Spatial and Temporal Patterns of Urban Vulnerability in Guangzhou

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Abstract

The evaluation of urban vulnerability is of great significance to improve the quality of urbanization. An urban vulnerability index system was developed from four aspects of population vulnerability, economic vulnerability, social vulnerability and ecological vulnerability. The Spatial and temporal patterns of urban Vulnerability in Guangzhou were evaluated by a comprehensive index model and GIS analysis from three time sections (2005、2010、2014). The results indicated that: (1) economic density, population density, and per capita GDP are the main factors affecting the vulnerability of Guangzhou. (2) The population vulnerability is considerably higher for the central group cities than for the peripheral group cities. The economic vulnerability reflects a crisscross pattern, consisting of a central group and a peripheral group. The social and ecological vulnerabilities are higher for the peripheral group than for the central group. (3) The comprehensive vulnerability has a layered structure, with a high vulnerability in the inner ring layer, low vulnerability in the middle layer, and medium vulnerability in the outer layer.

Keywords: urban vulnerability, Guangzhou, comprehensive index model, GIS

1. Introduction

Urban vulnerability is an important part of urban sustainable development research. It mainly refers to the city's ability to resist the interference of natural and human factors such as resources, ecological environment, economic and social development in the process of development (Fang, Wang, & Fang, 2016). In addition, new-type urbanization requires the reduction of urban vulnerability and improvement in urbanization quality.

The concept of "vulnerability" originated from natural disasters (White & Haas, 1975). Vulnerability research outside of China has mainly concentrated on two aspects, including the concept's connotation and the research paradigm. With regard to the concept's connotation, the research has moved away from the limits of "internal risk", extending to external factors such as nature, food security, society, economy, poverty and development, global environmental change, as well as ecology, resulting in an evolution from single-factor to multi-factor evaluation and from assuming a unitary structure to multiple structures (Chambers, 1989; Janssena et al., 2006; Janssen, 2007; Briguglio et al., 2009; Gaillard, 2010; Li & Zhang, 2011; Wang et al., 2013). In particular, vulnerability has become a collective concept, which includes the components of risk, sensitivity, adaptation, and response (Newell et al., 2005). With regard to the research paradigm, there are five models: the risk hazard model (R-H model; Burton, Kates, & White, 1978), the pressure and release model (PAR model; Wisner et al., 2004), the hazard of place model (HOP model; Cutter, 1996), the "Diamond model" (Cutter, 2003), and the coupling system model (Turner et al., 2003). For instance, the coupling system, proposed by Turner et al. (2003) considers the degrees of exposure and sensitivity and restoring force to be at the core of vulnerability. In addition, it emphasizes the vulnerability from multiplicity and multi-scale disturbance, highlighting the formation mechanism of system vulnerability (Turner et al., 2003).

In China, urban vulnerability research has

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concentrated catastrophology and ecology. A number of research studies on urban vulnerability of disaster have investigated areas in the Circum-Bohai-Sea Region, the Yangtze River Delta, and the Pearl River Delta (Shi, 2010; Tang, Liu, & Li, 2013; Gang, Han, & Chu, 2015). In addition, several research studies on the ecological vulnerability of certain regions have involved the area of the Yangtze River, Dianchi Lake in Yunnan province, and the Tarim River Basin in Xinjiang (Gong et al., 2007; Yu, Li, & Zhang, 2015; Shao et al., 2016). In terms of research reviews, the vulnerability of resource cities, social vulnerability about the concepts, characteristics, methods, and preventive measures have been summarized (Li, Zhang, & Cheng, 2008; Guo, 2010; Wang, Fang, & Zhang, 2013). In background of the new urbanization process in China, the coordinated and sustainable development of cities is becoming increasingly important (Ma, Cheng & Qi, 2018).

2. Study area and data sources

2.1. *Study area*

Guangzhou is the national central city, the capital of Guangdong Province, and the core city of the Pearl River Delta urban agglomeration (Figure 1). Located at 112° 57'–114° 3' E, 22° 26'–23° 56' N, it covers an area of 7434.4 km^2. Guangzhou is located in a hilly area, with higher terrain in the northeast and lower terrain in the southwest, in the downstream area of the Pearl River. The area has a

typical subtropical marine monsoon climate. As a typical megacity, Guangzhou is susceptible to two threats: disturbances within the urban system and the potential of an external disaster (e.g., floods and typhoons). Because Guangzhou carried out a larger reform of administrative divisions in 2015, so this paper adopted the administrative divisions of 2014.

