Study on mechanism and application of water resources system adaptability under changing environment

Pan Zhengwei, Zhou Yuliang, Wang Jing and Qiu Yingying

ABSTRACT

The water resources system is in a vulnerable situation because of the influence of climate change and the changing environment. The adaptation mechanism was discussed through the analysis of the process of passive response, adaptation and even active adjustment of water resources system under changing environment. The adaptability of the water resources system can be described as natural resilience (*NR*) of natural system and artificial adaptation (*AA*) social (artificial) system. The natural resilience indexes were identified and analyzed from the aspects of water quantity, water quality and water ecology. The artificial adaptation indexes were identified and analyzed from the aspects of resource, eco-environment, socio-economic and technical factors. On this basis, the index system was constructed in accord with process mechanism of water resources system adaptability. Besides, to address the two-dimension factors of water resources system adaptability, a method of system analysis based on connection numbers–fuzzy risk matrix was proposed based on the theory of risk matrix. The synthesis interval [A_{pess}, A_{opt}] of water resources system adaptability is obtained, by defining the pessimistic criterion when two-dimension factors meet the evaluation standard at the same time, and the optimistic criterion when either of the two-dimension factors meets evaluation standard. Finally, the case study in the Huaihe River basin in China was carried out. The results show that the adaptability level of water resources system in the Huaihe River basin expressed fluctuating uprising tendency in 2006–2015. The adaptability level is the lowest [1.856, 2.625] in 2009, the highest [2.500, 3.536] in 2015.

Key words | changing environment, Huaihe River basin, mechanism analysis, risk matrix theory, set pair analysis, water resources system adaptability

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HIGHLIGHTS

- First, the adaptation mechanism of water resources system under changing environment was discussed.
- Second, the method of system analysis based on connection numbers–fuzzy risk matrix is proposed based on the theory of risk matrix.
- Third, the synthesis interval [A_{pess}, A_{opt}] of water resources system adaptability was obtained by defining pessimistic criterion and optimistic criterion.

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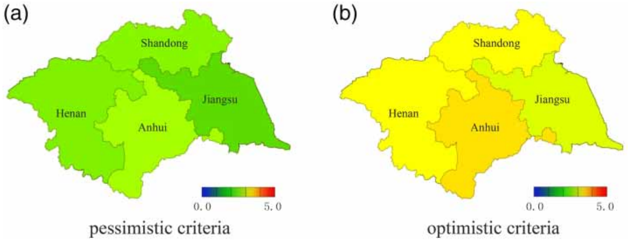
GRAPHICAL ABSTRACT



INTRODUCTION

Adaptation, an ecology term which represents the survival and continuity of the population, is used here to define an ability of the system adapting to new situations via appropriate spontaneous changes under a certain range of environmental perturbations. Recently, with the continuous development of adaptation, the concept and research field of adaptation have been expanding. It has been widely used in anthropology, sociology, disaster science and environmental science.

The Intergovernmental Panel on Climate Change (IPCC 2001, 2007, 2014, 2018) has identified the key elements that affect global change from different perspectives, and emphasized the importance of adaptation of human development to climate change. The study of adaptation by IPCC is a process of gradual development and improvement. The adaptation in the third assessment report (IPCC 2001) is an adjustment of natural or human systems to a new or changing environment. The adaptation in the fourth assessment report (IPCC 2007) is initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects. The adaptation in the fifth assessment report (IPCC 2014) is adjustment to actual or expected climate as well as its effects. And in human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. The concept of adaptation in the IPCC special report placed more emphasis on human systems. In human systems, the adjustment to actual or expected climate as well as its effects is to moderate harm or exploit beneficial opportunities (IPCC 2018). Adaptation has gradually been recognized as an effective way for reducing vulnerability to climate change (Schipper & Burton 2009; Khir-Eldien & Zahran 2016).

Koutroulis *et al.* (2019) presented a conceptual framework for the assessment of the global freshwater vulnerability to high-end climate change based on the climate change impacts and socio-economic developments. Al-Zubari *et al.* (2018) obtained the vulnerability assessment and the effectiveness of the adaptation measures of a municipal water management system by using a dynamic mathematical model representing the water sector in Bahrain. A novel assessment methodology was designed by Seif-Ennasr *et al.* (2016), taking into account benefits, implementation times, costs, and feasibility to evaluate the climate change adaptation measures. Yatesa *et al.* (2015) demonstrated the application of a decision-centric adaptation appraisal process under large uncertainty about future climatic and non-climatic stressors, and using the Upper Colorado River basin as a case study. Goosen *et al.* (2014) identified three different steps that usually followed in climate change adaptation were impact or vulnerability assessment, the design and the selection of adaptation options, and the evaluation of adaptation options. Georgakakos *et al.* (2012a) assessed the response of the Northern California reservoir system under two reservoir management policies and two hydrologic scenarios, using adaptive decision model (HRC-GWRI 2007) coupled with a dynamic downscaling and hydrologic modeling system described in Georgakakos *et al.* (2012b). Fisher-Vanden *et al.* (2011) proposed the three main categories of adaptation that should be considered in modeling the economic impacts of climate change: passive general market reactions, specific reactive adaptation investments, and specific proactive adaptation investments.

This work is divided into four sections. The first section discusses the adaptation mechanism of water resources system under changing environment. The second section describes theoretical basis and progress of set pair analysis and fuzzy risk matrix. The third section proposes a method of system analysis based on connection numbers–fuzzy risk matrix, and this method is used to analyze the water resources system adaptability of Huaihe River basin. The final section discusses the result of case study and present suggestions.

Adaptation mechanism of water resources system under changing environment

Water resources system includes natural system and social (artificial) system. When the water resources system is disturbed by climate change and human activities, the natural system can respond passively to climate change, thus restore system function, meanwhile, a social (artificial) system has the ability to deal with a changing environment through active adjustment and to reduce adverse effects of the changing environment, which is achieved by the adaptive agent through feedback effect of adaptive factors (Pan *et al.* 2017). Here, we focus particularly on the adaptive process mechanism of water resources system under a changing environment (Figure 1).

