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INTERACTION BETWEEN CONTINENTAL WATERS AND THE ENVIRONMENT

A Three-Way Decision Approach for Water Resources System Resilience Evaluation and Its Application

Yafeng Yang[a, b], **Hongrui Wang**[a, *], **Yong Zhao**[c], **and Shuxin Gong**[a]
[a] College of Water Sciences, Beijing Normal University, Beijing, 100875 China
[b] College of Sciences, North China University of Science and Technology, Tangshan, 063210 China
[c] State Key Laboratory of Simulation and Regulation of Water Cycle in River Basins, China Institute of Water Resources and Hydropower Research, Beijing, 100038 China
*e-mail: henrywang@bnu.edu.cn

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Abstract—Resilience is a significant uncertainty thought of water resources system security. Compared with risk analysis, resilience pays more attention to the ability of water resources system itself to deal with adverse events. However, a standard system of water resources system resilience's concept and evaluation have not yet formed. In view of this, this study had attempted to decompose the process of resisting interference of water resources system and analyzed the characteristics and influencing factors of three sub processes of resistance, recovery and adaptation. Furtherly, a new resilience evaluation index system of water resources system was explored and a three-way dicision approach for water resources system resilience analysis based on variable fuzzy sets and partial connection number was developed. Specifically, a multi-grade quantitative evaluation of water resources resilience was carried out based on variable fuzzy sets method, and then the quantitative evaluation results were transformed into qualitative decision-making results using a new three-way decision model based on partial connection number of set pair analysis. Finally, a case study of China's Yangtze River Economic Belt (YEB) in 2008–2017 was performed and the results show that the resilience of water resources system in the YEB does not show an obvious improvement trend, or even almost stagnant. Of the 110 samples, 83.6% were at the medium level. Only 6.4% are barely at the excellent level, but they are basically in Shanghai.

Keywords: water resources system, resilience, resistibility-recoverability-adaptability, variable fuzzy sets method, grade eigenvalue, set pair analysis, partial connection number, three-way decision, Yangtze River Economic Belt

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INTRODUCTION

A consensus has been reached that water shortages, floods and droughts, and the deteriorationare of water environment becoming increasing serious, which seriously affect the sustainable development of global economy, society, environment and resources [2, 5, 21, 28]. In 2012, the United Nations World Water Assessment Programme pointed out that with the impact of climate change, the amount of water resources available in many regions will be reduced, and the imbalance between water supply and demand and the water shortage will be aggravated [22]. The frequent occurrence of water resources problems has prompted human beings to find more reasonable strategies for sustainable utilization of water resources. Risk analysis is one of the important paths to deal with this problem, which has provided a scientific basis for water resources security [13, 14]. However, it tends to emphasize the probability of adverse events and the degree of loss, and ignores the response capacity of water resources system itself. In fact, the outbreak of COVID-19 has sounded the alarm for us. We have exposed great vulnerability in the face of sudden risks. Water resource is one of the rigid constraints of economic and social development, which is of great significance, but it also presents vulnerability [15]. Therefore, it is particularly urgent to shift from "anti vulnerability" to "resilience" [6, 11, 12, 16].

Resilience origined from "resilio" in Latin, which means "reset to the original state." It was introduced into ecological field by Holling [7] to describe the extent to which disturbances can be absorbed before the system's structure was changed. Subsequently, it was gradually extended to many fields, such as human ecology, social ecology, water science, etc. In the application expanding, its core concept is from focusing on the engineering resilience of "single steady state" to "building new steady state" ecological resilience, and then gradually weakening the emphasis on the steady state, while focusing on the learning adaptation process, namely, the improvement of resilience. Resilience has more flexibility than carrying capacity or resistance strategies, which can adapt to various uncertain changes [24].

Resilience emphasizes the system's resistibility to cope with the disturbance, recoverability after disturbed and adaptive learning ability, which provides a new analytical framework for the sustainable development of water resources system. At present, scholars have paid attention to the water resources system resilience. Alessa et al. established the Arctic water resources vulnerability index to express the resilience [1]. Tanner et al. evaluated the resilience of water resources systems from 5 aspects: decentralization and autonomy, transparency and accountability, responsiveness and flexibility, participation and inclusiveness, and governance experience [20]. Sandoval-Solis et al. established the sustainability index of water resources from three aspects of reliability, recoverability and vulnerability based on "deficit" [17]. Liu et al. established a quantitative evaluation model of water resources system resilience from three aspects of drought, waterlogging and water pollution based on Holling's resilience thought [10]. Yu et al. considered that water system has the characteristics of resilience [25]. Huang and Ling used GIS spatial analysis and ABM model to study the resilience of urban water resources system [8]. Sun and Meng introduced "soft power" factors such as culture and system into the evaluation index system of regional water system resilience [19], and so on. Obviously, a series of research results on water resources resilience system provide support for the sustainable development of water resources system. However, to the best of our knowledge, no studies have focused on the process decomposition of water resources resilience system, that is, the mechanism and connection of absorbing disturbance, recovering structure and lifting function. In addition, the current evaluation of water resources system resilience is often based on the static index data, and the fuzziness and dynamic of the data are not sufficiently considered. Such questions bear importantly on clarifying the connotation of water resources system resilience, and may shed light on how to formulate better water resources security policies that perform well facing various interference of adverse events.

In view of this, this study firstly referred to the resilience concept, analyzed the characteristics and influencing factors of water resources system resilience from the perspective of process decomposition, and constructed a evaluation index system of resilience; Secondly, focusing on the fuzziness, variable fuzzy sets method was used to describe the unity of opposites of the resilience between adjacent grades, and the grade eigenvalues were used to describe the resilience; Thirdly, considering the dynamics of information, a new three-way decision model was constructed based on partial connection number method to analyze the internal evolution direction of resilience; Finally, the proposed model framework was applied to the multi-level and multi-scale quantitative evaluation of the water resources system resilience of China's YEB from 2008 to 2017.

METHODS

Firstly, a new evaluation index system of water resources system resilience based on subsystem decomposition was explored. Then, a complete three-way decision approach for resilience evaluation based on variable fuzzy sets and partial connection number was constucted.