2.2. *Data sources*

We used data on population, socio-economics, infrastructure, and other statistics, obtained from the yearbooks of various districts in Guangzhou City, the China City Yearbook, and the Guangdong Province Construction Yearbook. Due to the lack of data in some areas, missing data was replaced with the subsequent year.

3. Methodology

3.1. *Index system of urban vulnerability*

Exposure refers to the degree of contact that a person, group or system has with a particular stress or impact factor (Sanjeev, William, & Dana, 2003). The degree of exposure should not only be related to the characteristics of the hazard factors themselves, such as the frequency, intensity, and duration of disasters, but also have a direct relationship with the population size, age structure, population quality, occupational composition, and the level of economic development.

Sensitivity refers to the degree of influence of a region affected by stress or disturbance. In the Turner framework, it is related to the interaction of
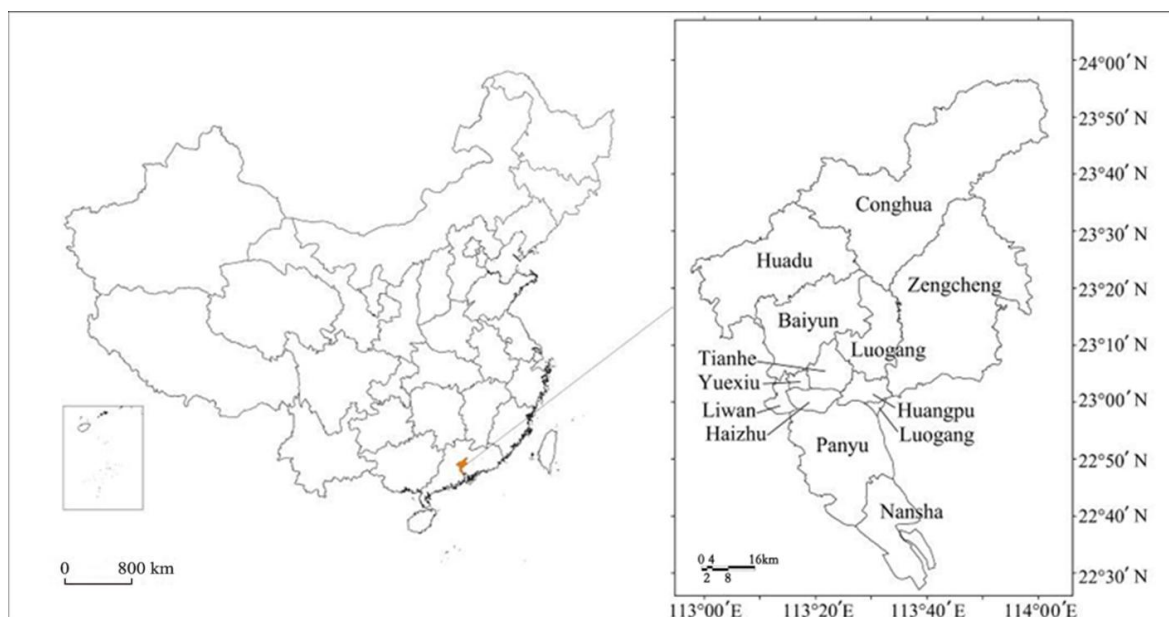

Figure 1. Location of the study sites in Southeast China development of Guangzhou.

the social/human capital (population size, social institutions, and economic structures) and the environmental conditions (Turner et al., 2003). With increasing urbanization, there is a clear agglomeration of urbanization, the city's population, economy, and space. The occurrence of external interference and internal disasters will affect the whole system: secondary disasters caused by the main disaster, indirect losses caused by the direct loss, and a single disaster developing into a variety of disasters.

Restoring force refers to the ability of the region to resist external risks and internal disturbances without damaging its function and structure (Adger & Hughes, 2005). Resilience becomes the adaptive capacity of the regional response to a disturbance. It is a positive feedback mechanism (Liu, Shi, & Xu, 2006). Research on the restoring force includes two parts: engineering resilience and ecological restoring force. Engineering resilience emphasizes the maintenance of functional effectiveness. Its primary objective is security engineering and has a relatively clear measure. Meanwhile, the ecological restoring force emphasizes on retaining the system function. Research shows that a scientific and rational green space ecosystem plays an important role in disaster prevention and mitigation in urban areas (Holling, 1996; Huang et al., 2009; Ge et al., 2010).

