



Comprehensive evaluation of urban flood-bearing risks based on combined compound fuzzy matter-element and entropy weight model

Hong Lv¹ · Xinjian Guan¹ · Yu Meng¹

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Abstract

The extreme precipitation events caused by climate change and the rapid development of urbanization have brought hidden flood risks to the cities. This paper comprehensively considered two major factors of vulnerability of urban flood-bearing and disaster prevention and mitigation (DPAM) capacity and built a comprehensive evaluation index system for urban flood-bearing risks. Secondly, a combined model consisted of composite fuzzy matter-element and entropy weight model was constructed to calculate the comprehensive risk indicator. Finally, the Zhengzhou City was taken as an example, the comprehensive indices of urban flood-bearing risk from 2006 to 2015 were evaluated. The results showed that the comprehensive risk of Zhengzhou City was generally on a slow upward trend, from II level (moderate-risk) in 2006 to III level (secondary high-risk) in 2015, which was mainly due to the mismatch between the rapid development of urbanization and the slow improvement of DPAM capabilities. This paper is expected to provide scientific reference and technical support for urban flood disaster prevention and sponge city construction.

Keywords Vulnerability of urban flood-bearing · Disaster prevention and mitigation capacity · Comprehensive risk · Urbanization process · Sponge city

1 Introduction

Floods have been an important global issue in recent years especially urban flood, as it poses growing threats to urban areas (Duan et al. 2016; Liu et al. 2018). Of all weather-related disasters over the past 20 years, floods are the most common (47%), affecting 2.3 billion people, and the third largest economic loss (662 billion USD) (CRED and UNISDR 2015). Moreover, low infiltration or storage capacity during high-intensity rainfall can easily trigger flooding, especially in urban areas. With the future changes in urban climate and land use, the risk of urban floods will increase (Hai-Min et al. 2018; Wing et al. 2018). The rapid concentration of buildings and populations generated by

✉ Yu Meng
mengyu8@zzu.edu.cn

¹ School of Water Conservancy Science and Engineering, Zhengzhou University, Zhengzhou 450001, China

the rapid urbanization process will also lead to an increased risk of urban floods (Abdulrazzak et al. 2019). Urban floods are characterized by sudden onset, large peak heights, short forecast periods, and complex temporal and spatial changes (Huong and Pathirana 2013). Research on pre-disaster risk assessment of urban floods is one of the effective ways to mitigate floods (Abebe et al. 2019), and it also provides technical support for the formulation of disaster prevention and mitigation policies.

The Urban Flood Risk Evaluation (UFRE) research has attracted worldwide attention. For example, disaster risk reduction project was implemented by the cooperative research center for international Disaster Risk Reduction (Black et al. 2011). And the global risk information platform project was carried out by the United Nations development program "towards applications, strengthening cooperation and enhancing the capacity of cities and regions to avoid risks and mitigate disasters" (Yin and Xu 2012). Additionally, the forecasting, warning, risk assessment, monitoring and prevention of urban flood disaster were put forward in the China Twelfth Five-Year Plan for Integrated Disaster Reduction.

The UFRE is the analysis of the state of urban system risk factors for risk management, reduction or control of risks. From the development stage of the UFRE research, the following transformation characteristics can be roughly seen : (1) from large-scale study to high-precision scenario simulation; (2) from the mathematical statistics of the disaster after the disaster to the risk assessment before the disaster; (3) single index analysis to multi-index comprehensive evaluation. Generally, the primary methods for UFRE are divided into 4 types including evaluation method of scenario simulation, GIS and remote sensing, historical flood data and index system (Quan 2014).

The scenario simulation assessment method refers to the initial characteristics of a given flood disaster, then performs computer simulations based on the disaster evolution mechanism to obtain the flood evolution process and finally conducts disaster risk assessment (Ding et al. 2017). The model can accurately identify the potential flood risk in the region and provide strong support for urban flood decision-making and risk management. However, its over-reliance on data accessibility and model construction is complex. The spatial analysis method is based on remote sensing image data of flood disasters, combined with the spatial analysis function of GIS to analyze the disaster risk in flooded areas. (Youssef et al. 2011). The model can well study the temporal and spatial characteristics of urban flooding evolution based on flood disaster historical data. However, long-term accuracy historical disaster data are often incomplete or lack of data, and the spatial precision is low, which is difficult to reflect the spatial difference of risk.

Burton et al. (1993) used human social and economic conditions as the basis of flood disaster risk assessment for the first time, and used demographic characteristics and housing structure as the disaster vulnerability assessment index system. Since then, the indicator system method has been widely used in flood disaster assessment (Deo et al. 2015). The index system evaluation method considers the causes of flood disasters, the performance characteristics of disasters, and the impact of disasters. Generally, the evaluation indicators include four categories: hazards of hazards, fragility of the affected body, environmental sensitivity to disasters, and disaster prevention and reduction capabilities. For example, Wang et al. (2011) considered altitude, drainage network, population, vegetation cover, traffic and other factors; Cristina et al. (2018) selected regional economy, flood factors, population density, disaster prevention level and other factors; but in traditional research, its indicator construction principles and formula descriptions are not clear. And there are only a few studies on potential disaster risk assessment that considers pre-disaster floods in cities, and it is impossible to make refined management and prevention of urban risks.

Based on the index construction, the index system evaluation method adopts mathematical methods to determine the weight of each index and comprehensively calculates the regional flood risk. Commonly used mathematical calculation methods include objective or subjective methods such as entropy weight method (Wang et al. 2012), analytic hierarchy process (Stefanidis and Stathis 2013), and principal component analysis method (Roshan and Robert 2017). But the single mathematical methods have the limitation of not making full use of the characteristic information of the index data. As a result, the evaluation of flood risk index system evaluation method has entered a new stage-based on the combination model evaluation. For example, Scheuer et al. (2011) used the analytic hierarchy process and fuzzy mathematical model to carry out urban flood risk assessment for Leipzig in Germany. Based on the combination weight model and fuzzy comprehensive evaluation, Lai et al. (2015) constructed flood risk zoning map in Dongjiang River Basin of China. However, traditional combined evaluation models cannot quantitatively describe the relative grading level of evaluation results. The compound fuzzy matter-element model, as a multi-index evaluation field (Zhang et al. 2011, 2018), performs relatively well in the relative ranking of the evaluation results. However, in traditional research, the problems of strong subjectivity of index weights and unclear classification of risk indicators are prominent.