Evaluation Index System of Water Resources System Resilience

This study holds that water resources resilience refers to the ability that can maintain stable operation in the disturbed state, recover the original function quickly when impacted, and acquire certain adaptability after one impact process. So, resilience process can be seen as a cycle in which the system improves adaptability and constantly adapts to risks and disturbances. In this process, the system has experienced "be disturbed," to "maintain system stability after disturbed," and then to "recovering stability." In this process, the ability of adaptation and learning has been improved, and then achieve innovative development and enhance resilience (Fig. 1).

Corresponding to three sub processes: before disturbance, during disturbance and after disturbance, three ability goals of water resources system, that is, resistibility, recoverability and adaptability respectively, and their influencing factors, should be explored.

Influencing factors of resisting process: In disaster science, the impact of disaster process is mainly composed of two parts: external pressure and endogenous pressure. It is caused by the instability and effect accumulation of natural or human activity regional system, including endogenous problems such as population, resources and environment [18]. Similarly, in the water resources system, the main factors affecting the water resources resilience depend on the frequency of external natural disasters and the endogenous factors related to the regional water resources. Therefore, in the water resources system, the greater the potential risk it faces, the more disturbance it will be subjected to, and the weaker its resistibility will be. When there are more exogenous factors such as flood and drought, the impact of water resources system will be greater, the system's ability to resist risk will be weaker, and the performance of resilience in the resisting process will be worse. In particular, the drought and flood affected area refers to the sowing area where the yield of crops is reduced compared with that in normal years due to flood and drought disasters and it can characterize the frequency and scope of natural disasters closely related to water, that is, the number and range of exogenous factors, and is closely related to the agricultural pro-

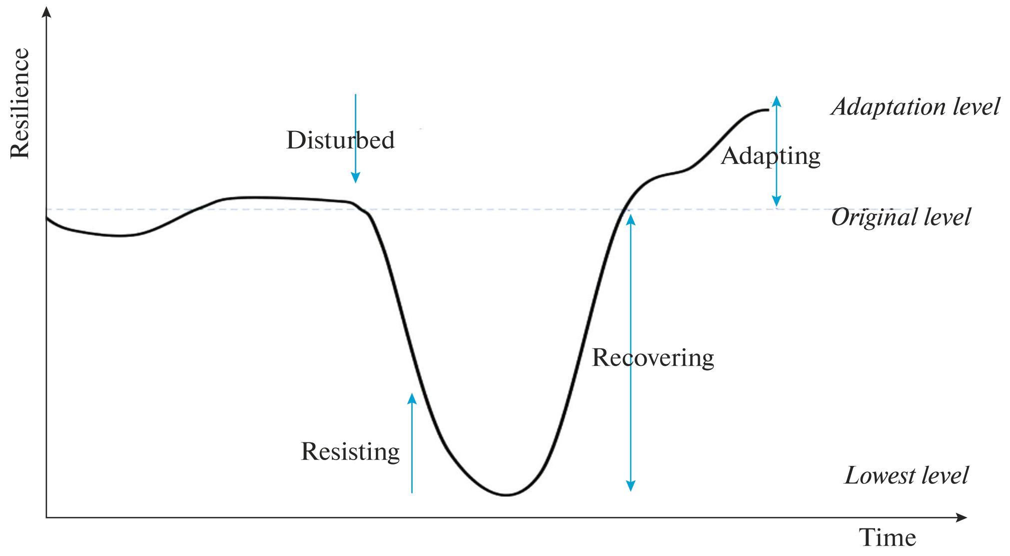

Fig. 1. Resilience process of water resources system.

duction system. Correspondingly, endogenous factors such as regional water resources pressure and population pressure will also affect the water resources system to suffer huge impact, leading to the weakening of resistibility.

Influencing factors of recovering process: After the system is disturbed, it will go through a recovering process, and the influencing factors in this process are affected by the stability of the internal factors.The recovering process is affected by internal factors such as water environment, economy and water use structure, which determine the speed of the system recovering process. The recoverability is affected by environment, ecology, economy, society and other aspects: for example, sewage treatment determines the carrying capacity of the water environment; economic structure will affect the water consumption, and industrial and agricultural water consumption will be far greater than that of the tertiary industry; different water use efficiency will also affect the resilience of water resources. For instance, agricultural water consumption includes irrigation of cultivated land and forest land, gardens and pastures, replenishment of fish ponds and livestock water, which in a certain sense reflects the potential ability of the agricultural production system to restore various normal functions after disasters, etc.

Influencing factors of adapting process: After recovering process, the system will learn to adapt to the next disturbance through this disturbance, which is the adaptability in the resilience system. The adapting process of water resources resilience system is mainly affected by regional innovation factors, security factors and so on. Different adaptability levels determine the new initial state level that the system can move to in the next impact.In the water resources system, the impact on adaptability mainly focuses on regional sustainable development and sustainable utilization of water resources. For example, water consumption of ecological environment reflects the water consumption used for ecological environment restoration and construction or maintaining the current ecological environment; the input cost of environmental protection in the region will greatly affect the level of water environment adaptation; high quality R & D platform will promote the efficient use of water resources; the construction level of the region itself can assist the smooth operation of urban water system. These factors do not belong to the water resources endowment, nor in the scope of economic structure and ecological environment, but they have a profound impact on the water resources system and make it change in a better direction.

According to the above analysis, when selecting the evaluation index of water resources resilience, we should pay more attention to the problem orientation and risk pertinence, and consider the diversity of the pressure faced by the water resources system, the complexity of the water resources system and the anti-interference ability [9]. The resilience of water resources system depends on the interaction of various factors such as water resources endowment, ecological environment, economic society, population and system, and different index selection will affect the results of water resources resilience evaluation. In view of this, this study based on the concept of resilience, followed the principles of scientificity, systematicness and operability, screened the corresponding indicators from three aspects of resistibility, recoverability and adaptability. Furtherly, a new evaluation index system of water resources system resilience was constructed, as shown in Table 1.

