

Water resource system vulnerability assessment of the Heihe River Basin based on pressure-state-response (PSR) model under the changing environment

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ABSTRACT

As one of the most important inland rivers in China, the shortage of water resources and ecological deterioration of the Heihe River has increasingly attracted attention, and it is very significant to undertake the water resources sustainable utilization for its vulnerability assessment in the river basin. Using the pressure-state-response (PSR) model, a vulnerability index of the water resources system was developed and used to carry out a vulnerability assessment on the Heihe River in the current year (2010) and the comparison year (2003). The PSR of water resource vulnerability included 11 indexes, which are domestic water quota of urban residents, rural water quota of urban residents, million yuan GDP water consumption, per capita water consumption, ecological water proportion, drought index, per capita water resources, water modulus, water quality grade, water saving irrigation rate, per capita GDP, respectively. The vulnerability of water resources was evaluated by the attribute recognition model. The results show that water resources in the Heihe River Basin were in a quite vulnerable state in both 2003 and 2010 according to the values of scenario A1 (not vulnerable) and scenario B1 (severely vulnerable). It is urgent to protect and restore the water resources system in the Heihe River Basin.

Key words | attribute recognition model (ARM), Heihe River Basin water resource, PSR index system, water resource vulnerability

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INTRODUCTION

Because of climate change and human activities, human society is facing water resources shortage, deterioration of the water environment, frequent droughts and floods, and a series of problems (Alcamo *et al.* 1997; Bates *et al.* 2008), which increase the vulnerability of water resource systems. The increasingly frequent occurrence of extreme climatic events in recent years illustrates that water resource systems are more vulnerable. According to the fourth report of the Intergovernmental Panel on Climate Change (IPCC) which was published in 2007, the global average temperature has increased by 0.6 °C since the middle of the 20th century (IPCC 2007). The latest technical report of the

IPCC especially discussed the issues of climate change and water. It pointed out that observation records and climate predictions provided substantial evidence that the fresh-water resources of the planet were vulnerable. The evidence suggests that freshwater resources may be strongly influenced by climate change, resulting in a series of consequences for human society and ecological systems in the near future (Bates *et al.* 2008).

Establishing an index to evaluate the vulnerability of water resources is fundamental to support quantitative assessments and variability. However, there are still some serious issues with current index systems. For example, the

coverage is neither extensive nor comprehensive, and it is difficult to obtain some data to calculate the index. Furthermore, because a range of theories of water resource vulnerability have been proposed by different researchers, all of which have different research objectives and present different information, the number of indicators and their scope of selecting varies widely. These differences mean that there is no unified index system for vulnerability assessments of water resources, and the evaluation results are not comparable (Vörösmarty *et al.* 2000; Ma *et al.* 2012; Won *et al.* 2015; Zarafshani *et al.* 2016). Therefore, a comprehensive and universal evaluation index system is urgently needed.

Assessment of the vulnerability of water resource systems to climate change is very important for regional disaster prevention and mitigation, post-disaster reconstruction, regional water resources, and regional economics. Predictions of the vulnerability of water resource systems to a changing climate have important implications for guiding the development and long-term planning of regional water resource systems, disaster prevention, mitigation policies, and mitigation plans (Hao *et al.* 2011). The core of vulnerability assessment, however, is to establish an evaluation index.

The origin of the concept of vulnerability of water resource systems can be traced back to France, where, in 1968, Margat proposed 'groundwater vulnerability' (Margat 1968). Following this introduction, many researchers conducted in-depth discussions on the concept. Different concepts of water resource vulnerability have been proposed (Tang *et al.* 2000; Yang & Zhang 2002; Yu & Hao 2007; Adler 2010; Somaratne *et al.* 2013; Hunter *et al.* 2015; Zhao *et al.* 2015; Meerkhan *et al.* 2016); these concepts can be grouped into two types. One view (Yu & Hao 2007) is that water resources are vulnerable when the normal natural structure and function of the water resource system are damaged; once this happens, it is difficult to restore the original function and status because of the disturbance in a particular environment from climate change, human activities and other external factors and stress. Another view (Xia *et al.* 2012) is that water resource vulnerability is a function of factors such as sensitivity and resistance to adapting to pressures from relative climate change.