Above all, in order to improve the city's disaster prevention capacity and urban flood risk management level, this paper built a comprehensive evaluation index system of urban flood-bearing risk, which contained two major categories of vulnerability of urban flood-bearing (VOUF) and DPAM capacity. And evaluation criteria for each index are constructed. Next, a combined compound fuzzy matter-element and entropy weight model was constructed to calculate the comprehensive risk of urban flood-bearing which made the flood risk assessment process objective and rationalized. Finally, Zhengzhou City is taken as an example to evaluate the comprehensive flood risk from 2006 to 2015. Taking the urbanization process, DPAM capacity and sponge city construction into account, influence factors of flood-bearing were analyzed. This study is expected to provide technical support for urban flood prevention and sponge city construction realizing the transformation from post-disaster relief to pre-disaster prevention, from reduction of disaster loss to reduction of disaster risk.

2 Materials and methods

2.1 Study area

Zhengzhou is located at 112°42'–114°14' east longitude and 34°16'–34°58' north latitude, whose terrain slopes from southwest to northeast, and transitions from mountainous and hilly to plain (Fig. 1). Zhengzhou's rich water system and uneven distribution of rainfall are the natural factors for frequent urban floods. Its river network density is about 0.094 km/km², and the rainfall in the flood season (from June to September) accounts for 60% of the whole year. In October 1948, the Henan provincial government upgraded Zhengzhou county to Zhengzhou city. As a relatively young provincial capital city, the urbanization problems left by the rapid social and economic development are prominent. In 2016, the state council of China announced the 13th five-year plan to support Zhengzhou in building a national central city, which leads to an inevitable trend of rapid urban economic development and population explosion. If the construction of

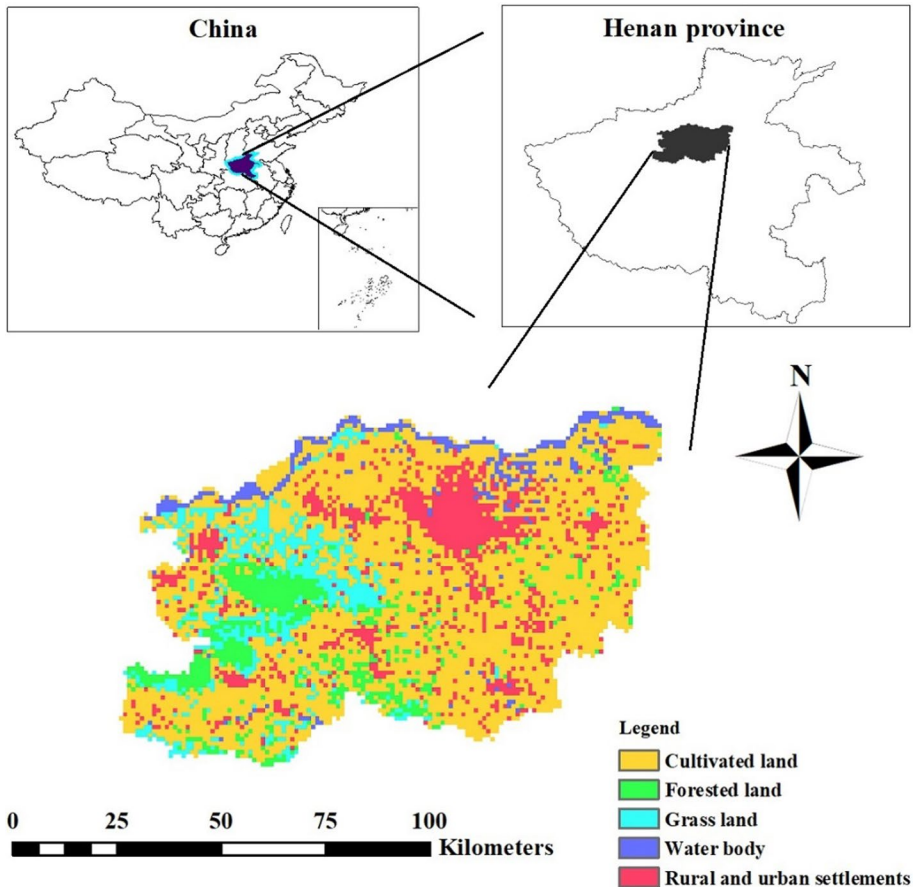


Fig. 1 Location of Zhengzhou city and its land-used situation In 2015

DPAM infrastructure cannot match the urbanization level, the urban flood will cause huge economic loss and even threaten the social and economic development of the city (Fig. 2).

2.2 Comprehensive evaluation index system of urban flood-bearing risk

The UFRE takes into account VOUF and DPAM capacity. The VOUF indicates the loss degree of cities with different development degrees facing floods. The vulnerability is related to the development of urban society and economic and the concentration of population. The urban DPAM capacity refers to the rescue capability of the government, the self-rescue capability of the people and the ability of urban infrastructure to reduce disaster losses when disasters occur. When the urban DPAM capacity cannot match the risks from VOUF, the city will suffer huge loss as the flood occurs. Therefore, the two together constitute the comprehensive evaluation index system of urban flood disaster risk.