Table 1. Evaluation index system of water resources system resilience

Subsystem	Index	Unit	Attribute
Resistibility	Population	10^4	–
	Drought affected area	10^3 ha	–
	Flood affected area	10^3 ha	–
	Water consumption per 10^4 yuan GDP	m^3	–
	Total water supply	10^8 m^3	+
	Total water resources	10^8 m^3	+
Recoverability	Water resources per capita	m^3	+
	Industrial water consumption	10^8 m^3	–
	Agricultural water consumption	10^8 m^3	–
	Sewage treatment capacity	10^8 m^3	+
	Proportion of tertiary industry	%	+
	Energy consumption per unit output value	KWh/10^4 RMB yuan	–
Adaptability	Water consumption of ecological environment	10^8 m^3	+
	Investment in environmental protection	10^8 RMB yuan	+
	Growth rate of fiscal revenue	10^8 RMB yuan	+
	R & D investment	10^8 RMB yuan	+
	Urban greening rate	%	+
	Forest coverage	%	+

A New Three-Way Decision Approach Based on Variable Fuzzy Sets and Set Pair Analysis

The proposed three-way decision approach in this study includes three main steps: (1) Calculate the membership degrees of each object relative to each grade by using the variable fuzzy set method, and analysis the time series evolution trend of resilience level based on the grade eigenvalue; (2) Transform the relative membership degree into connection number, and express the uncertain state of each object relative to each resilience grade by a unified mathematical structure; (3) Describing the decision cost by considering dynamic evolution between components by partial connection number, and then construct a new generalized three-way decision model.

Grade Eigenvalue (in Variable Fuzzy Sets Theory)

In 1965, the concept of fuzzy sets was proposed by Professor Zadeh [26], and theory of fuzzy sets was established. This theory promotes the development of the direction and practical application of traditional mathematical theories. However, with the gradual increase in the scope of application fields, this theory fails to consider the dynamic variability of development of objects. To address this shortcoming, Chen [3] established variable fuzzy sets theory based on the principle of mutual transformation of contradictions in natural dialectics, which has been applied to the relative research of water resources system.

The water resources system resilience is also a fuzzy concept, and there is no absolute clear boundary between its adjacent grades. For the resilience level of a specific water resources system, it is difficult to judge it as a certain grade absolutely, because it always maintains a fuzzy unity of opposites between two adjacent grades. The relative membership degree method in variable fuzzy sets theory provides an effective tool to describe this problem.

As stated by Chen [3], U is a fuzzy concept, u is a random element in U, and $u \in U$. A and A^C represent attractability and repellency. Then form a pair of continuous number lines expressed by the closed intervals of [1, 0] and [0, 1]. For u in U, $\mu_A(u)$ and $\mu_{A^c}(u)$ are the relative membership functions of u to A and A^C that respectively express attractability and repellency degree. The mapping is presented as follows:

$$\begin{cases} \mu_A, \mu_{A^c}: \ U \to [0,1] \\ u| \to \mu_A(u),\ \mu_{A^c}(u) \in [0,1]. \end{cases} \tag{1}$$

This mapping is called the relative membership function of A and A^C, where $\mu_A(u) + \mu_{A^c}(u) = 1$, $0 \le \mu_A(u) \le 1; 0 \le \mu_{A^c}(u) \le 1$.

If any two adjacent grades constitute an opposite events group, according to variable fuzzy sets, the eval-

Table 2. Basic conditions of relative membership degree

Conditions	Relative membership degree
$x_{ij} \le k_{jh}$	$\mu_{j(h-1)}(O_i) + \mu_{jh}(O_i) = 1,\ \mu_{j(h+1)}(O_i) = 0$
$x_{ij} \ge k_{j(h+1)}$	$\mu_{jh}(O_i) = 0,\ \mu_{j(h+1)}(O_i) + \mu_{j(h+2)}(O_i) = 1$
$k_{jh} \le x_{ij} \le k_{j(h+1)}$	$\mu_{jh}(O_i) + \mu_{j(h+1)}(O_i) = 1$

uation object only has relative membership relationship with one group (record as A and A^C), and satisfies the unity of opposites.

Let $U = \{u_j\}, (j = 1,2,\cdots n)$, $T = \{t_i\}, (i = 1,2,\cdots m)$ be the indexs set. $X_{ij} = \{x_{ij}\}$ refer to the value of u_j for t_i. t_i is divided into s grades, and the corresponding interval matrix is as follows:

$$I_{t_i} = [a_{ih}, b_{ih}](h = 1, 2, \cdots, s), \tag{2}$$

where, a_{ih}, b_{ih} are the upper and lower limits of t_i at grade h.

According to the theorem of the unity of opposites of variable fuzzy sets, there must be two gradual change points k_{ih} and $k_{i(h+1)}$ of index t_i in the interval of grade h and $h + 1$ respectively and the relative membership degree meets the conditions in Table 2.

The gradual change points k_{ih}, (h = 1, 2, ..., s) can be obtained by:

$$k_{ih} = \frac{s-h}{s-1}a_{ih} + \frac{h-1}{s-1}b_{ih}. \tag{3}$$

When $k_{ih} \le x_{ij} \le k_{i(h+1)}$, the relative membership degree of x_{ij} to grade h can be calculated as:

$$\mu_{ih}(u_j) = 0.5\left(1 + \frac{b_{ih} - x_{ij}}{b_{ih} - k_{ih}}\right) x_{ij} \in [k_{ih}, b_{ih}], \tag{4}$$

$$\mu_{ih}(u_j) = 0.5\left(1 - \frac{b_{ih} - x_{ij}}{b_{ih} - k_{i(h+1)}}\right) x_{ij} \in \left[b_{ih}, k_{i(h+1)}\right]. \tag{5}$$

Then, the combining relative membership degree of u_j to grade h is:

$$v_h(u_j) = \sum_{i=1}^{m} w_i \mu_{ih}(u_j), \tag{6}$$

where: w_i is the weight of t_i, and $\sum_{i=1}^{m} w_i = 1$.

The principle of maximum membership is widely used in many fuzzy decision making fields. However, this principle exhibits evident defects when fuzzy concepts are graded. The grade eigenvalue was proposed to address this defect [4].

$$H(u_j) = \sum_{h=1}^{s} v_h^0(u_j)\,h, \tag{7}$$

is called grade eigenvalue of u_j. $v_h^0(u_j)$ refers to the normalized vector of $v_h(u_j)$. Grade eigenvalue transforms relative membership degrees into a real number, which can reflect the approximate range of the evaluation object. However, for different relative membership degrees, the same or close grade eigenvalues may appear, which will lead to deviation in the grade determination. Therefore, it is still necessary to consider the size and dynamic evolution of each membership degree for the grade determination. Here, a new three-way decision model is proposed in Section 2.3 to solve this problem.

