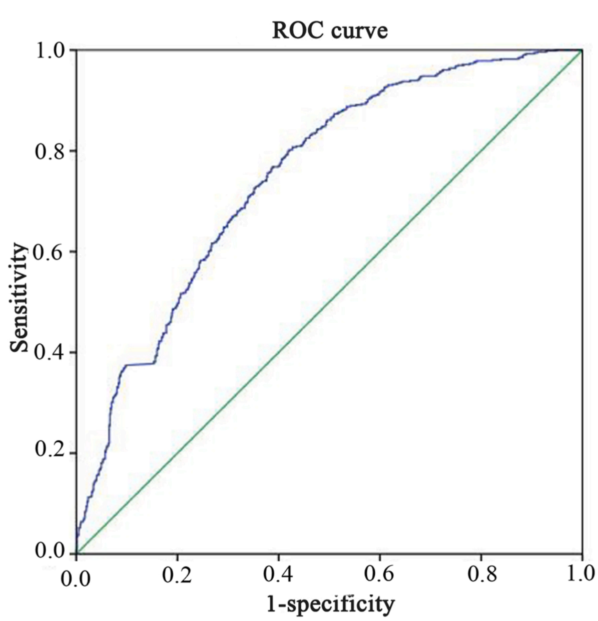

Fig. 10. Accuracy assessment result of hazard of geological disaster.

In recent years, the occurrence of natural disasters has increased, and the risk assessment of natural disasters has gradually been emphasized in disaster prediction (Liu and Shang, 2014), loss assessment and disaster reduction decision-making(Xu et al., 2004). However, the current disaster risk assessment focuses more on the hazard assessment of natural disasters in the region (Gong et al., 2012a, 2012b), while the ecological risk assessment that comprehensively considers the characteristics of the landscape pattern and exposure receptors in the region is relatively small. In this study, the ecological risk of geological disasters is divided into three dimensions: hazard, vulnerability and exposure, to construct an assessment framework for ecological risk assessment of geological disasters. Compared with the earlier geological disaster risk assessment, two new dimensions of landscape vulnerability and population exposure have been added, which can more comprehensively reflect the true ecological risks of geological disasters in the region, and make the disaster prevention and control strategies formulated more effective. In addition, based on the assessment results of the ecological risk of geological disasters, the combined pattern of ecological risk is explored from the three dimensions of hazard, vulnerability and exposure, and then ecological risk model of geological disasters is obtained.

4.3. Combination of greater likelihood in hazard

The study classifies the nine assessment indicators into different

Table 4
Types and connotations of regional ecological risk assessment.

Type	Object	Connotation
Disaster ecological risk	Landslides, mudslides, collapses, floods, droughts	The relationship between ecological risks and disasters is very close. Natural disaster ecological risks take various natural ecosystems as risk receptors, and at the same time pay attention to the impact of disasters on human society
Land ecological risk	Cultivated land, grassland, construction land, woodland	Quantitative characterization of the possibility of unreasonable land use leading to the deterioration of the land system, such as desertification, salinization, soil erosion, etc., thereby causing ecological damage or degradation
Watershed ecological risk	Rivers, lakes, ecologically fragile areas	With the increasing interference of human activities on the natural ecosystem of the basin, the landscape pattern and natural ecosystem of the basin have changed, which will affect the ecological security of the region
Urban ecological risk	Urban system, social system, economic system	Unfavourable changes and processes in urban ecological environment elements, ecological processes, ecological patterns and system ecological services in the process of urban development and urban construction

levels based on the actual natural geographical characteristics in the area and collects the number of disaster points, area by section and their information value at each level. As shown in Table 5, the elevation of 600–800 m, slope of 5 ~ 15°, aspect as southwest, NDVI of 0.4–0.6, lithology of metamorphic rocks, land use type as farmland, multi-year average precipitation of >1600 mm, distance to river of less than 200 m and distance to fault of less than 1000 m are the combination of greater likelihood of inducing geological disasters in the urban agglomeration in the Fujian Delta region.