A water resources system is vulnerable because its stability and coordination could be easily destroyed by the direct or indirect impacts of climate change and human activities. The ability of a system to adjust to climate change, to moderate potential damages, to cope with the consequences or to take advantage of opportunities is defined as water resources system adaptability (Khir-Eldien & Zahran 2016). The adaptation of water resources system goes through the process of passive response, adaptation and active adjustment.

The passive response of natural system to actual climate or its effects is defined as natural resilience (*NR*) or natural adaptation. The natural resilience can restore original function of water resources system in the case of low system vulnerability. The active adjustment, which is defined as artificial adaptation (*AA*), is a response of social (artificial) system to actual climate and its effects. The adjustment of adaptive indexes by adaptive agents is according to the feedback effect of adaptive factors. The vulnerability of water resources system is decreased under the combined effect of natural resilience and artificial adaptation. In summary, the adaptability of water resources system refers to the passive response and active adjustment ability of water resources system under changing environment. It is a function of natural resilience (*NR*) and artificial adaptation (*AA*), expressed as

$$A = f(NR, AA) \tag{1}$$

(1) Natural Resilience Indexes

The natural resilience is the potential of natural system to adapt or repair the damaged water resources system in

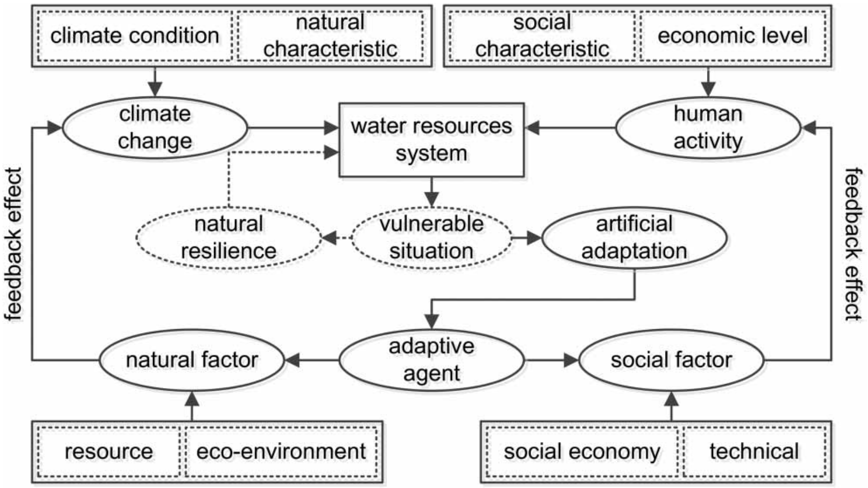


Figure 1 | Adaptive process mechanism of water resources system under changing environment.

a changing environment through self-regulation of water resources endowment, ecological environment and other factors. From the functional point of view, water has the functions of resources, environment and ecology, which are embodied in water quantity, water quality and water ecology. As such, the natural resilience indexes should include water quantity, water quality and water ecology indexes. The natural resilience indexes are selected by using frequency degree analysis methods, statistical method, expert consultation method, system analysis method, etc. The water quantity indexes mainly include precipitation, precipitation variability, drought index, total water resources, and per unit area available amount of water resources. The water quality indexes mainly include surface water environment quality and water pollution incident. The water ecological indexes mainly include the ratio of water areas, wetland areas, and soil erosion areas.

(2) Artificial Adaptation Indexes

Artificial adaptation refers to the positive respond of social (artificial) system to the vulnerability of water resources systems. The purpose of artificial adaptation is to mitigate the adverse effects of climate change on natural ecosystems and human social systems by actively adjusting human behavior. For water resources system, the adaptive factors of natural system mainly refer to resource and eco-environment factors, while the adaptive factors of social (artificial) system mainly refer to socio-economic and technical factors. Meanwhile, the above adaptive factors positively adjust to vulnerability of the water resources system by means of water quantity, water quality or water ecological. The artificial adaptation indexes are selected by using frequency degree analysis methods, statistical method, expert consultation method, system analysis method, etc. The resource indexes mainly include total water consumption, water utilization rate, and per unit area total water consumption. The eco-environment indexes mainly include forest cover, total sewage discharge, treatment rate of urban sewage, ratio of soil erosion control areas, ratio of ecological water consumption, and standard-reaching rate of water function area. The socio-economic indexes mainly include regional development level, per capita GDP, and total investment in fixed assets. The technical indexes mainly include water use efficiency (irrigation consumption of water per mu of farmland, water consumption for 10^4 ￥ industrial added value, and per capita domestic water consumption), and ratio of R&D expenditure.

METHODOLOGY

Set pair analysis and connection number

Set pair analysis method (SPA) is a new system analysis method proposed by Zhao in 1989 (Zhao 1989). In this method, the certainty and uncertainty are taken into account as a system to carry on identical-discrepancy-contrary analysis and further quantitative mathematical process using the connection number.

In the case of specific questions, two sets A and B which have a certain relationship form a set pair H (A, B), and further analyzing the identity, discrepancy and opposition of this set pair H. Assuming the set pair H have N characteristics, where S is the total number of identical characteristics, P is the total number of contrary characteristics and $F = N - S - P$ is the total number of discrepancy characteristics. Then S/N, F/N, P/N represent the degree of identity, discrepancy and contrast, respectively. If $a = S/N$, $b = F/N$, and $c = P/N$, then the connection number expression of set pair H is shown as follows:

$$u = a + bI + cJ \tag{2}$$

where a, b, $c \in [0, 1]$, and $a + b + c = 1$; a denotes the identical degree of set pair H; b is the discrepancy degree, c is the contrary degree, $I \in [-1, 1]$ is the coefficient of discrepancy degree, which is sometimes only used to indicate the difference of tags; J is the coefficient of contrary degree and has been ruled to be unity, sometimes only a mark of the opposites.