Based on these proposals, the concept of water resource vulnerability was present as follows:

- (1) Water resource vulnerability is an attribute of a water resource system. The vulnerability results from internal features; when the internal features of the water resource system change under the influence of climate change, human activities and other external driving factors, the vulnerability also changes (Yu & Hao 2007).
- (2) Vulnerability of water resources includes two aspects: sensitivity and adaptability of water resource systems to external driving factors. Sensitivity refers to the changes in the water resource system that result from damage, while adaptability includes not only the ability to adapt to external drivers, but also includes the recovery capability of the system after damage (Xia *et al.* 2012).
- (3) Water resource vulnerability includes vulnerability of water quality and quantity. Vulnerability is highly variable because of regional differences in the water resources system, natural conditions and socioeconomic status, therefore the vulnerability of water resources can be considered as a regional characteristic. In addition, the level of social productivity varies with the stage of social development; therefore, water resource vulnerability is related to the stage of social development (Yang & Zhang 2002).
- (4) Factors that influence water resource systems have many dimensions and levels. The water resource system also operates at multiple scales, therefore, water resource vulnerability should be multi-dimensional. A water resource system will have a certain threshold of vulnerability, and once this value of the threshold is reached, the system will be damaged (Tang *et al.* 2000).

This paper reviews the research progress of the evaluation index system of water resources system vulnerability at home and abroad:

- (1) The weight method is the most widely used method to assess the vulnerability of water resources. The degree of water shortage has an important role to play in the evaluation of water resource vulnerability. Water resource vulnerability was analyzed according to the degree of human dependency on water resources, the

balance between supply and demand of regional water resources and the thresholds of each factor (Brouwer & Falkenmark 1989; Falkenmark & Widstrand 1992). It was suggested that a vulnerability index should provide national, regional and public vulnerability assessment scores, and the goal of a vulnerability index was to identify adaptation strategies that were feasible and practical in communities (Smit & Wandel 2006). With cities expanding and population growing, the complexity of future vulnerability will also increase. In global high resolution water resource vulnerability assessment, some factors were selected to reflect vulnerability, such as future climate change, population growth and migration, and industrial development (Vörösmarty *et al.* 2000); the output from global climate models was combined with the water balance model, and then forecast global water resource vulnerability for 2025. Thirty-one indicators were selected and recommended by the IPCC for vulnerability assessment (Hamouda *et al.* 2009), and these indicators were used to evaluate the three countries in the east of the Nile River Basin and displayed the results in the form of radar charts. The two aspects that were water supply and water demand were studied, and the water resource vulnerability index (WVI) was figured out by an additive combination of relevant social, economic, environmental, and resource factors according to their weights (Sullivan 2002). In China, the indicator parameters were built from the runoff, physical design, economy, demand, power generation and 11 other aspects of the three attributes which were the hydrological system, water conservancy system and its design, natural geographical environment, and social vulnerability, respectively (Tang *et al.* 2000). Water resource vulnerability was divided into two aspects: natural vulnerability and special vulnerability, and 17 indicators were selected to establish an evaluation index for water resource vulnerability according to the properties of surface water and groundwater (Liu & Feng 2012). It was believed that there were two aspects of the vulnerability of groundwater: water quality and water quantity. The research should not focus the same in different regions, but needs to have different research aims (Zou *et al.* 2007). An index evaluation system that comprised a

total of 16 indicators related to the vulnerability of the water cycle, the social economy and the ecological environment was developed (Feng *et al.* 2010). Water resource system vulnerability was described by using the driver forces–pressure–state–impact–responses model (DPSIR), the vulnerability index system of which combines five drivers including stress, status, impact, and response indicators (Dong *et al.* 2010). Lv *et al.* (2012) gave 13 indicators from the three aspects of natural factors, human factors and comprehensive factors, and determined the weights of each index by AHP. The standard values of each index were determined by comprehensive research and experience, and then the water resource vulnerability of Yongding River Basin was assessed comprehensively (Lv *et al.* 2012).

