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Evaluation of social vulnerability to floods in Huaihe River basin: a methodology based on catastrophe theory

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Evaluation of social vulnerability to floods in Huaihe River basin

W. J. You and Y. L. Zhang

Abstract

Huaihe River is one of the seven largest rivers in China, in which floods occurred frequently. Disasters cause huge casualties and property losses to the basin, and also make it famous for high social vulnerability to floods. Based on the latest social-economic data, the index system of social vulnerability to floods was constructed, and Catastrophe theory method was used in the assessment process. The conclusion shows that social vulnerability as a basic attribute attached to urban environment, with significant changes from city to city across the Huaihe River basin. Different distribution characteristics are present in population, economy, flood prevention vulnerability. It is important to make further development of social vulnerability, which will play a positive role in disaster prevention, improvement of comprehensive ability to respond to disasters.

1 Introduction

The frequent occurrence of disasters is a combined result of hazards and vulnerability. In the past, we focused more on the mitigation of natural hazards to reduce losses caused by disasters, which, however, did not achieve satisfactory results. Vulnerability, especially social vulnerability, considered as an important factor in disaster preparedness and mitigation, gradually become the main research content of social risk to disasters. The degree of social vulnerability is determined by the nature and exposure level of disasters. With increasing levels of exposure, social vulnerability gradually increased. Then, what dose social vulnerability mean, different scholars give different definitions from the perspective of their own studies. Adger believed that social vulnerability refers to a series of acts triggered by efforts that people respond to or deal with disasters (Adger, 2000). While, social vulnerability believed to be derived from the inherent characteristics of the human ramifications, according to Clark et al. (1998). Watts et al. focus on the affect macroeconomic system have on the vulnerability from the perspective of social, economic and political, etc. (Watts et al., 1993). Susan et al. (2003), Peet et al. (1989) and Sen (1981) made an analysis of the relationship between political, economic and social factors with vulnerability.

Recent social vulnerability research can be divided into two areas, one is concerned about the impact that social, economic and political macroscopic systems have on vulnerability. For example, Wilhelmi et al. (2013) studied Fort Collins case and made an overall analysis of societal vulnerability in an extreme precipitation. Sammy et al. (2008) made an analysis of social vulnerability to floods of Texas from the perspective of natural and construction environment. Sigridur et al. (2011) explored the relationship between global environmental change and vulnerability in coastal zones. On the other hand, the relationship between the factor of politics, economy and society with the vulnerability will be discussed in the research of social vulnerability. For example, Robert et al. (2013) studied the hinder relationship between natural, political boundaries with social vulnerability, Melissa et al. (2008) made an analysis of the connection between vulnerability and death of elder people with the social vulnerability, and Segun et al. (2012) made people's perception of safety and community involvement as a starting point to study vulnerability. Social vulnerability is quite different from natural vulnerability in the inherent characteristic. Actually, complex social vulnerability factors give rise to the differences, including both the existing political and cultural factors, as well as population structural factors, such as race, ethnicity, personal wealth, social status, age, even environmental factors. The factors that produce their susceptibility to suffer losses have not been identified or studied systematically. Vast differences in social vulnerability factors make it difficult to construct social vulnerability indexes. In addition, there is no uniform standards to construct the index system is also a problem. The original indexes of social vulnerability have a lot crossover phenomenon. The objectivity and science of research on social vulnerability are seriously affected by duplication and redundancy of indexes. The existing assessment methods of vulnerability are integrating qualitative analysis with quantitative analysis. For example, Kyung soo Jun et al. (2013) used the fuzzy multi-criteria approach to study flood risk vulnerability in South Korea by considering climate change impacts. GIS applications were used to spatially assess the relative vulnerability of Cologne by Depietri et al. (2013). Kevin et al. (2007) made an assessment of environmental disaster vulnerability among different cities in the America with the method of simple average. By simply summarizing indicators without using weightings and by using zero-mean normalization to standardize the indicators, Lee (2014) calculates social vulnerability scores for each township. Tiodora et al. (2014) utilized ArcView GIS to identify districts with relative high social vulnerability level. These studies indicated that semi-quantitative evaluation methods are more subjective, which is led by human factors, and the results of the subjectivity evaluation are not suitable for the strong demand for higher accuracy.

In this paper, Huaihe River basin was taken as an object of study. We created the social vulnerability index system according to Cutter's place-hazard model and the theory of emergency management cycle. Using the sensitive analysis method, evaluation indexes were chosen from original indexes accurately. Catastrophe progression method which has strong stability can be used in the assessment of social vulnerability to floods in Huaihe River basin. The results demonstrate that vulnerability manifests itself as a place-based regional phenomenon, which is of great significance to reveal the characteristics of social vulnerability, as well as integrate regional disaster reduction and prevention.