Connection Number and Partial Connection Numbe in Set Pair Analysis

For the similar problems, set pair analysis (SPA) method proposed by Zhao [31] has another expression, which uses the ternary connection number $u = a + bi + cj$ to express the relationship among the three grades. Where, a, b, c represents the membership degrees (correlation degrees) between the resilience grades (1 to 3) of water resources system. i and j are the marking symbols. Furthermore, the partial connection number was developed to describe the dynamic evolution of information and has been deeply studied and applied [29, 30]. Obviously, for the problem with three grades, we only need to set h (in variable fuzzy sets method of Section 2.2) to 3. Then, the three relative membership degrees can be recorded as each component of the connection number, that is, a, b, and c. In this way, the relationship between relative membership degree of variable fuzzy set and connection number is established, and the evolution characteristics of connection number components are also the evolution characteristics of relative membership degree.

Let a ternary connection number be $u = a + bi + cj$, $a, b, c \in [0,1], a + b + c = 1$, then:

$$\partial^+\mu = \partial^+ a + i\partial^+ b = \frac{a}{a+b} + \frac{b}{b+c}i, \tag{8}$$

is recorded as First-order partial positive connection numbe (FPCN). Where, $\partial^+ a$ is the positive evolution rate from b to a. $\partial^+ b$ is the positive evolution rate from c to b.

$$\partial^-\mu = i\partial^- b + j\partial^- c = \frac{b}{a+b}i + \frac{c}{b+c}j, \tag{9}$$

is recorded as First-order partial negative connection numbe (FNCN). Where, $\partial^{-}b$ is the negative evolution rate from a to b. $\partial^{-}c$ is the negative evolution rate from b to c.

Furthermore, if the FPCN is calculated again by partial positive evolution, we can get the Second-order partial positive connection number (SPCN) as follow:

$$\partial^{2+}\mu = \frac{\dfrac{a}{a+b}}{\left(\dfrac{a}{a+b} + \dfrac{b}{b+c}\right)}. \tag{10}$$

Similarly, Second-order partial negative connection number (SNCN) is:

$$\partial^{2-}\mu = \left(\frac{\dfrac{c}{b+c}}{\left(\dfrac{b}{a+b} + \dfrac{c}{b+c}\right)}\right) j. \tag{11}$$

A New Three-Wey Decision Approach Based on Partial Connection Number

Three-way decision (3WD) is a granular computing method developed in recent years to deal with uncertain decision-making [23]. It is a "rule by three" model gradually evolved from decision rough set theory, which is in line with human cognition. The core idea of 3WD is to divide a unified set into three disjoint paired regions, and formulate corresponding decision-making strategies for each region. In fact, due to the fuzziness and limitations of human thinking, most of the affairs we encounter can be understood as 3WD problem in a broad sense [27]. For instance, if the resilience is set to three grades, the problem of resilience evaluation will turn into a 3WD issue. Therefore, we only need to construct the condition set and establish the corresponding decision rules between conditions and resilience grades.

Generally, in the connection nember $u = a + bi + cj$, the size of a, b, c directly affects the decision results, so it is certainty that the evolution path and degree (based on partial connection number) between them will promote the adjustment of decision results. If the part of b evolving to a is used as the information component of support grade 2, there will be a certain decision cost which can be expressed by $b\partial^{-}b$. Based on the same analysis, the decision cost (DC) of each component for each grade is expressed as follows:

$$DC = \begin{pmatrix} 0 & a\partial^{+}a & a\partial^{2+}a \\ b\partial^{-}b & 0 & b\partial^{+}b \\ c\partial^{2-}c & c\partial^{-}c & 0 \end{pmatrix}. \tag{12}$$

Based on connection number be $u = a + bi + cj$, the decision cost of each grade are as follows:

$$DC(\text{Grade1}) = b\partial^{-}b + c\partial^{2-}c, \tag{13}$$

$$DC(\text{Grade2}) = a\partial^{-}a + c\partial^{-}c, \tag{14}$$

$$DC(\text{Grade3}) = a\partial^{2+}a + b\partial^{+}b. \tag{15}$$

In general, decision makers tend to choose the grade with a lowest cost.

Finally, the state of water resources system resilience can be evaluated and analyzed combining with the results of variable fuzzy sets and three-way decision method.

RESULTS

Study Area and Data Sources

YEB refers to the economic belt along the Yangtze River in China, covering 11 provinces (cities), including Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Chongqing, Guizhou, Sichuan and Yunnan (Fig. 2). It covers a vast area of about 2.05×10^6 km^2, accounting for 21.4% of China's total. YEB's population and GDP both exceed 40% of China's total. YEB, spanning the eastern, central and western regions of China, is a key area for developing national productive forces in the new era.

In this study, 11 provinces (cities) with 10-year water resource data (from 2008 to 2017) were downloaded from the National Bureau of Statistics (http://www.stats.gov.cn/) and government websites of the Water resource Agency in each region. The datasets are available and have been processed with quality control with a missing data rate of less than 0.1%.

Grade Eigenvalue of Resilience

Taking 2017 as an example, this study shows the relative membership degrees and grade eigenvalue in various provinces (cities) in more detail (Table 3). According to the results of grade eigenvalue, the spatial and temporal variation of water resources system resilience in YEB from 2008 to 2017 is visualized by using ArcGIS, as shown in Fig. 3. According to Fig. 3, the distribution of water resources resilience grade in each province of the YEB is uneven. In terms of regional spatial change, the water resources resilience grade of 11 provinces (cities) in the YEB is developing in a balanced way, and the gap between provinces is gradually decreasing.

Three-Way Decision of Resilience Based on Information Evolution

The grade eigenvalue reflects the approximate range of resilience level, but we still need to further consider when judging the grade, because different relative membership degrees may produce similar grade eigenvalues, but in fact they are quite different.