- (2) GIS overlay and index matching methods are optimized for water resource vulnerability calculations and drawing. New index and overlay matching method technology was reported in which dynamic links could be developed between numerical models, and the overlay and index methods (Gogu & Dassargues 2000). In the USA, a socioeconomic and environmental vulnerability assessment index was constructed based on socioeconomic and demographic county-level data in the 1990s, and the number of indicators was reduced from 42 to 11 by factor analysis, and this reduced number was deemed to represent 76.4% of the variance among all counties (Cutter *et al.* 2003). The evaluation results showed that there were different spatial patterns in socioeconomic vulnerability. Eleven key vulnerability indicators were identified which most closely related to climate disasters in recent years (Brooks *et al.* 2005). The GIS-based DRASTIC model was used to evaluate the vulnerability of shallow groundwater in Aligarh, India, and results showed that more than 80% of the groundwater was facing middle- to high-level pollution (Rahman 2008). GIS was used to carry out a comprehensive evaluation of water resource vulnerability in Yangqu County in Shanxi Province (Liu & Feng 2012).
- (3) The simple index function method is important in the vulnerability of water resources. In 1992, the water resources pressure index (IWS) was defined to measure the regional water resource scarcity (Falkenmark & Widstrand 1992). The United Nations World

Meteorological Organization, UNESCO and other agencies proposed that the annual volume of fresh water available per capita could be used to measure shortages of fresh water. They established thresholds of water availability as follows: 1,700 m³ is the annual amount of water per capita in water-rich areas; 1,000 m³ is the minimum threshold; the threshold of the absolute lack of water is 500 m³ per capita; while the threshold for an extreme lack of water is 100 m³. This method is used by the United Nations Food and Agriculture Organization (FAO), the World Resources Institute and other international organizations to evaluate world water resources. The mean annual available water resources were evaluated and determined and compared the relationships between the supply and demand of water resources (Shiklomanov 1998; Shiklomanov & Rodda 2003). The International Water Management Institute constructed a model to evaluate water resource shortages based on the supply, demand and balance of water resources (Seckler 1998). They considered the effect of water facilities development and irrigation efficiency of different countries for 2000–2025, and divided areas into ‘natural water’ areas and ‘economic water scarcity’ areas depending on whether the water resources were sufficient to support the social economy. Professor Sullivan of the Hydrological and Ecological Research Institute proposed an index of water poverty (IWP) based on five indicators: resources, methods, capacity, utilization, and environment. The five indexes of the IWP ranged from 0 to 100, and a larger value for the index indicated a higher status of water resources (Sullivan *et al.* 2006; Sullivan & Meigh 2007; Sullivan 2010).

- (4) Examples of water resource vulnerability evaluation based on only one property. The impacts of climate variability were examined on the balance between supply, demand and vulnerability in the Laizhou Bay area (Deng & Zhao 2001). Ecological problems caused by water resource vulnerability were analyzed in the Heihe River Basin (Huang *et al.* 2004), and some suggestions were proposed for water resource development and ecological protection.

Water shortage and ecological deterioration are increasingly affecting the vulnerability of water resources in the

Heihe River Basin, China’s second largest inland river. Thus, how to objectively evaluate the vulnerability of water resources in the region becomes a top priority. This paper contains the following three aspects. (1) Organize the concept and connotation of water resource vulnerability. (2) Establish the evaluation index system of water resource vulnerability based on pressure-state-response (PSR). (3) Apply the attribute recognition method to evaluate the water resource vulnerability of the Heihe River Basin.

DATA AND METHODS

Study area

The Heihe River (Zhang 2007; Cheng *et al.* 2014; Zhang *et al.* 2017) in northwest China is China’s second largest inland river. It originates in the Qilian Mountains, and is 821 km long. It shares its eastern boundary with the Shiyang River Basin, while the western part of the basin is connected to the Shule River Basin. It extends northwards to Juyan Lake, north of Ejina Banner in the Inner Mongolia Autonomous Region. The Heihe River Basin flows through several counties in Gansu and Qinghai Provinces, and Inner Mongolia. The Heihe River Basin has 35 small tributaries, and, as water consumption has increased, some of the tributaries and part of the main stream have gradually lost their connection via groundwater; as a result, three independent water systems (Cheng *et al.* 2014) have formed in the east, middle, and west (see Figure 1).

Data

The current year is defined as 2010. The precipitation in the Hexi Corridor in 2003 was 128.2 mm; because this is similar to what was recorded in 2010 (133.1 mm), and is close to the mean annual precipitation of 137.2 mm (Bureau of Hydrology and Water Resources in Gansu Province of China 2012), 2003 was chosen as the comparison year.