2 Materials and methodology

2.1 Catastrophe theory

The majority of existing vulnerability assessment methods are a kind of combination of quantitative and qualitative, such as fuzzy evaluation method, fuzzy matter-element evaluation method, the composite index method, etc. Semi-quantitative evaluation methods are more subjective, which are led by human factors, and the results of the subjectivity evaluation are not suitable for the strong demand for higher accuracy.

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In this paper, the evaluation method is based on catastrophe theory. The advantage of the method is that it can be used to explain the mutation process according to the analysis of the non-continuous phenomenon near critical point. It can not only reduce the influence of human factors, but also show the scientific of the study. The characteristic of this method is that there is no weight of indexes, but the relative importance of each index has been considered, so it can reduce the subjective influence on the evaluation results. Social vulnerability can be thought as the comprehensive effects caused by the continuous change of many aspects. The gradual process of many social factors can be reflected in it. So, catastrophe progression method is more scientific, accurate and simple in the assessment process of social vulnerability when comparing with other methods.

In 1972, Catastrophe theory was founded by a French mathematician Renethom, marked by the publication of the book named "Structural stability and morphogenesis". The research mode is a mathematical model used to describe the image of the continuity of a sudden interruption in an action which leads to deterioration of the process. The basic principle is to construct the evaluation model with the use of features, that the nature of mutations can be produced by the control variables which is fallen within the bifurcation sets (Thorn, 1994). The main calculation is as follows.

2.1.1 Construction of multi-level hierarchical structure model

According to the final goal of the evaluation, the contradictory issues should be decomposed by the general index to lower index, which finally be arranged in a tree hierarchy. Generally, the upper indexes in the tree hierarchy are more difficult to directly quantify, while the underlying indexes can be directly measured, so the raw data of the evaluation come from the underlying indexes. Then, according to the importance of each index in the same property on the same level, the relative important indexes should be put in front of the ranking, and relatively minor indexes are on the back. Since the number of control variables in the common catastrophe model is no more than four, therefore the number of sub-indexes in each layer should be less than four.

2.1.2 Establish multiple levels of catastrophe model

When the number of sate variable is one, four types of elementary catastrophe model are related to the multi-objective decision as shown in Table 1. $G(x)$ is the potential function of the state variables x. a, b, c, d are the control variables. The primary control variables are in front of the minors. Table 1 shows that when an index can be decomposed into one, two, three or four sub- indexes, this model can be considered as folding mutation, sharp point mutations, mutation swallowtail or butterfly catastrophe model.

2.1.3 Multiple criteria evaluation method based on catastrophe theory

Catastrophe evaluation method is a comprehensive evaluation method developed on the mutation theory, its main calculation steps are divided into three steps. First, evaluation system should be built. According to the internal mechanism of the system, the target would be decomposed by a number of multi-evaluation systems, followed by that the raw data should be normalization. The mutation theory and fuzzy mathematics combined to product the mutations fuzzy membership values, which is multidimensional, and valued between [0, 1]. In the normalization equation, the control variable characterized the different aspects of the state variables, which cannot be compared with each other for the difference in the range of original data and the unit of measurement. Therefore, before the normalization equation is used, the original data of the control variable should be transformed into non-dimensional value ranged by 0–1. Namely, the raw data should be normalized. Then, normalized formula can be used to calculate the total mutation membership value of the evaluation system, as well as the respective intermediate values of control variables (indexes) in the same system. When making a comprehensive evaluation of the intermediate values, two principles must be considered, namely “complementary” and “non-complementary”.

2.2 Study area

Huaihe River basin is located in eastern China between Yangtze River Basin and Yellow River Basin. In the basin, the longitude is 111°55′–121°25′ E and the latitudes is 30°55′–36°36′ N with the land area $270 \times 103\,\text{km}^2$. Population of the area is 167 millions, the highest population density among the seven river basins. This profile starts from Tongbaishan, Funiushan in the west and Yellow Sea at its east end, south to the Dabie Mountain, Jianghuai Hill, Tongyang Canal and the demarcation line of south Rutai Canal between the Yangtze River, north of Yellow River and Mount Tai as the boundary, adjacent to Yellow River Basin. Huaihe River basin includes 28 cities which come from Henan province, Anhui province, Shandong province, Jiangsu province from west to east (Zhang et al., 2014).

In history, floods occurred frequently in Huaihe river basin. From 246 BC to 1948, there were about 979 times of disasters occurred during the 2194 years. Since the Yellow River's flooding into the Huaihe River in 1194, it influenced the lower reaches and caused 594 times of floods from 1194 to 1948 (Huaihe River commission ministry of water resources, 2007). Huaihe River basin was historically the worst place affected by flood disasters.The severity of the floods in the basin ranks first among the seven rivers in our country.

