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Large-scale natural disaster risk scenario analysis: a case study of Wenzhou City, China

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Abstract Based on the analysis and calculation of the hazard intensity of typhoon rainstorms and floods as well as the vulnerability of flood receptors and the possibility of great losses, risk scenarios are proposed and presented in Wenzhou City, Zhejiang Province, China, using the Pearson-III model and ArcGIS spatial analyst tools. Results indicate that the elements of risk scenarios include time–space scenarios, disaster scenarios, and man-made scenarios. Ten-year and 100-year typhoon rainstorms and flood hazard areas are mainly concentrated in the coastal areas of Wenzhou City. The average rainfall across a 100-year frequency is 450 mm. The extreme water depth of a 100-year flood is 600 mm. High-vulnerability areas are located in Yueqing, Pingyang, Cangnan, and Wencheng counties. The average loss rate of a 100-year flood is more than 50%. The greatest possible loss of floods shows an obvious concentration-diffusion situation. There is an area of about 20–25% flood loss of 6–24 million Yuan RMB/km^2 in the Lucheng, Longwan and Ouhai districts. The average loss of a 100-year flood is 12 million Yuan RMB/km^2, and extreme loss reaches 49.33 million Yuan RMB/km^2. The classification of risk scenario may be used for the choice of risk response priorities. For the next 50 years, the 10-year typhoon rainstorm-flood disaster is the biggest risk scenario faced by most regions of Wenzhou City. For the Yueqing, Ruian, and Ouhai districts, it is best to cope with a 100-year disaster risk scenario and the accompanying losses.

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1 Introduction

With global warming, sea levels rising, and the accelerated urbanization process, the intensity and frequency of natural disasters and the vulnerability of society and the economy are growing quickly (Ruisong et al. 2010). More and more scholars are concerned about the risks of natural disasters in coastal cities (Yafeng et al. 2000; PeiJun et al. 2001; Shiyuan et al. 2006; Dapeng et al. 2008; Beibei et al. 2009; Yong et al. 2010). Currently, the basic method of disaster risk analysis is to build risk models (Chongfu 1999). Sophisticated risk assessment models and methods in China and abroad include the Disaster Risk Index (UNDP 2004), the Hotspots Projects (UNDP 2004), the System of Indicators for Disaster Risk Management (IDEA, IDB 2005), Multi-risk Assessment (Stefan 2006), HAZUS (FEMA 2004), and CBDRM (Bollin 2006). The spatial scales of disaster assessment are involved in global, continental, national, and local communities.

As one of the crucial competitive intelligence methods in enterprises (Gilbert 2000), scenario analysis has been widely used in economics (Yiming et al. 2006; Shrestha et al. 2007), environmental impact (Jawjit et al. 2008; Zhixi et al. 2010), ecology and ecosystem (Carpenter et al. 2006; Märker et al. 2008, Ferng 2009), and global change areas (Abildtrup et al. 2006; Tao and Watson 2010). Applied in hazard risk study, it is mainly used in earthquake (Klügel et al. 2006), flood disaster (Yanyan et al. 2009), environmental and man-made disaster (Tsai and Su 2004; de Bruin and Swuste 2008) risk assessment. Natural disaster risk scenario analysis is a scenario-based expression and characterization of natural disaster risk, which is often combined with GIS (Shaping et al. 2004; Pessina and Meroni 2009).

Specifically, based on the conditions of disaster risk scenarios, spatial distribution of risk is carried out. As for the risk scenario, it includes the time and space scenarios, disaster scenarios, and man-made scenarios. Taking Wenzhou City as a large spatial scale empirical area, this paper launched a typhoon rainstorm-flood disaster risk analysis study under the conditions of different time frames and disaster scenarios.

2 Materials and methods

2.1 Background about the study area

Wenzhou City is located in the Zhejiang Province in southeastern China (Fig. 1) with geographical coordinates between latitude 27°03′ and 28°36′ N and longitude 119°37′ and 121°18′ E. The city has a total population of about 0.75 million, covering an area of 11,784 km^2. Wenzhou has a subtropical marine monsoon climate with an average annual temperature of 18°C. Due to plenty of rain, its annual precipitation ranges from 1,100 to 2,200 mm. The average annual precipitation is 1,800 mm, and its spatial distribution and seasonal variation are uneven.