Equation (2) is called the identical-discrepancy-contrary connection number or three dimensional connection numbers, which is established on the basis of the distinction: identical, discrepancy, and contrary. However, it is generally not enough to divide the described object into three components (Zhao 1989). Thus, the multi-dimensional connection numbers were proposed by Zhao based on hierarchy and malleability of connection number (Zhao 2000), and is described as follows:

$$u = (a_1 + a_2 + \cdots + a_r) + (b_1 I_1 + b_2 I_2 + \cdots + b_s I_s) + (c_1 J_1 + c_2 J_2 + \cdots + c_t J_t) \tag{3}$$

where a_x, b_y, c_z are connection components, $a_x, b_y, c_z \in [0, 1]$, and $\sum_{x=1}^{r} a_x + \sum_{y=1}^{s} b_y + \sum_{z=1}^{t} c_z = 1$; $I_1, I_2, \ldots, I_s$ are the discrepancy coefficients, and $I_1, I_2, \ldots, I_s \in [-1, 1]$, which sometimes perform the functions of a discrepancy mark only. Furthermore, $J_1, J_2, \ldots, J_t$ denote the coefficient of contrary degrees that have been ruled to be minus unity and sometimes only marks the contrary.

On the basis of Equation (3), the multi-connection numbers and the construction of the identical-discrepancy-contrary hierarchical structure of connection numbers can be expressed as follows:

$$u = a_1 + a_2 + b_1 I_1 + b_2 I_2 + b_3 I_3 + c_1 J_1 + c_2 J_2 \tag{4}$$

where a_1 and a_2 represent the identical degree and partial differential identical degree, respectively, and their coefficients can be assumed to be unity. Furthermore, $b_1 I_1$, $b_2 I_2$, $b_3 I_3$ indicate partial similar, middle, and partial opposite discrepancy degrees, and their coefficients are $I_1 \in [-1, 0]$, $I_2 \in [-0.5, 0.5]$, and $I_3 \in [0, 1]$. Lastly, $c_1 J_1$ and $c_2 J_2$ indicate partial differential contrary degree and contrary degree, respectively, J_1 and J_2 are their coefficients, which are regulated to be minus unity.

The water resources research is generally divided into five levels (Wang *et al.* 2009; Jin *et al.* 2012; Pan *et al.* 2017; Men & Liu 2018). Assuming x_{ij} ($i = 1, 2, \ldots, n$; $j = 1, 2, \ldots, m$) denotes the index sample and s_{kj} ($k = 0, 1, 2, \ldots, 5$) denotes the threshold value of standard, then the connection numbers of the identical-discrepancy-contrary hierarchy method is described as follows (Pan *et al.* 2017):

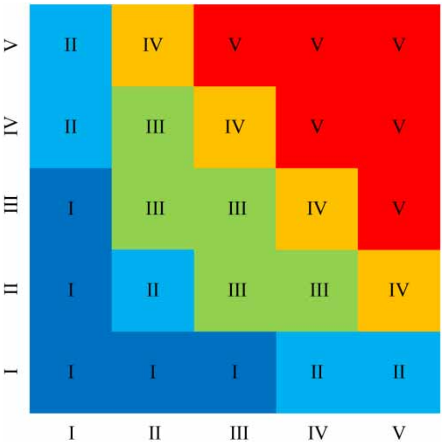
$$u_{ij} = \begin{cases} \dfrac{x_{ij} - s_{1j}}{2(s_{0j} - s_{1j})} + 0.5 + \dfrac{s_{0j} - x_{ij}}{2(s_{0j} - s_{1j})} I_1 + 0I_2 + 0I_3 + 0J_1 + 0J_2 & x_{ij} \in \text{grade V} \\ 0 + \dfrac{x_{ij} - s_{2j}}{2(s_{1j} - s_{2j})} + 0.5I_1 + \dfrac{s_{1j} - x_{ij}}{2(s_{1j} - s_{2j})} I_2 + 0I_3 + 0J_1 + 0J_2 & x_{ij} \in \text{grade IV} \\ 0 + 0 + \dfrac{x_{ij} - s_{3j}}{2(s_{2j} - s_{3j})} I_1 + 0.5I_2 + \dfrac{s_{2j} - x_{ij}}{2(s_{2j} - s_{3j})} I_3 + 0J_1 + 0J_2 & x_{ij} \in \text{grade III} \\ 0 + 0 + 0I_1 + \dfrac{x_{ij} - s_{4j}}{2(s_{3j} - s_{4j})} I_2 + 0.5I_3 + \dfrac{s_{3j} - x_{ij}}{2(s_{3j} - s_{4j})} J_1 + 0J_2 & x_{ij} \in \text{grade II} \\ 0 + 0 + 0I_1 + 0I_2 + \dfrac{x_{ij} - s_{5j}}{2(s_{4j} - s_{5j})} I_3 + 0.5J_1 + \dfrac{s_{4j} - x_{ij}}{2(s_{4j} - s_{5j})} J_2 & x_{ij} \in \text{grade I} \end{cases} \tag{5}$$

where x_{ij} suggests the ith sample value in the jth index, s_{kj} ($k = 0, 1, 2, \ldots, 5$) indicates the kth standard node value in the same index, and I_1, I_2, I_3, J_1, J_2 are the same as in Equation (4).

Fuzzy risk matrix

Risk matrix approach was first developed by Electronic System Center, US Airforce in 1995, which refers to maps risks on a two-dimensional plane with associated probability and loss severity, being a kind of quantitative structural method to identify risks (Qazi *et al.* 2018). The calculation process of risk matrix producing is presented by the classical logic implication as follows: if probability is '*P*' category and loss severity is '*S*' category then risk is '*R*' category (Markowski & Mannan 2008). The input variables of risk matrix can generally be divided into five levels (Cox 2008). The value levels s of probability are very low (I), low (II), medium (III), high (IV), and very high (V). Meanwhile, the value levels of loss severity are negligible (I), minor (II), major (III), hazardous (IV), and catastrophic (V) (Skorupski 2016). Figure 2 shows an original 5 × 5 risk matrix approach, which is used to generate risk index from probability and loss severity (Peace 2017).