To simulate the Heihe River basin water resource vulnerability threshold, this paper sets up the ecological environment improving level of two scenarios in different circumstances, which are A1 and B1, respectively. A1 means the level year that could be reached in a future

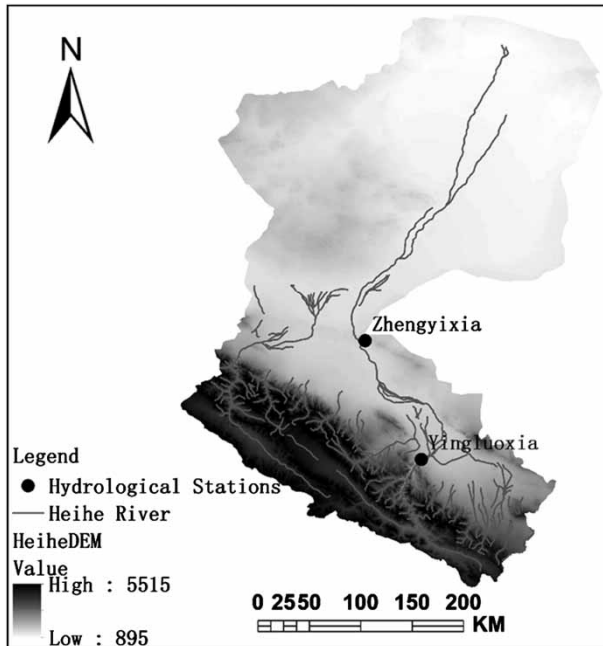


Figure 1 | Study area in the Heihe River Basin.

period when the control of the ecological environment development is wonderful, while B1 means the level year that happened in the past or will happen in a future period of time when ecological environment development control is poor. In the case of A1, to achieve the lowering of river basin water resource vulnerability, the population distribution is determined by the average per capita water resource quantity of $5,000 \text{ m}^3$ and the excess of population that can be settled by immigrating. Because the urban and rural resident per capita living water consumption increasing to the highest point will gradually decline into balance, this paper adopts index clustering center intermediate values for calculations. Per acre water consumption, 10,000 yuan GDP water consumption can achieve the minimum in theory due to social and economic development. As per acre water consumption and 10,000 yuan GDP water consumption are very small, the water resources exploitation and utilization ratio will reach the minimum state. The water-saving irrigation rate and per capita GDP take the maximum values to minimize the water resource vulnerability threshold. As for B1, with unlimited population growth, per capita water quantity reaches 200 m^3 ; urban and rural resident per capita water consumption is less where the economy is

underdeveloped and the population is more; per acre water consumption and 10,000 yuan GDP water consumption take the maximum values; and at this point, the utilization rate of water resources will reach the highest state. In this scenario, only pressure and condition factor indicators are considered, regardless of the adaptability index, to make the upper limit for the vulnerability bigger.

Methods

It was believed that the vulnerability of water resources includes not only the sensitivity of the water resource system, but also the adaptation of human society to water resources systems. The water resource vulnerability was defined as the tendency of water resource systems to break down because of the external influences of climate change and human activities associated with societal development. Based on this understanding, the PSR model was used to establish the index system, and the attribute recognition method was used to establish the water resource vulnerability evaluation model.

PSR model

Based on the understanding of the influencing factors of water resource vulnerability, the PSR physical concept model (PSR model) proposed by Canadian statistician Anthony Fred was adopted. The pressure factor P in the PSR model is understood as the force exerted on the system by the external environment, which can lead to a certain change in the system. The state factor S is understood to be the state of damage, loss, or adverse effect due to vulnerability after the system is subjected to force. The response factor R is understood as the measures taken by human society to adapt to the system or subject.

Based on the scientific conceptual model of PSR, this paper establishes the evaluation index system of water resource vulnerability of four layers according to the scientific, holistic, operable, coordinated and independent principles of index selection (see Table 1). The fourth layer or sub-index layer, which is the water stress part, places the drought index under ecological water demand to characterize the pressure of climate factors on the water system

Table 1 | PSR model index system of water resource vulnerability

Target layer	Criterion layer	Index layer	Sub-index layer
Water resource vulnerability	Water resource pressure (P)	Living water	Domestic water quota of urban residents Domestic water quota of rural residents
		Production water	Million yuan GDP water consumption Per capita water consumption
		Ecological water	Ecological water proportion Drought index
	Water resource state (S)	Water quantity	Per capita water resources Water production modulus
		Water quality	Water quality grade
	Water resource response (R)	Engineering technology	Water saving irrigation rate
		Policy management	Per capita GDP

which can directly reflect the water resource ecology essential attributes of the watershed or region. As for the water resources response part, policy management is measured by per capita GDP. Per capita GDP reflects the development of the basin or regional economic and social conditions and to a certain extent reflects people’s social quality, the water conservation awareness which indicates that the region has a certain degree of economic capacity to reduce vulnerability.