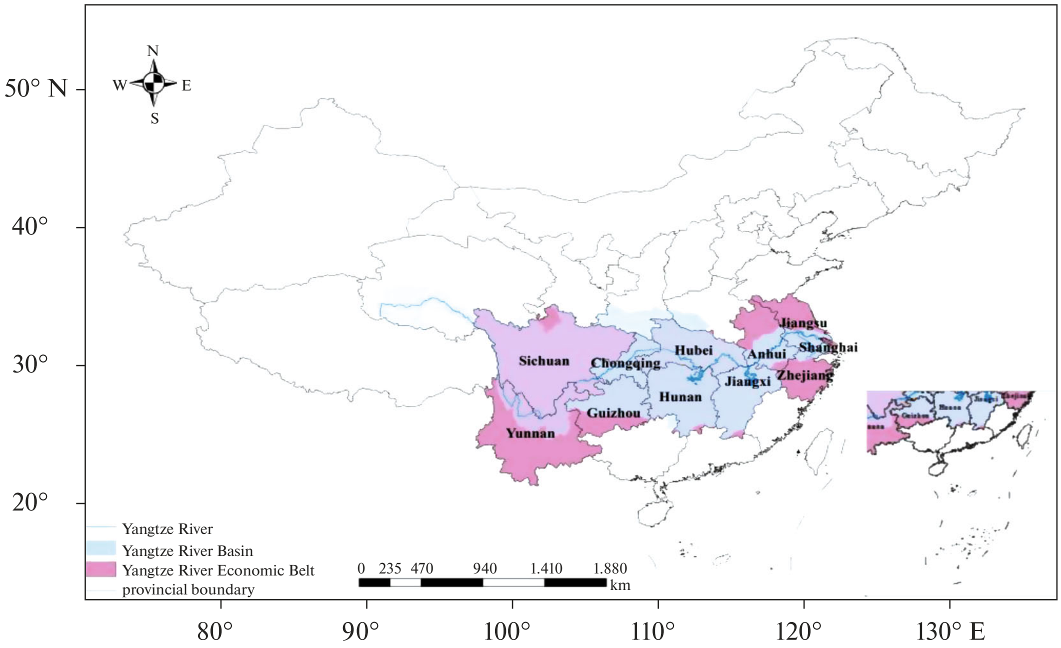

Fig. 2. Location of the administrative division of the YEB.

For instance, the connection number(transformed from relative membership degrees) of 2008 and 2017 in Shanghai are $0.2389 + 0.4266i + 0.3346j$ and $0.3726 + 0.161i + 0.4663j$ respectively, and the corresponding grade eigenvalues are 2.0958 and 2.0936. Obviously, they are almost the same, but the intuition tells us that they should not have the same grade of resilience. In view of this, we make the three-way decision analysis based on information evolution. The results show that the decision costs of judging 2008 as grade 1, 2 and 3 are 0.608, 0.2328 and 0.4779 respectively. Correspondingly, 0.5149, 0.6068, and 0.414 for 2017. According to the principle of minimum decision cost, it is grade 2 in 2008 and grade 3 in 2017. All results are shown in Table 4.

DISCUSSIONS

Taking 2017 as an example, the range of resilience grade eigenvalues of 11 provinces (cities) is [1.62, 2.09], accounting for three grade ranges. In the analysis, the resilience level is expressed by higher, medium

Table 3. Grade eigenvalue of water resources system resilience in YEB in 2017

	Relative membership degree			Grade eigenvalue
	grade1/E (excellent)	grade 2/M (medium)	grade 3/P (poor)	
Shanghai	0.37	0.16	0.47	2.09
Jiangsu	0.29	0.35	0.35	2.06
Zhejiang	0.45	0.48	0.07	1.62
Anhui	0.33	0.49	0.18	1.85
Jiangxi	0.29	0.56	0.15	1.86
Hubei	0.31	0.58	0.12	1.81
Hunan	0.41	0.47	0.11	1.70
Chongqing	0.26	0.46	0.29	2.03
Sichuan	0.47	0.42	0.11	1.64
Yunnan	0.35	0.49	0.16	1.81
Guizhou	0.17	0.60	0.23	2.06