In the context of the original risk matrix, the value of risk is a discrete value (Duijm 2015). And if the values of the same input variable of different risks are near the critical



	I	II	III	IV	V
V	II	IV	V	V	V
IV	II	III	IV	V	V
III	I	III	III	IV	V
II	I	II	III	III	IV
I	I	I	I	II	II

Figure 2 | Original risk matrix.

value of adjacent intervals, the original risk matrix may produce two totally different assessment results (Ni *et al.* 2010). Therefore, the original calculation process of the risk matrix must be redefined in a better way to provide an accurate assessment of the risk level (Gadd *et al.* 2004). The fuzzy risk matrix was proposed by Markowski & Mannan (2008). The fuzzy sets for each variable and the fuzzy inference system were constructed in the fuzzy risk assessment matrix. The multiplication formula could naturally be selected as the new calculation process to quantify risk index (Cox 2008; Ni *et al.* 2010; Levine 2012). Ni *et al.* (2010) described four classical logic combinations, which are multiplication formula, division formula, subtraction formula and addition formula. Figure 3 shows one example of the graphical edition of multiplication formula, where the total area is divided into six parts.

The logical combination result of the multiplication formula shown in Figure 3 is significantly different from the original risk matrix result shown in Figure 2. Therefore, the risk level was obtained according to the distance from origin of risk matrix, and the Euclidean distance formula is as follows:

$$d = \sqrt{P^2 + S^2} \tag{6}$$

Figure 4 illustrates one example of the graphical edition of Euclidean distance formula.

Water resources system adaptability analysis in Huaihe River basin

The Huaihe River basin locates in the eastern of China, between the Yangtze River and the Yellow River. The basin has 170 million people on the total area of 270,000 km^2, and the average amount of water per person is less than 500 m^3, meaning it is suffering a serious lack of water resources. Huaihe River basin is located in the climate transition zone of China, and the seasonal and interannual variations of precipitation are large. The annual precipitation is about 920 mm, and its distribution gradually decreases from southeast to northwest. Because of this special geographical location and climate condition, flood and draught disasters occur frequently in Huaihe

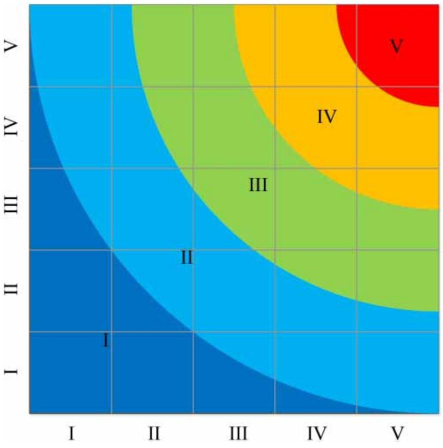


Figure 3 | Risk level of multiplication formula.

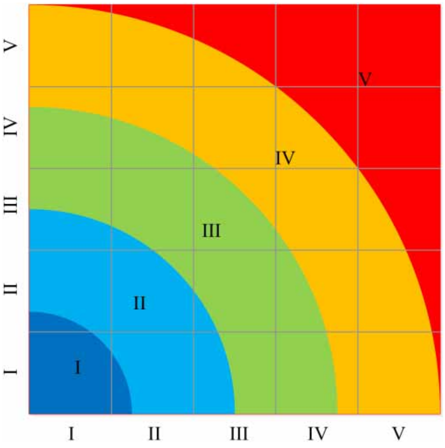


Figure 4 | Risk level of Euclidean distance formula.

River basin. The impact of climate change on water resources of Huaihe River basin and its adaptation are particularly noteworthy (Tian *et al.* 2012).

The water resources system adaptability of Huaihe River basin from 2006 to 2015 was analyzed by using the water resources system adaptability analysis method.

Optimization of adaptive indexes

The adaptive indexes of water resources system are optimized using fuzzy analytic hierarchy process (Mikhailov & Tsvetinov 2004; Jin *et al.* 2005). Thus, the natural restorative indexes of water resources system were confirmed as per unit area available amount of water resources, surface water environment quality and ratio of soil erosion areas. As well, the artificial adaptation indexes of water resources system were confirmed as water utilization rate, standard-reaching rate of water function area, ratio of ecological water consumption, per capita GDP, irrigation consumption of water per mu of farmland, and water consumption for 10^4 ￥ industrial added value.

Evaluation standard of adaptation indexes

According to the results of adaptive process mechanism of water resource system in a changing environment in this paper, and the research results of references (Liu and Chen 2016; He *et al.* 2017; Pan *et al.* 2017), the water resources system adaptability was divided into five levels, which are very low (I), low (II), medium (III), high (IV), and very high (V), respectively. The evaluation standards of water resources system adaptation indexes are determined, as shown in Table 1.

Connection number of adaptation indexes

Utilizing the sample data of water resources system adaptation indexes, the connection numbers of water resources system adaptation indexes of Huaihe River basin are determined by Equation (5). The connection numbers of adaptation indexes in 2015 is shown in Table 2.

Weight of adaptation indexes

The weights of natural restorative factors obtained by using fuzzy analytic hierarchy process (Mikhailov & Tsvetinov 2004; Jin *et al.* 2005) were 0.358, 0.333 and 0.309, respectively. The weights of the artificial adaptation indexes obtained based on the same method were 0.186, 0.155, 0.163, 0.147, 0.178 and 0.171, respectively, as shown in Table 2.