According to the characteristics of the urban area and the mechanisms of vulnerability formation, an urban vulnerability assessment framework is established （Tang, Liu, & Shang, 2012）(Figure 2).

In this paper, we developed an urban vulnerability index system from population vulnerability, economic vulnerability, social

vulnerability and ecological vulnerability (Table 1).

3.2. *Measurement model for urban vulnerability*

3.2.1. *Normalizing of raw data*

To facilitate the comparison of the indicators in the evaluation index system, it is necessary to standardize each evaluation index one by one, so that the value of each evaluation index is in the range of 0–1. The evaluation indicators can be either a positive or a negative index.

Positive parameters: a larger value indicates a higher vulnerability. The function is:

$$X_{positive} = (x_i - x_{min})/(x_{max} - x_{min}) \quad (1)$$

Negative parameters: a larger value indicates a lower vulnerability. The function is:

$$X_{negative} = (x_{max} - x_i)/(x_{max} - x_{min}) \quad (2)$$

X_i is the nondimensionalized value of the 18 parameters, while X_{max} and X_{min} are the maximum and minimum values of the same parameter, respectively.

3.2.2. *Determining the weight of the indicator*

The weight of each parameter is calculated using the TOPSIS method. The main advantages of this method are the ability to describe objectively the importance of the index in the entire evaluation system, weaken the influence of individual anomalies, and avoid the interference of subjective factors of weight.
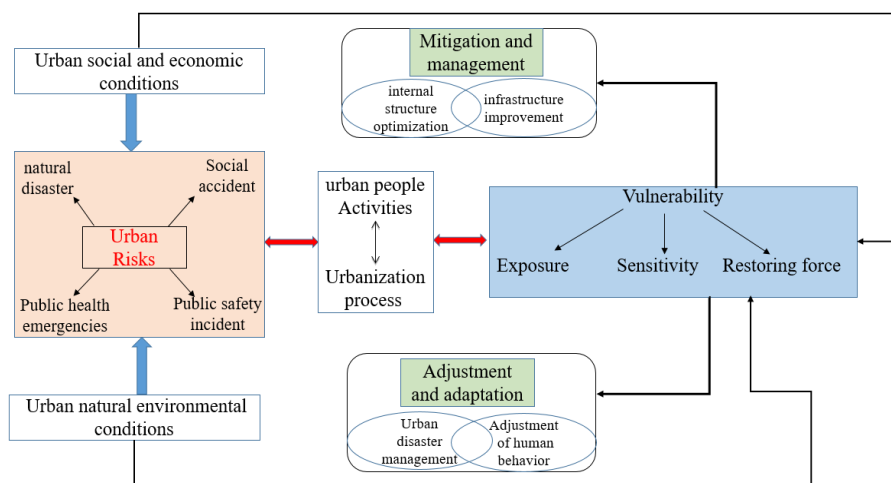

Figure 2. Framework of urban vulnerability

Table 1. Evaluation Index System of Urban Vulnerability

Target hierarchy	Parameter hierarchy	Calculation formula	Unit
Population vulnerability	Population density	Resident population / area	-
	Population age structure	Proportion of population over 60 years of age	(%)
	Population education level	Junior high school or above / total population	(%)
	Natural population growth rate	Population born in that year / total population of the year	(‰)
	Population immigration rate	number of incoming population / total population	(‰)
	Per capita GDP	GDP/total population	_
Economic vulnerability	Foreign exports	Foreign exports	Billion dollars
	Proportion of the increased value of tertiary industry in GDP	Output value of tertiary industry/GDP	(%)
	Consumption level index	Total retail sales of social consumer goods/GDP	(%)
	Economic density	GDP/area	_
	Engel coefficient	Household food expenditure / total expenditure	(%)
Social vulnerability	Employment rate of urban unemployed	Unemployed persons employed / registered unemployed	(%)
	Thousands of people have hospital beds	Number of hospital beds / resident population	_
	Investment in fixed assets per capita	Fixed assets input / resident population	_
	Overall energy consumption per GDP	Overall energy consumption per GDP	Tons/10^4 yuan
	Urban centralized wastewater treatment ratio	Urban centralized wastewater treatment ratio	(%)
Ecological vulnerability	Ratio of days with good air quality	Ratio of days with good air quality	(%)
	Green coverage ratio in built-up areas	Green coverage ratio in built-up areas	(%)

3.2.3. *Comprehensive measurement model*

Based on the data standardization and comprehensive weight, we can determine the vulnerability of target hierarchy (population vulnerability, economic vulnerability, social vulnerability, and ecological vulnerability):

$$WVD' = \sum_{i=1}^{n}(W_i U_i) \qquad (3)$$

where *WVD*' is the vulnerability of target hierarchy, W_i the comprehensive weight value; U_i represents the normalized results for the indicators; i is the number of indicators.