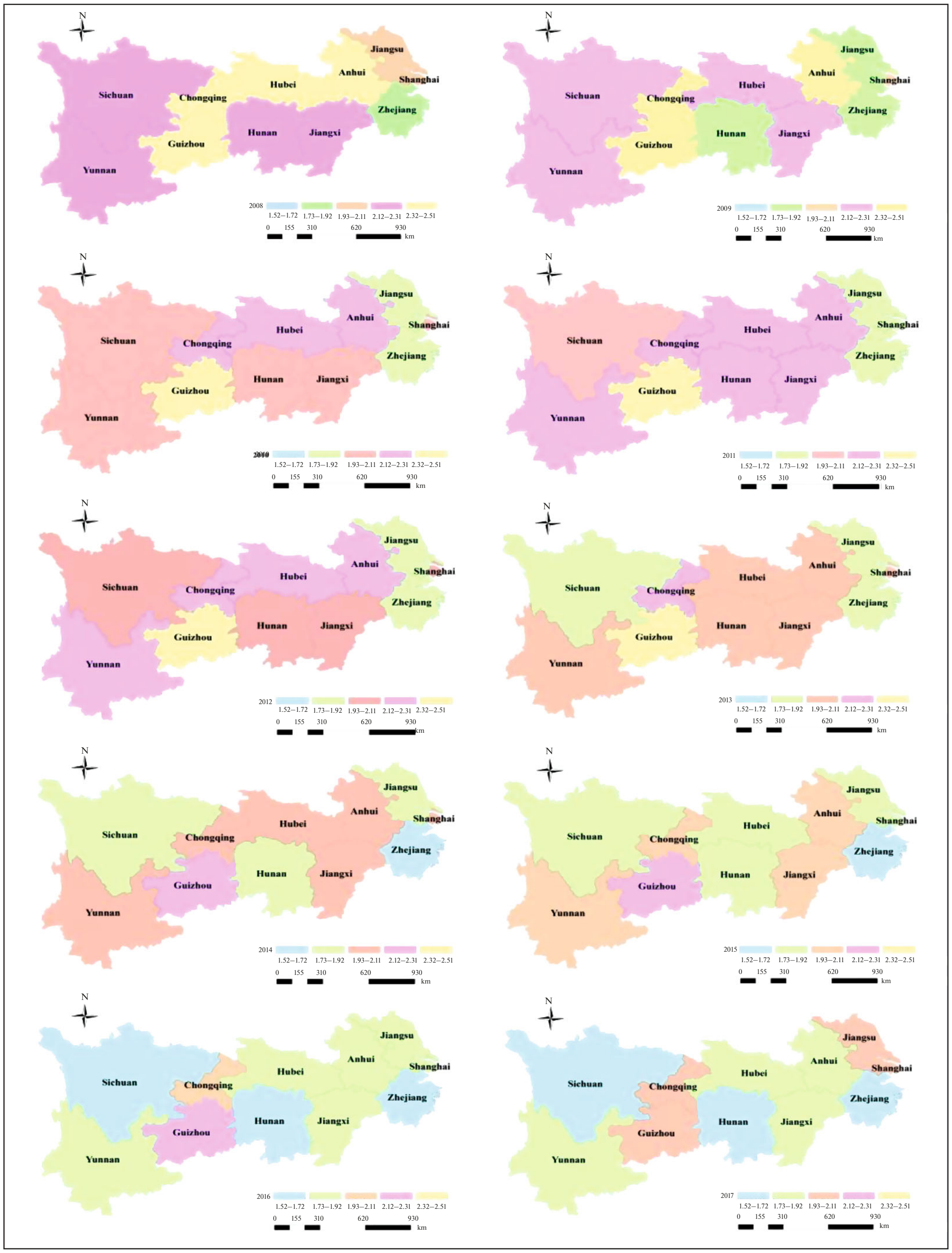

Fig. 3. Grade eigenvalues of water resources system resilience in YEB from 2008 to 2017.

and lower. Jiangsu, Shanghai and Zhejiang are located in the plain Delta, with high level of coastal economic development, mature and stable industrial structure, and high scientific and technological innovation productivity. However, due to the regional population density, water resources endowment and other factors, the water resources resilience level of Jiangsu and Shanghai is relatively low. Comparatively, Zhejiang benefits from the advantages of better water resource endowment and higher level of science and technology, and its water resource resilienve level is higher. For Anhui, Jiangxi and Hubei, their economic development level is insufficient, their water resources endowment has few advantages, and their water resources resilience is in the medium level; Hubei's water resource endowment is good, but its adaptability indexes such as environmental governance investment and financial revenue prospect are weak, and its water

Table 4. Three-way decision results

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Shanghai	M	M	M	E	E	E	E	E	E	P
Jiangsu	M	M	M	M	M	M	E	M	M	M
Zhejiang	M	M	M	M	M	M	M	M	M	M
Anhui	P	M	M	M	M	M	M	M	M	M
Jiangxi	M	M	M	M	M	M	M	M	M	M
Hubei	P	M	M	M	M	M	M	M	M	M
Hunan	M	M	M	M	M	M	M	M	M	M
Chongqing	P	P	P	M	M	M	M	M	M	M
Sichuan	M	M	M	M	M	M	M	M	M	M
Yunnan	M	M	M	M	M	M	M	M	M	M
Guizhou	P	P	P	P	P	M	M	M	M	M

resource resilience is in the medium level; The resilience of water resources in Chongqing and Guizhou is relatively poor, and the adaptability index level of ecological water use, environmental governance investment and scientific research investment is relatively low; The output value of drought and flood in Sichuan is relatively low, but the water consumption per unit is relatively reasonable; As far as Yunnan is concerned, the sewage treatment capacity, scientific research investment and other indicators in this area are relatively low, the water resource endowment is good, and the water resource resilience is generally at the medium level.

The time series evolution trend of water resources system resilience in the YEB from 2008 to 2017 is shown in Fig. 4.

On the whole, the grade eigenvalues of water resources resilience of all provinces in the YEB are [1.51, 2.52]. In 2008, the eigenvalue interval of 11 provinces in the YEB is [1.90, 2.51], the average value is 2.24, and the eigenvalue interval of 2017 is [1.62, 2.09], the average value is 1.87. The grade eigenvalue decreases, the resilience level increases, and the change trend presents a good trend year by year.

As far as each region is concerned, Shanghai, Zhejiang and Jiangsu are located in the lower reaches of the Yangtze River, belonging to the Yangtze River Delta region, with good economic development, scientific and technological level, and better economic status than other regions. Therefore, their own water resources resilience foundation is good. In 2008, the regional water resources resilience level was signifi-

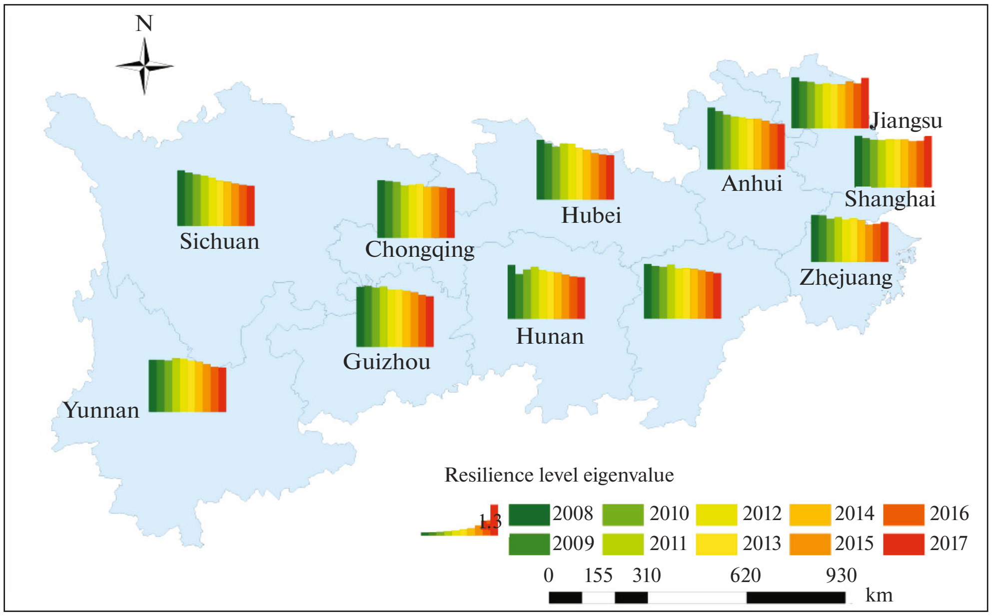

Fig. 4. The time series evolution of water resources system resilience in YEB from 2008 to 2017.

cantly better than other regions, and the eigenvalues were about 2.0. However, in recent years, due to the overall development of the YEB showing a gradually balanced trend, the regional water resources resilience advantage has declined, and the resilience level has declined. In the past ten years, the water resources resilience characteristic values of the three provinces or cities are within [1.55, 2.10] as a whole, and the water resources resilience is in a good level range.

