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Risk Assessment of Flood Disaster Induced by Typhoon Rainstorms in Guangdong Province, China

Jiayang Zhang and Yangbo Chen *

School of Geography and Planning, Sun Yat-Sen University, Guangzhou 510245, China;
zhangjy225@mail2.sysu.edu.cn

* Correspondence: eescyb@mail.sysu.edu.cn; Tel.: +86-020-8411-4269

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Abstract: China's coastal areas suffer from typhoon attacks every year. Rainstorms induced by typhoons characteristically are high intensity with a large amount of rain and usually induce floods and waterlogging in the affected area. Guangdong province has the highest frequency of typhoon hits in China. It has a special geographical position as well as unique climatic features, but the typhoon flood disaster risk has not been fully assessed in this area. This article attempts to fill this gap by providing a comprehensive risk assessment for the area. By combining the Analytical Hierarchy Process (AHP) and multi-factor analysis through geographic information system (GIS) and the comprehensive weighted evaluation, the typhoon flood disaster risk is evaluated from four different aspects with seventeen indicators. A comprehensive study of the typhoon flood disaster risk is carried out, and the risk maps with a resolution of 1 km² have been made. There is a good coherence between the typhoon flood risk map and historical records of typhoon floods in Guangdong province. The results indicate that the comprehensive typhoon flood disaster risk in the coastal regions of Guangdong province is obviously higher than in the Northern mountainous areas. Chaoshan plain and Zhanjiang city have the highest risk of typhoon flood disaster. Shaoguan and Qingyuan cities, which are in the Northern mountainous areas, have the lowest risk. The spatial distribution of typhoon flood disaster risks shows that it has certain regulations along the coast and rivers, but it may be affected by economic and human activities. This article is significant for environmental planning and disaster management strategies of the study area as well as in similar climatic regions in other parts of the world.

Keywords: typhoon rainstorms; flood disaster; analytical hierarchy process (AHP); comprehensive weighted evaluation (CWE); risk assessment

1. Introduction

A typhoon is one of the most destructive disasters, which usually causes floods, storm surges and mudslides [1–3]. Heavy rainfall phenomena occur frequently because of typhoons' strong ascending motion and sufficient water vapor. Typhoon rainstorms have the features of high frequency, strong suddenness, a wide influence range, and a high disaster intensity [4]. The center of a typhoon rainstorm can drop 100–300 millimeters of rain a day, sometimes as much as 500–800 millimeters. When a typhoon makes landfall, the rainstorm intensity and the possibility of a flood disaster increase due to topographical influences [5,6]. China is frequently affected by typhoons, and, on average, nine typhoons per year make landfall in China [7–9]. In China, rainstorms caused by typhoons account for 52.7% of all rainstorms, which is more than half of the total annual rainstorms [7,10]. The frequent occurrences of typhoon rainstorms and floods indicate that it is not realistic to predict and prevent the occurrence of typhoons and rainstorms completely and accurately. However, if effective disaster management strategies are adopted, the huge losses caused by typhoon floods can be avoided or

reduced. Therefore, it is of great practical significance to accomplish a risk analysis and risk map compilation of typhoon rainstorm flood disasters to decrease disastrous losses from typhoon rainstorms and floods [11]. Guangdong province is close to the South China Sea and has a high drainage density, so typhoon flood cases appear more frequently in this province than in other provinces, and the number of disasters is increasing year by year [12,13]. Therefore, assessment of the typhoon flood risk is necessary for Guangdong province [14,15].

The study of disaster has a long history, but the study of disaster risk assessment originated in the middle of the last century [16]. Early studies on disaster risk assessment methods mainly focused on qualitative assessment methods, but due to the uncertainty of disaster assessment, the qualitative assessment could not meet the research needs; thus research gradually moved from qualitative methods to a combination of qualitative and quantitative methods, or fully quantitative methods [17–20]. At present, risk assessments are based on four main methods: (1) Mathematical statistics, a method usually used to calculate the intensity and frequency of disaster occurrence from historical disaster data and loss data [21,22]; (2) an indicators system, which usually selects reasonable disaster indicators and determines the weight of each indicator to build a risk assessment model and then conduct a comprehensive risk assessment [8,23–26]; (3) RS-GIS technique, in which the satellite remote sensing data are processed and analyzed to determine the flood area and disaster high-risk area with the help of GIS technology [27,28]; and (4) scenario simulation, a method that conducts hydrological and hydrodynamic models to simulate flood scenarios [29–31]. Lots of studies show that the second disaster risk assessment method can reflect the regional risk situation on a macro level, and it has been widely applied because it is simple to conduct. There are several ways to conduct the indicators system method, such as fuzzy comprehensive evaluation (FCE), principal component analysis (PCA), gray relative analysis method (GRA), and comprehensive weighted evaluation (CWE) [32–34]. Among these methods, CWE combined with the analytic hierarchy process (AHP) is commonly used to assess the flood disaster risk [26,35–41].