The attribute recognition model

The specific steps of the attribute recognition model (ARM) are presented as follows (Men & Liang 2005; An et al. 2014). Firstly, establish the attribute space matrix. There are n objects and m indexes in object space R ; n evaluated objects are selected (a_1, a_2, \dots, a_n), and m indexes are selected x_1, x_2, \dots, x_m for each evaluated object. The j th index x_j of the i th evaluated object a_i is r_{ij} , therefore, the object attribute matrix can be expressed as R :

$$R = \begin{matrix} & a_1 & a_2 & \dots & a_n \\ \begin{matrix} x_1 \\ x_2 \\ \vdots \\ x_m \end{matrix} & \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \dots & r_{mn} \end{bmatrix} \end{matrix} \tag{1}$$

Suppose F is some sort of attribute space in X , and (C_1, C_2, \dots, C_K) is an ordered series of ranks in attribute space F , satisfying $C_1 > C_2 > \dots > C_K$. Therefore, the classification standard for each index is known and the

classification standard matrix can be expressed as A :

$$A = \begin{matrix} & C_1 & C_2 & \dots & C_K \\ \begin{matrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{matrix} & \begin{bmatrix} s_{11} & s_{12} & \dots & s_{1K} \\ s_{21} & s_{22} & \dots & s_{2K} \\ \vdots & \vdots & \ddots & \vdots \\ s_{n1} & s_{n2} & \dots & s_{nK} \end{bmatrix} \end{matrix} \tag{2}$$

where $s_{j1} < s_{j2} < \dots < s_{jK}$, or $s_{j1} > s_{j2} > \dots > s_{jK}$, and C_1, C_2, \dots, C_K is the rank value of water resource vulnerability.

Secondly, the attribute measure is determined by the following method. The attribute measure $\mu_{ijk} = \mu(x_{ij} \in C_k)$ of index value r_{ij} , which takes the attribute levels from the set C_K , is calculated. Suppose that $s_{j1} < s_{j2} < \dots < s_{jK}$, then:

When $r_{ij} \leq s_{j1}$, assume that

$$\mu_{ij1} = 1, \mu_{ij2} = \dots = \mu_{ijK} = 0 \tag{3}$$

When $r_{ij} > s_{jK}$, assume that

$$\mu_{ijK} = 1, \mu_{ij1} = \dots = \mu_{ijK-1} = 0 \tag{4}$$

When $s_{jl} < r_{ij} < s_{j(l+1)}$, assume that

$$\begin{aligned} \mu_{ijl} &= |r_{ij} - s_{j(l+1)}| / |s_{il} - s_{j(l+1)}|, \\ \mu_{ij(l+1)} &= |r_{ij} - s_{jl}| / |s_{il} - s_{j(l+1)}|, \mu_{ijk} = 0, k < l \text{ or } k > l + 1 \end{aligned} \tag{5}$$

Once the attribute measure of the i th evaluated object is known, the attribute measure of x_i can be calculated and the i th evaluated object $\mu_{ijk} = \mu(x_{ij} \in C_k)$. M represents

the total of the indicators, and the importance of each index may, or may not, be the same. Therefore, the weights can be calculated as $\omega_1, \omega_2, \dots, \omega_n, \omega_j \geq 0, \sum_{j=1}^n \omega_j = 1$. Considering the weights, the attribute measure of x_i is shown as:

$$\mu_{ik} = \mu(x_i \in C_k) = \sum_{j=1}^n \omega_j \mu_{ijk}, 1 \leq i \leq m, 1 \leq k \leq K \tag{6}$$

In this paper, the grey relational degree model is used to determine the weight. Assume that the corresponding values for not vulnerable, mildly vulnerable, moderately vulnerable, severely vulnerable, and extremely vulnerable are 1–5, respectively. As the various dimensions of the different indicators, the indicators are normalized to the standard value firstly:

$$x'_{ij} = \frac{x_{ij} - x_{ij, \min}}{x_{ij, \max} - x_{ij, \min}} \tag{7}$$

where x_{ij} is the normalized value, $x_{ij, \max}$ and $x_{ij, \min}$ are the maximum value and minimum value.

