

# Integrated flood risk assessment and zonation method: a case study in Huaihe River basin, China

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**Abstract** Flood risk assessment and risk level zonation is very important for preventing the watershed flood disaster and making disaster mitigation plans. We establish a flood disaster risk assessment model based on GIS and natural disaster risk assessment theory. We build up a risk assessment index system based on hazard of natural environment and vulnerability of economic society. Furthermore, we propose two indices, reservoir storage modulus and flood detention basin modulus, and use them to characterize human intervention capability on flood in the hazard index set. To reduce the occurrence of the inconsistency problems when using analytic hierarchy process (AHP) method in multi-indices comparison, we use the coupled AHP and expert scoring method to determine the weights of indices. We apply the methodology to the Huaihe River basin. The results show that the multi-year average risk zonation map from 1960 to 2010 is consistent with the historical flood disaster distribution, which verifies the applicability of this method in flood disaster risk assessment.

**Keywords** Flood risk assessment · Risk level zonation · Index system · AHP · GIS

## 1 Introduction

In China, flood disaster occurs frequently in a wide range. It is the most serious natural disaster that causes great economy loss and threatens human life (Chen et al. 2013). The increasing flood occurrences and economy loss necessitates the development of flood risk

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assessment and flood risk map. Flood risk is usually calculated by the product of the occurrence probability of flood hazard and the casualties and property losses resulted from the flood hazard (Li et al. 2013). Flood risk assessment and risk level zonation is widely applied in planning land use, economic development, and disaster evacuation, as well as determining the protection standards, flood insurance, and flood management. It is of great importance in terms of preventing watershed disasters and mitigating economy losses.

In general, methods for assessing flood risk include two typical types, the simulation model that is based on the hydrodynamic mechanism (Dutta et al. 2007; Mani et al. 2014; Mazzoleni et al. 2014; Tingsanchali and Karim 2005) and index system-based assessment method (Chen et al. 2011; Ji et al. 2013; Sinha et al. 2008; Yoon 2012). For simulation-based hydrodynamic model, Mani (2014) used three parameters, the flood depth, cross-product of flood depth and velocity, and flood duration for assessing the flood hazard and proposed a one-dimensional and two-dimensional coupled hydrodynamic model for assessing flood hazard in the northern area of India. Tingsanchali (2005) employed a hydrodynamic model to simulate a 100-year return period flood with a duration of 4 months in the southwest region of Bangladesh. Considering the flooding depth and duration, the results show that 54 % of the study area is the medium hazard zone, 26 % of which is the higher-hazard zone, and the rest 20 % is the lower-hazard zone. For index system-based assessment method, Chen (2011) proposed several indices that considered seven factors related to broken dikes or the failure of stormwater drainage systems and used GIS coupling with analytic hierarchy process (AHP) for flood risk assessment in Taiwan. Sinha (2008) proposed a flood risk index (FRI) considering geomorphological, land cover, topographic, and social economy parameters and used AHP to analyze the flood risk in the Kosi River basin of eastern India. Index system-based assessment method is a comprehensive assessing method that uses multiple indices. It is particularly applicable for assessing flood risk for large-scale basins. When using the simulation-based hydrodynamic model for flood risk assessment in large-scale basins, large amount of data is often required, resulting in vast computational demand (Stefanidis and Stathis 2013).

In this paper, we use the index system-based assessment method to assess flood risk. Natural disaster is formed by the combined effects of the hazard of the disaster-inducing environment, the exposure of the disaster-bearing body, and the vulnerability of the disaster-bearing body (Guo et al. 2014; Jiang et al. 2009), which is also affected by the interaction of natural environment and human society. Many researchers (Castillo-Rodriguez et al. 2014; Haynes et al. 2008; Liu et al. 2010) used the indices according to three major aspects that include hazard, exposure, and vulnerability. However, various aspects of indices may be correlated with each other, which lead to the redundancy of indices in the evaluation process and may impact the flood risk assessment results. We select indices considering hazard of natural environment and vulnerability of social economy (Ji et al. 2013; Jiang et al. 2009; Yoon 2012; Zou et al. 2013).

There are varieties of methods to compute the comprehensive risk indices. The United Nations Disaster Relief Organization (1991) considers that risk can be assessed by the expect loss of people's lives and property and economy in certain areas during a given time period, caused by a natural disaster. It can be characterized as:  $\text{Risk} = \text{Hazard} \times \text{vulnerability}$  (Castillo-Rodriguez et al. 2014; Li et al. 2013). Maskrey (1989) believed that risk is a total loss caused by a natural disaster. Specifically, it can be defined as:  $\text{Risk} = \text{Hazard} + \text{vulnerability}$  (Liu et al. 2008, 2009; Wang et al. 2011). It is interesting to note that using the loss of life and property to define the risk is very intuitive, as it usually occurs in human habitat when the discharge of the stormwater is greater than the discharge capacity of the river channel or rainfall exceeds the storage capacity of