The purpose of this study was to establish a regional model of typhoon flood risk zones in Guangdong province. Semi-quantitative estimates of natural risk assessment are considered useful when the possibility of accessing multi-source data is limited [26,42,43]. Therefore, the semi-quantitative method was chosen. We selected 17 factors that impact the typhoon flood disaster risk and used the AHP to determine the weight of each factor. Then, we used comprehensive evaluation techniques to assess the typhoon flood disaster risk and obtain a risk level map with a higher spatial resolution (1 km²) than that of previous research whose space scales were usually administrative divisions. The rest of the paper is organized as follows: Section 2 introduces the geographical situation, climatic environment, population and economy of Guangdong province. Section 3 mainly introduces the data and methods adopted in this research, including establishment of indicators system and building the comprehensive superposition model. Section 4 shows standardization results and the calculation of each factor's weight, besides, the risk level of typhoon flood disaster and its aspects in Guangdong province are presented in this part, and then the accuracy of the risk map is validated with historical records. Section 5 summarizes the process and draws the conclusions, aiming at summarizing a set of risk grades of flood disaster caused by typhoons in coastal areas to provide a basis for the deployment and prediction of flood control and risk resistance work.

2. Study Area

Guangdong Province is located in the Southern part of China near the South China Sea, spanning 109°45′–117°20′ E and 20°09′–25°31′ N (Figure 1). The whole region covers approximately 179.7 thousand km², accounting for 1.87% of the total area of China. Topographically, Guangdong province's higher area is in the North, and its lower area is in the South, so the North area is mostly mountainous and hilly and the South is covered by plains. The Pearl River delta plain is the largest delta plain in Guangdong province; it is open terrain and is easily waterlogged. The climate presents typical subtropical monsoons, and it ranks first among all provinces of China for the number of

typhoons that make landfall in China every year. The precipitation from July to September is mainly brought by typhoons, accounting for 40–50% of the annual precipitation in the Southern area and 30% in the Northern mountainous area of Guangdong Province [44]. According to *The flood, drought and wind disasters in Guangdong*, the major floods in the Pearl River Delta in 1994 (No. 9403), 1915 (No. 1506), 1949 (No. 4902), and 1833 were predominantly caused by typhoon rainstorms.

Figure 1. Location and terrain properties of the study area.

Guangdong Province, with its rapid economic development, is one of the fastest growing provinces of China in terms of the progress of urbanization. The population of Guangdong is about 111.69 million (until the end of 2017), and the population in cities is 78.02 million, accounting for 69.85% of the total. Major cities of Guangdong province are distributed in Pearl River Delta, including Guangzhou, Shenzhen, Foshan, Dongguan, Zhongshan, Zhuhai, Jiangmen, Zhaoqing, Huizhou. In the process of rapid urbanization, land use changes lead to increases in impervious areas such as roads and houses and decreases in urban natural vegetation and river networks. The above urbanization process leads to a decline in the urban drainage capacity. After typhoon rainstorms, the interception, depression filling, and infiltration of the underlying surface decrease, and the runoff is increased while concentration time is shortened. Most cities in Guangdong province are located in low-lying areas such as Pearl River Delta, and these areas are highly urbanized and populated, which making them more vulnerable to typhoon-induced rainstorms and floods [13].

3. Data and Methodology

3.1. The Model of Typhoon Flood Risk Assessment

3.1.1. The Theory of Typhoon Flood Risk Assessment

Risk assessment of natural disasters refers to the assessment and estimation of the intensity of natural disaster factors and the potential disaster degree, which is the application of risk analysis technology in natural disaster science [45]. The natural and social attributes of natural disasters should be taken into account in risk assessment [46,47]. Typhoon flood disasters are a kind of natural disaster, so they are also considered from natural and social attribute points of view. Considering the natural attributes, including the severity of typhoon flood hazard causing factors and the sensitivity of hazard breeding environments, these two aspects directly affect the formation and risk level of a disaster. The

severity of a typhoon flood hazard causing factor mainly refers to the risk factors that may cause the flooding of farmlands and houses, as well as urban waterlogging and property or personnel losses. The sensitivity of a hazard breeding environment refers to the promotion and inhibition of typhoon flood disasters. Considering the social attributes, including the vulnerability of hazard bearing objects and hazard prevention and mitigation capability, these two aspects directly reflect the ability of the region to respond to an emergency as well as its post-disaster recovery capability. The vulnerability of a hazard bearing objects refers to the extent to which people and property in the risk assessment area suffer losses in the event of a typhoon flood. Hazard prevention and mitigation capability refers to disaster prevention and post-disaster recovery capability, which are related to the installation of hydrological stations and medical facilities as well as personnel allocation and traffic conditions in disaster areas. Based on the above analysis, the risk of typhoon flood disaster can be regarded as a composite function with four aspects, as shown in the following formula:

$$\text{TFDR} = (H^{wh})(S^{ws})(V^{wv})(1 - R^{wr}) \quad (1)$$

where, TFDR (Typhoon Flood Disaster Risk) represents the comprehensive risk index of typhoon flood disasters. The smaller of the value of TFDR is, the smaller the comprehensive index of typhoon flood disaster risk is and vice versa. H, S, V, and R represent four aspects of typhoon flood risk assessment: The severity of hazard causing factors, the sensitivity of the hazard breeding environment, the vulnerability of hazard bearing objects, and the capability for hazard prevention and mitigation. In addition, wh, ws, wv, and wr are the corresponding weights of each evaluation aspect.