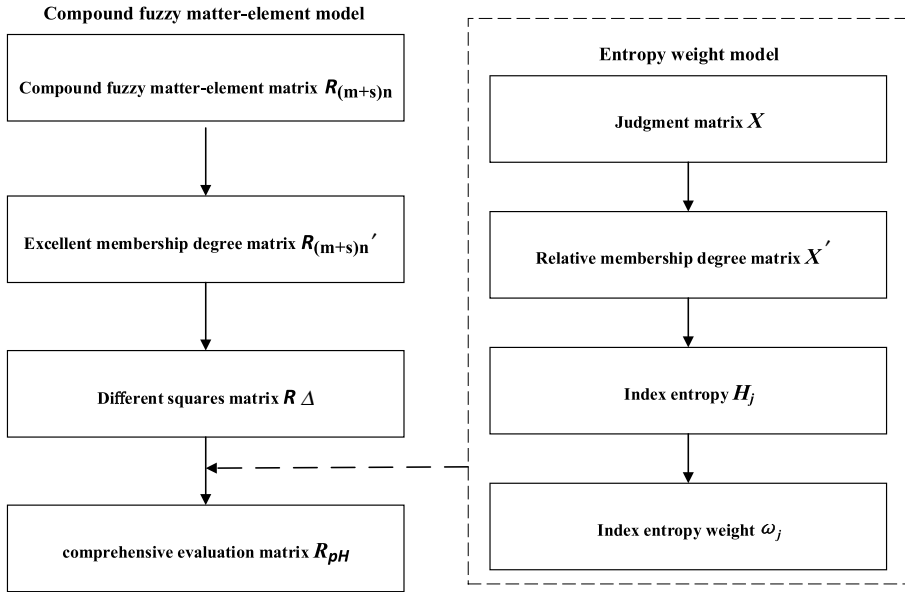


Fig. 2 Flowchart of Combined compound fuzzy matter-element and entropy weight model

2.2.1 Vulnerability of urban flood-bearing

The VOUF represents the flood-bearing risk caused by the high level of social and economic development in cities. Comprehensively considering urban flood-bearing situation, and related research (Zhang et al. 2016; Rana and Routray 2018), five representative indicators are selected.

- (1) The Ratio of Built-up Area (RBA, %)

Built up area (Ba) refers to the land with basically perfect municipal public facilities in urban area. RBA (Eq. 1) is the percentage of built-up areas in urban areas, which is one of the indicators to measure the development scale of cities.

$$RBA_i = \frac{Ba_i}{Ua_i} \times 100\% \tag{1}$$

where i is in a given year; Ba_i is urban built-up area, km^2 ; Ua_i is total urban area, km^2 .

- (2) The Ratio of Urban Masonry and Concrete Area (RMC, %)

To a certain extent, urban masonry and concrete area represent urban impermeable areas. The larger this index (Eq. 2) value, the higher the VOUF.

$$RMC_i = 1 - \frac{Uwa_i + Uga_i + Uula_i}{Ua_i} \times 100\% \quad (2)$$

where Uwa_i , Uga_i , $Uula_i$ are urban water area, green area and unused land area, km^2 .

(3) The Density of Urban Population (DUP, thousand persons/ km^2)

As one of the main victims of natural disasters, the population is very sensitive to natural disasters. With the development of economy and society, the greater the DUP (Eq. 3), the greater the VOUF.

$$DUP_i = \frac{Nup_i}{Ua_i \times 10000} \quad (3)$$

where Nup_i is the number of urban permanent residents at the end of a given year.

(4) Regional Average GDP (A-GDP, million yuan/ km^2)

The high A-GDP (Eq. 4) indicates that the higher the level of development and economic concentration of per unit area, the greater the damage to the region after flood.

$$A - GDP_i = \frac{GDP_{1i} + GDP_{2i} + GDP_{3i}}{Ua_i} \quad (4)$$

where GDP_{1i} , GDP_{2i} , GDP_{3i} are, respectively, GDP of first, second and third industry in urban area, million yuan.

(5) Fixed Asset Investment (FAI, billion yuan)

The total social FAI reflects the city's fixed asset investment situation and the degree of urban economic development and concentration. Through the construction and purchase of social FAI, cities continue to adopt advanced technology and equipment, resulting in a more concentrated regional distribution of economic structure and productivity, and a greater vulnerability to floods.

$$FAI_i = FAI_{1i} + FAI_{2i} + FAI_{3i} \quad (5)$$

where FAI_{1i} , FAI_{2i} , FAI_{3i} , respectively, represent the fixed asset investment of the first, second and third industries, billion yuan.

2.2.2 Urban disaster prevention and mitigation capacity

The urban DPAM capacity indicates the ability to reduce flood risk. Considering urban underlying surface, construction of DPAM facilities, disaster relief capacity of government and civilian and other factors, seven representative indicators are selected based on related researches (Wang et al. 2011; Rana and Routray 2018).

(6) The Proportion of Urban Green Area (PUG, %)

The high PUG (Eq. 6) can enhance the absorption of precipitation, and effectively alleviate the damage of rainstorm and waterlogging, which lead to less danger of urban flood.

$$PUG_i = \frac{Kga_i + Dga_i + Oga_i}{Ua_i} \times 100\% \tag{6}$$

where Kga_i , Dga_i , Oga_i are, respectively, park green area, protected green area and other green area, km^2 .

(7) Per Capita GDP (P-GDP, yuan)

P-GDP (Eq. 7) is an important index to measure the economic development of a region. It can also reflect the resilience of urban residents after disasters.

$$P - GDP_i = \frac{GDP_{1i} + GDP_{2i} + GDP_{3i}}{Nup_i} \tag{7}$$

(8) The Density of Urban Drainage Pipe (DUDP, km/km^2)

DUDP (Eq. 7) plays an important role in reducing the time of precipitation detention and the risk of flood.

$$DPD_i = \frac{Dpl_i}{Ua_i} \tag{7}$$

where Dpl_i is the length of the urban drainage pipe, km .

(9) Drainage Density (DD, km/km^2)

DD refers to the ratio of the length of urban dry branches to urban area. The inflow of the river network carrying pipe network in the city signifies the comprehensive ability of urban flood control. It is an important level for alleviating urban waterlogging and drainage. Its calculation formula is as follows:

$$DD_i = \frac{DI_i}{Ua_i} \tag{8}$$

where DD_i is urban river length, km .