Then the indicator sequence can be calculated:

$$X_{m_0} = (x_{m_0}(1), \dots, x_{m_0}(g))(m_0 = 1, \dots, n) \tag{8}$$

and the vulnerability rank sequence can be calculated:

$$X_0 = (x_0(1), \dots, x_0(g)) \tag{9}$$

where the correlation degree g is the number of factors included.

First, the maximum difference value and the minimum difference value were obtained, which were as follows:

$$\Delta_{\min} = \min \min(\Delta) \tag{10}$$

$$\Delta_{\max} = \max \max(\Delta) \tag{11}$$

Then the grey correlation degree between X_0 and X_{m_0} should be calculated:

$$r(X_0, X_{m_0}) = \frac{1}{g} \sum_{k=1}^g \frac{\Delta_{\min} + \rho \Delta_{\max}}{\Delta_{m_0}(k) + \rho \Delta_{\max}} \tag{12}$$

where ρ is the resolution coefficient, which is defined as 0.5 in this study, and $\Delta_{m_0} = (|x_{m_0}(1) - x_0(1)|, \dots, |x_{m_0}(g) - x_0(g)|)$.

If the threshold is set for r , then the vulnerability degree can be obtained based on the threshold before using these data for modeling and calculations.

Then the weights are calculated as follows:

$$\omega(X_0, X_{m_0}) = \frac{r(X_0, X_{m_0,i})}{\sum_i r(X_0, X_{m_0,i})} \tag{13}$$

where $X_{m_0,i}$ is the sequence for the i th indicators.

Finally, the attribute recognition theoretical model is established by confidence level λ ($0.5 \leq \lambda \leq 1.0$). The confidence level λ is used to determine the rank of x_i and described as follows:

$$k_i = \min \left\{ k: \sum_{l=1}^k \mu_{x_i}(C_l) \geq \lambda, 1 \leq k \leq K \right\} \tag{14}$$

where x_i is taken to belong to C_{k_i} , and K means the grade of vulnerability of water resources. The confidence level λ was set to be 0.6 in this paper (Men & Liang 2005).

RESULTS AND DISCUSSION

Establishing a water resource vulnerability index system based on the PSR

The values of the Heihe River Basin PSR indicators of water resource vulnerability (Table 1) for each year are presented in Table 2 (Bureau of Hydrology and Water Resources in Gansu Province of China 2012). The index data for the current year and the comparison year were obtained from 2003 and 2010 Gansu Water Resources Bulletins. Under scenario A1, the social economy is prosperous. There is a small gap between urban and rural areas, and the gap between urban and rural water supply is small. The indicators of 10,000 yuan GDP water consumption, per capita water consumption, ecological water proportion, water quality, water saving irrigation rate, and per capita GDP are all at an advanced level, and they are not in a vulnerable state. In scenario B1, the social economy is poor, there is a big gap between urban and rural areas, and the gap between urban and rural water supply is small; the indicators of

Table 2 | PSR model values of water resource vulnerability in the Heihe River Basin for different years and scenarios

Evaluation index	2003	2010	A1 scenario	B1 scenario
City residents living water quota (L/d)	114	121	122	122
Rural residents living water quota (L/d)	41	79	112	42
10,000 yuan GDP water consumption (m ³)	2,286	533	74	984
Per capita water consumption (m ³)	695	586	168	981
Ecological water proportion (%)	0.06	1.08	11.36	0.67
Drought index	8.5	8.5	8.5	8.5
Per capita water resources (m ³)	1,013	1,389	987	987
Water modulus (10,000 m ³ /km ²)	3.29	4.62	3.45	3.45
Water quality grade	I	III	I	V
Water saving irrigation rate (%)	66.73	75.49	95	–
Per capita GDP (10,000 yuan)	0.79	2.77	15	–

10,000 yuan GDP water consumption, per capita water consumption, ecological water proportion, water quality, water saving irrigation rate, and per capita GDP are at a poor level, and the status is vulnerable.

Water resource vulnerability evaluation ranks and weight calculation result

The existing water resource vulnerability evaluation grade was adopted to describe the water resource characteristics in the Heihe River Basin as follows by Li *et al.* (2013): not vulnerable, mildly vulnerable, moderately vulnerable,

severely vulnerable, and extremely vulnerable. Values of each index are shown in Table 3. According to Equations (7)–(13), the calculation results of the weights of each index are shown in Table 4.