3.1.2. Data Acquisition

We collected sufficient data in different fields including meteorology, hydrology, geography, topography, and statistics. Then a database has been established in a geospatial environment. The meteorological data in Guangdong Province were obtained from the National Meteorological Information Center during 1988–2017, which includes 36 meteorological stations [48]. Typhoon data were downloaded from the China Meteorological Administration (CMA) Tropical Cyclone Data Center [49,50]. The land use and land cover data and administrative division data were provided by the Chinese Academy of Sciences [51]. Digital elevation model data were selected from the Shuttle Radar Topography Mission (STRM) system of digital elevation model data (90 m resolution) [52]. Social and economic data were collected from the Statistical Yearbook of Guangdong Province (2017) and the Guangdong statistical information website [53]. Population density data were collected from the Gridded Population of the World (GPW) of Socioeconomic Data and Applications Center (SEDAC) [54]. Road data were taken from OpenStreetMap [55].

3.1.3. Establishment of the Indicators System

In this study, four aspects of risk assessment (H, E, V, and R) were disaggregated into more specific indicators, and seventeen factors were selected based on literature reviews. Each indicator of the different risk assessment aspects is shown in Figure 2.

As Figure 2 shows, the hazard aspect includes four indicators, which are the mean maximum wind, typhoon frequency, mean daily rainfall, and frequency of heavy rainfall. The mean maximum wind and typhoon frequency reflect the destruction of typhoon wind on the underlying surface. The mean daily rainfall and frequency of heavy rainfall are the two factors that contribute most to disasters, and they represent the impact of a typhoon rainstorm. There are 36 meteorological stations in Guangdong province, and these four indicators were all identified from meteorological data. The typhoons which passed through Guangdong were identified from the typhoon data of the CMA. Typhoon frequency is the number of typhoons that passed through each city in Guangdong province. Additionally, the typhoon-induced rainstorms that influence Guangdong province were filtrated by the characteristics of each typhoon that passed through Guangdong and the 500 km buffer zone around

Guangdong. Heavy rainfall frequency refers to the frequency of mean daily rainfall greater than 50 mm.

The sensitivity aspect includes four indicators: Elevation, slope, drainage density, vegetation coverage. Elevation and slope reflect the topography of a disaster-prone environment, while drainage density and vegetation coverage reflect the surface of a disaster-prone environment.

The vulnerability aspect includes four indicators, which are population density, industrial production, cultivated land, and urbanization density. The population density is used to reflect the impact on human life, industrial production and cultivated land are used to reflect the impact on industrial and agricultural production, and urbanization density reflects the phenomenon of urban waterlogging in urbanized areas.

As for the restorability aspect, we used road density and drainage density to represent the emergency response, GDP per capita, hospital bed capacity, and the number of medical staff to represent the recovery capability. Hence, typhoon flood disaster risk is the result of the combined action of these factors [56].

Figure 2. Hierarchy of the typhoon flood risk multi-factor system in Guangdong Province. Yellow represents the goal—typhoon flood risk assessment, green represents four aspects in the assessment, and pink and blue are the factors used to construct the assessment model. Besides, pink factors have positive effects on risk, while blue factors have negative effects.

3.2. The Methods Used in the Typhoon Flood Risk Assessment

3.2.1. GIS Spatial Interpolation

Spatial interpolation is an important method for the spatial analysis of geographic information systems. This method can be used to deduce the position and characteristics of unknown points based on known points, and it is a method to extend points to the surface. The spatial interpolation method is mainly used for raster data analysis. The most widely used spatial interpolation methods include Thiessen Polygons, Inverse Distance Weighted (IDW), Kriging interpolation, and Spline Function. In this study, IDW interpolation was carried out for the spatial interpolation of discrete data related to the mean maximum wind, mean daily rainfall, and frequency of heavy rainfall to obtain regionally continuous raster data.

IDW interpolation is an interpolation method that uses the distance search strategy to select the interpolation reference point. The closer the unknown point is to the interpolation point, the greater

the contribution to the interpolation result will be, and thus, the higher the weight will be. The IDW interpolation formula is as follows:

$$Z(x_0) = \left(\sum_{i=1}^n \frac{Z_i}{d_i^m} \right) / \left(\sum_{i=1}^n \frac{1}{d_i^m} \right) \quad (2)$$

where $Z(x_0)$ is the predicted value of the estimated point x_0 , Z_i is the measured value of the given point i , n is the number of given points, d_i is the distance between the estimated point x_0 and given point i , m is the power, $\frac{1}{d_i^m}$ is the weight based on distance.