(10) The Number of Medical Beds Per Thousand People (NMBT, beds)

In the event of a disaster, the greater the value of NMBT (Eq. 10), the stronger the emergency rescue capacity of the injured, which reflects the capacity of bed support in response to flood.

$$NMBT_i = \frac{NMB_i}{Nup_i/1000} \tag{10}$$

where NMB_i is the number of medical beds.

(11) The number of health-care workers per thousand people (NHWT, persons)

NHWT (Eq. 11) reflects the ability of medical security for the injured to cope with floods.

$$\text{NHWT}_i = \frac{\text{NHW}_i}{\text{Nup}_i/1000} \quad (11)$$

where NHW_i is the number of health-care workers.

(12) The ratio of government revenue and expenditure (RRE, %)

The high local RRE (Eq. 12) indicates that governments have a large financial surplus and strong ability to resist risks of disasters.

$$\text{RRE}_i = \frac{\text{Gr}_i}{\text{Ge}_i} \times 100\% \quad (12)$$

where Gr_i is the government revenue, billion yuan; Ge_i is the government expenditure, billion yuan.

2.3 Index evaluation standard

Index evaluation criteria are divided into four levels: low risk (level I), intermediate risk (level II), second highest risk (level III), and high risk (level IV).

The level I is mainly based on the combination of high disaster prevention and mitigation construction levels in China's developed cities, such as Shanghai and Qingdao, and low disaster vulnerability in cities with low and medium development levels., which is in line with the ideal state of balanced development of urban social and economic development and disaster prevention and mitigation, and has a very low risk of urban flood disasters.

The level II and level III, respectively, combine the multi-year average levels of urban construction in Henan Province and China, respectively. Comprehensive statistics from the "Chinese Bulletin of Flood and Drought Disasters" in the past 10 years show that Henan Province generally has a national level of flood damage. Therefore, Henan Province, where Zhengzhou City is located, is selected as the level II. In recent years, China's urban flood risk has been at a relatively high level due to extreme climate and uneven urban economic development.

Finally, the level IV is mainly combined with cities with higher risk of flood disasters such as Wuhan and Nanjing, with a higher level of urbanization, but disaster prevention facilities are at a lower level (Li et al. 2012). The flood losses in these cities are large all the year round. When the level of indicators is at level IV, they need to be taken seriously by city management departments.

Therefore, the index evaluation criteria are as follows (Table 1).

2.4 Combined compound fuzzy matter-element and entropy weight model

To make full use of the characteristic information of the index data and quantitatively describe the relative grading level of the evaluation results, this study uses a combined mathematical model-composite fuzzy matter-element combined entropy weight

Table 1 Comprehensive evaluation index standard of urban flood-bearing risk

Category	Index	Level I	Level II	Level III	Level IV
VOUF (–)	<i>RBA</i>	<4.5	(4.5, 5.5)	(5.5, 6.5)	>6.5
	<i>RMC</i>	<66	(66, 72)	(72, 78)	>78
	<i>DUP</i>	<5	(5, 10)	(10, 15)	>15
	<i>A-GDP</i>	<40	(40, 80)	(80, 120)	>120
	<i>FAI</i>	<210	(210, 420)	(420, 630)	>630
DPAM capacity (+)	<i>RUG</i>	>42	(38, 42)	(34, 38)	<34
	<i>P-GDP</i>	>110,000	(70,000, 110,000)	(30,000, 70,000)	<30,000
	<i>DPD</i>	>9.1	(8.6, 9.1)	(8.6, 8.1)	<8.1
	<i>DD (km/km²)</i>	>0.6	(0.4, 0.5)	(0.2, 0.4)	<0.2
	<i>NMBT</i>	>7.8	(5.9, 7.8)	(4.3, 5.9)	<4.3
	<i>NHWT</i>	>9.0	(7.1, 9.0)	(4.2, 7.1)	<4.2
	<i>RRE</i>	>92	(87, 92)	(82, 87)	<82

combination model to make a new attempt for disaster risk assessment. The fuzzy matter-element model was constructed to transform multiple evaluation indexes and index standards into comprehensive index values. The weight in the fuzzy matter-element model is obtained through the entropy weight model. The flowchart is shown in the following figure:

2.4.1 Compound fuzzy matter-element model

In 1983, a Chinese scholar, Caiwen professor first proposed the theory of matter-element analysis (Feng and Hong 2014), usually used to solve incompatible multi-index evaluation problems and tried to formalize the process of solving problems. Using matter-element analysis to combine fuzzy sets and Euclid approach degree, the combined compound fuzzy matter-element was constructed to calculate the comprehensive risk indicator of urban flood-bearing in this paper. The weight of index was estimated by entropy weight model. The built model is expected to provide a feasible new approach to risk assessment of urban flood-bearing.

In the matter-element analysis, the ordered triples formed by matter *M*, its characteristic *C* and its value *x* are called basic elements $R = (M, C, x)$ (Feng and Hong 2014). If the matter *M* has *n* characteristics, C_1, C_2, \dots, C_n , and the corresponding fuzzy values have, x_1, x_2, \dots, x_n , then *R* is named as *n* dimensions fuzzy matter-element. *m* matters with *n* dimensions fuzzy matter-element form the compound fuzzy matter-element of the multi-objective R_{mn} (Zhang et al. 2018).

Multiple characteristics of matters are converted into a comprehensive indicator by compound fuzzy matter-element mode in the assessment index system. The main steps are as follows:

- (1) Compound fuzzy matter-element matrix

Compound fuzzy matter-element matrix $R_{(m+s)n}$, which has *m* evaluated matters, *s* boundary conditions and *n* evaluated characteristics, is denoted by Eq. (13):

$$R_{(m+s)n} = \begin{bmatrix} & C_1 & C_2 & \cdots & C_n \\ M_1 & x_{11} & x_{12} & \cdots & x_{1n} \\ M_2 & x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ M_m & x_{m1} & x_{m2} & \cdots & x_{mn} \\ M_{m+1} & x_{(m+1)1} & x_{(m+1)2} & \cdots & x_{(m+1)n} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ M_{m+s} & x_{(m+s)1} & x_{(m+s)2} & \cdots & x_{(m+s)n} \end{bmatrix} \tag{13}$$

where M_i is the i -th matter ($i = 1 \sim m$), M_{m+i} is the i -th boundary condition ($i = 1 \sim s$), C_j is the j -th characteristic ($j = 1 \sim n$), x_{ij} ($i = 1 \sim m + s, j = 1 \sim n$) is the value of the i -th matter on the j -th characteristic.