Located in the sea–land interface area, the effect between human and geography in Wenzhou is quite strong. There are frequent typhoons, torrents, floods, droughts, tides, cold snaps, and hailstones, and the floods caused by typhoons and storms occur quite often.

Fig. 1 The sketch map of the study area

According to the historical records, 73 floods and 64 large droughts took place from 684 to 1948 A.D. (1,264 years). Since the foundation of the People's Republic of China in 1949, there have been 198 typhoons affected Wenzhou in which large waves and heavy rain floods occurred 44 times. Due to global climate changes, the frequency and intensity of typhoon rainstorms and floods have gradually increased in Wenzhou.

2.2 Definition of risk scenarios

Risk scenario is defined as an outcome that is determined by combining a set of conditions, such as time span, spatial scale, the type of disaster, and man-made factors of hazards. Among them, spatial and temporal scenarios include time span (the next X years), spatial scales (large, medium, and small scale), and return period (X-year hazards). Disaster scenarios refer to the type of disaster, such as typhoon, rainstorm, flood, water-logging, etc. Man-made scenarios involve demographic, economic levels, land-use change, etc. (Figure 2). Scenario-based analysis of disaster risk involves exploring the demographic, economic, and social potential risks of different kinds of disasters and disaster groups, which are in the specific time and space situational conditions.

Wenzhou City's disaster risk scenario is defined as follows:

(a) In large spatial scale,
(b) In the next 50 years,
(c) 10-year and 100-year hazards,

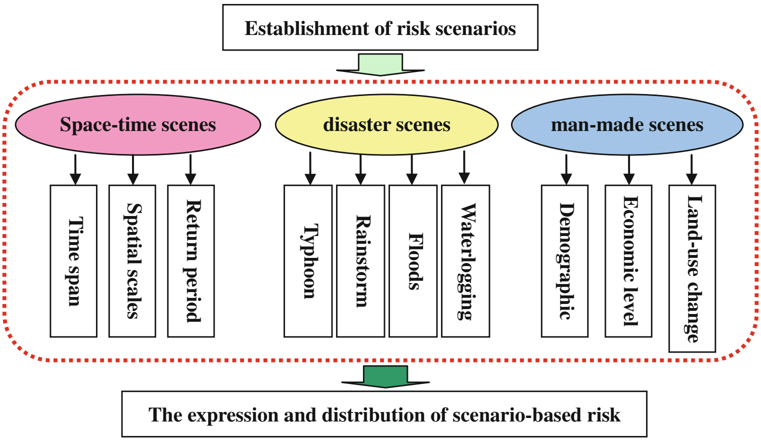


Fig. 2 The definition and types of risk scenarios

(d) Occurring in the form of typhoon rainstorm-floods, and
(e) The size and distribution of the disaster risk.

For the coastal cities, the large spatial scale refers to provinces, cities, and prefecture-level cities; the middle spatial scale refers to counties; and the small spatial scale refers to the community and the streets. Choosing two typical return periods, the paper explores the risk differences of Wenzhou City in the next 50 years.

2.3 Data collection and processing

In this study, the historical typhoon rainstorm monitoring data of Wenzhou city during the period of 1952–2006 were obtained from the Northwest Pacific tropical cyclone tracks retrieve information system, Wenzhou Historical Flood and Drought Information, Wenzhou City Annals, Wenzhou City Water Annals, and Zhejiang Meteorological Disasters Annals (2003–2007) (http://www.zjmb.gov.cn).

The hazard-bearing objects type and spatial distribution data were derived from land-use maps of the Zhejiang Province (1997) and the Zhejiang Province land-use plan (1997–2010) (http://gtt.zj.gov.cn/). The per unit area GDP data for Wenzhou City and the surrounding districts and counties were obtained from the Wenzhou Statistical Yearbook 2008 (http://www.wzstats.gov.cn/), the Zhejiang Statistical Yearbook 2008 (http://tjj.zj.gov.cn/), and the Fujian Statistical Yearbook 2008 (http://www.stats-fj.gov.cn/). All the original data are publicly available at the websites listed here or in the publications.