Anhui and Jiangxi are located in the middle and lower reaches of the Yangtze River. Compared with the three provinces in the Yangtze River Delta, the regional economic level is slightly weak. In the water resources resilience system, the process of recovery and adaptability is slightly worse than the previous three provinces. In terms of eigenvalue changes, Jiangxi reached 2.23 in 2008, while Anhui reached 2.51, which belong to the degree of poor resilience. In the following 10 years, the resilience level of Anhui province gradually increased, especially the resilience level of water resources and water infrastructure. In 2017, the characteristic value of water resources resilience of the two provinces was about 1.85, which was higher than that of the three provinces in the Yangtze River Delta.

For Hubei, Hunan and Chongqing, the three provinces or cities are located in the middle reaches of the Yangtze River and have good water resources endowment. They are also restricted by the economic structure and the level of scientific research and innovation. In 2008, the resilience level of water resources in the three provinces or cities was poor, with the eigenvalue interval of [2.19, 2.43]. With the change of time, the index level changes of the three provinces or cities mainly come from the restorative indicators, such as environmental governance investment, ecological water consumption, science and technology R & D investment and other indicators have been greatly improved, and the improvement of the restoration ability has improved the resilience of the water resources system. As of 2017, the resilience eigenvalues of Hubei, Hunan and Chongqing were 1.81, 1.70 and 2.03, respectively, indicating that the resilience is stable and there were obvious changes between the two groups.

Sichuan, Yunnan and Guizhou are located in the middle and upper reaches of the Yangtze River, and also in Southwest China. In 2008, the resilience characteristic values of the three provinces were 2.26, 2.12, and 2.44 respectively. Compared with other provinces or cities in the YEB, there is a certain gap in their water resources endowment, and their resilience level is relatively low due to the restrictions of economic development, backward science and technology, and environmental protection investment. With the change of time, the indexes of resistance, resilience and adaptability of the region have improved, which promotes the improvement of resilience level. However, in terms of adaptability, the level of environmental governance investment, scientific research investment, ecological water consumption and other indicators is still poor. In 2017, the resilience characteristic values of Sichuan, Yunnan and Guizhou reached 1.64, 1.81 and 2.06, respectively, and the resilience level improved significantly.

Among the three-way decisions of water resource system resilience in the YEB as shown in Fig. 5. In 2008, Anhui, Hubei, Chongqing and Guizhou have the decision results of grade 3, and their water resource resilience decision-making performance is poor, and the other provinces are all grade 2, and the resilience decision-making of these provinces is medium; in 2011, only Guizhou was decisioned as grade 3, while the results of Shanghai are changed from grade 2 to grade 1, which indicates that the water resource resilience of Shanghai has improved qualitatively compared with 2008. The decision results of other provinces (cities) are all grade 2; in 2014, Jiangsu's decision-making results were improved to grade 1, Guizhou's decision-making results were improved to grade 2, and the water resource resilience of both was also improved qualitatively. Except Shanghai and Jiangsu, the three-way decision results of other provinces or cities were all grade 2; in 2017, the decision results are all grade 2 except Shanghai, and the water resources resilience of Shanghai and Jiangsu have decreased compared with 2014, which should be given more attention. Shanghai, in particular, plummeted to grade 3 in 2017. Compared with 2016, although Shanghai has increased investment in science and technology research and development, limited by natural conditions, the amount of water resources has declined seriously, with the per capita water resources decreasing by 39.3%. In addition, the growth rate of fiscal revenue has slowed down, with a year-on-year decrease of 75.9%, which may be the main reason for the sharp decline in the resilience of the water resources system.

CONCLUSIONS

Based on the resilience theory, this paper constructs a new index system of water resources system resilience from three aspects: resistibility, recoverability and adaptability. Then, the grade eigenvalues of water resources system resilience of 11 provinces (cities) in the YEB were calculated using variable fuzzy sets and the resilience grades were judged combining the proposed three-way decision model. The main conclusions are as follows: (1) The resilience level of water resources systems in 11 provinces (cities) of the YEB has increased year by year, and the average value of level eigenvalues has changed from [1.90, 2.51] in 2008 to [1.62, 2.09] in 2017, but the effect is not significant. (2) From 2008 to 2017, the three-way decisions results in the YEB showed of the 110 samples, 83.6% were at the medium level. Only 6.4% are barely at the

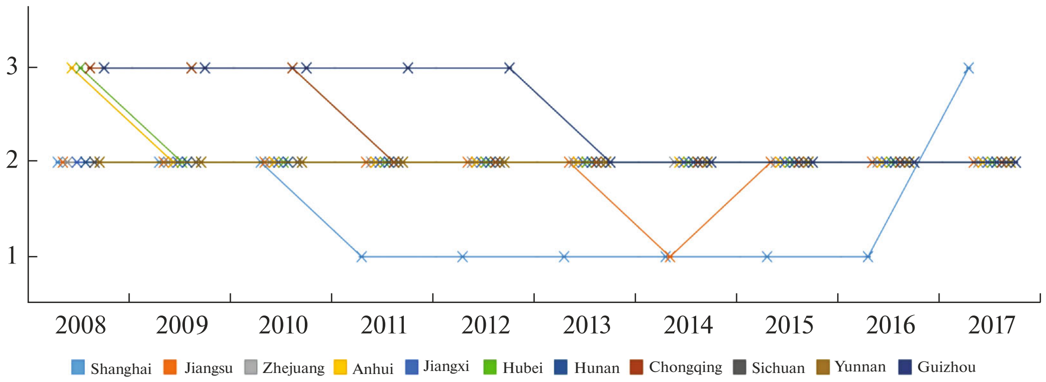

Fig. 5. Three-way decision results of water resource system resilience in YEB from 2008–2017.