3.2.2. Standardization

Natural disaster risk assessment indicators are from multiple sources. After data processing, each assessment factor has different dimensions and magnitude orders, it is impossible to directly compare them and calculate. In order to compare all evaluation indexes uniformly, it is necessary to normalize them, so that each index value is converted to a range [0,1]. In the assessment, indicators can be divided into positive indicators and negative indicators, which have opposite effects on typhoon rainstorm flood disaster. Therefore, different formulas should be adopted for calculation. The positive index has an aggravating effect on typhoon flood disaster, that is, the greater the value is, and the more harmful it will be. In this paper, the minimum method (Equation (3)) was used for positive indicators. The negative index has a mitigating effect on typhoon rainstorm flood disaster, that is, the greater the value is, and the lower the harm will be. In this paper, the maximum method (Equation (4)) is adopted for s negative indicators. The classes of positive indicators are shown in Figure 2 in pink; on the contrary, negative indicators are shown in blue.

$$Y_i = \frac{X_i - \min_{(i)}}{\max_{(i)} - \min_{(i)}} \quad (3)$$

$$Y_i = \frac{\max_{(i)} - X_i}{\max_{(i)} - \min_{(i)}} \quad (4)$$

where, for the indicator i , Y_i is a standardized value, X_i is an initial value, $\min_{(i)}$ is the minimum value, and $\max_{(i)}$ is the maximum value.

3.2.3. Analytic Hierarchy Process (AHP)

The American operational research expert T. L. Saaty put forward AHP in the 1970s [57]. This method can quantify qualitative problems and has been successfully applied to natural disaster risk studies [57–59]. The main procedure is to divide the level according to the correlation of each factor and then determine the importance between two elements of the same level. Saaty proposed a comparative scale which was composed by integer numbers of 1–9, where 1 means that the compared factors have the same importance, while 9 means that some factors are much more important than others [60]. We evaluated the relative importance of risk factors based on Saaty's method. Then, a judgment matrix was constructed to rank the evaluation indicators and to determine each evaluation indicator's weight [61]. Finally, to check the consistency, if the consistency ratio (CR) was less than 0.1, the judgment matrix was deemed to be of satisfactory consistency, and if not, it needed to be adjusted or abandoned.

3.2.4. The Comprehensive Weighted Evaluation (CWE)

The comprehensive weighted evaluation method selects several evaluation factors that can reflect the research problem, and comprehensively considers the influence of each factor on the research problem, weighting the evaluation factors, finally obtains the evaluation result after comprehensive

consideration [62]. In this paper, GIS and comprehensive evaluation method are combined, which is clear and easy to understand. The input data is a set of spatial data with the same evaluation criteria, after grouping, standardization, weighting and calculating in raster environment, one or more "comprehensive index map(s)" are output. The final product is typically presented as a map(s), with each grid cell getting a score based on a range of weights specified [63]. The overall performance index A_j for each aspect can be calculated using a formula

$$A_j = \sum_{i=1}^n W_{ij} Y_{ij} \quad (5)$$

$j = 1, 2, 3, 4$

In this paper, j is an integer of 1–4 representing different criteria (hazard, sensitivity, vulnerability, and restorability). The weights (W_{ij}) are non-negative and add up to 1, and Y_{ij} is the standardization value of an indicator on a scale of 0–1, where 1 represents the best performance. The larger the value of A_j is, the higher the risk of typhoon flood disaster is, and the more likely the typhoon flood disaster is to occur in this region.

4. Results and Discussions

4.1. Standardization and Weight Determination

4.1.1. Standardization

The standardizations of each indicator are shown in Figures 3–6, and it should be noted that there are two different methods of standardization that are aimed at positive indicators and negative indicators, respectively.

Figure 3. Standardized hazard indicators: (a) mean daily rainfall, (b) frequency of heavy rainfall, (c) mean maximum wind, and (d) typhoon frequency.

Figure 4. Standardized sensitivity indicators: (a) Elevation, (b) slope, (c) drainage density, and (d) vegetation coverage.

Figure 5. Standardized vulnerability indicators: (a) Population density, (b) industrial production, (c) cultivated land, and (d) urbanization density.

Figure 6. Standardized restorability indicators: (a) gauging station density, (b) road density, (c) hospital bed capacity, (d) medical staff number, and (e) GDP per capita.

4.1.2. Determination of Weights

There are four aspects including seventeen indicators in typhoon flood disaster risk assessment. The AHP method was used to determine the weights of the evaluation indicators. By pairwise comparison with each aspect and their indicators, the judgment matrixes were constructed to rank the evaluation indicators and to determine each evaluation indicator's weight. Due to the space limitation, the judgment matrixes are shown in the Appendix A. The consistency ratio (CR) and the largest eigenvalue of judgment matrixes were shown in Table 1. The CR of each judgment matrixes were all less than 0.1, so the judgment matrixes were deemed to be of satisfactory consistency. Finally, we calculated the weights of each aspect and their indicators based on the judgment matrixes, the weights are shown in Table 2.