2.3 The constrcution of evaluation system of social vulnerability to floods

Currently social vulnerability indexes are usually built in two ways (Yook et al., 2012), one is the deductive method, based on the concepts or principles of social vulnerability, the indexes constructed in this method are qualitative, but hard to be quantified. The other is inductive approach, based on the population data and socio-economic data. This method selects sensitivity indicators but independent from a large number of social vulnerability indexes with mathematical methods. It has been widely used for overcoming the drawbacks of the deductive method. Vulnerability is seen as the outcome of a mixture of environmental, social, cultural, institutional, and economic structures

(Brouwer et al., 2007). For the reason, there are many influent factors of social vulnerability which covers a wide range of areas, and the interactions between the indexes are complex, social vulnerability index system is built based on the theory of emergency management cycle. According to Cutter's place-hazard model, as well as the principle of selecting indexes that is practicality, science, integrity, social vulnerability index system is created from three dimensions of population, economy, and flood prevention. Population indexes are an important part of social vulnerability index system, which can determine the degree of social vulnerability directly by the indexes such as age, sex ratio, education, income and so on. Economic indexes are the key factor to influence economic vulnerability, which include household income levels and regional economic conditions. Economically developed regions are able to bear the loss and be fast recovery from losses through insurance, social safety nets, welfare policies (Susan et al., 2003). Vulnerability of flood prevention among areas is largely based on transportation, communication, medical treatment and other aspects of these places. Convenient traffic and clear road conditions are guarantee of flood prevention. Timely delivery of the warning information and emergency notification depend on complete communication equipment, what's more, good health conditions are effective protection to reduce regional vulnerability. Social vulnerability index system covers the aspects of population, economic and flood prevention, the content of the original indexes is shown in Table 2 (Zhang et al., 2014).

During present research, it has caused difficulties for quantitative research of social vulnerability indexes for the serious overlapping of information in original indexes. Sensitivity analysis of social vulnerability index has been the foundation of present social vulnerability quantitative research. In this paper, principal component analysis with SPSS 19.0 software was used for the z score standardization of original data. The original data were from the sixth national population census bulletin and 2011 statistical yearbook of the 28 cities. Based on the SPSS 19.0 software, principal component analysis was carried out on the normalized data. First ten main components were put forward according to the principle of eigenvalues greater than 1. The first ten main

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components of the cumulative contribution rate were 82.49 %, which has covered most parts of the original index information. In order to make the index content further concentrated to sensitivity factors, orthogonal varimax rotation would be better used. The indexes which have the highest load in the first ten main components can be chosen as the preferred indexes in each component. The sensitivity index system would be constructed with the preferred indexes. The content of indexes after principal component analysis was present in Table 3.

The importance of indexes needs to be sorted in the application of catastrophe progression method. If we want to avoid the subjectivity of ordering, the activity of indexes in principal component analysis screening can be used to confirm the importance degree of indexes. Activity level of indexes are sorted according to the principle that the important is in front, the secondary is in the back. Then we get the mutations evaluation system after a comprehensive evaluation shown in Table 4.

The index system consists of 10 indexes, which covers a lot of factors that are easily caused floods, such as the age distribution of the population, education level, regional economic development, flood hedging instruments and so on. These factors described the floods which have caused different consequences in these areas for the regional differences in population, economic and flood prevention. It can be more fully reflected the situation of social vulnerability to floods in Huaihe River basin.

2.4 Assessment model of social vulnerability to floods

The nature of the 11 indexes in the mutations evaluation system is not the same. As the index values increase vulnerability enhanced called positive indexes, as the index values decrease vulnerability reduced called positive indexes. So the indexes need consistent treatment, also need to eliminate the influence of magnitude in indexes, so that the data can be compared with each other in the same index. Before the mutation model is used, the data with different magnitude need to be standardized, in order to be transformed into non-dimensional value ranged by 0–1. The following formula can be used to deal with indexes from the aspect of positive and negative.

For the positive indexes:

$$x_{i\bar{j}} = \left(a_{i\bar{j}} - \min a_i\right) / (\max a_i - \min a_i)\,. \tag{1}$$

$x_{i\bar{j}}$ is the standardized indexes, $\max a_i$ is the maximum value of the ith row in matrix **A**, $\min a_i$ is the minimum value of the ith row in Matrix **A**.

For the negative indexes:

$$x_{i\bar{j}} = \left(\max a_i - a_{i\bar{j}}\right) / (\max a_i - \min a_i)\,. \tag{2}$$

$x_{i\bar{j}}$ is the standardized indexes, $\max a_i$ is the maximum value of the ith row in matrix **A**, $\min a_i$ is the minimum value of the ith row in matrix **A**.

According to the social vulnerability index system of Huaihe River basin, the evaluation model is constructed in two levels. The first level consists of three kinds of catastrophe models in the value of B_1–B_3, in which the state variables are B_1–B_3, the control variables are C_1–C_{11}. The second level is the mutation model constructed of the value of the target layer A, in which the state variable is A, the control variables are B_1–B_3, as shown in Fig. 1. Then catastrophe model of social vulnerability in Huaihe River basin will be created based on the normalized formula shown in Fig. 2.