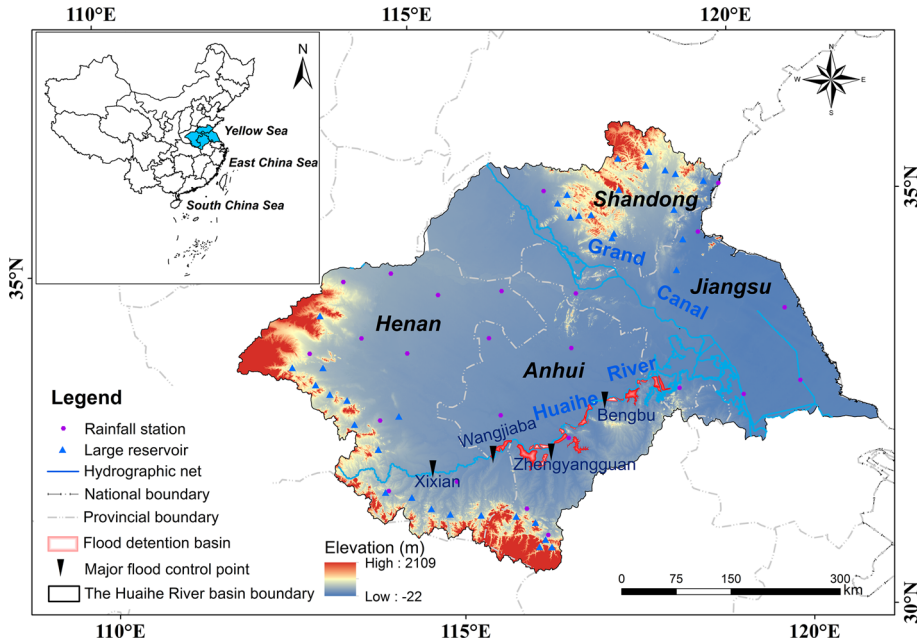
reservoirs. Actually, even in the place where no human lives, flood risk exists objectively, but it cannot be assessed by the first expression ( $\text{Risk} = \text{Hazard} \times \text{vulnerability}$ ). This is because the risk calculated by the first expression equals to zero due to the zero-value vulnerability (Xiang 2004). Therefore, this paper uses Maskrey's risk definition to assess flood risk.

The above studies only considered the natural factors that determine the flood hazard, neglecting to incorporate the influences of reservoir operation and other flood control engineering projects in establishing the index system. We apply the index system-based assessment method to the Huaihe River basin. The Huaihe River basin has the highest population density in China, which is as much as four times of the country's average value. The basin includes 1.333 million hectares sown areas of farm crops and produces 17.3 % of the country's total grain output. The Huaihe River basin is one of the most important agricultural production bases and energy bases, and it plays a significant role in the national economy and social development. The Huaihe River basin is also the disaster-prone area in China (Zhang and You 2014). The main objectives of this study are to (1) propose an integrated flood risk assessment method; (2) build up an index system considering the major flood disasters factors and the influences of reservoirs as well as other flood control engineering projects; (3) calculate the weight for each index using the combined method of the AHP method and the expert scoring method; (4) obtain the flood risk level zones in the study area, the Huaihe River basin, by the proposed methodology. The study on integrated flood risk assessment method can provide a theoretical basis and technical support for decision-making departments.

## 2 Study area

The Huaihe River basin locates at the eastern part of China, between the Yangtze River basin and the Yellow River basin, and lies between longitude  $111^{\circ}55'E$ – $121^{\circ}25'E$  and latitude  $30^{\circ}55'N$ – $36^{\circ}36'N$ . Its area is 270,000 km<sup>2</sup>. The entire river basin includes two major river systems named the Huaihe River system and the Yishusi River system. About one-third of the entire river basin, which locates in the west, southwest, and northeast region, is mountain and hilly area. The other two-thirds of the basin are wide plain areas. The annual mean precipitation of the entire basin, the Huaihe River system, and the Yishusi River system are 898, 939, and 795 mm, respectively. The precipitation in the southern region is higher than the precipitation in the northern region. Furthermore, the precipitation in the mountain area is higher than that in the plain area, and the precipitation in the coastal area is higher than that in the inland area. The precipitation is unevenly distributed throughout the year and is mainly concentrated in the flood season (June–August), taking up about 63 % of the annual total precipitation. The map of the study area is shown in Fig. 1.

The Huaihe River basin locates in the overlapping area of a high-temperature area and a low-temperature area and consists of a coastal region and an inland region, which is a typical zone of disaster-breeding environment. The large rainfall in the basin leads to excessive stormwater, and the low-flat terrain reduces the velocity of stormwater, which reduces the flood subsiding speed as well. Because of these reasons, flood events occur in the Huaihe River basin frequently. Flood disasters in the Huaihe River basin threaten human life and food production. During the past two decades, the Huaihe River basin has been attacked by floods several times. The basin-wide floods, which occurred at the year of



**Fig. 1** Map of the study area

1991, 2003, and 2007, respectively, were the most destructive disaster events on historical record. The flood disasters caused 605 deaths and a direct economic loss of 78 billion yuan.

There are 51 years of daily observed precipitation data at 25 rainfall stations in the Huaihe River basin, which starts from 1960 and ends at 2010. The digital elevation model data (DEM) with the resolution of 90 m are obtained from the Geospatial Data Cloud (<http://www.gscloud.cn/>). Flood detention basin data and 39 large reservoirs (20 of which locate at the Huaihe River system and the other 19 locate at the Yishusi River system) characteristic data are supplied by the Huaihe River Commission of the Ministry of Water Resources. We obtain the vulnerability indices population, sown area of farm crops, and gross domestic product (GDP) data, from 1960 to 2010, of 21 major cities in the four provinces, Anhui, Jiangsu, Henan, and Shandong from the Department of Comprehensive Statistics of the National Bureau of Statistics.

### 3 Methodology

#### 3.1 Risk assessment and zonation method

We apply the natural disaster risk assessment theory proposed by Maskrey (1989) to assess flood risk, which can be expressed as follows:

$$R = f(H, V) = H \times \alpha_H + V \times \alpha_V \tag{1}$$

$$H = \sum_{i=1}^p (-1)^j H_i^{w_{H_i}} \tag{2}$$

$$V = \sum_{i=1}^q (-1)^j V_i w_{V_i} \tag{3}$$

where  $R$  is flood risk index; the term  $H$  is flood hazard index, and  $V$  is flood vulnerability index; the term  $\alpha_H$  is the weight of the flood hazard index, and  $\alpha_V$  is the weight of flood vulnerability index; the value of  $j$  is 1 or 2. When the subindex,  $H_i$  or  $V_i$ , negatively correlates with the flood risk index, the value of  $j$  is 1. Otherwise the value of  $j$  is 2. The terms  $p$  and  $q$  are the number of flood hazard subindices and vulnerability subindices, respectively; the terms  $w_{H_i}$  and  $w_{V_i}$  are the weights of each flood hazard subindex and flood vulnerability subindex, respectively.