2.3.1 Pearson-III model frequency analysis

The Pearson-III probabilistic model was used to estimate the intensity of typhoons rainstorms in different frequencies. Its probability density function is as follows:

$$f(x) = \frac{\beta^{\alpha}}{\Gamma(\alpha)}(x - \alpha_0)^{\alpha-1}e^{-\beta(x-\alpha_0)} \tag{1}$$

where $\Gamma(\alpha)$ is α's gamma function and α, β, α_0 are three parameters.

$$\alpha = \frac{4}{C_s^2}; \beta = \frac{2}{\bar{x}C_v C_s}; \alpha_0 = \bar{x}\left(1 - \frac{2C_v}{C_s}\right) \tag{2}$$

where $\bar{x}$ is the average value; C_v is the deviation coefficient; and C_s is the deviation coefficient.

The relationship between the return period T_n (years) and the annual frequency p (%) is as follows:

$$T_n = \frac{1}{p} \tag{3}$$

By the formula (1) and (2), the intensity frequency distribution of typhoon rainstorm disasters in Wenzhou City was calculated at different frequencies p (%). By the formula (3), the return period of T_n (a) at different frequencies p (%) was calculated.

2.3.2 ArcGIS spatial analyst

The ArcGIS spatial analyst has proved to be a powerful tool for comprehensive, raster-based spatial modeling and analysis (Beibei et al. 2009). In this article, the Kriging Interpolation, the Reclassification and the Rater Calculator, and statistics tool were used to analyze the data. The Kriging Interpolation model was used to create the raster surface of the spatial distribution with storm rainfall and per unit area GDP. The Reclassification tool was used to reclassify and determine statistical spatial areas of hazards, vulnerability, and losses. The Rater Calculator tools were widely used in the conversion of rainfall to the surface runoff (water depth), water depth to disaster loss rate, and disaster loss rate to losses.

The resolution of all thematic raster maps is 500 × 500 m, and the image resolution is 150 dpi. The rainfall runoff transfer function is as follows:

$$h = 188.425 + 2.143 * p - 3.572 * m + 1.007 * s$$

where h is the flood depth (mm); p is the typhoon storm's daily rainfall (mm); m is the surface permeable area (%); and s is the terrain slope (°). The Submergence-Disaster loss rate function is as follows (Guoqing 1990; Vrisou van Eck and Kok 2001):

$$\beta = 51.087 + 28.2778\chi \text{ (for agricultural and garden land)}$$

$$\beta = -3.182 + 17.1306\chi \text{(for forest land)}$$

where β is the flood disaster loss rate (%) and χ is the depth of flood (m).

The disaster loss rate-losses function is as follows:

$$L = k\beta$$

where L is the flood disaster losses (million Yuan RMB/km^2) and k is the per unit area GDP (million Yuan RMB/km^2).

2.3.3 Disaster risk rating matrix

Disaster risk is characterized by great loss and its probability. The disaster losses are divided into five categories, namely micro-disaster, small disaster, mid-disaster, large disaster, and catastrophe. The probability can be divided into five, namely very low, low, intermediate, high, and extremely high. Determined by the discriminant matrix of the

Table 1 Disaster risk grading matrix

Probability	Losses				
	Micro-disaster	Small disaster	Mid-disaster	Large disaster	Catastrophe
Very low	Low risk	Low risk	Medium risk	Medium risk	High risk
Low	Low risk	Medium risk	Medium risk	Medium risk	High risk
Intermediate	Medium risk	Medium risk	Medium risk	High risk	High risk
High	Medium risk	Medium risk	High risk	High risk	Extremely high risk
Extremely high	High risk	High risk	High risk	Extremely high risk	Extremely high risk

Table 2 The grading table of disaster losses (million Yuan RMB/km^2) and probability (%)