Table 1. Consistency ratio and the largest eigenvalue of the judgment matrix.

Assessment Objectives	Consistency Ratio (CR)	λ_{max}	Weight
Comprehensive risk	0.0235	4.0627	1.0000
Hazard risk	0.0179	4.0477	0.5074
Sensitivity risk	0.0029	4.0078	0.2108
Vulnerability risk	0.0268	4.0716	0.1858
Restorability risk	0.0451	5.2019	0.0960

Table 2. The weights of the four aspects, the aspect weights, and the overall weight of each indicator in the multi-factor system.

Aspect	Indicator	Aspect Weight	Overall Weight	Aspect	Indicator	Weight	Overall Weight
Hazard (0.5074)	Frequency of heavy rainfall	0.5871	0.2979	Vulnerability (0.1858)	Population density	0.5402	0.1004
	Mean daily rainfall	0.2560	0.1299		Industrial production	0.1767	0.0328
	Typhoon frequency	0.0991	0.0503		Cultivated land	0.1568	0.0291
	Mean maximum wind	0.0578	0.0293		Urbanization density	0.1262	0.0235
Sensitivity (0.2108)	Drainage density	0.5305	0.1118	Restorability (0.0960)	Gauging station density	0.3943	0.0378
	Slope	0.2556	0.0539		Hospital bed capacity	0.2280	0.0219
	Vegetation coverage	0.1374	0.0290		Medical staff number	0.1774	0.0170
	Elevation	0.0765	0.0161		Road density	0.1261	0.0121
					GDP per capita	0.0742	0.0071

As Table 2 shows, the sum of indicators' weights in each aspect was equal to 1.0. It can be seen that the hazard aspect had a heavier weighting than the three other aspects in the multi-factor system. Because the severity of hazard-causing factors plays an important role in disaster risk, it directly determines the level of disaster threat. Theoretically, the frequency of heavy rainfall is the number one factor that leads to rainstorms and floods. Meanwhile, the bigger the frequency of heavy rainfall is, the higher the hazard risk is. Then, sensitivity and vulnerability follow; they also play important roles in the indicator system. Among them, sensitivity and population density are of great importance in each aspect. In terms of the restorability aspect, the gauging station density is the most important factor. Overall, the four factors at the top of the list are the frequency of heavy rainfall, the mean daily rainfall, the drainage density, and the population density. They are the most important factors whose weights exceed 0.1 in the indicator system, especially the frequency of heavy rainfall, the weight of which is close to 0.3.

4.2. The risk Assessment of Typhoon Flood Disaster

After the determination of indicator, standardization, and weighting indicators, all weighted indicator maps were overlaid using addition function in Raster Calculator of ArcGIS 10.2 software which provided a raster environment [62]. The risk indexes of four aspects were primarily calculated and the comprehensive risk of typhoon flood disaster was obtained after the weighted synthesis of the evaluation results of the four risk assessment aspects. In this study, there are five categories of risk—very high, high, medium, low, and very low—using the natural breaks method [64]. The risk levels of the four aspects and each level of risk coverage are shown in Table 3.

As Table 3 shows, the hazard causing factor risk values range from 0.04–0.90. Disregarding pixels with zero values, the closer these numbers are to 1, the higher the risk is. Very low, low, medium, and high risk zones make up 14.82%, 28.72%, 22.93%, and 18.97% of the study area, respectively. The very high risk area accounts for 14.56%. The spatial distribution of risk factors of different levels is shown in Figure 7a. As the figure shows, the very high and high risk areas are mainly located in coastal cities, and the very high risk areas are mainly in Zhanjiang, Jiangmen, Shantou, Shanwei, and Jieyang. The very low risk areas are mainly located in the Northern mountainous area of Guangdong province; Qingyuan and Shaoguan cities account for a large proportion of these areas.

Table 3. The risk levels and each level of risk coverage for the four risk assessment aspects.

Four Aspects	Risk Value Range	Level	Coverage (%)
The severity of hazard causing factors	0.04–0.20	Very low	14.82
	0.20–0.35	Low	28.72
	0.35–0.50	Medium	22.93
	0.50–0.65	High	18.97
	0.65–0.90	Very high	14.56
The sensitivity of the hazard breeding environment	0.16–0.50	Very low	13.76
	0.50–0.60	Low	32.14
	0.60–0.70	Medium	37.51
	0.70–0.80	High	13.98
	0.80–0.96	Very high	2.61
The vulnerability of hazard bearing objects	0–0.10	Very low	69.99
	0.10–0.20	Low	24.70
	0.20–0.30	Medium	4.45
	0.30–0.40	High	0.70
	0.40–0.80	Very high	0.16
The capability for hazard prevention and mitigation	0.16–0.40	Very low	1.66
	0.40–0.60	Low	3.21
	0.60–0.75	Medium	15.09
	0.75–0.85	High	39.91
	0.85–1.00	Very high	40.13

Figure 7. Different risk levels' spatial distribution of four typhoon flood risk assessment aspects: (a) hazard, (b) sensitivity, (c) vulnerability, (d) restorability.