For each index, the flood hazard index, the flood vulnerability index, and the flood risk index, we divide its value into five levels, ranging from the low level, the moderate-to-low level, the moderate level, the moderate-to-high level, and the high level, using the optimization method of natural breaks. The Jenks optimization method (Jenks 1967), which is also named the Jenks natural breaks classification method, tries to minimize the variance within each level and maximize the variance between different levels (Stefanidis and Stathis 2013). We obtain the flood hazard zonation map, the flood vulnerability zonation map, and the flood risk zonation map using spatial analysis of ArcGIS.

In this paper, we build up the index system of hazard and vulnerability, obtain the spatial distribution of each subindex data, and determine the weight for each index. Figure 2 shows the flowchart of the methodology used in the study.

### 3.2 Build up the index system

Flood risk assessment involves in multifactors, which synthesizes the assessing results of each individual index using the weighted sum method. In this paper, we select subindices considering hazard and vulnerability indices and use the hazard subindices involving climate, land surface, and human intervention capability factors, which include extreme rainfall in the main flood season, elevation, terrain slope, drainage density, reservoir storage modulus, and flood detention basin modulus. Moreover, we utilize the vulnerability subindices of economic society-bearing body, including population, GDP, and sown area of farm crops.

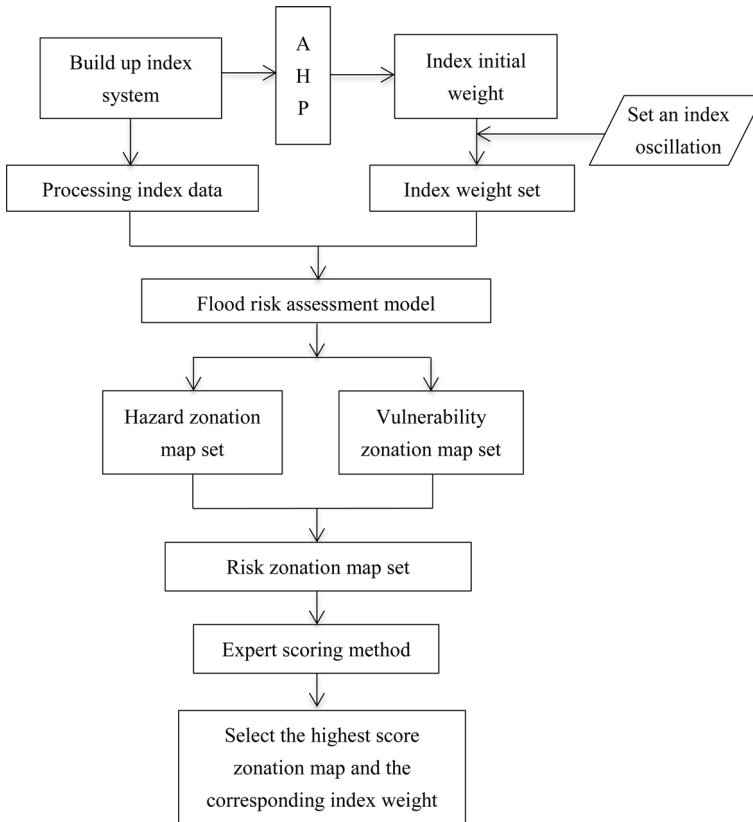
#### 3.2.1 Hazard index ( $H$ )

- (1) Extreme rainfall in the main flood season ( $H_1$ )

The large-scale, high-intensity, and long-duration rainfall is a direct cause of flood. Thus, flood disaster is highly correlated with extreme rainfall events in the main flood season. In this paper, we sample the extreme rainfall events in which the precipitation is 30 % higher than the average rainfall in the main flood season (June to August in the Huaihe River basin). The more the extreme rainfall is, the greater the hazard of flood disasters cause, the extreme rainfall positively correlates with the flood hazard index. Therefore,  $j = 2$ .

- (2) Elevation ( $H_2$ )

Most flood disasters occur at low-flat areas. Likewise, flood events are less likely to occur in those high-elevation areas. The higher the elevation is, the lower the hazard of flood disasters cause, the elevation negatively correlates with the flood hazard index, such that  $j = 1$ .



**Fig. 2** Flowchart of flood risk assessment and risk level zonation

### (3) Terrain slope ( $H_3$ )

Slope is an important factor that affects water velocity. In the upper reaches, water flows quickly in the steep slope district. Therefore, flood subsides quickly, reducing the chance of flooding. In the downstream part of a river, the elevation is low and the terrain is usually flat, so that water is easier to detain and stay for a long time, causing more floods. The steeper the terrain slope is, the lower the hazard of flood disasters cause, such that  $j = 1$ .

### (4) Drainage density ( $H_4$ )

Flood disasters usually happen in the regions that are close to rivers and lakes. The larger the drainage density is, the larger amount of water flows into the river, increasing the probability of occurrence of flood disaster. Therefore, the flood disaster causes greater hazard, and the term  $j = 2$ .

### (5) Reservoir storage modulus ( $H_5$ )

Reservoir is an important flood control project, which helps to store stormwater and reduces flood peak. The larger the flood control capacity above flood control section is, the lower the hazard of flood disasters cause. Therefore,  $j = 1$ .

(6) Flood detention basin modulus ( $H_6$ )

Flood detention basin is a common emergency flood control project that satisfies the economy and benefit in those less-developed districts for the sake of protecting those highly developed and populated districts. The larger the flood detention basin modulus is, the lower the hazard of flood disasters cause, such that  $j = 1$ .