Losses	Categories	Micro-disaster	Small disaster	Mid-disaster	Large disaster	Catastrophe
	Standard	≤10	10–20	20–30	30–40	≥40
Probability	Categories	Very low	Low	Intermediate	High	Extremely high
	Standard	0–20	20–40	40–60	60–80	80–100

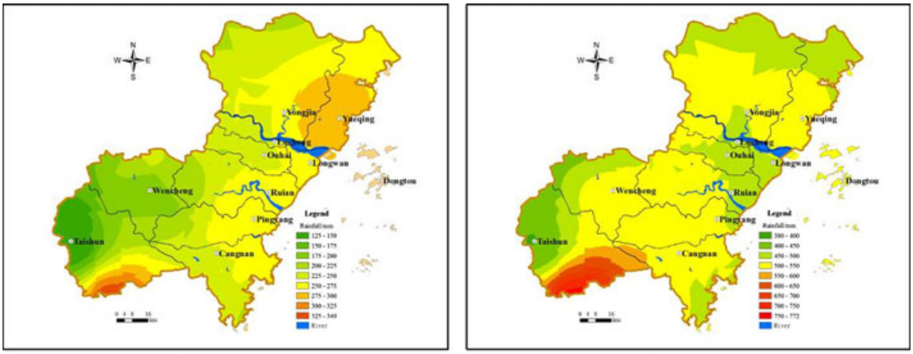
losses and its probability, disaster risk is divided into four categories, namely low risk, medium risk, high risk, and extremely high risk with the corresponding warning signal followed by green, yellow, orange, and red (Table 1). Among them, low risk includes three combination types of losses and their probability. Medium risk includes 10 types; high risk includes 9 types; and extremely high risk includes 3 types. The quantitative classification standard of disaster losses and probability is seen in Table 2.

3 Results and discussion

3.1 The distribution of hazard

Typhoon rainstorm hazard areas are mainly concentrated in the coastal areas in Wenzhou, such as Yueqing City, Longwan district, Ruian City, and Pingyang County. Among them, 10-year frequency storm rainfall distribution shows an increased northeast–southwest pattern from coastal to inland areas. There are noticeable “extreme rainfall” centers of 100-year storm rainfall in Yueqing City, Taishun County, which is the south junction of Ruian City and Pingyang (Fig. 3). Ten-year frequency rainfall ranged between 125 and 349 mm in which 225–275 mm occupy a total area of 61.71%. The average rainfall of 100-year frequency is 450 mm or more, and the level of extreme rainfall reached 772 mm. Additionally, 500–550 mm accounted for 56.69% in Wenzhou City (Table 3).

Typhoon rainstorm-flood depth is affected by the rainfall, runoff coefficient, slope, and other factors. The flood hazard areas are mainly concentrated in coastal areas in Wenzhou. Individual point areas, such as Taishun and the west of Yongjia County, are also flood hazard areas. 10-year flood distribution also shows an increased northeast–southwest pattern. 100-year flood “submerged” centers also appear in Yueqing, Wen Cheng County,



10-year hazard 100-year hazard

Fig. 3 The spatial distribution of typhoon rainstorms

Table 3 The statistics of typhoon rainstorm spatial areas

Return period = 10 a	Return period = 100 a				
Classification/mm	Area/km^2	Area ratio/%	Classification/mm	Area/km^2	Area ratio/%
125–150	474.89	4.03	380–400	22.68	0.19
150–175	298.35	2.53	400–450	721.80	6.13
175–200	1,018.98	8.65	450–500	3,593.79	30.50
200–225	1,406.89	11.94	500–550	6,679.97	56.69
225–250	3,600.81	30.56	550–600	333.89	2.83
250–275	3,670.25	31.15	600–650	179.11	1.52
275–300	1,155.06	9.80	650–700	140.06	1.19
300–325	101.01	0.86	700–750	84.64	0.72
325–349	57.29	0.49	750–772	27.59	0.23
Total	11,784.00	100.00	–	11,784.00	100.00

west of Yongjia County, and south of Taishun County (Fig. 4). 10-year flood depth focuses on 150–250 mm, which accounts for 75.83% of the total area. 100-year flood depth focuses on 400–500 mm, accounting for 77.07% (Fig. 4). The average depth of a 100-year flood caused by a typhoon rainstorm in Wenzhou is 0.5 m with an extreme water depth of 600 mm (Table 4).