The sensitivity index values range from 0.16–0.96, with low, medium, and high risk zones accounting for 32.14%, 37.51%, and 13.98% of the study area, respectively. The very low and very high risk area account for 13.76% and 2.61%. The assessment result of environmental sensitivity is also shown in Figure 7b. Very high and high risk areas are mainly located in the Pearl River Delta and distributed along the river networks of Guangdong province. Very high areas are mainly in Guangzhou, Foshan, Zhongshan, and Dongguan, which are mainly concentrated in the Pearl River Delta.

The exposure vulnerability index values range from 0–0.80. Very low risk areas account for the largest proportion of 69.99%, and the low risk area comes in second place, accounting for 24.70%; these

two levels account for 94.69% of the study area. Medium, high, and very high risk zones make up 4.45%, 0.70%, and 0.16%, respectively. The assessment result of the hazard-affected bodies' vulnerability is shown in Figure 7c. The medium to very high risk areas are mainly located in the Pearl River Delta, including Shenzhen, Guangzhou, Foshan and Dongguan, while the very high risk areas are mainly located in Shenzhen and Guangzhou. This is mainly because these cities have large proportions of the population and relatively developed economies, so they are relatively vulnerable to disasters.

The restorability values range from 0.16–1.00. The lower the restorability value is, the higher the risk is. The proportion of very low, low, medium, high, and very high risk zones are 1.66%, 3.21%, 15.09%, 39.91%, and 40.13%. We can also see the spatial distribution of the capability of hazard prevention and mitigation in Figure 7d. In terms of the restorability, the very low risk areas are mainly located in the cities around Pearl River Delta, especially in Guangzhou and Foshan. This is because Guangzhou, as the capital of Guangdong province, has the highest medical level, a developed road network, and a high per capita GDP.

After obtaining the risk index maps of the four aspects, the general risk assessment map of typhoon flood disaster was weighted by stacking the risk maps of the four aspects. Then, we used the natural breaks method to distinguish the risk value into five levels. As shown in Table 4, the risk values range from 0.17–0.80, disregarding pixels with zero values, and the closer these numbers are to 1, the more likely typhoon flood disaster happens. A proportion of 16.63% of the study area was of very low risk. Low, medium, and high risk zones account for 30.37%, 18.82%, and 19.77%, respectively, and the very high risk area is 14.41%.

Table 4. The risk levels and each level of risk coverage for typhoon flood comprehensive risk assessment.

Typhoon Flood Risk Value Range	Level	Coverage (%)
0.17–0.32	Very low	16.63
0.32–0.40	Low	30.37
0.40–0.47	Medium	18.82
0.47–0.55	High	19.77
0.55–0.80	Very high	14.41

According to the above classification, the typhoon flood risk index map can be shown (Figure 8). Most of the Guangdong Province are found between low and high zones. Near the coastline (Zhanjiang, Jieyang) or adjacent to the river (Pearl River Delta), the area of high risk zones is larger than others. Because the values of some hazard and sensitivity indicators are high, such as the frequency of heavy rainfall and the drainage density, which leads to high susceptibility to typhoon flooding when combined with high sensitivity values. Although Zhanjiang City is not near a river network, the areas with very high risk are still large because of the high typhoon frequency. So, high frequencies of typhoons and heavy rainfall as well as high drainage density are the reasons for high typhoon flood risk, and also the reason why the high risk areas are mainly distributed especially in the coastal zone.

As natural disaster risk assessments in most studies are always accomplished by administration cell, the risk index values of typhoon rainstorm flood disaster in Guangdong province are also analyzed for the administrative cities [62]. Table 5 summarizes the percentages of each city under different typhoon flood risk levels. As shown in Table 5, there are four cities with more than 50% very high-risk areas: Shantou, Jieyang, Zhanjiang, and Shanwei. Nine cities have mainly high risk areas, among which a high typhoon flood risk is present in more than 50% of the area for six cities and 39% to 50% of the area in three cities. Only two cities have a predominantly medium risk level, four cities have a predominantly low risk level, and two cities in the mountain area (Qingyuan and Shaoguan) have a very low risk level. Moreover, cities located on the coast of Guangdong Province are at a high or very high risk level. Table 6 shows ten cities which has more than 50% high or very high risk areas. Due to the high risk of typhoon flood disaster in these cities, it is necessary to conduct in-depth studies on these cities in the future and focus on disaster prevention.

Figure 8. Different risk levels' spatial distribution of typhoon flood disaster.

Table 5. Percentage of each city with different typhoon flood risk levels.