3.2.2 Vulnerability index ( $V$ )

(1) Population ( $V_1$ )

Population is the index that illustrates the degree of social development in the region. A highly populated district is usually a highly vulnerable place that may suffer from flood disasters. The population positively correlates with the flood risk index. Therefore,  $j = 2$ .

(2) GDP ( $V_2$ )

GDP is the index that shows the level of economy development of the region. The higher the GDP is, the greater the vulnerability is. Therefore,  $j = 2$

(3) Sown area of farm crops ( $V_3$ )

In general, crops are easily attacked by flood events. Flood threatens food security. The more the sown area of farm crops is, the greater the vulnerability of flood disasters cause, such that  $j = 2$

3.3 Data processing for the indices

(1) Extreme rainfall spatial distribution in the main flood season

The inverse distance weighted method is a common spatial interpolation method (Wang et al. 2013). This method uses the distance between the sampled points and interpolation points as the weights and sets those interpolation points that are closer to the sampled points with larger weights. For instance, if there are  $n$  points with plane coordinates of  $(x_i, y_i)$  and vertical heights of  $z_i, i = 1, 2, \dots, n$ , the inverse distance weighted interpolation formula can be expressed as follows:

$$f(x, y) = \begin{cases} \frac{\sum_{j=1}^n z_j}{\sum_{j=1}^n d_j^2} & (x, y) \neq (x_i, y_i), i = 1, 2, \dots, n \\ z_i & (x, y) = (x_i, y_i), i = 1, 2, \dots, n \end{cases} \quad (4)$$

where  $d_j = \sqrt{(x - x_j)^2 + (y - y_j)^2}$  is the horizontal distance from  $(x, y)$  to  $(x_j, y_j), j = 1, 2, \dots, n$ .

We select the extreme rainfall records observed at each rainfall station from 1960 to 2010 and take the average of the selected extreme rainfall sequences. We then input the results and rainfall station locations into ArcGIS software to generate main flood season of extreme rainfall dot layer. We use the IDW method to interpolate the extreme rainfall of each rainfall station. Finally, we create a raster surface to establish the average extreme rainfall spatial distribution from 1960 to 2010.

## (2) Elevation and terrain slope

We obtain the DEM data from the Geospatial Data Cloud and use the DEM data to extract the slope of the Huaihe River basin.

## (3) Drainage density spatial distribution

Drainage density is an important factor of basin structural characteristics. We use ArcGIS to generate grid maps and overlay the grid maps and river maps. We then employ the spatial analysis function of ArcGIS to calculate the length of river in each grid. Finally, we divide the length of river in each grid by the area of each grid. It can be characterized as follows:

$$D_i = \frac{l_i}{a_i} \quad i = 1, 2, \dots, n \quad (5)$$

where  $n$  is the number of grids;  $D_i$  is the drainage density for the  $i$ th grid, [km/km<sup>2</sup>];  $l_i$  is the length of the  $i$ th grid, [km]; and  $a_i$  is the area of the  $i$ th grid, [km<sup>2</sup>].

## (4) Reservoir storage modulus spatial distribution

For calculating the reservoir storage modulus spatial distribution, we divide the study area into several sub-basins, considering the factors of terrain and major flood control points. For each sub-basin, we calculate the reservoir storage modulus. The steps are listed as follows:

1. Set the numerical matrix  $A_{1 \times k} = (a_1, \dots, a_i, \dots, a_k)$  of area for  $k$  sub-basins and the numerical matrix  $V_{1 \times n} = (v_1, \dots, v_p, \dots, v_n)$  of reservoir storage for  $n$  reservoirs.
2. Establish the topology relationship matrix  $B = (b_{ij})_{n \times k}$  for  $n$  reservoirs and  $k$  sub-basins, where  $b_{ij}$  denotes the relative location between reservoir  $i$  and sub-basin  $j$ . For example, if reservoir  $i$  locates in sub-basin  $j$  or in the upstream of sub-basin  $j$ ,  $b_{ij} = 1$ . Otherwise,  $b_{ij} = 0$ .
3. Build the sub-basin and sub-basin interpositional relationship matrix  $C = (c_{pq})_{k \times k}$  for the  $k$  sub-basins, according to the river flow direction, where  $c_{pq}$  is the position relationship between sub-basin  $p$  and sub-basin  $q$ . If sub-basin  $p$  is located in the upstream of sub-basin  $q$ ,  $c_{pq} = 1$ . Otherwise,  $c_{pq} = 0$ .
4. Calculate the reservoir storage modulus for each sub-basin. Particularly, the reservoir storage modulus  $\alpha_m$  for the sub-basin  $m$  can be calculated by Eq. (6).

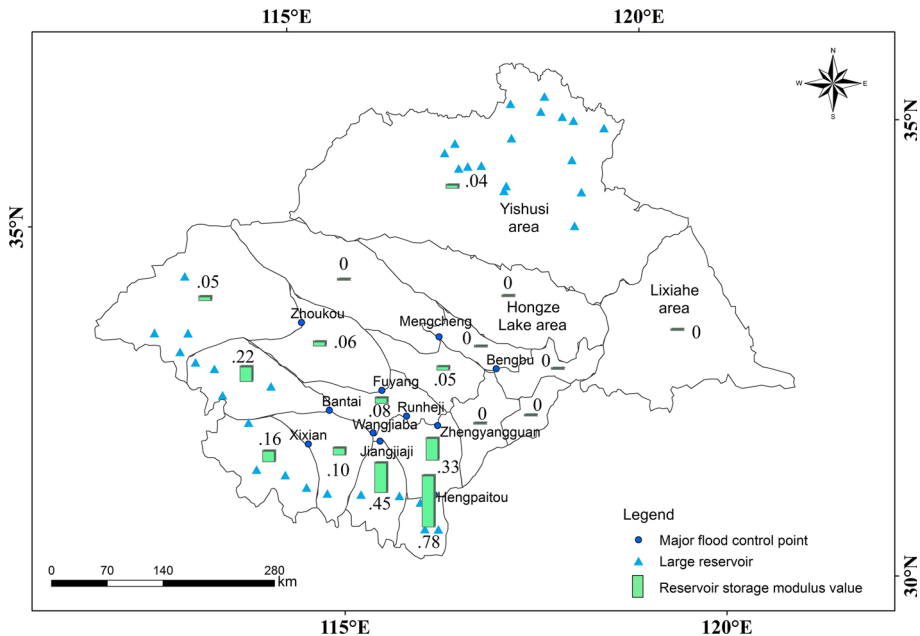
$$\alpha_m = \frac{\sum_{i=1}^n v_i b_{im}}{\sum_{p=1}^k a_p c_{pm}} \quad (6)$$