From Table 4, it can be seen that the most relevant indicators of vulnerability are per capita water resources, 10,000 yuan GDP water consumption, per capita water consumption and per capita GDP. This shows that the water resource vulnerability of the Heihe River is mainly driven by large population density and high socioeconomic pressures. After the vulnerability calculation, some improvement measures are presented in the following section.

Table 3 | Clustering centers of indexes

Level	Not vulnerable	Mildly vulnerable	Moderately vulnerable	Severely vulnerable	Extremely vulnerable
City residents living water quota (L/d)	122	191	230	289	350
Rural residents living water quota (L/d)	42	70	112	148	207
10,000 yuan GDP water consumption (m ³)	74	180	295	428	984
Per capita water consumption (m ³)	168	378	559	741	981
Ecological water proportion (%)	11.36	5.06	3.47	2.07	0.67
Drought index	1	2	4	6	8
Per capita water resources (m ³)	5,000	3,000	1,700	1,000	500
Water modulus (10,000 m ³ /km ²)	136.3	112.6	69.3	42.4	10.5
Water quality grade	I	II and III	IV	V	Inferior to V
Water saving irrigation rate (%)	95	50	0	–	–
Per capita GDP (10,000 yuan)	15	6	0	–	–

Table 4 | The result of water resource vulnerability

Evaluation index	Weights
City residents living water quota (L/d)	0.112
Rural residents living water quota (L/d)	0.093
10,000 yuan GDP water consumption (m ³)	0.158
Per capita water consumption (m ³)	0.134
Ecological water proportion (%)	0.027
Drought index	0.032
Per capita water resources (m ³)	0.284
Water modulus (10,000 m ³ /km ²)	0.051
Water saving irrigation rate (%)	0.015
Per capita GDP (10,000 yuan)	0.114

Evaluation of the results and analysis of vulnerability of water resources

According to ARM and the data (Table 2), the attribute space matrix R_{Heihe} of water resource vulnerability in the Heihe River Basin is built by Equation (1):

$$R_{\text{Heihe}} = \begin{bmatrix} 114 & 121 & 122 & 122 \\ 41 & 79 & 112 & 42 \\ 2,286 & 533 & 74 & 984 \\ 695 & 586 & 168 & 981 \\ 0.06 & 1.08 & 11.36 & 0.67 \\ 8.5 & 8.5 & 8.5 & 8.5 \\ 1,013 & 1,389 & 987 & 987 \\ 3.29 & 4.62 & 3.45 & 3.45 \\ \text{I} & \text{III} & \text{I} & \text{V} \\ 66.73 & 75.49 & 95 & - \\ 0.79 & 2.77 & 15 & - \end{bmatrix} \quad (15)$$

In addition, according to ARM and the data (Table 3), the standard matrix A_{Heihe} of water resource vulnerability in Heihe River Basin is built by Equation (2):

$$A_{\text{Heihe}} = \begin{bmatrix} 122 & 191 & 230 & 289 & 350 \\ 42 & 70 & 112 & 148 & 207 \\ 74 & 180 & 295 & 428 & 984 \\ 168 & 378 & 559 & 741 & 981 \\ 11.36 & 5.06 & 3.47 & 2.07 & 0.67 \\ 1 & 2 & 4 & 6 & 8 \\ 5,000 & 3,000 & 1,700 & 1,000 & 500 \\ 136.3 & 112.6 & 69.3 & 42.4 & 10.5 \\ \text{I} & \text{II and III} & \text{IV} & \text{V} & \text{inferior to V} \\ 95 & 50 & 0 & - & - \\ 15 & 6 & 0 & - & - \end{bmatrix} \quad (16)$$

According to Equations (15) and (16), Equations (3)–(6) and the weight of water resource vulnerability (Table 4), the water resource vulnerability distribution for each year in Heihe River Basin by ARM (see Table 5) can be calculated. In Table 5, not vulnerable of the water resources system in 2003 is 0.2372, while not vulnerable of the water resources system in 2010 is 0.1566. So the not vulnerable in 2003 is 1.5 times higher than that of 2010. Mildly vulnerable of the water resources system in 2003 is 0.076, while mildly vulnerable of the water resources system in 2010 is 0.1681, so that mildly vulnerable of 2010 is 2.2 times higher than that of 2003. Moderately vulnerable of the water resources system in 2010 is 0.216, while moderately vulnerable of water resources system in 2003 is 0.114, and so the moderately vulnerable in 2010 is 1.9 times higher than that of 2003. It is obvious that water resource vulnerability is greater in 2010 than in 2003, mildly vulnerable and moderately vulnerable are zero in Scenario B1, while mildly vulnerable is zero in scenario A1.