Connection numbers of natural restorative/artificial adaptation

The connection numbers of adaptive indexes can be obtained by Equation (5). The connection numbers $u_{(NR)}$ of natural restorative adaptation was calculated by an

Table 1 | Evaluation standard of water resources system adaptation indexes

Indexes			Evaluation standard				
			Very low (I)	**Low (II)**	**Medium (III)**	**High (IV)**	**Very high (V)**
Natural resilience	x_1	per unit area available amount of water resources, $10^4 \cdot m^3/km^2$	[0, 10)	[10, 20)	[20, 40)	[40, 80)	[80, 120]
	x_2	surface water environment quality, %	[0, 25)	[25, 40)	[40, 60)	[60, 80)	[80, 100]
	x_3	ratio of soil erosion areas, %	[30, 60)	[20, 30)	[10, 20)	[5, 10)	[0, 5]
Artificial adaptation	x_4	water utilization rate, %	[85, 100)	[60, 85)	[45, 60)	[35, 45)	[0, 35]
	x_5	standard-reaching rate of water function area, %	[0, 50)	[50, 65)	[65, 80)	[80, 95)	[95, 100]
	x_6	ratio of ecological water consumption, %	[0, 1)	[1, 2.5)	[2.5, 4)	[4, 5.5)	[5.5, 15]
	x_7	per capita GDP, 10^4 RMB	[0, 0.3)	[0.3, 0.7)	[0.7, 2)	[2, 5)	[5, 8]
	x_8	irrigation consumption of water per mu of farmland, m^3/mu	[420, 800)	[360, 420)	[300, 360)	[240, 300)	[0, 240]
	x_9	water consumption for 10^4 ￥ industrial added value, $m^3/10^4$ RMB	[180, 230)	[120, 180)	[65, 120)	[35, 65)	[0, 35]

Table 2 | Connection number of adaptation indexes of Huaihe River basin in 2015

Indexes	Connection number	Weight
x_1	$u_{2015,1} = 0 + 0 + 0.242\,5I_1 + 0.500\,0I_2 + 0.257\,5I_3 + 0J_1 + 0J_2$	0.358
x_2	$u_{2015,2} = 0 + 0 + 0.115\,0I_1 + 0.500\,0I_2 + 0.385\,0I_3 + 0J_1 + 0J_2$	0.333
x_3	$u_{2015,3} = 0 + 0 + 0I_1 + 0.387\,8I_2 + 0.500\,0I_3 + 0.112\,2J_1 + 0J_2$	0.309
x_4	$u_{2015,4} = 0 + 0 + 0I_1 + 0.366\,7I_2 + 0.500\,0I_3 + 0.133\,3J_1 + 0J_2$	0.186
x_5	$u_{2015,5} = 0 + 0 + 0I_1 + 0.486\,7I_2 + 0.500\,0I_3 + 0.013\,3J_1 + 0J_2$	0.155
x_6	$u_{2015,6} = 0 + 0 + 0I_1 + 0.208\,0I_2 + 0.500\,0I_3 + 0.292\,0J_1 + 0J_2$	0.163
x_7	$u_{2015,7} = 0 + 0.301\,5 + 0.500\,0I_1 + 0.198\,5I_2 + 0I_3 + 0J_1 + 0J_2$	0.147
x_8	$u_{2015,8} = 0 + 0.430\,0 + 0.500\,0I_1 + 0.070\,0I_2 + 0I_3 + 0J_1 + 0J_2$	0.178
x_9	$u_{2015,9} = 0.092\,9 + 0.500\,0 + 0.407\,1I_1 + 0I_2 + 0I_3 + 0J_1 + 0J_2$	0.171

additive weighting method (Hashemy Shahdany & Roozbahani 2016; Pan *et al.* 2017), which is shown as follows:

$$u_{j(NR)} = \sum_{i=1}^{3} w_{i(NR)} \cdot u_{ij(NR)} \tag{7}$$

where $w_{i(NR)}$ is the weight of natural restorative indexes.

As well, the connection numbers $u_{(AA)}$ of artificial adaptation is shown as follows:

$$u_{j(AA)} = \sum_{i=1}^{6} w_{i(AA)} \cdot u_{ij(AA)} \tag{8}$$

where $w_{i(AA)}$ is the weight of artificial adaptation indexes.

The connection numbers of natural restorative or artificial adaptation of Huaihe River basin in 2006–2015 is illustrated in Table 3, and the connection numbers of natural restorative or artificial adaptation of different province in 2015 is exhibited in Table 4.

Fuzzy risk matrix based on connection number

The value of the discrepancy coefficients in Equation (5) can be measured with the application of the mean method (Pan *et al.* 2017): $I_1 = 0.5$, $I_2 = 0$, and $I_3 = -0.5$. Moreover, the value of the coefficient of contrary degrees J_1 and J_2 become equal to -1. Thus, the value of connection number of natural restorative/artificial adaptation is measured using Equation (7) or (8). Then, the connection number of natural restorative and artificial adaptation were used as the two elements of fuzzy risk matrix, and

Table 3 | Connection numbers of natural restorative or artificial adaptation in 2006–2015