Subsequently, the urban comprehensive vulnerability (WVD) was calculated according to the equation below:

$$WVD = \sum_{i=1}^{p} WVD' \qquad (4)$$

where *WVD*' is the vulnerability of target hierarchy, *p* is the number of target hierarchy (p = 4).

4. Results

4.1. *Analysis of the contribution rate of urban vulnerability index*

As shown in Figure 3, the contribution rate of economic density and population density is the highest at approximately 0.15, with a gradual upward trend between 2005 and 2014, indicating that the urban population and the degree of economic agglomeration are the most important perturbation factors for urban risk, per capita GDP, and per capita investment in fixed assets. The proportion of tertiary industry and the number of hospital beds per capita are important negative indicators, with values in the range of 0.05–1,
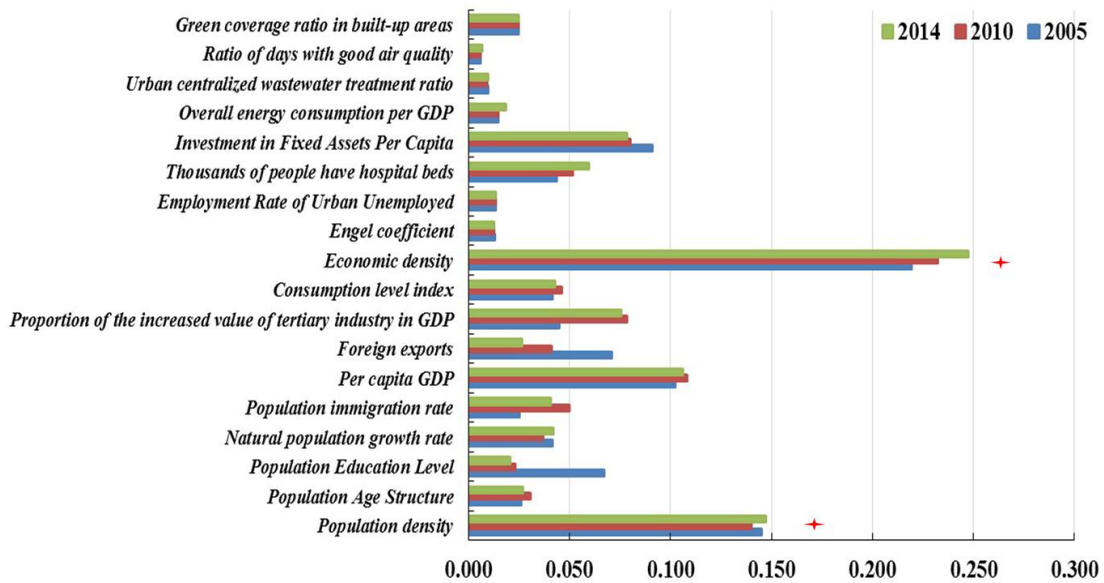
Figure 3. Contribution of urban vulnerability indicators

indicating that the regional per capita income level, infrastructure investment and construction, optimization of economic industrial structure, and the improvement of medical facilities play an important role in the reduction of urban vulnerability. Although the other factors caused minimal change (less than 0.05), but they cannot be ignored.