We divide the Huaihe River basin into 18 sub-basins. As shown in Fig. 3, there are 39 large reservoirs in the Huaihe River basin. We sort their sequence by the time of the construction. We calculate the Huaihe River basin reservoir storage modulus of each year using the storage of the reservoirs that have been built before the considered year. We then take the average reservoir storage modulus for each sub-basin from 1960 to 2010.

## (5) Flood detention basin modulus spatial distribution

Flood detention basin is an important flood control project that helps to mitigate floods and ensure the safety of the key important areas. The methods for calculating the flood





**Fig. 3** Reservoir storage modulus map of the Huaihe River basin

detention basin modulus and spatial distribution are the same with that used to calculate the reservoir storage modulus.

(6) Spatial distribution of population, GDP, sown area of farm crops

The Huaihe River basin covers four provinces: Jiangsu, Shandong, Henan, and Anhui. We take the statistical data using the average value of the population, GDP, and sown area of farm crops of 21 major cities in the Huaihe River basin.

(7) Normalization of data

To eliminate the impact of magnitude and dimension of the indices, we normalize the value of the indices in the range between 0 and 1, using Eq. (7).

$$r_i = \frac{x_i - x_{i\min}}{x_{i\max} - x_{i\min}} \tag{7}$$

where  $r_i$  is the normalized value of index  $i$ ;  $x_i$  is the original value of index  $i$ ;  $x_{i\max}$  and  $x_{i\min}$  are the maximum and the minimum values, respectively, of the original index  $i$ .

**3.4 Calibrating the index weight**

We use the combined method of the AHP and the expert scoring method to determine the index weight. First, we use the AHP method to obtain the initial weight of each subindex. We then set an index oscillation,  $\Delta$ , and generate groups of index weights based on the initial weight and the index oscillation. We denote  $W$  as the set of index weights. Subsequently, we put the weight set into the risk assessment model to obtain hazard, vulnerability, and risk zonation map sets, respectively. Finally, we take the scores according to

the suggestions of many experts through multiple rounds of feedback, consultation, and adjustment. We take the average highest-score hazard, vulnerability, and risk zonation map as the final results and corresponding index weights as the final weights.

### 3.4.1 Analytic hierarchy process

The AHP (Saaty 1980) is a method for solving complex, ambiguous decision-making problems that are difficult to analyze quantitatively. The major steps involved in this method to determine the initial weights include:

1. Calculate the judgment matrix. We use several numbers, from one to nine, to compare the relative importance of two given indices. The element  $y_{ij}$  ( $i = 1, 2, \dots, n; j = 1, 2, \dots, n$ ) in the judgment matrix  $Y = (y_{ij})_{n \times n}$  represents the relative importance of index  $i$ , when it is compared with index  $j$ , where  $n$  is the number of indices. If  $y_{ij} = d$ ,  $d \in (1, 2, \dots, 9)$ , then  $y_{ji} = 1/d$ .
2. Obtain the maximum eigenvalue ( $\lambda_{\max}$ ) of the judgment matrix  $Y = (y_{ij})_{n \times n}$ . Eigenvalues  $\lambda_1, \lambda_2, \dots, \lambda_n$  are calculated by solving the characteristic equation  $|Y - \lambda E| = 0$ .
3. Check the consistency. We calculate the consistency ratio (CR) with Eq. (8) to check whether the judgment matrix  $Y = (y_{ij})_{n \times n}$  is acceptable. If  $CR > 0.1$ , the judgment matrix is untrustworthy and needs appropriate adjustments. The relationship between  $n$  and  $RI$  can be found in Table 1.

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad CR = \frac{CI}{RI} \tag{8}$$

4. Calibrate the weight of each index. We solve the equation  $(Y - \lambda_{\max}E) e = 0$  and obtain the eigenvector  $e = (e_1, e_2, \dots, e_n)$  that corresponds to the maximum eigenvalue  $\lambda_{\max}$  after the consistency check. We normalize the eigenvector  $e = (e_1, e_2, \dots, e_n)$  to obtain the weight of each index  $W_X = (w_{X_i})_{n \times 1}, i = 1, 2, \dots, n$ , using Eq. (9).

$$w_{X_i} = \frac{e_i}{\sum_{i=1}^n e_i} \tag{9}$$

### 3.4.2 Expert scoring method

The expert scoring method uses the relevant experts' experiences to make decisions. This method objectively synthesizes most of experts' experiences and subjective judgment to make a reasonable estimate for factors that are difficult to analyze quantitatively, through repetitive consultation, feedback, and adjustment.