3.2 The distribution of vulnerability

The vulnerability of floods is impacted by the surface water depth and underlying surface properties. The flood disaster loss rates for the coastal areas are relatively high in Wenzhou, especially Yueqing City, the Longwan District, Ruian City, and Pingyang County. 10-year flood vulnerability increased from inland to coastal areas. 100-year flood statistics showed a clear "high vulnerability" center mainly in Yueqing City, Pingyang, Cangnan, and WenCheng County (Fig. 5). The 10-year flood loss rate is usually <2%,

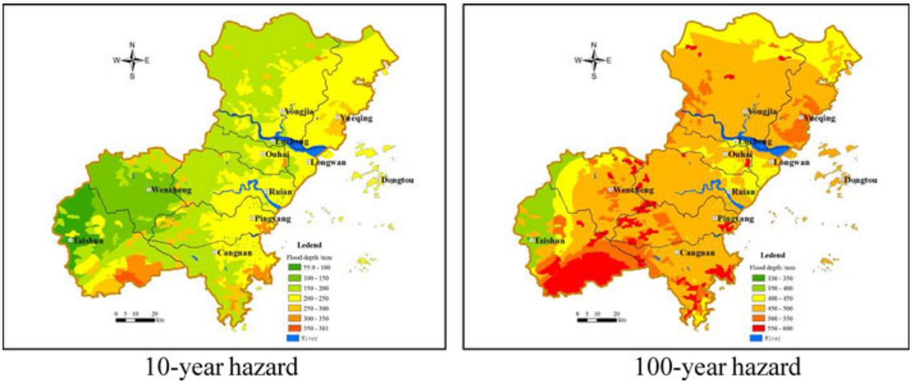


Fig. 4 The spatial distribution of water-logging submergence

Table 4 The statistics of water-logging submergence spatial areas

Return period = 10 a			Return period = 100 a		
Classification/mm	Area/km^2	Area ratio/%	Classification/mm	Area/km^2	Area ratio/%
60–100	468.11	3.97	330–350	2.58	0.02
100–150	1,456.78	12.36	350–400	591.75	5.02
150–200	4,691.17	39.81	400–450	1,977.82	16.78
200–250	4,244.37	36.02	450–500	7,105.01	60.29
250–300	597.37	5.07	500–550	1,123.56	9.53
330–350	271.64	2.31	550–600	983.29	8.34
350–380	54.56	0.46	–	–	–
Total	11,784.00	100.00	–	11,784.00	100.00

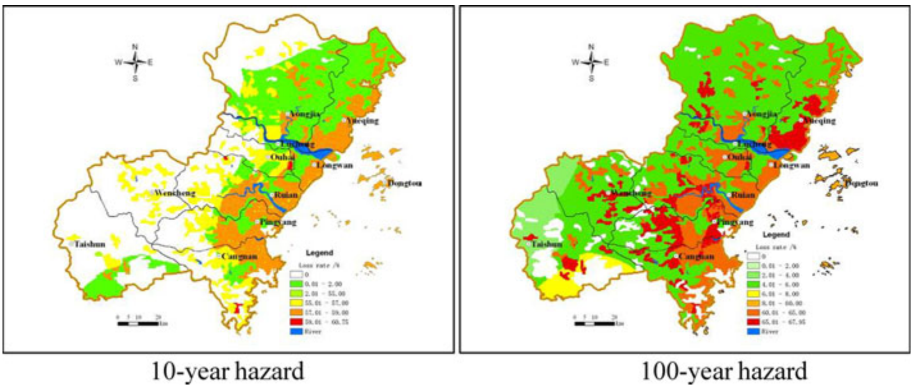


Fig. 5 The spatial distribution of flood vulnerability

accounting for 70.82%. The loss rate of 50–60% has a stabile spatial distribution, which is mainly for agricultural land. The average loss rate of a 100-year flood caused by a typhoon rainstorm in Wenzhou is 50%. The extreme loss rate is 67.95% (Table 5).