4.2. Population vulnerability

From 2005 to 2014, the total population and population density of Guangzhou increased steadily, while the overall education level of the population also increased. With the continuous immigration of people from outside the city and the aging of the population, spatial and temporal differences in the population vulnerability of Guangzhou have become obvious. Using the natural breakpoint method in GIS, this is a statistical classification method that is based on the law of numerical statistical distribution. In this method, the population vulnerability is automatically divided into three levels, as shown in Figure 4. In general, population vulnerability is higher in the central cities than in the peripheral cities, especially for the three districts (Yuexiu, Haizhu, and Liwan), which exhibit a high population vulnerability for the three years because of their high population density, constant aging of the population, and high immigration rates. According to the analysis of the demographic data for Guangzhou in 2015, the average aging rate of the household population in
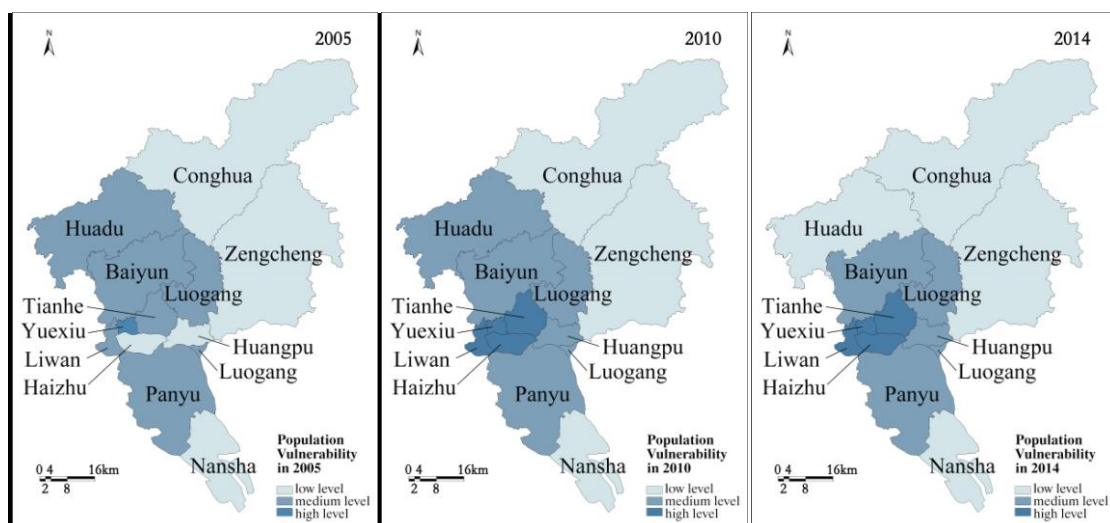

Figure 4. Spatial distribution of population vulnerability in Guangzhou in 2005, 2010, and 2014

the three old districts reached 20%, with the Liwan District showing a rate of 21.37%. In addition, the population migration rate indicates that the urban household population of the central group remains between 15% and 25%. As a result, to a certain extent, the increase in the urban vulnerable groups and the management of the floating population intensify the difficulty of the central group to cope with urban risk. Despite the relatively low urban vulnerability of the peripheral groups, the general population growth rate is increasing, with the vulnerability of these cities in the later period representing a larger, hidden danger.

4.3. Economic vulnerability

Economic vulnerability mainly focuses on urban economic quality and economic benefits, such as industrial structures, the degree of openness to foreign economies, and the level of consumption. During 2005 to 2014, Guangzhou experienced its fastest economic development, with the degree of economic agglomeration enhancing openness to foreign economies, optimizing industrial institutions, and greatly stimulating the per capita GDP and consumption index of Guangzhou. However,

because of the geographical location of Guangzhou district and the economic basis of the differences, the economic vulnerability of Guangzhou City exhibits large spatial differences. As shown in Figure 5, the medium to high vulnerability is mainly distributed in the central group and the western part. The northern and the central groups have a high vulnerability with upward tendencies, such as in Yuexiu and Tianhe. The main reason for the high vulnerability values in these areas is the high economic density. The eastern and northern peripheral groups, such as Zengcheng and Conghua, also show a high vulnerability, which is mainly related to per capita GDP and relatively low openness to foreign economies. Low economic vulnerabilities occur mainly in the center of Luogang and the outer group of the eastern and southern areas, such as Nansha and Panyu, due to geographical and policy advantages (Technology Development Zone, Nansha New Area, "the Belt and Road"). The top three exports from Guangzhou in 2014 originate in these three regions. With a low economic density, the economic vulnerability is relatively low.
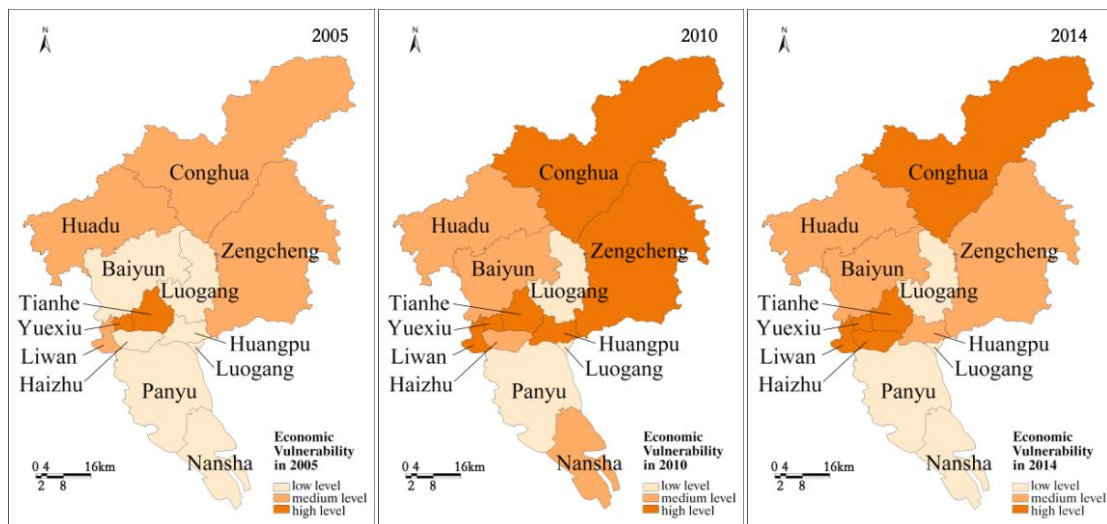