(2) Excellent membership degree matrix

According to the optimization principle, the excellent membership degree function u_{ij} is calculated by different formulas Eqs. (14) and (15).

$$\text{The ideal maximum } \mu_{ij} = x_{ij} / (x_{ij})_{\max} \tag{14}$$

$$\text{The ideal maximum } \mu_{ij} = x_{ij} / (x_{ij})_{\max} \tag{15}$$

where $(x_{ij})_{\max} / (x_{ij})_{\min}$ are the maximum and minimum values of each evaluation index.

Therefore, the matrix of excellent membership degree $R'_{(m+s)n}$ is as follows Eq. (16):

$$R'_{(m+s)n} = \begin{bmatrix} & C_1 & C_2 & \cdots & C_n \\ M_1 & \mu_{11} & \mu_{12} & \cdots & \mu_{1n} \\ M_2 & \mu_{21} & \mu_{22} & \cdots & \mu_{2n} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ M_m & \mu_{m1} & \mu_{m2} & \cdots & \mu_{mn} \\ M_{m+1} & \mu_{(m+1)1} & \mu_{(m+1)2} & \cdots & \mu_{(m+1)n} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ M_{m+s} & \mu_{(m+s)1} & \mu_{(m+s)2} & \cdots & \mu_{(m+s)n} \end{bmatrix} \tag{16}$$

(3) The different squares of compound fuzzy matter-element

The standard fuzzy matter-element R_{0n} refers to the optimal membership degree of each index, which is given by Eq. (17):

$$R_{0n} = \begin{bmatrix} & C_1 & C_2 & \cdots & C_n \\ M_0 & 1 & 1 & \cdots & 1 \end{bmatrix} \tag{17}$$

where M_0 is standard matter.

Therefore, the different squares of compound fuzzy matter-element R_{Δ} through $R'_{(m+s)n}$ and R_{0n} are calculated by Eq. (18):

$$R_{\Delta} = \begin{bmatrix} & C_1 & C_2 & \cdots & C_n \\ M_1 & \Delta_{11} & \Delta_{12} & \cdots & \Delta_{1n} \\ M_2 & \Delta_{21} & \Delta_{22} & \cdots & \Delta_{2n} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ M_m & \Delta_{m1} & \Delta_{m2} & \cdots & \Delta_{mn} \\ M_{m+1} & \Delta_{(m+1)1} & \Delta_{(m+1)2} & \cdots & \Delta_{(m+1)n} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ M_{m+s} & \Delta_{(m+s)1} & \Delta_{(m+s)2} & \cdots & \Delta_{(m+s)n} \end{bmatrix} \tag{18}$$

where $\Delta_{ij} = (1 - \mu_{ij})^2 (i = 1 \sim m + s, j = 1 \sim n)$.

(4) The Euclid approach degree and comprehensive evaluation

The Euclid approach degree can indicate the degree of proximity of evaluated scheme and standard scheme. A larger Euclid approach degree means a larger degree of proximity, which can judge the quality of the matter. This is shown in Eqs. (19) and (20):

$$\rho H_i = 1 - \sqrt{\sum_{j=1}^n \omega_j \Delta_{ij}} \tag{19}$$

$$R_{\rho H} = \begin{bmatrix} M_1 & M_2 & \cdots & M_m \\ \rho H_1 & \rho H_2 & \cdots & \rho H_m \end{bmatrix} \tag{20}$$

where $\rho H_i (i = 1, 2, \dots, m)$ is the Euclid approach degree of the i -th matter, which also is the comprehensive indicator of the i -th matter. ω_j is the weight of the j -th characteristic, which is estimated by entropy weight model in this paper, $R_{\rho H}$ is the comprehensive evaluation matrix.

2.4.2 Entropy weight model

Information Entropy was first proposed by Shannon. (1948) to measure the uncertainty of the things. In the comprehensive evaluation, a greater variation of index value means the index provides less information and also indicates smaller weights. Entropy weight method is an objective system analysis method evaluating complex multi-index system and overcomes the irrationality of judgement by subjective experience. In this paper, entropy weight method is introduced into the compound fuzzy matter-element model to calculate the weight value of each index. The steps are as follows:

(1) Judgment matrix

The judgment matrix composed of m evaluation matters and n evaluation index is shown in Eq. (21):

$$X = (x_{ij})_{m \times n}, (i = 1 \sim m, j = 1 \sim n) \tag{21}$$

(2) Relative membership degree matrix

Through normalization treatment, the relative membership degree function r_{ij} is calculated by different formulas Eqs. (22) and (23).

$$\text{The ideal maximum } r_{ij} = (x_{ij} - x_{\min}) / (x_{\max} - x_{\min}) \quad (22)$$

$$\text{The ideal minimum } r_{ij} = (x_{\max} - x_{ij}) / (x_{\max} - x_{\min}) \quad (23)$$

Therefore, the matrix of relative membership degree X' is as follows Eq. (24).

$$X' = (r_{ij})_{m \times n}, (i = 1 \sim m, j = 1 \sim n) \quad (24)$$

(3) Index entropy

According to the concept of entropy, the entropy value H_j of j evaluation index is shown in Eq. (25):

$$H_j = - \sum_{i=1}^m (f_{ij} \ln f_{ij}) / \ln m, (i = 1 \sim m, j = 1 \sim n) \quad (25)$$

In the j -th index, the proportion f_{ij} of the i -th matter in all matters is calculated by Eq. (26):

$$f_{ij} = (1 + r_{ij}) / \sum_{i=1}^m (1 + r_{ij}) \quad (26)$$

(4) Index entropy weight

The entropy weight ω_j of the j -th index is calculated by Eq. (27):

$$\omega_j = (1 + H_j) / \sum_{j=1}^n (1 + H_j) \quad (27)$$

and $0 \leq \omega_j \leq 1, \sum_{j=1}^n \omega_j = 1$.