Year	Connection numbers
2006	$u_{(NR)2006} = 0.000\,0 + 0.000\,0 + 0.096\,0I_1 + 0.426\,8I_2 + 0.404\,0I_3 + 0.073\,2J_1 + 0.000\,0J_2$
	$u_{(AA)2006} = 0.000\,0 + 0.037\,9 + 0.121\,7I_1 + 0.282\,3I_2 + 0.343\,1I_3 + 0.179\,8J_1 + 0.035\,3J_2$
2007	$u_{(NR)2007} = 0.000\,0 + 0.020\,5 + 0.179\,0I_1 + 0.422\,5I_2 + 0.321\,0I_3 + 0.057\,1J_1 + 0.000\,0J_2$
	$u_{(AA)2007} = 0.000\,0 + 0.114\,0 + 0.257\,9I_1 + 0.227\,0I_2 + 0.217\,3I_3 + 0.159\,0J_1 + 0.024\,7J_2$
2008	$u_{(NR)2008} = 0.000\,0 + 0.000\,0 + 0.122\,3I_1 + 0.419\,1I_2 + 0.377\,7I_3 + 0.080\,9J_1 + 0.000\,0J_2$
	$u_{(AA)2008} = 0.000\,0 + 0.045\,8 + 0.217\,5I_1 + 0.308\,7I_2 + 0.270\,7I_3 + 0.145\,5J_1 + 0.011\,8J_2$
2009	$u_{(NR)2009} = 0.000\,0 + 0.000\,0 + 0.057\,5I_1 + 0.412\,4I_2 + 0.442\,5I_3 + 0.087\,6J_1 + 0.000\,0J_2$
	$u_{(AA)2009} = 0.000\,0 + 0.028\,1 + 0.239\,7I_1 + 0.240\,9I_2 + 0.213\,6I_3 + 0.230\,9J_1 + 0.046\,7J_2$
2010	$u_{(NR)2010} = 0.000\,0 + 0.000\,0 + 0.107\,4I_1 + 0.418\,4I_2 + 0.392\,6I_3 + 0.081\,6J_1 + 0.000\,0J_2$
	$u_{(AA)2010} = 0.000\,0 + 0.067\,4 + 0.248\,0I_1 + 0.259\,5I_2 + 0.222\,2I_3 + 0.173\,1J_1 + 0.029\,8J_2$
2011	$u_{(NR)2011} = 0.000\,0 + 0.000\,0 + 0.070\,7I_1 + 0.405\,9I_2 + 0.429\,3I_3 + 0.094\,1J_1 + 0.000\,0J_2$
	$u_{(AA)2011} = 0.000\,0 + 0.108\,6 + 0.248\,0I_1 + 0.220\,1I_2 + 0.251\,1I_3 + 0.171\,3J_1 + 0.000\,9J_2$
2012	$u_{(NR)2012} = 0.000\,0 + 0.000\,0 + 0.036\,7I_1 + 0.431\,3I_2 + 0.463\,3I_3 + 0.068\,7J_1 + 0.000\,0J_2$
	$u_{(AA)2012} = 0.000\,0 + 0.155\,1 + 0.248\,0I_1 + 0.163\,9I_2 + 0.230\,3I_3 + 0.181\,0J_1 + 0.021\,7J_2$
2013	$u_{(NR)2013} = 0.000\,0 + 0.000\,0 + 0.010\,7I_1 + 0.452\,9I_2 + 0.489\,3I_3 + 0.047\,1J_1 + 0.000\,0J_2$
	$u_{(AA)2013} = 0.000\,0 + 0.147\,1 + 0.248\,0I_1 + 0.139\,4I_2 + 0.162\,9I_3 + 0.213\,5J_1 + 0.089\,1J_2$
2014	$u_{(NR)2014} = 0.000\,0 + 0.000\,0 + 0.105\,9I_1 + 0.489\,1I_2 + 0.394\,1I_3 + 0.010\,9J_1 + 0.000\,0J_2$
	$u_{(AA)2014} = 0.011\,5 + 0.183\,0 + 0.236\,5I_1 + 0.170\,6I_2 + 0.252\,0I_3 + 0.146\,4J_1 + 0.000\,0J_2$
2015	$u_{(NR)2015} = 0.000\,0 + 0.000\,0 + 0.125\,1I_1 + 0.465\,3I_2 + 0.374\,9I_3 + 0.034\,7J_1 + 0.000\,0J_2$
	$u_{(AA)2015} = 0.015\,9 + 0.206\,4 + 0.232\,1I_1 + 0.219\,2I_2 + 0.252\,0I_3 + 0.074\,5J_1 + 0.000\,0J_2$

Table 4 | Connection numbers of natural restorative or artificial adaptation of different province in 2015

Province	Connection numbers
Henan	$u_{(NR)} = 0.000\ 0 + 0.000\ 0 + 0.006\ 2I_1 + 0.251\ 6I_2 + 0.493\ 8I_3 + 0.248\ 4J_1 + 0.000\ 0J_2$ $u_{(AA)} = 0.057\ 2 + 0.223\ 2 + 0.272\ 3I_1 + 0.233\ 0I_2 + 0.170\ 5I_3 + 0.043\ 8J_1 + 0.000\ 0J_2$
Anhui	$u_{(NR)} = 0.000\ 0 + 0.000\ 0 + 0.310\ 3I_1 + 0.500\ 0I_2 + 0.189\ 7I_3 + 0.000\ 0J_1 + 0.000\ 0J_2$ $u_{(AA)} = 0.004\ 4 + 0.091\ 4 + 0.341\ 5I_1 + 0.327\ 2I_2 + 0.154\ 1I_3 + 0.081\ 4J_1 + 0.000\ 0J_2$
Jiangsu	$u_{(NR)} = 0.000\ 0 + 0.018\ 7 + 0.314\ 3I_1 + 0.354\ 8I_2 + 0.185\ 7I_3 + 0.126\ 5J_1 + 0.000\ 0J_2$ $u_{(AA)} = 0.030\ 0 + 0.159\ 0 + 0.129\ 0I_1 + 0.076\ 1I_2 + 0.288\ 8I_3 + 0.264\ 9J_1 + 0.052\ 2J_2$
Shandong	$u_{(NR)} = 0.000\ 0 + 0.066\ 6 + 0.166\ 5I_1 + 0.175\ 6I_2 + 0.285\ 3I_3 + 0.257\ 8J_1 + 0.048\ 2J_2$ $u_{(AA)} = 0.070\ 7 + 0.243\ 1 + 0.228\ 7I_1 + 0.163\ 9I_2 + 0.184\ 6I_3 + 0.093\ 0J_1 + 0.016\ 0J_2$

the fuzzy risk matrix based on the connection number is presented in Figure 5.

As shown in Figure 5(a), a rigorous criterion, which defined as a pessimistic criterion, is prosed based on the distance that both natural resilience and artificial adaptation are meet the standard. Figure 5(b) shows an indulgent criterion, which is based on the distance that either natural resilience or artificial adaptation meet the standard, and can be defined as an optimistic criterion. Therefore, the adaptive interval of water resources system [A_{pess}, A_{opt}] is obtained based on connection numbers–fuzzy risk matrix.