Table 5 The statistics of flood vulnerability spatial areas

Return period = 10 a	Return period = 100 a				
Classification/%	Area/km^2	Area ratio/%	Classification/%	Area/km^2	Area ratio/%
0.00	5,243.34	44.50	0.00	964.55	8.19
0.01–2.00	3,102.54	26.33	0.01–2.00	0.00	0.00
2.01–55.00	30.68	0.26	2.01–4.00	751.22	6.37
55.01–57.00	1,536.17	13.04	4.01–6.00	6,330.14	53.72
57.01–59.00	1,847.85	15.68	6.01–8.00	299.97	2.55
59.01–60.75	23.42	0.20	8.01–60.00	0.00	0.00
–	–	–	60.01–65.00	2,156.96	18.30
–	–	–	65.01–67.95	1,281.15	10.87
Total	11,784.00	100.00	–	11,784.00	100.00

3.3 The distribution of disaster losses

The potential for great loss from floods is influenced by the value and vulnerability of a disaster receptor. The spatial distribution of flood loss showed an obvious concentration-diffusion situation. The flood loss agglomeration areas are in the Lucheng District, Longwan, and Ouhai, which are the economic centers of Wenzhou. The first diffusion zone is located in the periphery of Ruian City, Yongjia County, and Yueqing City. The second diffusion area is located in Pingyang and Cangnan County. The third diffusion zone is concentrated in the southwest of Taishun County, Yongjia County, and the northwest of Wencheng County (Fig. 6).

It has been found that 70.96% of the 10-year flood damage area is less than 1 million Yuan/km^2. Hundred-year flood losses are 2 million Yuan/km^2. There is an area of about 20–25% flood loss of 6–24 million Yuan/km^2, which is located in three districts that are experiencing rapid economic development (Lucheng, Longwan, and Ouhai). The average loss from a 100-year flood caused by a typhoon rainstorm in Wenzhou is 12 million Yuan/km^2. The extreme losses reached 49.33 million Yuan/km^2 (Table 6).

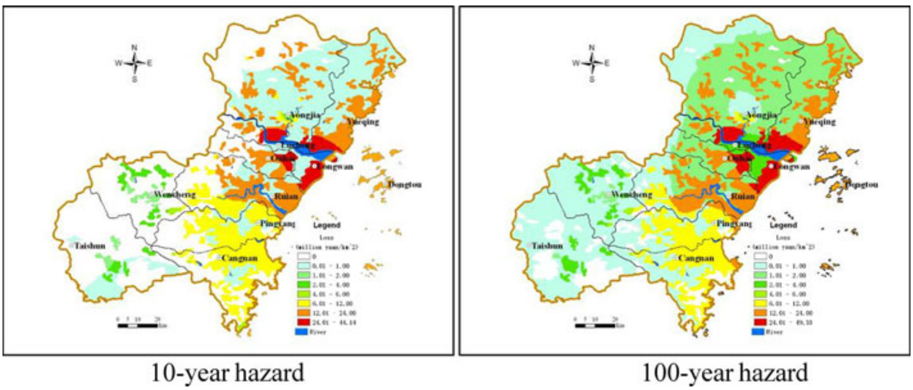
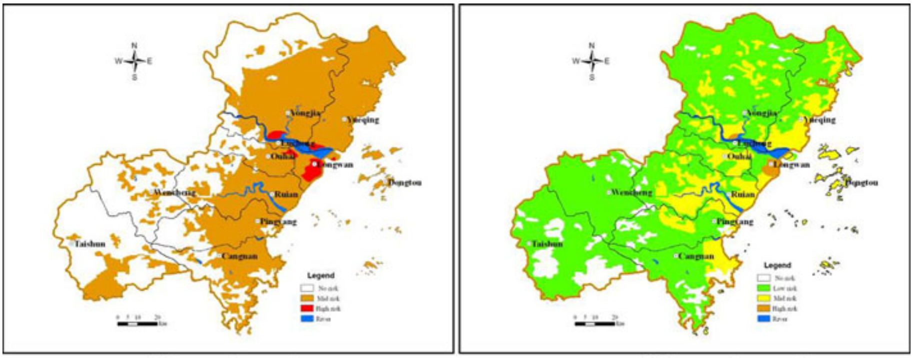