City	Very Low Risk (%)	Low Risk (%)	Medium Risk (%)	High Risk (%)	Very High Risk (%)	Main Level
Shantou	0.00	0.00	0.00	2.55	97.45	Very high
Jieyang	0.00	0.00	0.30	10.15	89.55	Very high
Zhanjiang	0.00	0.00	0.00	13.66	86.34	Very high
Shanwei	0.00	0.00	2.95	41.30	55.76	Very high
Zhuhai	0.00	0.00	14.06	85.94	0.00	High
Zhongshan	0.00	0.00	13.06	84.34	2.60	High
Dongguan	0.00	0.00	16.59	82.32	1.09	High
Shenzhen	0.00	0.00	11.83	68.56	19.61	High
Yangjiang	0.00	1.97	20.19	65.54	12.30	High
Jiangmen	0.00	0.00	8.49	59.84	31.66	High
Chaozhou	0.00	4.69	26.12	49.20	19.99	High
Huizhou	0.02	16.43	40.62	42.88	0.05	High
Maoming	0.00	20.95	31.47	39.48	8.10	High
Foshan	0.00	6.32	65.81	27.79	0.08	Medium
Meizhou	0.00	39.64	49.31	10.04	1.02	Medium
Zhaoqing	6.71	77.12	16.17	0.00	0.00	Low
Heyuan	12.95	66.45	19.44	1.16	0.00	Low
Yunfu	0.10	60.76	37.58	1.56	0.00	Low
Guangzhou	4.49	58.59	26.81	10.11	0.00	Low
Qingyuan	56.91	42.94	0.14	0.00	0.00	Very low
Shaoguan	82.06	17.94	0.00	0.00	0.00	Very low

Table 6. Ten cities with larger typhoon flood risk areas.

Four cities with more than 50% of very high risk	Percentage (%)
Shantou	97.45
Jieyang	89.55
Zhanjiang	86.34
Shanwei	55.76
Six cities with more than 50% of high risk areas	Percentage (%)
Zhuhai	85.94
Zhongshan	84.34
Dongguan	82.32
Shenzhen	68.56
Yangjiang	65.54
Jiangmen	59.84

4.3. Validation

In order to verify the accuracy of the typhoon flood risk assessment model, this paper collected the records of rainstorm disasters induced by typhoons in Guangdong province from China's flood and drought disaster bulletin from 2000–2017, and 77 flood event records were found. The locations of relevant records were marked in ArcGIS10.2 to obtain the distribution map of historical typhoon floods, which were superimposed with the typhoon flood risk map of Guangdong province, as shown in Figure 9.

Figure 9. Historical floods induced by typhoons overlaid with a typhoon flood risk index map.

According to the results, a total of 20 floods occurred in very high risk areas, 26 occurred in higher risk areas, 16 occurred in medium risk areas, 13 occurred in low risk areas, and two occurred in very low risk areas. This means that the four-fifths of typhoon disasters occurred in areas with medium level risk or greater, and three-fifths of typhoon disasters occurred in areas with higher risk or greater. According to historical records, the typhoon flood disasters usually happened in the areas near the coastline or alongside the rivers. The results show that the risk assessed map is in good agreement with the historical records, as most of the floods caused by typhoons occurred in high and above risk areas. However, there are still some historical typhoon floods which occurred in the very low risk areas of the assessed map, and these floods mainly happened alongside the rivers in the very low risk areas. The reason why some places near the rivers have been defined as low risk areas could be explained as follows: The weight of drainage density is lower than the weight of heavy rainfall's

frequencies, and frequencies of heavy rainfall near the coastline are much higher than that inland, so the risk of inland cities is lower than that of coastal cities, but typhoon floods would still happen in low risk areas. Due to limited data, the flood disaster records caused by typhoon rainstorms are not covered all, but the above results are also of certain reference significance. In conclusion, the typhoon flood risk area was calculated by selecting factors from four evaluation aspects and their weights. This method was able to produce accurate results in Guangdong province. It can be seen that the typhoon flood risk area assessment method can be used to accurately predict the possibility of typhoon flood disaster in an area when a typhoon comes.

4.4. Remaining Deficiencies and Future Research Direction

However, there are still some deficiencies in this study that we should be aware of and continue to explore in future studies. Firstly, we chose the AHP to determine the weights of 17 evaluation factors, mainly because the AHP is considered to be suitable for producing a layered staggered evaluation index system of the target, but the subjectivity of AHP could not be overlooked. For example, some historical typhoon floods occurred in the very low risk areas because the calculation of weight considered much about the typhoon and its factors and neglected the amount of information and indicator outputting. Future research should combine AHP with other methods, for example, random forests or the entropy weight methods, to reduce the subjectivity. Secondly, the selected indicators were regarded as unrelated to each other, but we did not carry out any calculations to exclude the existence of correlations. In future studies, we will calculate these correlations to make sure that only unrelated indicators were selected for the experiment. Thirdly, we could make use of historical typhoon flood records as a variable or indicator to modify this model and make it more consistent with the actual situation. Besides, the distinction of flood-prone areas could also be carried out based on flood depth, and some researchers have done this before. De Risi (2015) used the topographic wetness index (TWI) threshold to detect the region which was potentially exposed to flood inundation and applied it to a hydraulic inundation model to demonstrate that it was useful for the potentially flood-prone areas zoning in micro and meso-scale [65]. Based on these researches, we could combine the hydraulic inundation model and calculate the flood depth so as to define flood risk during typhoon process.