Adaptive levels assessment of water resources system adaptability based on fuzzy risk matrix

Based on the fuzzy risk matrix, the adaptive levels assessment of water resources system adaptability was quantified, and the adaptive level formula was proposed as follows:

$$A_{\text{pess},i} = 1.25\sqrt{2}d_i \tag{9a}$$

$$A_{\text{opt},i} = \begin{cases} 2.5d_i & d_i \leq 2 \\ 5 & d_i > 2 \end{cases} \tag{9b}$$

where $A_{\text{pess},i}$ and $A_{\text{opt},i}$ is the pessimistic and optimistic adaptive levels of water resources system adaptability, respectively; d_j is the distance of fuzzy risk matrix, and its calculation formula is as follows:

$$d_i = \sqrt{(u_{i(NR)} + 1)^2 + (u_{i(AA)} + 1)^2} \tag{10}$$

Adaptive level of water resources system adaptability

According to the criteria of water resources system adaptability based on fuzzy risk matrix, the adaptive levels of water resources system adaptability is determined using formulas (10) and (9), as shown in Tables 5 and 6. The trend of water resources system adaptation of Huaihe River basin in 2006–2015 is presented in Figure 6, and the distribution map

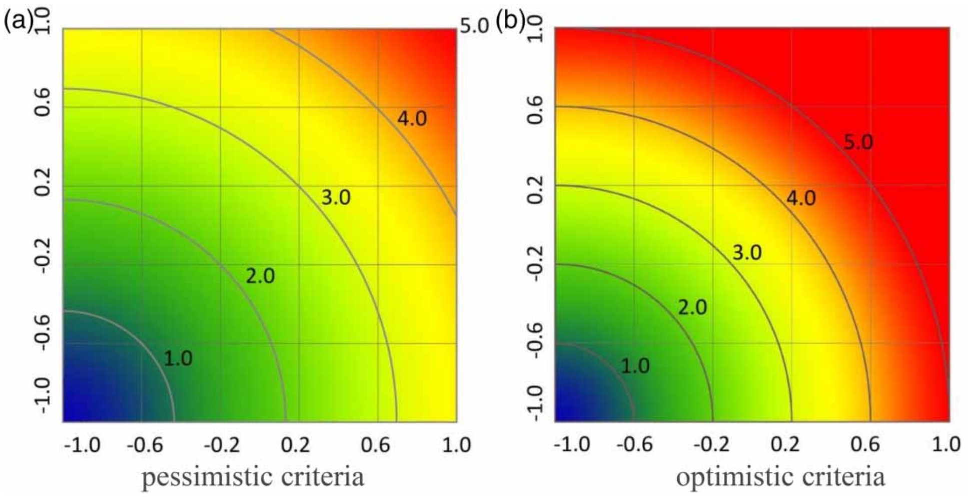


Figure 5 | Fuzzy risk matrix based on connection number.

Table 5 | Water resources system adaptability of Huaihe River basin in 2006–2015

	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
$u_{(NR)}$	−0.227	−0.108	−0.209	−0.280	−0.224	−0.273	−0.282	−0.286	−0.155	−0.160
$u_{(AA)}$	−0.288	−0.049	−0.138	−0.236	−0.123	−0.065	−0.039	−0.113	0.040	0.138
A_{pess}	1.858	2.305	2.068	1.856	2.070	2.094	2.121	2.013	2.369	2.500
A_{opt}	2.627	3.260	2.925	2.625	2.928	2.961	2.999	2.847	3.350	3.536

Table 6 | Water resource system adaptability of different province in 2015

	Henan	Anhui	Jiangsu	Shandong
$u_{(NR)}$	−0.492	0.060	−0.044	−0.299
$u_{(AA)}$	0.287	0.108	−0.208	0.227
A_{pess}	2.446	2.711	2.195	2.498
A_{opt}	3.459	3.833	3.104	3.533

of water resources system adaptation of different provinces in Huaihe River basin in 2015 is shown in Figure 7.

ANALYSIS OF RESULTS

Table 5 shows that the water resource system adaptability level of Huaihe River basin in 2006–2015 is not higher than 3.536. Figure 6 shows that the level of adaptability fluctuates, but generally it shows an upward trend. The lowest level of adaptability is in 2009, i.e [1.856, 2.625], the standard of pessimistic and optimistic criteria is very low and low, respectively. The highest level of adaptability is in 2015, i.e [2.500, 3.536], the standard of pessimistic and optimistic criteria are low and medium level, respectively.

The results of Table 6 show that the water resources system adaptability level of provincial administrative regions in 2015 from high to low was: Huaihe River basin in Anhui province ([2.711, 3.833]), Huaihe River basin in Shandong province ([2.498, 3.533]), Huaihe River basin in Henan province ([2.446, 3.459]), and Huaihe River basin in Jiangsu province ([2.195, 3.104]). Figure 7 shows that the adaptability of the water resources system in Huaihe River basin in 2015 has obvious space distribution characteristics. The adaptability level of the upper region of the basin is better than that of the lower region, and the adaptability level of the regions between Yangtze River and Huaihe River is better than that of the northern part of Huaihe River basin.