Figure 5. Spatial distribution of economic vulnerability in Guangzhou in 2005, 2010, and 2014

4.4. Social vulnerability

Social vulnerability is an important part of urban vulnerability and reflects the regional social problems from the aspects of income distribution, social security, and social welfare. It also reflects the happiness of a city's population and the quality of urbanization. Figure 6 show that the social vulnerability of Guangzhou exhibits a slightly upward trend from 2005 to 2014. While the spatial pattern of the peripheral group is consistently higher

than that of the central group. Peripheral groups such as Conghua, Zengcheng, and Huadu have a greater deficiency with regard to medical care and medical facilities, with the distribution of income being more unequal. In addition, the Engel coefficient is higher, while the social investment in fixed assets is lower, attributing social vulnerability to a high value area. Being located in the center of relatively high urbanization, central groups such as Tianhe, Yuexiu, and Haizhu have a relatively greater

advantage with regard to social infrastructures, such as fixed assets and per capita hospital beds. It is worth mentioning that the re-employment rate of urban unemployed people in Guangzhou remained at approximately 72% in 2014, demonstrating that solving the unemployment problem to improve social security is an effective measure to reduce urban vulnerability.
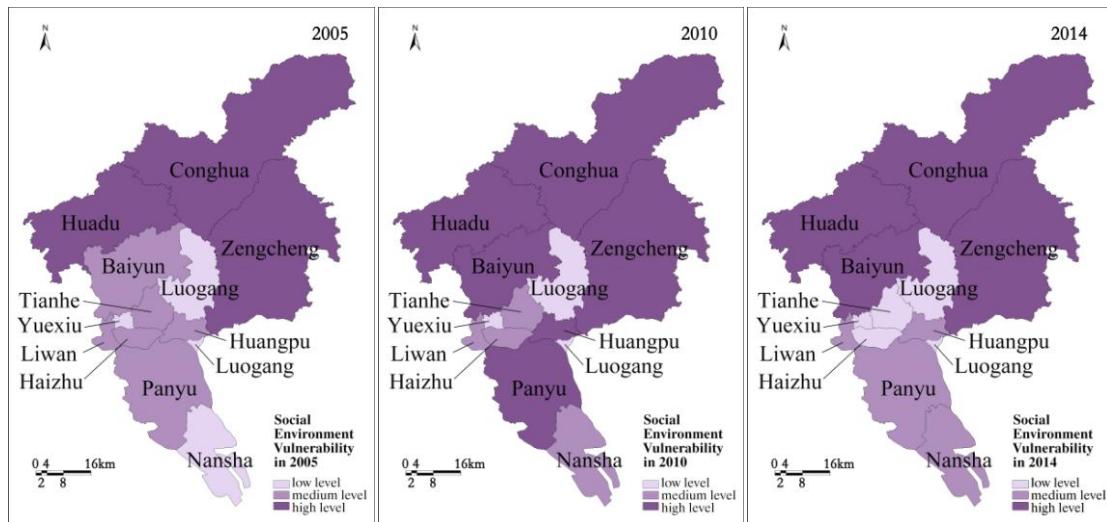

Figure 6. Spatial distribution of social vulnerability in Guangzhou in 2005, 2010, and 2014