For example, there are  $m$  experts who are about to determine the scores for  $k$  groups of map where each group includes a hazard, a vulnerability, and a risk zonation map. Score ranges from 0 to 100 points. The final score for each map is averaged from the experts'

**Table 1**  $n$  values versus  $RI$  values

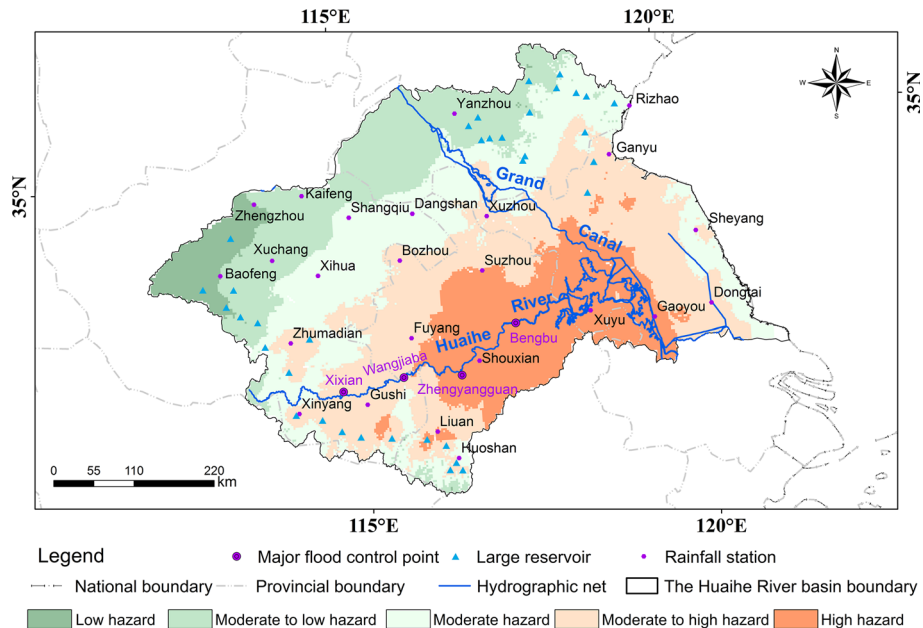
$n$	1	2	3	4	5	6	7	8	9
$RI$	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45

scores. Using the expert scoring method for scoring map sets to determine the final weights includes the following steps:

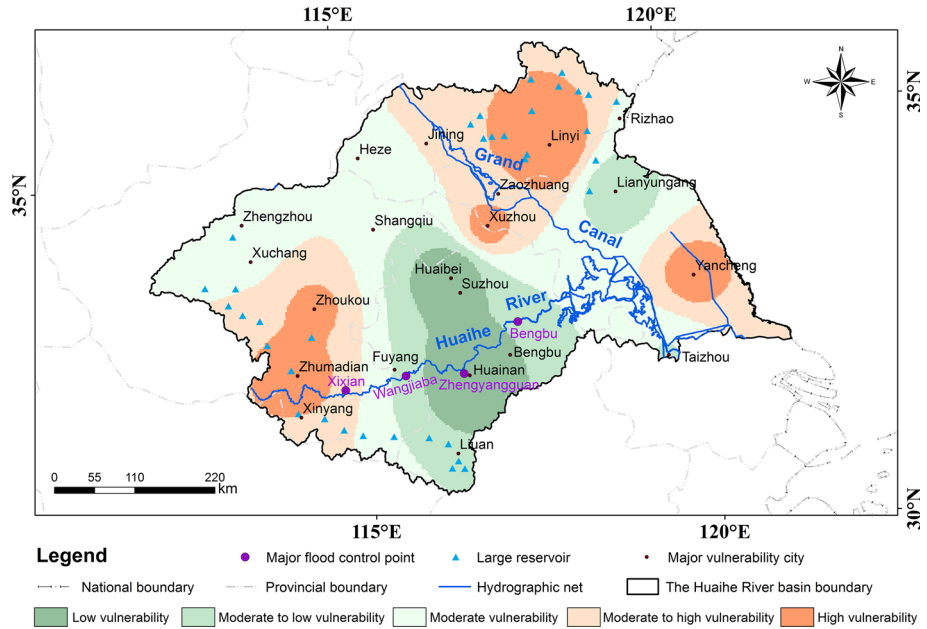
1. Establish an expert score matrix  $R = (r_{ij})_{m \times k}$ , where  $r_{ij}$  is the score of map  $j$  given by expert  $i$ .
2. Calculate the average score matrix  $L = (l_{ij})_{1 \times k}$  of each map, such that  $l_{ij} = \sum_{i=1}^m r_{ij}/m$ .
3. Experts are allowed to change their scores. If so, go back to step (2) and repeat the scoring procedures. Otherwise the final score is determined.
4. Select the highest average score hazard, vulnerability, and risk zonation map as the final results and corresponding index weights as the final weights.

### 4 Results

After establishing the flood risk assessment index system of the Huaihe River basin, we obtain the multi-year average (from 1960 to 2010) spatial distribution of GIS map for each index using the proposed methodology. We then normalize the spatial distribution map for each subindex. We calibrate the initial weights of the indices by AHP. The results of the weights for the hazard subindices are  $W_H = (0.255, 0.231, 0.023, 0.231, 0.134, 0.126)$  and the weights of the vulnerability subindices are  $W_V = (0.631, 0.218, 0.151)$ . The terms  $\alpha_H$  and  $\alpha_V$  are set at 0.5. Let  $\lambda$  be 0.05, and we generate the index weight set  $W$ . We use the multi-year average spatial distribution of each normalized index and the index weight set  $W$  as the inputs to the risk assessment model to obtain the hazard, vulnerability, and risk multi-year average spatial distribution maps, based on Eq. (1)–(3). The scores of each map



**Fig. 4** Hazard level zonation map of flood disaster in the Huaihe River basin from 1960 to 2010



**Fig. 5** Vulnerability level zonation map of flood disaster in the Huaihe River basin from 1960 to 2010

are determined by the technicians who worked at the Huaihe River Commission of the Ministry of Water Resources. The highest-score maps, including the hazard, vulnerability, and risk zonation maps, are selected as the final maps, and they are shown in Figs. 4, 5, and 6. The corresponding weights are listed in Table 2.