3 Results

3.1 The entropy weight of evaluation index

The 12 kinds of evaluation index data in 10 years $x_{ij} (i = 1 \sim 10, j = 1 \sim 12)$ of Zhengzhou city were input into entropy weight model to calculate the entropy weight of each index $\omega_j (j = 1, 2, \dots, 12)$, which are shown in Table 2:

There were four indices weight exceeding 0.09, including *PUG*, *NHWT*, *RMC* and *A-GDP*, which indicated the government of Zhengzhou attached great importance to improve the quality of life of residents, the area of green gardens, urban basic roads and medical services during the past decade. There were six indices weight between 0.07 and 0.09, including *DD*, *P-GDP*, *RRE*, *DUP*, *FAI* and *NMWT*. Urban living standards and social

Table 2 Entropy weight of comprehensive evaluation index of urban flood-bearing risk

Index	<i>PUG</i>	<i>NHWT</i>	<i>RMC</i>	<i>A-GDP</i>	<i>DD</i>	<i>P-GDP</i>
Weight	0.107	0.098	0.096	0.095	0.088	0.086
Index	<i>RRE</i>	<i>DUP</i>	<i>FAI</i>	<i>NMWT</i>	<i>RBA</i>	<i>DUDP</i>
Weight	0.081	0.078	0.073	0.07	0.065	0.063

infrastructure were steadily improved, and regional economy and population were also developing and concentrating rapidly, which means that DPAM capacity of urban flood and VOUF are both improved. There were two indicators with the weight of less than 0.07, including *RBA* and *DUDP*. Compared with China’s developed cities, Zhengzhou is located in the inland area and its urban expansion speed is relatively slow. The weight of *DUDP* was at the minimum, which means that the construction of urban drainage pipe network changed little. Combined with the current increase in urban extreme rainfall, Zhengzhou city is at great risk of flood.

3.2 Comprehensive evaluation results

The 12 kinds of evaluation index data and 3 kinds of evaluation standard data in 10 years $x_{ij}(i = 1 \sim 13, j = 1 \sim 12)$ were input into compound fuzzy matter-element model to calculate the different squares of compound fuzzy matter-element $\Delta_{ij}(i = 1 \sim 13, j = 1 \sim 12)$. Combined with the weight $\omega_j(j = 1 \sim 12)$, the comprehensive risk indicator of urban flood-bearing $\rho H_i(i = 1 \sim 13)$ in each year was calculated. The results are shown in Table 3 and Fig. 3.

Compared with evaluation standard, the comprehensive indicator of urban flood-bearing risk during the past decade was in a slow downward trend, that is, the increase

Table 3 Comprehensive index of evaluation standard

state level	Level I	Level II	Level III	Level IV
ρH_j	>0.824	(0.636, 0.824)	(0.487, 0.636)	<0.487

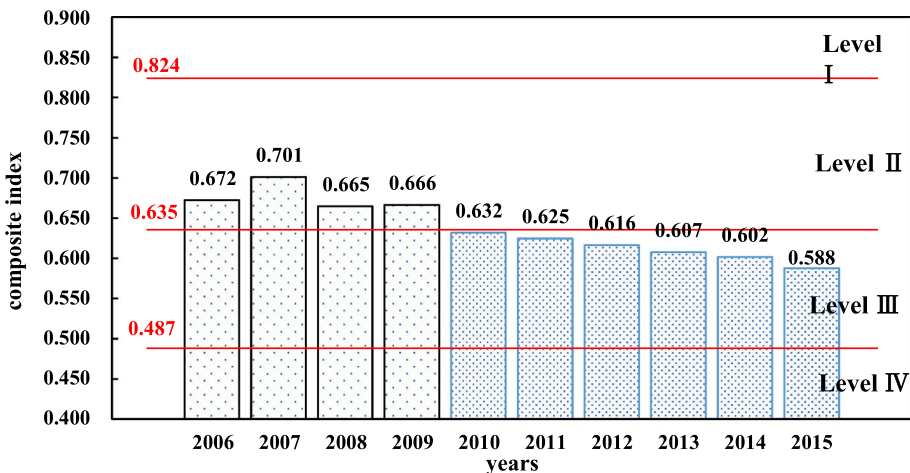


Fig. 3 The comprehensive index change of urban flood-bearing risk in Zhengzhou during the past decade

in disaster-bearing risk presented an upward trend. The comprehensive indicator fell from 0.672 in 2006 to 0.588 in 2015, with a rate of -12.5% . But there were four risk declines within 10 years, from 2006 to 2007, 2008 to 2009. The comprehensive indicator was the largest (0.701) in 2007.

From 2006 to 2009, urban economic construction was in a period of rapid development with *A-GDP* in a low level. Because of the small urban population in the early years, the urban per capita green area and road area were at a high level. VOUF and DPAM capacity achieved a relative balance. From 2010 to 2015, although the comprehensive index changed gently, the risk of flood-bearing was still increasing. During this period, the capacity of urban DPAM capacity was lower than the flood-bearing risk brought about by the acceleration of urbanization process and population growth.

4 Discussion

4.1 Urbanization process

Due to the rapid urbanization process, urban land-used situation changed (Figs. 1, 4) during the past decade. The change deepened the vulnerability of the urban flood-bearing environment. As shown in Table 4, the areas of rural and urban settlements increased by 2.3%, with a growth rate of 17.2%, while the area of cultivated land decreased by 2.5%. Also the change of the areas of forested land, grass land water body were small. With the acceleration of urbanization, the existing urban area was not enough to meet the economic construction and population scale. So the city began to expand outwards, the area of cultivated land and forested land decreased continuously. However, the large areas of hardened ground in cities hinders the infiltration process of rainfall, heightens the surface runoff coefficient and increases the surface runoff (Maniquiz-Redillas and Kim 2016).