4.5. *Ecological vulnerability*

The ecological vulnerability of Guangzhou city was evaluated based on four aspects: energy consumption, sewage treatment rate, air quality rating, and urban green space rating. In Figure 7, we can see that from 2005 to 2014, the vulnerability of the ecological environment in Guangzhou decreased slowly, while the area of high vulnerability decreased from four in 2005 to two in 2014. In Guangzhou, the variation in values for the management of air, energy, and ecological environment is evident, especially the effects of the centralized sewage treatment. In 2005, the centralized sewage treatment in Guangzhou City covered only 71.34%, which increased to 93.22% in 2015. The spatial pattern indicates that the peripheral group has higher values than the central group, which is attributed to the sewage treatment in the central city and the significantly higher energy consumption in the central group. The report "The Overall Planning of Guangzhou city Sewage Treatment" indicates that the peripheral groups such as Panyu, Nansha, and Huadu are key areas targeted for planning and management. Although the overall urban environmental vulnerability of Guangzhou has declined, the air quality rate was only 85.5% in 2015, which was clearly lower than the 92% and 97.5% in 2010 and 2005, respectively. In addition, relevant research has shown that urban ecological environment can be maintained when the proportion of green space is greater than 50% (Ye, 2001). However, in the built-up areas of Guangzhou, this proportion is only 40%, indicating that there is potential for improvement with regard to air quality and urban green space.

4.6. *Comprehensive vulnerability*

There are some spatial differences in the comprehensive vulnerability of Guangzhou City during 2005–2014 and that the average values are higher for the central group than for the outer group. The urban infrastructure has been improved in recent years, the community service and community security are closer to the people's livelihoods, the environment and the economic structure have been strengthened, and the residents' risk awareness has also improved. However, the urbanization process has resulted in a rapid increase in the urban population of Guangzhou's downtown area, and the population's mobility and the continuous improvement of economic density have rendered these areas more vulnerable to the city's internal perturbations and external risks, especially in some districts such as Yuexiu, Tianhe, and Liwan. Peripheral groups (such as Panyu and Nansha in the south, Luogang, Zengcheng, and Conghua in the north, and Huadu in the west) have a lower economic development and less urbanization than groups in the central urban district. Therefore, if the aggregation is not high, the district will fall into the category of low vulnerability.
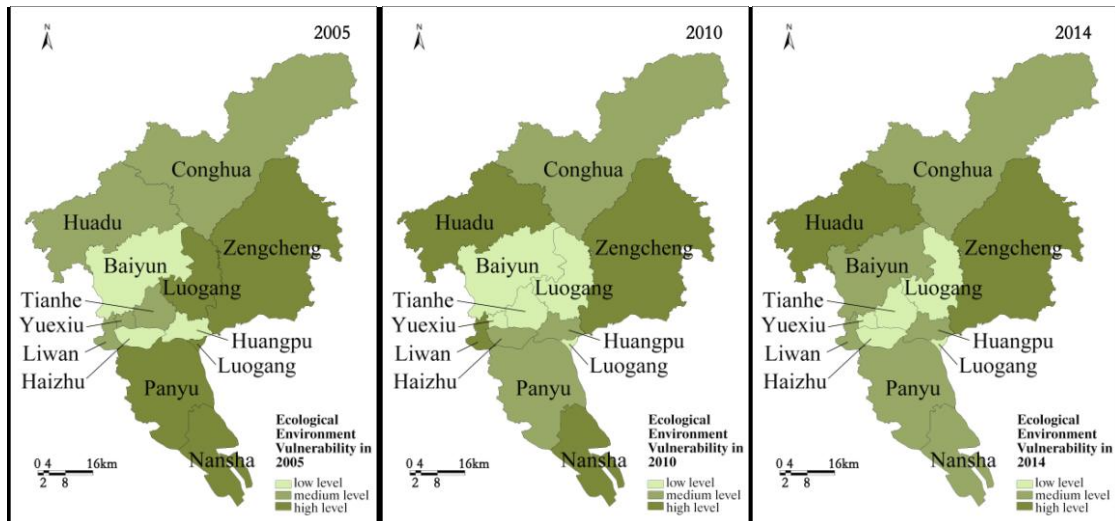
Figure 7. Spatial distribution of ecological vulnerability in Guangzhou in 2005, 2010, and 2014