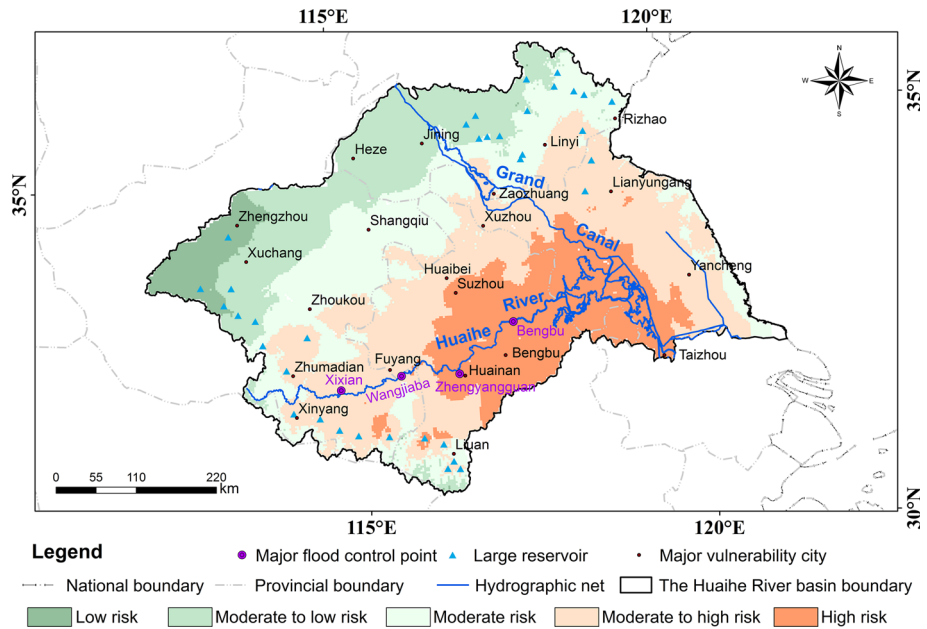
**4.1 Hazard assessment results**

We establish a hazard assessment model based on the weight of each subindex and the multi-year average spatial distribution of each subindex, using Eq. (10).

$$H = H'_1 \times 0.255 - H'_2 \times 0.231 - H'_3 \times 0.023 + H'_4 \times 0.231 - H'_5 \times 0.134 - H'_6 \times 0.126 \tag{10}$$

where  $H'_1$  to  $H'_6$  represent the normalized spatial distribution of the extreme rainfall in the main flood season, elevation, terrain slope, drainage density, reservoir storage modulus, and flood detention basin modulus, respectively.

The multi-year average (from 1960 to 2010) hazard zonation map is shown in Fig. 4. As can be seen from Fig. 4, the hazard zonation map presents zonal distribution in the Huaihe River basin. High-hazard areas are mainly distributed in the range of Wangjiaba to Hongze Lake on both left and right sides of the Huaihe River, accounting for 20 % of the total area of the Huaihe River basin. This is because that large rainfall leads to large volumes of water, and low-flat terrain reduces the velocity of stormwater, which reduces the flood subsiding speed. Moderate-to-high hazard areas are mainly located in the upstream of Wangjiaba, the lateral sides of the high-hazard area of the Huaihe River basin, as well as the south Jiangsu and south Shandong provinces, accounting for 31.5 % of the Huaihe



**Fig. 6** Risk level zonation map of flood disaster in the Huaihe River basin from 1960 to 2010

**Table 2** Weight of each index

Object layer	Index layer	Subindex layer	Weight
Flood risk (R)	Hazard (H) (0.750)	Main flood season extreme rainfall (H <sub>1</sub> )	0.255
		Elevation (H <sub>2</sub> )	0.231
		Terrain slope (H <sub>3</sub> )	0.023
		Drainage density (H <sub>4</sub> )	0.231
		Reservoir storage modulus (H <sub>5</sub> )	0.134
		Flood detention basin modulus (H <sub>6</sub> )	0.126
	Vulnerability (V) (0.250)	Population (V <sub>1</sub> )	0.531
		GDP (V <sub>2</sub> )	0.268
		Sown area of farm crops (V <sub>3</sub> )	0.201

River basin. Moderate-hazard areas distribute at the southeast Henan Province and south Shandong Province, accounting for 26.1 % of the Huaihe River basin. Due to the high elevation, moderate-to-low and low-hazard areas are located at west, north, and northwest of the Huaihe River basin accounting for 18.2 and 4.2 % of the entire Huaihe River basin, respectively.

**4.2 Vulnerability assessment results**

We establish the vulnerability index zonation model using Eq. (11).

$$V = V'_1 \times 0.531 + V'_2 \times 0.268 + V'_3 \times 0.201 \tag{11}$$

where  $V_1'$ ,  $V_2'$ , and  $V_3'$  represent the normalized spatial distribution of population, GDP, and sown area of farm crops.

We use the ArcGIS raster overlay and spatial analysis functions to draw the vulnerability spatial distribution map. The results are averaged from the multi-year records that are taken from 1960 to 2010. As shown in Fig. 5, the cities Zhoukou, Zhumadian, Linyi, and Xuzhou locate in the high-vulnerability region of the Huaihe River basin. This is because that Zhumadian has a large population and sown area of crops and Linyi has a large population and high GDP, while Xuzhou has high GDP and sown area of crops. These districts cover 14.8 % of the Huaihe River basin. Moderate-to-high vulnerability areas generally locate in the southwest of the basin and the southeast of the basin, including the south Henan Province and south Shandong Province, as well as north Jiangsu Province. These districts cover 25.6 % of the entire Huaihe River basin. Due to the small population and the sown area of crops, and low economy, low-vulnerability areas are generally distributed in Huainan and Huaibei of Anhui Province, accounting for 9.8 % of the Huaihe River basin. The vulnerability indices in moderate-vulnerability areas and moderate-to-low vulnerability areas are in a medium range, and these areas are accounting for 34.5 and 15.3 %, respectively. Areas with high vulnerability level means that economy loss may be relatively large, if flood disasters occurred in these districts.