5. Conclusions

This study mapped the spatial distribution of typhoon flood risk in Guangdong province in South China. According to our findings, areas with a very high risk of typhoon floods are mainly located in the coastal areas, including the Pearl River Delta and the Northeast (Chaoshan plains) and West (Zhanjiang, Maoming) of Guangdong province. According to the historical records of typhoon flood disasters, these areas have experienced greater numbers of typhoon flood disasters in the last 15 years. In these areas, the typhoon frequency is high, the elevation and slope are smaller, the distribution of the river network is dense, and the mean typhoon rainfall and heavy rainfall frequencies are high. These factors lead to the higher typhoon flood risk. In contrast, mountainous areas in the Northwest of Guangdong province are classified as areas with a very low to low risk of typhoon flooding, because typhoons dissipate before affecting these areas. The results indicate that the typhoon frequency, typhoon rainstorm frequency, drainage density, elevation, slope, land use type, population density, and urbanization density are the key factors that affect the typhoon flood risk of a particular area. Among them, the factors with large weights based on AHP are usually those related to precipitation, such as the frequency of heavy rainfall and the mean daily rainfall, followed by those related to the terrain and river network. The number of indicators in the model determines the weight of each evaluation factor. Generally speaking, if the number of evaluation factors is less than ten, it will generate an unrepresentative weight dominated by a single weight, thus increasing the possibility of overestimating some factors [60]. It is usually recommended to select more than ten indicators that are representative of each other but not related to each other. In this study, the disaster risk of flood-prone areas was calculated through a combination of qualitative and quantitative methods, so the results

visually show the risk level of the study areas. Considering fully quantitative methods, Life Cycle Cost (LCC) and Return on Investment (ROI) were used as decision variables to calculate the potential loss and impact [20]. So we could consider an indicator to quantify the typhoon flood disaster loss and make it useful for mitigation strategies.

The typhoon flood risk map has good coherence to historical typhoon flood records, so the adopted method could be applied to help with the early warning and prediction of typhoon flood disasters, so as to reduce personnel injuries and property losses as well as to aid in long-term land planning. However, more extensive tests should be carried out in other areas with different climatic conditions and topographic characteristics to identify typhoon flood risk areas. In addition, the importance of each assessment indicator and the number of representative assessment indicators to be included in the assessment model should be further identified based on the historical typhoon flood records of the area.

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Appendix A

The judgment matrix and consistency ratio (CR) of different aspect layers using AHP method are shown in Tables A1–A5.

Table A1. The judgment matrix and consistency ratios of typhoon flood risk.

Typhoon Flood Risk	Hazard	Sensitivity	Vulnerability	Restorability
Hazard	1	3	3	4
Sensitivity	1/3	1	1	3
Vulnerability	1/3	1	1	2
Restorability	1/4	1/3	1/2	1

$$CR = 0.0235 < 0.1.$$

Table A2. The judgment matrix and consistency ratios of the severity of typhoon flood hazard causing factors.

Hazard	Mean Maximum Wind	Mean Daily Rainfall	Frequencies of Heavy Rainfall	Typhoon Frequencies
Mean maximum wind	1	1/5	1/8	1/2
Mean daily rainfall	5	1	1/3	3
Frequency of heavy rainfall	8	3	1	6
Typhoon frequency	2	1/3	1/6	1

$$CR = 0.0179 < 0.1.$$

Table A3. The judgment matrix and consistency ratios of the sensitivity of hazard breeding environments.

Sensitivity	Elevation	Slope	Drainage Density	Vegetation Coverage
Elevation	1	1/3	1/7	1/2
Slope	3	1	1/2	2
Drainage density	7	2	1	4
Vegetation coverage	2	1/2	1/4	1

CR = 0.0029 < 0.1.

Table A4. The judgment matrix and consistency ratios of the vulnerability of hazard bearing objects.

Vulnerability	Cultivated Land than	Population Density	Industrial Production	Urbanization Density
Cultivated land than	1	1/3	1	1
Population density	3	1	4	4
Industrial production	1	1/4	1	2
Urbanization density	1	1/4	1/2	1

CR = 0.0268 < 0.1.

Table A5. The judgment matrix and consistency ratios of the hazard prevention and mitigation capability.

Restorability	Hospital Bed Capacity	Medical Staff Number	Gauging Station Density	GDP Per Capita	Road Density
Hospital bed capacity	1	1	1/2	3	3
Medical staff number	1	1	1/3	2	2
Gauging station density	2	3	1	4	3
GDP per capita	1/3	1/2	1/4	1	1/3
Road density	1/3	1/2	1/3	3	1

CR = 0.0451 < 0.1.

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