Previous studies on assessment of geological disasters paid more attention to the main driving forces of geological disasters, such as the impact of topography (elevation, slope, aspect), climate conditions (temperature, precipitation), latitude and other factors on the occurrence of geological disasters. In fact, the occurrence of geological disasters is not affected by any single factor, but by a variety of factors in a certain state. Under the condition of the greater likelihood combination, the probability of geological disasters is greater. The discovery can identify vulnerable areas in the region that are prone to geological disasters, and can formulate targeted management and control strategies based on local conditions for different levels and combinations of geological disaster-prone areas.

4.4. Development strategy for prevention and control of geological disasters

The occurrence of geological disasters has posed a serious threat to

Table 5
Hazard assessment indicators of geological hazard of urban agglomeration in the Fujian Delta region.

Indicators	Classification standard	Deological hazard points (number)	Area (km^2)	Information quantity	Information quantity ranking
Elevation (m)	<200	424	10899.88	−0.7391	44
	200–400	409	4104.30	0.2016	13
	400–600	446	3833.71	0.3564	9
	600–800	491	3471.22	0.5519	2
	800–1000	226	1849.06	0.4058	7
	>1000	33	750.38	−0.6164	41
Slope (°)	<5	321	7410.06	−0.6315	42
	5–15	721	5707.34	0.4388	5
	15–25	739	7356.87	0.2096	12
	25–35	231	3766.83	−0.2839	36
	>35	17	667.44	−1.1626	50
Aspect	Flat (−1)	128	3648.09	−0.8423	46
	North (0–22.5)	99	1198.39	0.0141	27
	Northeast (22.5–67.5)	250	2774.27	0.1010	21
	East (67.5–112.5)	262	2885.28	0.1086	19
	Southeast (112.5–157.5)	253	2828.48	0.0936	23
	South (157.5–202.5)	259	2694.81	0.1654	15
	Southwest (202.5–247.5)	274	2823.75	0.1750	14
	West (247.5–292.5)	226	2565.39	0.0783	24
	Northwest (292.5–337.5)	182	2364.45	−0.0566	30
	North (337.5–360)	96	1125.64	0.0459	26
NDVI	<0.2	78	2114.81	−0.7811	45
	0.2–0.4	179	2197.57	0.0111	28
	0.4–0.6	350	2635.43	0.5000	4
	0.6–0.8	720	6352.66	0.3415	10
	>0.8	702	11888.60	−0.3105	37
Lithology	Metamorphic rock	51	187.32	1.2244	1
	Sedimentary rock	194	4013.66	−0.5042	40
	Eruption rock	1178	9791.49	0.4077	6
	Intrusive rock	594	11210.56	−0.4124	38
Land use types	Farmland	284	2061.65	0.5502	3
	Garden land	504	4751.33	0.2889	11
	Forest land	862	13513.23	−0.2197	34
	Grassland	88	950.09	0.1533	16
	Construction land	262	3074.55	0.0699	25
	Unused land	1	220.05	−2.8614	53
	Wetland	17	825.22	−1.3499	51
Average annual precipitation (mm)	<1300	58	1699.96	−0.8647	47
	1300–1400	56	2162.12	−1.1403	49
	1400–1500	131	4009.56	−0.9080	48
	1500–1600	600	6728.65	0.0960	22
	>1600	1126	9730.83	0.3566	8
Distance from river (m)	<300	997	11231.14	0.1037	20
	300–600	585	7362.51	−0.0071	29
	600–900	267	3891.49	−0.1539	33
	900–1200	110	1603.19	−0.1538	32
	1200–1500	23	563.63	−0.6735	43
	>1500	34	540.55	−0.2408	35
Distance from fault (m)	<1000	607	6623.95	0.1329	17
	1000–3000	841	9295.64	0.1201	18
	3000–5000	360	4755.09	−0.0580	31
	5000–10,000	197	3758.09	−0.4256	39
	>10,000	12	707.22	−1.5536	52