### 4.3 Risk assessment results

The flood hazard index demonstrates the influences of natural factors and human intervention in flood disaster, and the flood vulnerability index represents the social characteristics of flood disaster. The flood risk zonation is a comprehensive outcome that combines natural characteristics and social characteristics. We establish the flood risk zonation model that combines the flood hazard index and the flood vulnerability index, using the flood hazard index weight and vulnerability index weight:

$$R = f(H, V) = H \times 0.750 + V \times 0.250 \quad (12)$$

Figure 6 shows that the high-risk areas locate in Wangjiaba to Hongze Lake and both left and right sides of the Huaihe River, the west Lixiahe area, and the south Yishusi area, and accounting for 19.7 % of the total area of the Huaihe River basin. This high-risk area is mainly caused by high hazard (i.e., flat terrain, abundant rainfall). Moderate-to-high risk zones mainly distribute at the upstream of both left and right sides of the Huaihe River, including most areas of Jiangsu Province, and south Shandong Province. Specifically, these districts cover high-vulnerability cities, such as Xuzhou, Yancheng, and Zhumadian, accounting for 34.4 % of the Huaihe River basin. The moderate-to-low risk and low-risk zones are mainly distributed in the western, northern, northwestern part of the Huaihe River basin that locate in high-elevation areas, and the vulnerability index, GDP, is low in these areas. The moderate-to-low risk areas and low-risk areas are the results of joint action of low hazard and low vulnerability, accounting for 17.6 and 4.1 %, respectively.

### 4.4 Results validation

Table 3 lists the statistics of major flood disasters that occurred during 1960–2010 in the Huaihe River basin. As seen, the flood disasters occurred frequently in Henan, Anhui, and Jiangsu provinces. Furthermore, north and central Anhui Province, central and south Henan Province, and north Jiangsu Province are the worst-hit areas. The historical flood disasters

**Table 3** Major historical records of flood disaster in the Huaihe River basin from 1960 to 2010

Year	The historical flood disaster	The worst-hit areas	The model results
1963	The typical devastating floods occurred in the Huaihe River basin. The main stream sustained high stage. Anhui Province in Huaihe domain had large-scale rainfall. Tributary floods cannot discharge because of the high stage of the main stream, causing serious waterlogging disaster along the Huaihe River, Huaibei	The central and north Anhui	The high-risk area
1965	Long period of rainy days made the northern part of Anhui, Jiangsu and most areas of Henan to suffer from flood disasters	The north Anhui, the north Jiangsu, the most areas of Henan	The moderate-to-high risk area
1968	A catastrophic flood occurred in the middle reaches of the Huaihe main stream. The flood detention basins in the upstream of Bengbu station were mostly used. Huaibin County was flooded. More than 507,000 hm <sup>2</sup> farmland in Henan, Anhui provinces were damaged. There were 374 deaths	The south Henan, the central and north Anhui	The high-risk area
1969	Tributaries of Shi River and Pi River were suffered from severe floods. Two large reservoirs named Mozitan and Foziling were dam overtopped	The central Anhui	The high-risk area
1972	The north Anhui, the central Henan, the north Jiangsu, and the south Shandong were flooded and lasted a longtime	The north Anhui, the central Henan, the north Jiangsu, and the south Shandong	The moderate-to-high risk area
1975	Tributaries in the upstream of the Huaihe River, Shaying River, and Hongru River encountered a catastrophic flood. Banqiao reservoir and Shimantan reservoir were dam broke. There were 5 million houses destroyed and 26,000 deaths	The south Henan, the central Anhui	The high-risk area
1984	The upper and middle reaches of the Huaihe River suffered a large flood. A part of the flood diversion areas were enabled. The flood disasters in the north Anhui and east Henan were heavier	The north Anhui, the east Henan	The moderate-to-high risk area
1991	The Huaihe River suffered the second large flood since 1949. The main stream underwent flood peak three times. Tributaries in the southern part of the Huaihe River were close to or reach to a 100-year return period flood. Shi River, Pi River, and Chi River were close to or exceed the highest water level record. There were 572 deaths and a direct economic loss of 34 billion yuan	The central Anhui	The high-risk area
2003	A large flood in the Huaihe River basin caused 29 deaths and a direct economic loss amounted to 28.5 billion yuan. The direct economic loss caused by flood in Anhui was 14.7 billion yuan, of which agricultural losses amounted to 11.2 billion yuan	The central and north Anhui	The high-risk area

**Table 3** continued

Year	The historical flood disaster	The worst-hit areas	The model results
2007	Flood disaster occurred in the Huaihe River basin was the worst in sixty years. Anhui Province was invaded by serious flood disaster again. The flood disaster caused four deaths and a direct economic loss of 15.5 billion yuan	The central and north Anhui	The high-risk area

show that once a flood disaster occurs, the probability that it occurs in the high-risk region and moderate-to-high risk region is 70 and 30 %, respectively. It demonstrates that the flood risk assessment result is reliable and can be used to support decision making and analysis.

## 5 Conclusions

Flood disaster is one of major natural disasters that threatens human survival and development. In order to develop disaster prevention and mitigation measures effectively, flood risk assessment is particularly important. We proposed an integrated flood risk assessment and zonation method with the background of macro-assessment, including building up index system, processing index data, and calibrating the weights for the indices. The results are as follows:

1. We added two indices, the reservoir storage modulus and the flood detention basin modulus, to consider the human intervention to alleviate flood disaster and improved the method for calculating the spatial distribution of the reservoir storage modulus.
2. We combined the AHP and the expert scoring method to determine the weights for the indices. This combinational method can reduce the occurrence of the inconsistency problems when using only AHP method in multi-indices comparison.
3. We applied the proposed methodology to assess the flood risk in the Huaihe River basin and obtained the risk level spatial distribution map that is made based on the multi-year average results taken from 1960 to 2010. The results are consistent with historical records of flood disaster distribution, which validate the reliability and applicability of the proposed methodology.

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