3 Evaluation results and discussion

3.1 Results

We choice Huaihe River basin to be the research object, and make a comprehensive assessment of social vulnerability among the 28 cities with the application of catastrophe evaluation method. First, original values of each index would be transformed by 0–1 standardized method, then normalization formula at all levels of the mutant gradual would be used to calculate up, until the final results are evaluated. The comprehensive evaluation results are shown in Table 4. We take the calculation of Zhengzhou City as an example to show the specific process.

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3.1.1 Evaluation value of the underlying index

In the underlying indexes B_1, C_1, C_2, C_3 constructed the swallowtail catastrophe. According to the normalization formula, we get that $X_{C_1} = (0.299)^{1/2} = 0.547$, $X_{C_2} = (0.652)^{1/3} = 0.867$, $X_{C_3} = (0)^{1/4} = 0$. For the three indexes are complementary, the average value of the three indexes is considered as the evaluation value of B_1. After calculation, we get that $X_{B_1} = 0.471$.

In the underlying indexes B_2, C_4, C_5, C_6, C_7 constructed the butterfly mutations.

So we got that $X_{C_4} = (0.045)^{1/2} = 0.212$, $X_{C_5} = (0.825)^{1/3} = 0.938$, $X_{C_6} = (0.730)^{1/4} = 0.924$, $X_{C_7} = (0.969)^{1/5} = 0.994$. For the four indexes are complementary, so the average value of the four indexes is considered as the evaluation value of B2. After calculation, we get that $X_{B_2} = 0.767$.

Similarly, the underlying index can be obtained as $X_{B_3} = 0.603$.

3.1.2 Upper index evaluation value

According to the evaluation value of the underlying index B_1, B_2, B_3, the value of upper index A_1 is calculated. For the underlying indexes are complementary, so the average value of underlying indexes is considered as the comprehensive evaluation. Shown in Table 5.

Differences in social vulnerability to floods among the 28 cities are distinguished through mutation analysis method. From Table 3 we can see that Fuyang is the most vulnerable city which vulnerability value is 0.941, Suzhou city and Huaibei city are the second and third vulnerable city which vulnerability values are above 0.9. While combination of indexes determines that comprehensive vulnerability of Zhengzhou city, Jining city and Huainan city are lower than other cities. From the perspective of population, Yangzhou city has a high ranking, while Huainan city is least vulnerable. Huainan city has the highest economic vulnerability, and Luan city is lowest in economic vulnerability. Huainan has a high ranking on flood prevention, while the vulnerability value

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of 0.646 defines the low flood prevention vulnerability of Zhengzhou. So, the vulnerability showed significant differences from city to city in the perspective of population, economic, flood prevention and complex.

3.2 Spatial variation of population vulnerability

In general, cities in the eastern basin have moderate to high levels of population vulnerability, while those in the western half exhibit relatively low levels of population vulnerability. The exceptions to this trend are Zaozhuang city and Huainan city witch values are far below the average. Southeast basin has the highest vulnerability which values are above 0.8. Zhengzhou is located in the northwestern part among the lower vulnerability cities, while the population vulnerability is also the lowest. On the contrary, Yangzhou city is in the Northeastern among the high vulnerability intensive areas, which has the highest population vulnerability.

Population vulnerability largely depends on the gender and population quality. In Huaihe River basin, Zhengzhou is the only provincial capital city among the 28 cities, although the city has the highest population density, the rich educational resources lead to high quality and cultural level in population, which mainly reflected in the 18.94 % of the college population which is twice as many as the second. The illiteracy rate of Zhengzhou is the lowest in 28 cities with the value of 2.14 %. From the perspective of gender distribution, the male resident population in the city is as high as 51.26 % for a large number of migrant workers flew in. All these indexes combined to contribute Zhengzhou to be the lowest in the population vulnerability.

Yangzhou city has a high ranking on population vulnerability, which is largely due to high female population density in the city. The proportion is as high as 50.75 %. As we all know, evacuation is an important way for flood prevention, women can't evacuate in time for the lack of adequate physical strength, social status. Thus they have a higher vulnerability. In addition, the proportion of the elderly population in Yangzhou is up to 12.44 %, witch influent the population vulnerability in the city. In the flood emergency evacuation, old people lack enough physical ability, and they depend mostly on the assist of young adults as well as the transport vehicles. Therefore, large numbers of aging population and empty nest elderly will expose the vulnerability of floods.

Overall, the high population vulnerability is largely due to excessive female population, serious population aging and low quality of population. In many areas, women, children, elderly are left behind because of mail taking jobs in cities. Underdeveloped educational conditions and quality of faculty may also have some limitations on personnel quality. The reasons have restricted the ability to improve flood prevention.