CONCLUSION AND SUGGESTIONS

This study analyzes the adaptability of water resources system in Huaihe River basin, using the adaptation mechanism of water resources system under changing environment and a method of system analysis that proposed based on connection numbers–fuzzy risk matrix. Results show that the adaptability is unsatisfactory. The highest adaptability level of water

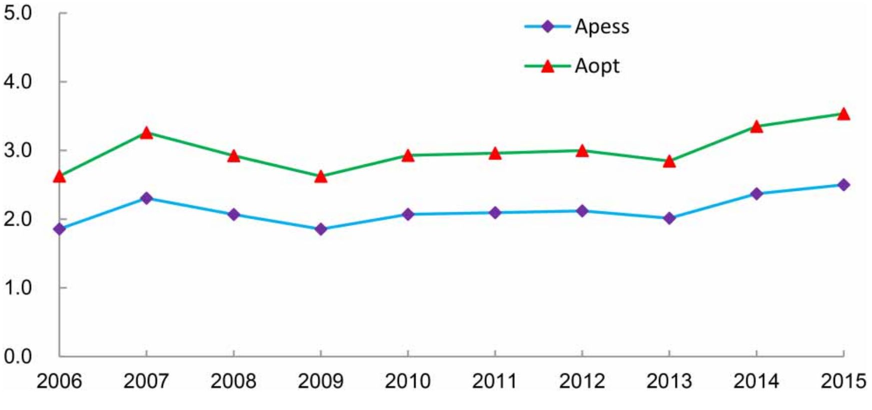


Figure 6 | Trend of water resource system adaptation of Huaihe River basin in 2006–2015.

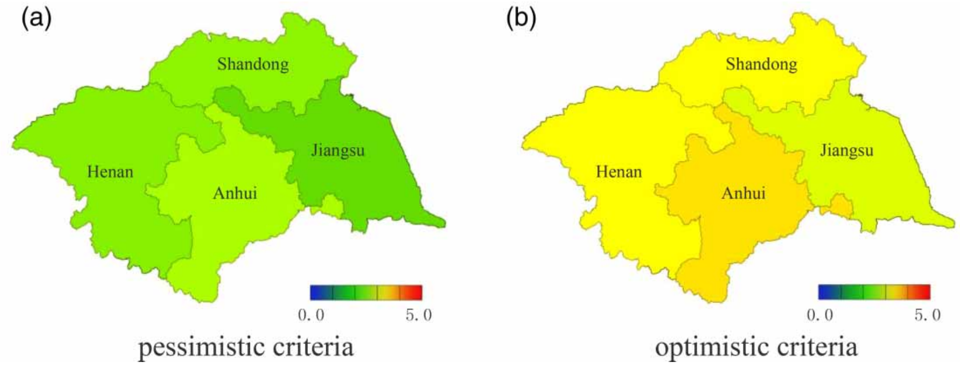


Figure 7 | Distribution map of water resource system adaptation of different provinces in 2015.

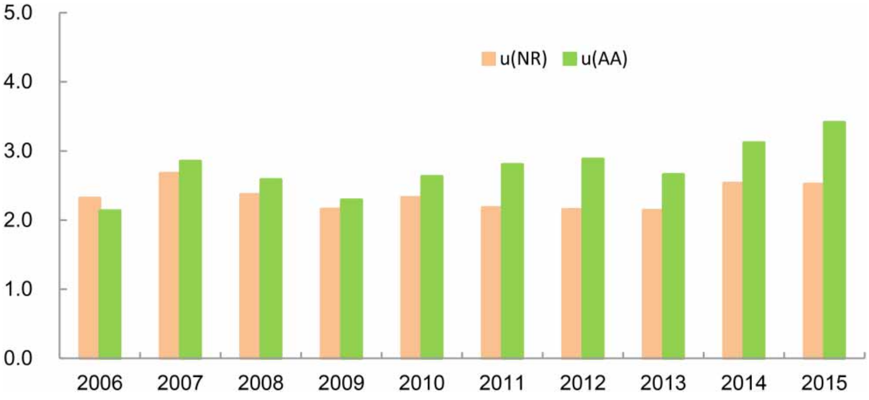


Figure 8 | Natural resilience and artificial adaptation of Huaihe River basin in 2006–2015.

resources system during 2006–2015 is 3.536. In 2015, it was found that Anhui province presented highest adaptability level of water resources system in provincial level administrative regions, followed by Shandong province, Henan province, and Jiangsu province. Furthermore, the adaptability of water resources system in Huaihe River basin is analyzed as follows.

Figure 8 shows that, in addition to 2006, the artificial adaptation is higher than natural resilience. And the artificial adaptation is becoming increasingly crucial for the vulnerability of water resources system of Huaihe River basin.

As shown in Figure 9, the artificial adaptation of the other three provinces except Jiangsu is higher than natural resilience, only, the artificial adaptation of Anhui province is a little higher than natural resilience. Further, from the artificial adaptation indexes angle analysis, the adaptive level of artificial adaptation indexes in Anhui and Jiangsu provinces is displayed in Figure 10.

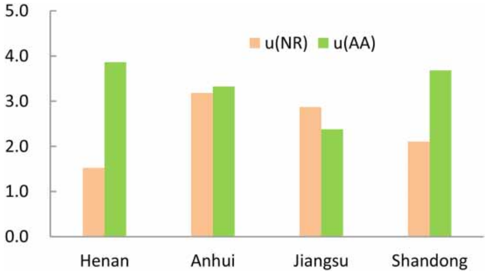


Figure 9 | Natural resilience and artificial adaptation in provincial level administrative regions in 2015.

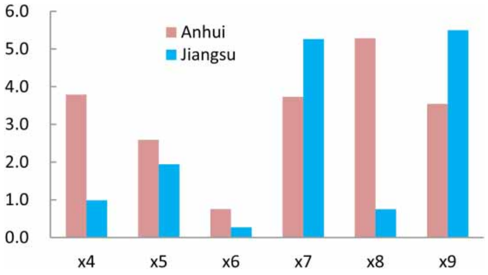


Figure 10 | Adaptive level of artificial adaptation indexes in Anhui and Jiangsu provinces.

Figure 10 shows that the adaptability of indexes x5 and x6 in Anhui province are at a low level, and the adaptability of indexes x4, x5, x6 and x8 in Jiangsu province are even lower. To improve the adaptability of water resources system in these areas, it is suggested to vigorously develop highly effective water-saving agriculture which can reduce the vibration consumption of water per mu of farmland to adjust industrial structure, shut high water consuming industries, reduce water consumption and ultimately improve the water utilization rate. In addition, water-saving agriculture can enhance ecological protection of river-lake and build beautiful and healthy river-lake with the aim of improving standards reaching rate of the water function area.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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