the lives and properties of residents in the region. In order to effectively prevent and control geological disasters, the government need to develop and implement scientific and reasonable prevention measures. This study analyzes the ecological risk of geological disasters and its patterns, which makes the disaster prevention measures more targeted in the future. The specific policy recommendations are as follows: (1) Focus on the disaster-prone areas under the combination of greater likelihood of inducing geological disasters. From the perspective the combination of greater likelihood, areas meeting multiple conditions of greater likelihood should be identified as areas of key concern. More conditions of greater likelihood that are met and more fragile disaster breeding environment indicate greater likelihood to induce geological disasters. Government can establish an automatic monitoring platform to monitor the disaster-prone areas. (2) Establish strong prevention and control measures in economically developed and populous areas. It is found that the harmfulness of geological disasters is not about their probability of occurrence, but about the consequent human casualties and social and economic losses. Therefore, it is necessary to set up emergency shelters, strengthen community disaster prevention drills, and even evacuate the crowd, so as to minimize the losses caused by geological disasters. (3) Persist with the sustainable development strategy that pays equal attention to development and protection. Along with the rapid economic and social development in urban agglomerations, population agglomeration in cities speeds up and land is developed continuously, intensifying the fragility of the ecological environment. Therefore, it is imperative to persist with the sustainable development strategy that pays equal attention to development and protection, avoid areas with high geological disaster hazard for economic construction, protect and restore ecologically fragile areas and even mark off construction forbidden areas to reduce the hazard of geological disasters.

5. Conclusion

The paper takes ecological risk of geological disasters as object of study and focuses on hazard, vulnerability and population exposure of geological disasters to establish an assessment indicator system. It uses the 169 watershed units as research units and comprehensively assesses the ecological risk of geological disasters in the urban agglomeration in the Fujian Delta region from the perspectives of spatial distribution, combination patterns and spatial aggregation characteristics. The main conclusions are as follows:

(1) The ecological risk of geological disasters shows a general trend of decreasing from southeastern coastal areas to northwestern inland areas. The sequence of different hazard levels by area is medium hazard > medium–high hazard > medium–low hazard > high hazard > low hazard, covering the area of 38.08%, 24.73%, 17.06%, 15.54% and 4.59% respectively. There is a significant spatial autocorrelation, and it is a significant spatial positive correlation, high-hazard areas are mainly distributed in the southeast coastal areas.

(2) The ecological risk is identified in eight different combination patterns that are predominated by high population exposure, and that under the combination of high vulnerability and high exposure is the highest. High hazard covers three combination patterns, among which low hazard–high vulnerability–high exposure is dominant, accounting for 63.64%.

(3) The combination of greater likelihood of inducing geological disasters is elevation of 600–800 m, slope of 5–15°, aspect as southwest, NDVI of 0.4–0.6, lithology of metamorphic rocks, land use type as farmland, multi-year average precipitation of >1600 mm, distance to river of less than 200 m and distance to fault of less than 1000 m.

(4) This study constructs a three-dimensional evaluation indexes system of hazard, vulnerability and exposure for the ecological risk assessment of geological disasters. It fully considers the importance of exposure receptors (human) and has achieved admirable results, which can further enrich the theories of ecological risk assessment.

CRediT authorship contribution statement

Jinhuang Lin: Conceptualization, Investigation, Methodology, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Mingshui Lin:** Conceptualization, Methodology, Resources, Writing - original draft, Writing - review & editing. **Wenhui Chen:** Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Validation, Writing - original draft, Writing - review & editing. **An Zhang:** Formal analysis, Supervision, Writing - original draft, Writing - review & editing. **Xinhua Qi:** Formal analysis, Funding acquisition, Supervision, Writing - original draft, Writing - review & editing. **Haoran Hou:** Data curation, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

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.

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