Fig. 6 The spatial distribution of disaster losses

Table 6 The statistics of disaster loss spatial areas

Classification (million Yuan/km^2)	Return period = 10 a		Return period = 100 a	
	Area/km^2	Area ratio/%	Area/km^2	Area ratio/%
0	5,243.34	44.50	964.55	8.19
0–1	3,118.47	26.46	4,213.69	35.76
1–2	129.03	1.09	2,984.52	25.33
2–4	204.20	1.73	519.39	4.41
4–6	50.11	0.43	36.76	0.31
6–12	1,331.03	11.30	1,182.10	10.03
12–24	1,350.24	11.46	1,429.85	12.13
24–49	357.58	3.03	453.12	3.85
Total	11,784.00	100.00	11,784.00	100.00



10-year hazard 100-year hazard

Fig. 7 The spatial distribution of disaster risk

3.4 The distribution of disaster risk

In considering the two factors of the possible loss and the probability, the same region in Wenzhou City bears a different risk level for a 10-year and a 100-year typhoon rainstorm-flood over the next 50 years. In addition to a risk-free region, there are medium- and high-risk levels of a 10-year typhoon rainstorm-flood disaster. Medium-risk areas are widely distributed in the central and eastern regions of Wenzhou. High-risk areas are concentrated in the Longwan and Lucheng Districts (Fig. 7).

There are four levels of 100-year typhoon rainstorm-flood disaster risk, which are risk-free, low, medium and high. Low-risk areas are the largest space and are located in most parts of Wenzhou. Risk-free and medium-risk areas reveal a spotty distribution throughout Cangnan County, Pingyang County, Ruian City, Yueqing City, and the Ouhai and Lucheng Districts. High-risk areas are concentrated in Yongzhong Street within the Longwan District.

4 Conclusions

In this study, the concept and elements of risk scenarios are proposed. The combinations of time and space scenarios, disaster scenarios, and man-made scenarios are the basis of risk expression. By using the Pearson-III Model and ArcGIS spatial analysis, the risk of typhoon rainstorms and floods, the vulnerability of flood receptors, and the potential for great losses are analyzed and calculated. The risk levels are characterized by flood losses and probability.

Typhoon rainstorm and flood hazard areas are mainly concentrated in the coastal areas of Wenzhou City. The average rainfall within a 100-year frequency is 450 mm. The extreme water depth of a 100-year flood is 600 mm. High-vulnerability areas are located in Yueqing City, Pingyang, and the counties of Cangnan and WenCheng. The 10-year flood loss rate is usually less than 2%, while the average loss rate of a 100-year flood is more than 50%. The potential for great flood loss showed an obvious concentration-diffusion situation. Additionally, 70.96% of the 10-year flood damage area is less than 1 million Yuan RMB/km^2. There is an area of about 20–25% flood loss of 6–24 million Yuan RMB/km^2 in the Lucheng, Longwan, and Ouhai Districts. The average loss from a 100-year flood is 12 million Yuan RMB/km^2. The extreme loss reached 49.33 million Yuan RMB/km^2.

The importance of the risk classification based on different scenarios is that it can help to determine the priority level for different disaster intensities within the same regions in a future time period. Over the next 50 years, it is recommended that most of Wenzhou City attempt to cope with the predicted 10-year typhoon rainstorm-flood disaster risk. For the regions in the same risk level, such as Yueqing, Ruian City and the Ouhai District, the possibility of a 100-year disaster risk should be considered. Obviously, a 100-year flood disaster would result in great losses.

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