excellent level, but they are basically in Shanghai. This shows that the toughness of the water resources system in the YEB is not satisfactory. With its ultra-high economic and scientific and technological level, Shanghai is at an excellent level, but it also exposes the problems of water shortage and low forest coverage. Therefore, with the east wind of "great protection of the Yangtze River" and "high-quality development of the YEB," 11 provinces (cities) still need to adjust measures to local conditions, implement accurate policies, and strive to improve the toughness level of water resources system, so as to deal with various uncertain problems that may occur in the future.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. Alessa, L., Kliskey, A., Lammers, R., Arp, C., White, D., Hinzman, L., and Busey, R., The Arctic water resource vulnerability index: an integrated assessment tool for community resilience and vulnerability with respect to freshwater, *Environ. Manage.*, 2008, vol. 42, no. 3, pp. 523–541.
2. Cao, R., Li, F., and Zhao, Y., Dynamic regulation of reservoir drought limit water level, *Water Resour.,* 2021, vol. 48, no. 2, pp. 194–203.
3. Chen, S.Y., Theory and model of engineering variable fuzzy set—Mathematical basis for fuzzy hydrology and water resources, *J. Dalian Univ. Technol.*, 2005, vol. 45, no. 02, pp. 308–312.
4. Chen, S.Y., Variable sets and the theorem and method of optimal decision making for water resource system, *J. Hydraul. Eng.*, 2012, vol. 43, no. 09, pp. 1066–1074.
5. Dadson, S., Hall, J.W., Garrick, D., Sadoff, C., Grey, D., and Whittington, D., Water security, risk, and economic growth: Insights from a dynamical systems model, *Water Resour. Res.*, 2017, vol. 53, no. 8, pp. 6425–6438.
6. Falkenmark, M., Building water resilience in the face of global change: from a blue-only to a green-blue water approach to land-water management, *J. Water Resour. Planning Management*, 2010, vol. 136, no. 6, pp. 606–610.
7. Holling, C.S., Resilience and stability of ecological systems, *Annu. Rev. Ecol. Syst.*, 1973, vol. 4, no. 1, pp. 1–23.
8. Huang, W.J. and Ling, M.Z., System resilience assessment method of urban lifeline system for GIS, *Computers, Environ. Urban Syst.*, 2018, vol. 71, no. SEP, pp. 67–80.
9. Li, Y., *Assessment and Safeguard Model of Water Security in Guangdong Province*, Xi'an Univ. Technol., Xi'an, 2019.
10. Liu, D., Chen, X., and Nakato, T., Resilience assessment of water resources system, *Water Resour. Manage.*, 2012, vol. 26, no. 13, pp. 3743–3755.
11. Ma, Y., Jiang, Y., and Swallow, S., China's sponge city development for urban water resilience and sustainability: A policy discussion, *Sci. Total Environ.*, 2020, vol. 729, pp. 139078.
12. Massoud, B. and Reza, K., Evaluating the resilience of water resources management scenarios using the evidential reasoning approach: The Zarrinehrud river basin experience, *J. Environ. Manage.*, 2021, vol. 284, no. 4, pp. 112025.
13. Naeini, M.M., Bussi, G., Elliott, J.A., Hall, J.W., and Whitehead, P.G., Assessment of risks to public water supply from low flows and harmful water quality in a changing climate, *Water Resour. Res.*, 2019, vol. 55, no. 12, pp. 10386–10404.
14. Qian, L., Wang, Z., Wang, H., and Deng, C., An improved method for predicting water shortage risk in the case of insufficient data and its application in Tianjin, China, *J. Earth Syst. Sci.,* 2020, vol. 129, no. 48, pp. 1–10.
15. Qian, L., Wang, H., Zhang, R., and Wang, Y., Nonlinear assessment model for water resources vulnerability analysis based on dimension reduction method and its

applications, *Adv. Eng. Sci.*, 2017, vol. 49, no. 03, pp. 60–67.

16. Rushforth, R.R. and Ruddell, B.L., The vulnerability and resilience of a city's water footprint: The case of Flagstaff, Arizona, USA, *Water Resour. Res.*, 2016, vol. 52, no. 4, pp. 2698–2714.
17. Sandoval-Solis, S., McKinney, D.C., and Loucks, D.P., Sustainability index for water resources planning and management, *J. Water Resour. Planning Management*, 2011, vol. 137, no. 5, pp. 381–390.
18. Shi, P., Theory on disaster science and disaster dynamics, *J. Nat. Disaster,* 2002, vol. 11, no. 03, pp. 1–9.
19. Sun, C. and Meng, C., Evaluation of the development coordination relationship between resilience and efficiency of regional water resources system in China, *Scientia Geographica Sinica*, 2020, vol. 40, no. 12, pp. 2094–2104.
20. Tanner, T., Mitchell, T., Polack, E., and Guenther, B., Urban governance for adaptation: assessing climate change resilience in ten Asian Cities, *IDS Working Papers*, 2009, vol. 2009, no. 315, pp. 1–47.
21. Walczykiewicz, T., Multi-criteria analysis for selection of activity options limiting flood risk, *Water Resour.*, 2015, vol. 42, no. 1, pp. 124–132.
22. *World Water Assessment Programme, The United Nations World Water Development Report 4*, UNESCO, Paris, 2012.
23. Yao, Y., Three-way decisions with probabilistic rough sets, *Information Sci.*, 2010, vol. 180, no. 3, pp. 341–353.
24. Yu, C. and Hao, Z., *Resilience Degree—A New Indicator of Sustainable Development to Water Resources System*, 2008, pp. 3499–3502.
25. Yu, K., Xu, T., Li, D., and Wang, C., A review: urban water resilience, *Urban Planning Forum*, 2015, vol. 01, pp. 75–83.
26. Zadeh, L.A., Fuzzy sets. *Information and Control*, 1965, vol. 8, no. 3, pp. 338–353.
27. Liu, D. and Liang, D., Generalized three-way decisions and special three-way decisions, *J. Frontiers Computer Sci. Technol.*, 2017, vol. 11, no. 3, pp. 9.
28. Wang, H., Qian, L., Zhao, Z., and Wang, Y., Theory and assessment method of water resources risk, *J. Hydraul. Eng.*, 2019, vol. 50, no. 08, pp. 980–989.
29. Yang, H. and Zhao, K., The calculation and application of partial connection numbers, *CAAI transactions on intelligent systems*, 2019, vol. 14, no. 05, pp. 865–876.
30. Yang, Y., Gong, S., Wang, H., Zhao, Z., and Yang, B., New model for water resources spatial equilibrium evaluation and its application, *Adv. Water Sci.*, 2021, vol. 32, no. 01, pp. 33–44.
31. Zhao, K., *Set pair analysis and its preliminary application*, Zhejiang Science and Technology Press, Hangzhou, 2000.