As shown in Fig. 5, per capita GDP increased from 27 million yuan /km² in 2006 to 98 in 2015, with a growth rate of 263%. In the eleventh and twelfth five-year development

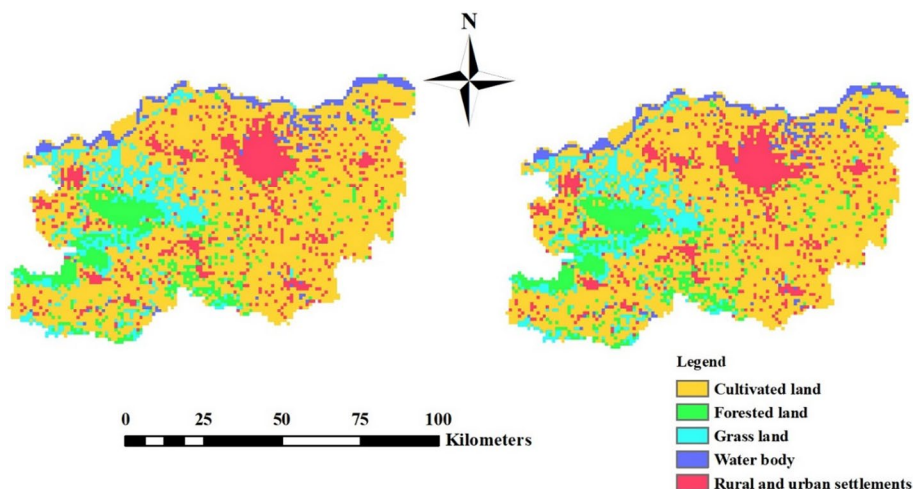


Fig. 4 Land-used Situation of Zhengzhou in 2005 and 2010

Table 4 Area ratio of land-used situation of Zhengzhou in 3 years

Land-used types	2005	2010	2015
Cultivated land (%)	63.4	62.3	60.9
Forested land (%)	9.7	9.7	9.6
Grass land (%)	9.1	9.1	9.1
Water body (%)	4.4	4.6	4.7
Rural and urban settlements (%)	13.4	14.3	15.7

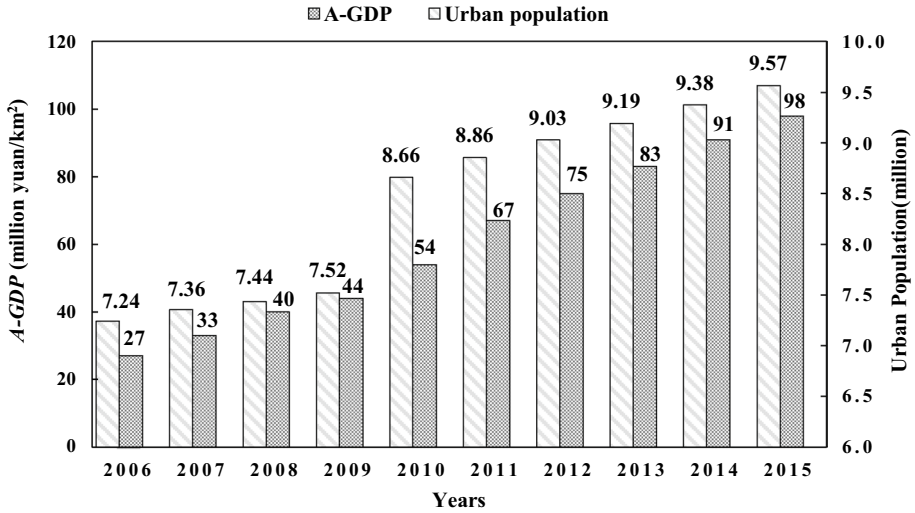


Fig. 5 A-GDP and urban population change in Zhengzhou during the past decade

plans, Zhengzhou strengthened its economic development, whose urban GDP kept rising continually, from 24th of China urban GDP in 2006 to 18th in 2015. The rapid economic growth of Zhengzhou was an epitome of China’s rapid urban development. The urban population grew from 7.24 million in 2006 to 9.57 million in 2015, with a growth rate of 32%. The airport economy zone and east new zone of Zhengzhou were developed and constructed by the government, which attracted many enterprises and a large number of people.

The direct economic loss of urban flood is closely related to the social development of disaster—bearing body. When the cities have the same level of flood, the higher economic and population density of disaster-bearing body mean greater urban loss. Due to the acceleration of urbanization in recent years, high flood risks have been brought to cities.

4.2 The construction of urban disaster prevention and mitigation

The urban flood DPAM capacity is mainly affected by urban greening, road and pipe network construction. Urban greening can enhance the absorption of rainwater, effectively alleviate the damage of flood, and improve the urban climate (Kim et al. 2016). The PUG of Zhengzhou presented an upward trend year by year, and the upward trend

gradually became obvious (Fig. 6). In 2012, in order to build an ecological and livable city, urban garden construction was incorporated into the national economic and social development plan and developed rapidly. In 2012, in order to build an ecological and livable city, urban garden construction was incorporated into the social development plan of government. After that, it developed rapidly. Urban road network is an important embodiment of transportation capacity and comprehensive disaster-bearing capacity. The proportion of urban road area decreased in previous years and increased later (Fig. 6). In order to strengthen the status of urban transport hub and change urban traffic congestion, the government strengthened the construction of urban road network in 2008.

Although the *PUG* and the proportion of urban road area increased on the whole, with the expansion of the city and population growth, per capita green area and per capita road area were gradually declining, respectively, from 9. to 6.2 m² and from 6.9 to 6.3 m² (Fig. 7). Urban greening and road construction could not keep pace with the speed of urban expansion and population growth. They both played a great role in urban flood DPAM. With the growth of urban impervious area, the proportion of urban road area is also increasing. When the floods come, the city roads are paralyzed, making the function of disaster reduction weaker.