3.3 Spatial distribution of economic vulnerability

The economic vulnerability of flood hazards shows a distinctively western bias in its geographic distribution. In west region, the vulnerability in the middle is higher than those of the sides. This is not unexpected given the rapid economic development in these areas, especially for the city of Luan, Bengbu, Yangzhou. It is obviously shown in the statistical data that these cities are at the forefront in their provinces, while the number of population is at a medium level, so per capita income of local government budgets naturally higher than other cities. In addition, as cities continue to increase accompanied with the improvement of consumption levels, complexity economic vulnerability will decrease as well. Such as Bengbu, which take measures to improve the living environment for the concern of housing quality, the average expenses of households living in the area is up to Yuan 15.54 million, in the highest rank of all the cities.

Huainan, Fuyang are among the most vulnerable cities, where the relatively economy growth slowly. Especially in Huainan, per capita income is only Yuan 760. The situation of agricultural income is the other factor impacted economic vulnerability. In the case of Huainan, the index that per capita agricultural income is the lowest in the 28 cities with the value of Yuan 591, leading to its top ranking on economic vulnerability. Form the map we can see that Huainan city, Fuyang city are adjacent to Luan city and Bengbu city which have lowest economic vulnerability. They are all in Anhui province. The cities with adjacent location as well as different characteristics of vulnerability indicate that regional characteristics of economic vulnerability are not strong. Factors affected economic vulnerability does not have a strong interaction.

3.4 Spatial distribution of flood prevention vulnerability

Cities in the north of the basin have moderate to high levels of flood prevention vulnerability, while those in the southern half exhibit relatively low levels of social vulnerability to flood prevention. These regional differences are largely due to health care conditions, transportation, communication, emergency coordination and other factors.

Zhengzhou and Jining are among the lowest vulnerable cities which comprehensive value is below 0.62. As the only capital city among the 28 cities, Zhengzhou has abundant medical resources, it can be seen from several data, such as the number of medical institution owned by million people is 1347, and the number of hospital beds is 47 094, the number of health workers is 49 519. Good medical condition improves the ability to control the regional flood. In addition, good internet conditions protect the convenient communication in the city. We can see from the data that the number of people using the Internet is 5.86 million. Developed communications protect the district staff to communicate with each other and the channels of communication to continue open. The medical conditions largely define the low flood prevention vulnerability of Jining, for the number of medical institutions in the city is 29 254, and the number of health workers is 33 055. Extensive transportation and communication facilities enhance the ability to withstand floods in the city.

For the places such as Huainan and Suzhou, the local vulnerability is more of a function of very high scores on the flood prevention index. The primary driver is the transport condition, especially the ownership of vehicles. In Huainan city, the number of farm vehicles owned by per million people is 18.6, which is far below the average level of the Huaihe River basin.

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3.5 Spatial distribution of social vulnerability to floods

The pattern of comprehensive vulnerability is a little different from that of the other indices. Higher values occur more often in the center, while lower vulnerability values are concentrated in periphery. The exceptions to this trend are Heze city and Linyi city witch values are above the average. It shows a radial center in Zhengzhou which is the least vulnerability city among the 28 cities. This is largely due to the leading position in economy, transportation, education and health care conditions. Strong comprehensive strength reduces the overall vulnerability of the region, so that Zhengzhou city became the lowest vulnerability in Huaihe River basin. The center position of the capital city attracts a lot of migrant workers flown from surrounding cities, which can not only promote economic development, but also influence the proportion of men and women settled in the city. With the addition of male population, the rapid development of economic as well as the linkage construction of the surrounding cities, the cities which are near to Zhengzhou developed rapidly. Low vulnerability is also reflected in these cities. Thus it presents the center of radiation around Zhengzhou city.Fuyang is the most vulnerable city in Huaihe River basin. This is mainly due to the high level of population vulnerability, flood prevention vulnerability, especially for the highest ranking of economic vulnerability. It shows that economic income of Fuyang city, especially per capita of agricultural and industrial need to increase, in order to reduce social vulnerability to floods.

Social vulnerability is a combination of the three sub-groups, reflecting a city's comprehensive ability when facing floods. In the case of Jining, for example, the low ranking on social vulnerability is a function of extremely low values on all three indices. For the other cities, such as Yancheng, the social vulnerability is more of a function of very low scores on the economy index. This suggests that cities have distinctive population vulnerability and flood prevention vulnerability, but the comprehensive and complex nature overshadows the overall vulnerability results.

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4 Conclusions

We should strength the research of social vulnerability in Huaihe River basin, which is helpful for government to plan resources and can also lay the foundation to disaster prevention and mitigation.

1. Mutations evaluation system of social vulnerability to floods is construced from three aspects, population, economic, flood prevention. Ten indexes is contained in the system.

2. From the perspective of population vulnerability, cities in the eastern basin have moderate to high levels, while those in the western half exhibit relatively low levels. Yangzhou city has the highest population vulnerability, followed by Taizhou and Fuyang city. Huainan city has the lowest population vulnerability, followed by Zhengzhou and Zaozhuang city. Population vulnerability largely depends on the gender and population quality.