Finally, the comprehensive vulnerability of Guangzhou city was divided into three classes using a GIS breakpoint method. As shown in Figure 8, the comprehensive vulnerability of Guangzhou city exhibits a circular structure, where the inner circle layer has a high vulnerability, the middle layer has a low vulnerability, and the outer layer has a medium vulnerability.
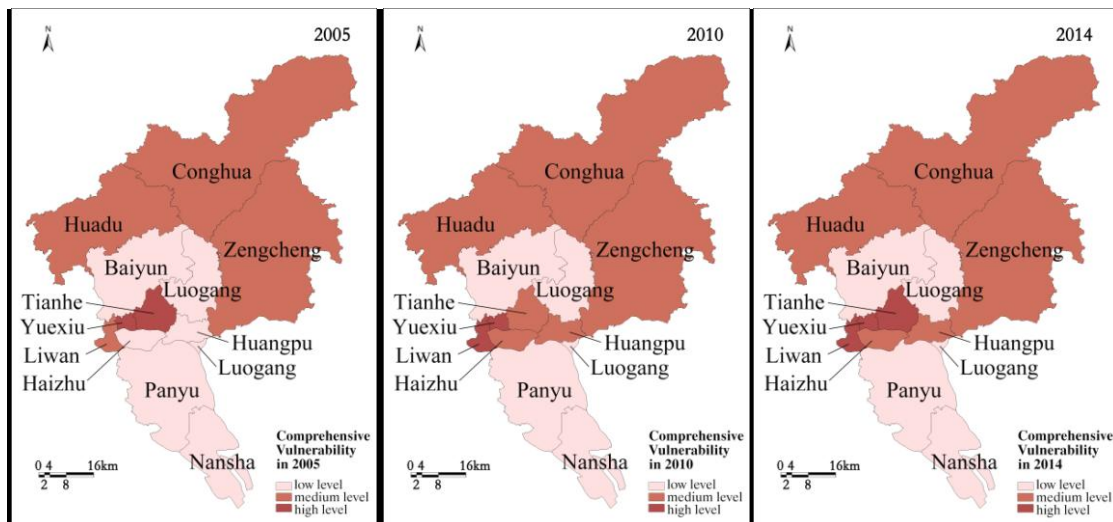

Figure 8. Spatial distribution of comprehensive vulnerability in Guangzhou in 2005, 2010, and 2014

5. Conclusions and discussions

The comprehensive vulnerability evaluation index is established based on the aspects of population vulnerability, economic vulnerability, social vulnerability and ecological vulnerability. Through the calculation of the index weights, it was determined that the main impact factors of urban vulnerability in Guangzhou are economic density, population density, GDP per capita, the proportion of tertiary industries, and the investment in fixed assets. These indicators provide an important direction for the management and regulation of Guangzhou's urban vulnerability.

During 2005, 2010, 2014, the urban vulnerability of Guangzhou underwent some spatial and temporal evolution, which is especially evident in the difference between the inner and outer groups. The population vulnerability is clearly higher for the central group than for the peripheral group, especially in the three older districts. The economic vulnerability follows the same pattern as population vulnerability for the central and peripheral groups, while the social vulnerability is higher for the peripheral group than for the central group. The ecological vulnerability exhibits a slow decline.

However, it is slightly higher for the peripheral group than for the central group. Finally, the comprehensive urban vulnerability of Guangzhou exhibits a circular structure, where the inner layer has high vulnerability, the middle layer has low vulnerability, and the outer layer has medium vulnerability. These variations in vulnerability also reflect the characteristics and problems of urban development in Guangzhou.

Based on the results of study, we recommend some actions or measures: A balanced development of regional economy should be achieved through industrial transfer and support for the economic development of outlying urban areas (Conghua, Zengcheng) to reduce economic density in the future, as mentioned in the draft "Guangzhou City Master Plan (2017–2035)". With regard to population density, the local government should gradually relocate the population of the inner group to the periphery of the city to prevent excessive concentration of population.In view of the unbalanced GDP per capita in Guangzhou, the government should transform the economic development model by strengthening institutional and technological innovation, while improving production efficiency. In order to increase the proportion of tertiary industries, the government should reduce industrial dependence on labor and natural resources, while strengthening technological innovation and structural optimization. In terms of investment in fixed assets, it should increase transport, medical care, and infrastructure development, while expanding the basic public service coverage of various areas. These measures will improve Guangzhou's urban resilience and promote sustainable development so that the city can respond better to the challenges arising from the "One Belt and One Road Initiative" and construction of the Guangdong-Hong Kong-Macao Greater Bay Area.

Urban vulnerability is a comprehensive problem, and the regulation path of urban vulnerability is one of the directions to be explored in the future. Every city will face various problems at different stages. However, excessive population concentration, irrational economic and urban structure, imperfect infrastructure, and resource-environment disruption are problems that cannot be avoided.

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