In the ten years, the urban drainage network construction of Zhengzhou rose sharply from 2006 to 2007, while it changed slowly in other years (Fig. 6). Urban drainage pipes covered only 70 percent of the city’s area, and rainwater pipes were not even laid on some of the built roads. Furthermore, the design standard of urban drainage website was low, and the pipe diameter was small. Part of the drainage pipes are still used in some regions between 1960 and 1980s, which may cause even greater damage during flood. In conclusion, the backward construction of urban greening and road can’t match the lagging construction of urban pipeline network, which leads to a lack of urban DPAM capacity.

Fig. 6, The proportion of urban green area, road area and density of urban drainage pipe change in Zhengzhou during the past decade.

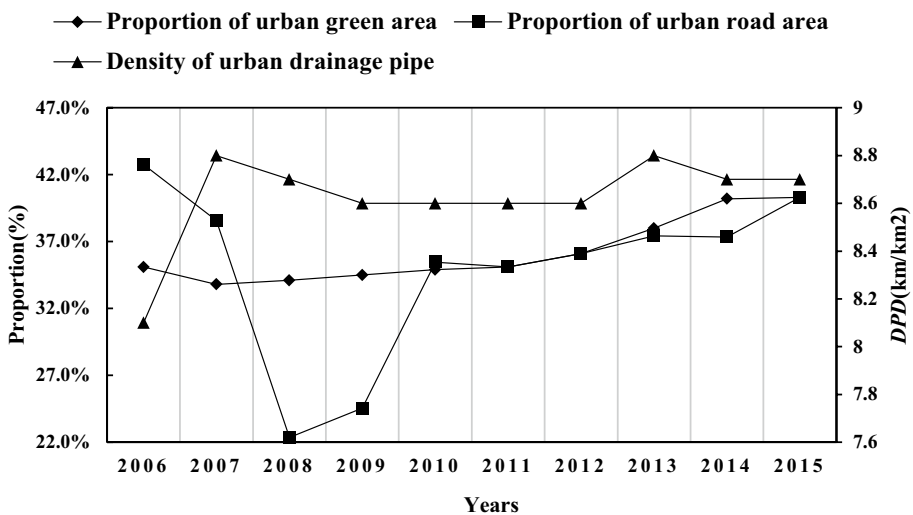


Fig. 6 Per capita green area and road area change in Zhengzhou during the past decade

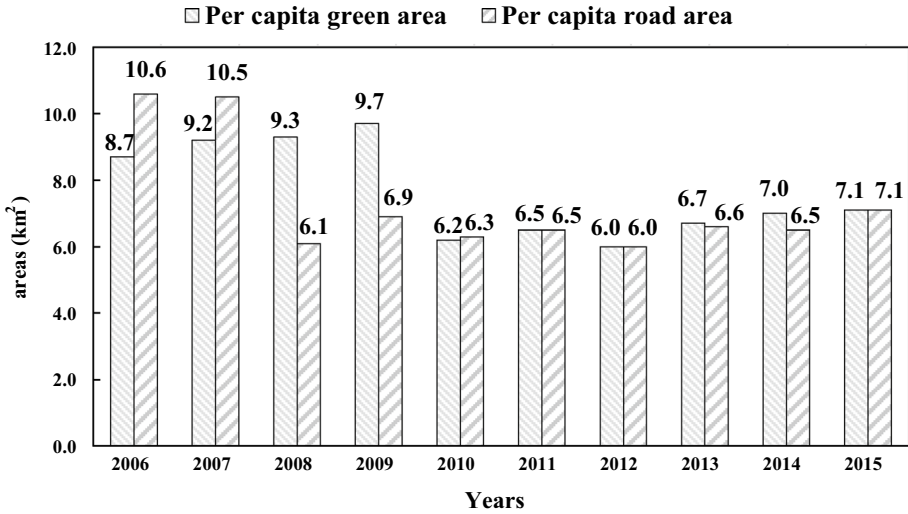


Fig. 7 The comparison of water resources per capita in different regions

4.3 Measures for balanced urban development

Since the reform and development, China’s cities have experienced rapid social and economic development. Due to the extensive development model, they have faced urban problems such as floods and water shortages (Wang 2017). In order to achieve a balanced development between urban economy, people, and nature, the construction of a sponge city using smart city functions to promote the coordinated development of urban systems was proposed (Farouk et al. 2011). Therefore, for the research area and other cities faced with an increased risk of flood disasters in the world, by adjusting the urban construction planning concept and constructing a sponge city, sufficient flood storage space can be created for rainstorm floods and used as resources, which will effectively mitigate the risks of urban floods and disasters, and increase the availability of urban water resources (literature). This study also proposes the following ways to reduce urban disaster risk: (1) increase the construction of urban drainage pipe network; (2) reasonably plan the urban water system structure; (3) increase the green area of the built-up area; and (4) reasonably optimize the regional economy and population space allocation.

5 Conclusion

For the purpose of risk assessment of urban flood disasters, this paper constructs a compound fuzzy matter-element–entropy weight model. Taking into account the vulnerability of urban floods and disasters, and the ability to prevent and mitigate disasters, a risk assessment index system for urban floods and disasters was constructed. Taking Zhengzhou City as the research area, the results show that although the urban socio-economic and population scale present a high-speed development model, the risk of urban floods and disasters is increasing. Urban disaster prevention construction can no longer match the high

vulnerability caused by the development of urbanization. It is very necessary for urban management departments to urgently forecast the construction of measures.

Combined with the development of urbanization and the construction of urban disaster prevention and mitigation, this paper analyzes the rationality of the results, which is in line with the current general situation of urban flood risk in China. The constructed index system and evaluation model complement and improve the urban flood risk assessment method, and have certain theoretical value and practical significance for the realization of urban flood risk management. However, there are still some areas that can be improved, the universality of the indicator system is insufficient, and the weight of the model does not consider the subjective experience advantages. These are the places that need further research in the future.

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