3. The economic vulnerability of flood hazards shows a distinctively western bias in its geographic distribution. The highest vulnerability is in Huainan city, followed by Fuyang city and Huaibei city. While the lowest city is Luan city, Bengbu and Yangzhou city are followed. Economic development is a major factor in determining economic vulnerability

4. Cities in the north of the basin have moderate to high levels of flood prevention vulnerability, while those in the southern half exhibit relatively low levels of social vulnerability to flood prevention. Huainan city has the highest vulnerability, Suzhou and Fuyang city followed. Zhengzhou has the lowest vulnerability, Jining and Rizhao followed. These regional differences are largely due to health care conditions, transportation, communication, emergency coordination factors.

5. Higher values of comprehensive vulnerability occur more often in the center, while lower vulnerability values are concentrated in periphery. Fuyang city has the high-

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est vulnerability, Suzhou and Huaibei city followed. The lowest vulnerability is in Zhengzhou city, and Jining and Huainan city followed. Comprehensive vulnerability is a consequence of the population, economy, flood prevention vulnerability.

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Table 1. Catastrophe model of one-dimensional state variable.

Catastrophe model	Number of variables	Potential function (model)	Bifurcation equation	Normalization formula
Folding model	1	$G(x) = x^3 + ax$	$a = -3x^2$	$x_1 = a^{1/2}$
Cusp model	2	$G(x) = x^4 + ax^2 + bx$	$a = -6x^2$, $b = 8x^3$	$x_1 = a^{1/2}$, $x_2 = b^{1/3}$
Dovetail model	3	$G(x) = 1/5x^5 + 1/3ax^5 + 1/2bx + cx$	$a = -6x^2$, $b = 8x^3$, $c = 3x^4$	$x_1 = a^{1/2}$, $x_2 = b^{1/3}$, $x_3 = c^{1/4}$
Butterfly model	4	$G(x) = 1/6x^6 + 1/4ax^4 + 1/3bx^3 + 1/2cx^2 + dx$	$a = -10x^2$, $b = 20x^3$, $c = -15x^4$, $d = 4x^5$	$x_1 = a^{1/2}$, $x_2 = b^{1/3}$, $x_3 = c^{1/4}$, $x_4 = d^{15}$

Table 2. Social vulnerability index system to floods.

Category	Variable
Population	Average number per house (one), resident male population ratio (%), resident female population ratio (%),resident population proportion less than 14 years old (%), resident population between the age of 5–65 (%), resident population proportion over 65 (%), population density (person km^{-2}), birth rate (‰), natural population growth rate (‰), college degree or above population ratio (%), high school (college) resident population ratio (%), junior resident population ratio (%), primary school resident population ratio (%)
Economy	Per capita disposable income of urban residents (Yuan), average net rural per capita income (Yuan), savings deposits of urban and rural residents per capita (Yuan), per capita income of local government budgets (ten thousand Yuan), per capita local government budget expenditure (ten thousand Yuan), per capita industrial output (ten thousand Yuan), per capita agricultural output (ten thousand Yuan), per capita gross output value of agriculture, forestry, animal husbandry and fishery (ten thousand Yuan), per capita GDP (ten thousand Yuan)
Flood prevention	Number of cars and motorcycles ownership per ten thousand people (one), number of mobile phone users per ten thousand people (one), number of Internet users per ten thousand people (%), number of hospital institutions per capita (one), number of health workers per ten thousand (one), number of hospital beds per ten thousand (one), number of township per ten thousand (one), the proportion of urban population (%), number of people resident committees per ten thousand (one), per capita living area of urban (m^2), rural per capita use of housing area of rural (m^2), annual consumption of urban households living expenses (ten thousand Yuan), rural households consumption expenditures of residence (ten thousand Yuan).

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Table 3. Indexes with higher load values in principal component.

Principal component	Index	Load value	Variance contribution rate	Percent variance explained	Vulnerability proportionality	Category
1	Average net rural per capita income	0.993	28.594	28.594	Positive	Economy
2	Number of hospital institutions per capita	0.838	11.720	40.314	Positive	Flood prevention
3	Resident female population ratio	0.965	9.395	49.709	Negative	Population
4	Junior resident population ratio	0.917	7.037	56.746	Negative	Population
5	Per capita agricultural output	0.965	5.995	62.741	Positive	Economy
6	Resident population proportion over 65	0.951	5.071	67.812	Negative	Population
7	Number of cars and motorcycles ownership per ten thousand people	0.968	4.577	72.389	Positive	Flood prevention
8	Number of Internet users per ten thousand people	0.841	3.737	76.126	Positive	Flood prevention
9	Per capita industrial output	0.601	3.510	79.636	Positive	Economy
10	Per capita gross output value of agriculture, forestry, animal husbandry and fishery	0.922	2.860	82.496	Positive	Economy

Table 4. Mutations evaluation system of social vulnerability to floods.

Target layer (code)	Guidelines layer (code)	Index layer (code)	Index nature
Social vulnerability to floods (A)	Population (B_1)	female resident population ratio (C_1)	–
		junior resident population ratio (C_2)	–
		proportion of the population aged over 65 (C_3)	–
	Economy (B_2)	average net rural per capita income (C_5)	+
		per capita agricultural output (C_6)	+
		per capita industrial output (C_7)	+
		per capita gross output value of agriculture, forestry, animal husbandry and fishery (C_8)	+
	Flood prevention (B_3)	number of hospital institutions per capita (C_9)	+
		number of cars and motorcycles ownership (C_{10})	+
		number of Internet users (C_{11})	+

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Table 5. Assessment results of social vulnerability to floods in 28 cities among the Huaihe River basin.

	Categorycity				
PoVI	EcVI	FPVI	SoVI	Ranking	
Zhengzhou	0.471	0.767	0.604	0.614	28
Kaifeng	0.761	0.706	0.948	0.805	21
Pingdingshan	0.721	0.926	0.919	0.855	14
Xuchang	0.752	0.829	0.940	0.841	19
Luohe	0.781	0.869	0.928	0.859	12
Shangqiu	0.842	0.855	0.901	0.866	10
Zhoukou	0.835	0.864	0.945	0.881	8
Zhumadian	0.833	0.912	0.938	0.894	4
Xinyang	0.819	0.804	0.907	0.843	17
Zaozhuang	0.563	0.860	0.869	0.764	25
Jining	0.778	0.781	0.618	0.726	27
Rizhao	0.821	0.824	0.652	0.765	24
Linyi	0.792	0.866	0.917	0.858	13
Heze	0.816	0.895	0.955	0.888	6
Bengbu	0.795	0.639	0.972	0.802	22
Huainan	0.334	0.959	0.993	0.762	26
Huaibei	0.814	0.935	0.955	0.901	3
Fuyang	0.891	0.952	0.981	0.941	1
Suzhou	0.856	0.923	0.991	0.923	2
Luan	0.796	0.603	0.962	0.787	23
Bozhou	0.796	0.925	0.948	0.890	5
Xuzhou	0.850	0.792	0.905	0.849	15
Lianyungang	0.784	0.834	0.910	0.843	18
Huaian	0.881	0.797	0.980	0.886	7
Yancheng	0.872	0.692	0.870	0.811	20
Yangzhou	0.939	0.655	0.941	0.845	16
Taizhou	0.923	0.708	0.964	0.865	11
Suqian	0.843	0.827	0.974	0.881	9

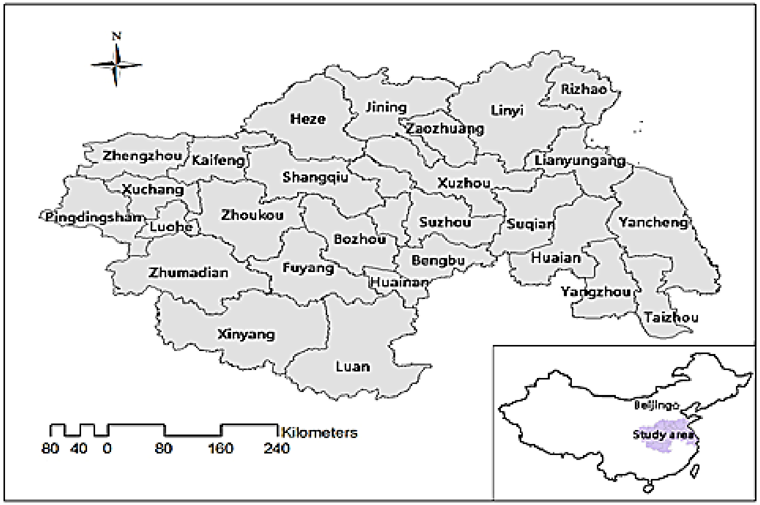

Figure 1. Huaihe River basin.

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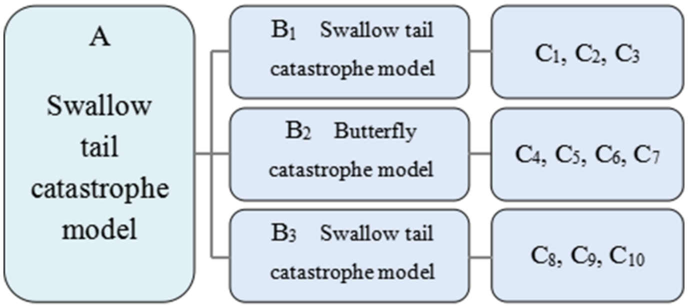

Figure 2. Catastrophe model of social vulnerability in Huaihe River basin.

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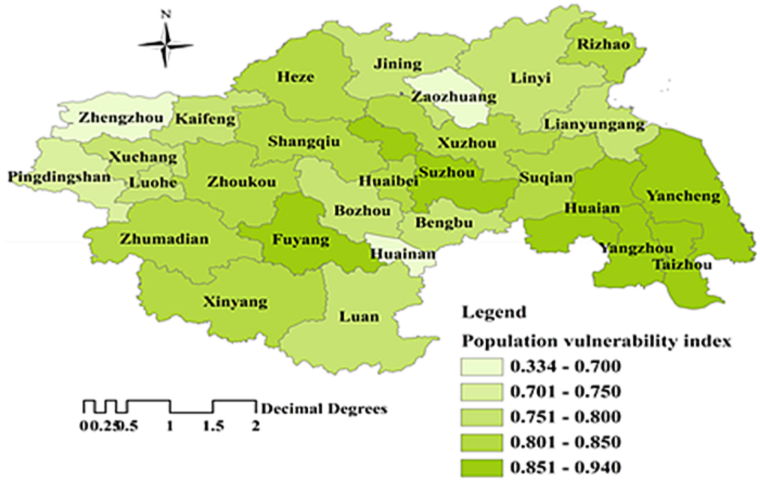

Figure 3. Spatial distribution of economic vulnerability in Huaihe River basin.

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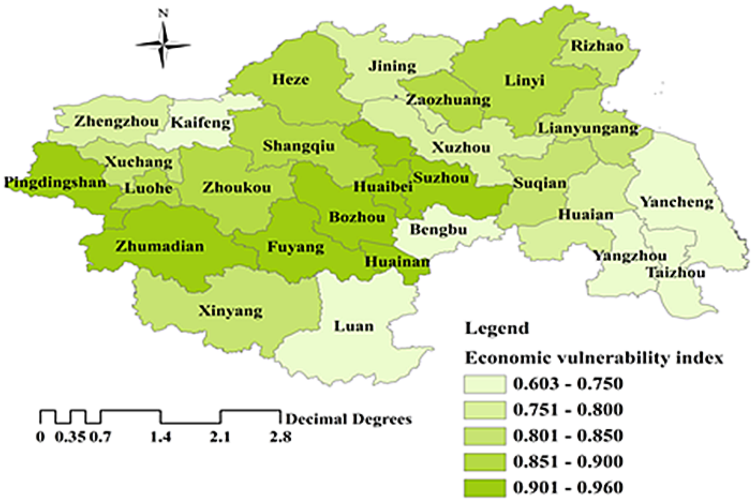

Figure 4. Spatial distribution of flood prevention vulnerability in Huaihe River basin.

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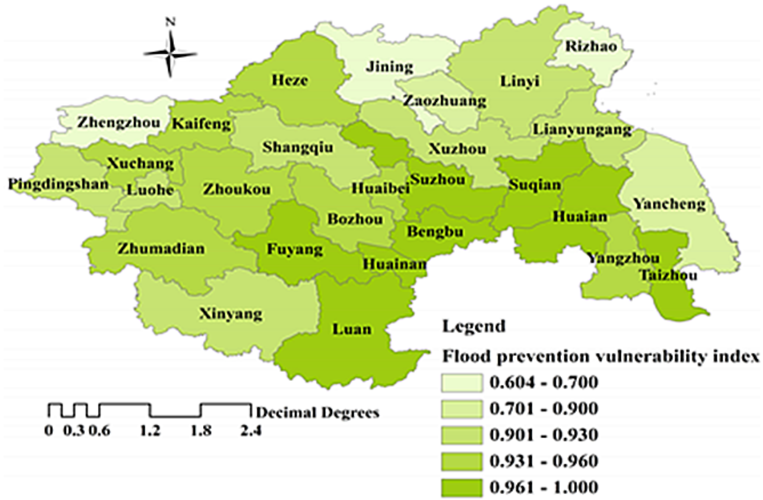

Figure 5. Spatial distribution of flood prevention vulnerability in Huaihe River basin.

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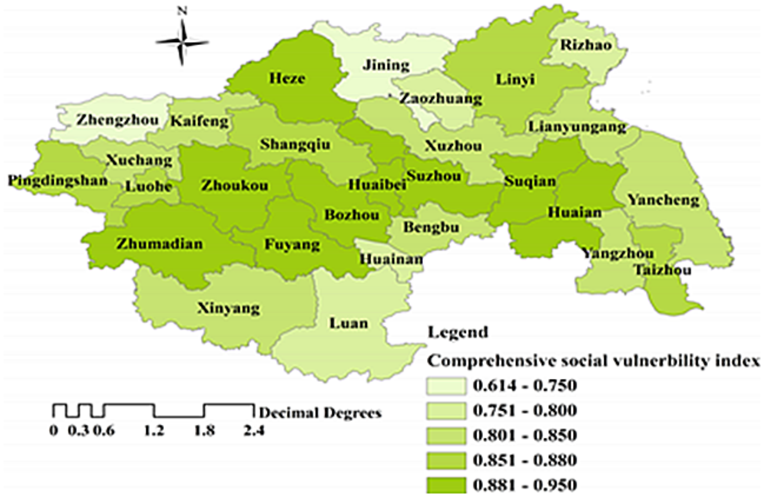

Figure 6. Spatial distribution of social vulnerability to floods.

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