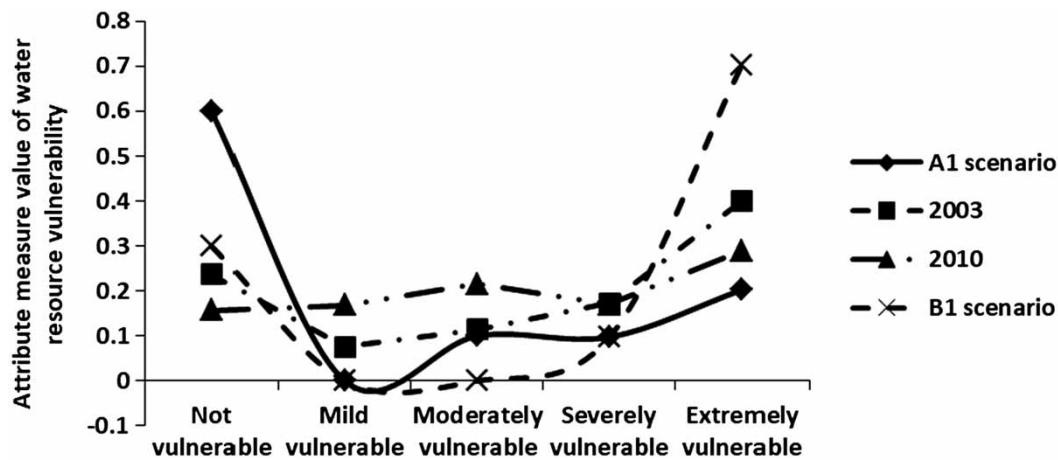
When $\lambda = 0.6$ in Equation (14), the water resource vulnerabilities of the Heihe River Basin for 2003 and 2010 are severely vulnerable (see Figure 2). It can be seen from Figure 2 that through the attribute recognition method to calculate the water resource vulnerability measure value, it has the following laws: 2003 and 2010, the change trend of water resource vulnerability is relatively slow, and the change trend of vulnerability is aggravating. Mildly vulnerable and moderately vulnerable and severely vulnerable in 2003 and 2010 are higher than those of Scenarios A1 and B1, and for the extremely vulnerable in 2003 and 2010, it is between Scenarios A1 and B1 and the order of the water resources of vulnerable are A1, 2010, 2003, B1. Scenario A1 is not vulnerable, and Scenario B1 is extremely vulnerable. Thus it can be seen that the attribute recognition method to calculate the water resource vulnerability set measure value conforms to not only the situation, but also the quantitative characterization of the fragility of the change trend of water resources.

The results are consistent with those in the literature (An *et al.* 2014); the evaluation model and the attribute recognition methods are clearly established, and the evaluation results can be obtained without complicated mathematical calculations.

Based on the above results and analysis of water resource vulnerability assessment, the following adaptive measures are proposed in this study. In agriculture,

Table 5 | Measure matrix of water resource vulnerability in Heihe River Basin

Item	Not vulnerable	Mildly vulnerable	Moderately vulnerable	Severely vulnerable	Extremely vulnerable
2003	0.2372	0.076	0.114	0.1729	0.4
2010	0.1566	0.1681	0.216	0.1697	0.2896
A1 scenario	0.6	0	0.1	0.0974	0.2026
B1 scenario	0.3	0	0	0.0974	0.7026

**Figure 2** | Attribute measure value of water resource vulnerability in the Heihe River Basin.

farmland water conservancy construction, expanding the water-saving irrigation area, and adjusting the planting structure, choosing water-saving crops, and improving agricultural water efficiency should be vigorously carried out. So the index of the water saving irrigation rate should be increased (Table 3), while the per capita water consumption should be reduced (Table 3). In life, water-saving appliances and water-saving facilities should be promoted. On the other hand, water pollution should be controlled.

CONCLUSIONS

In the framework of the PSR model, the water quality index system of the water resources system in the Heihe River Basin is established, which includes ten indicators of urban residents' domestic water quota, rural residents' domestic water quota and so on. Then the attribute identification method was used to evaluate the water resource vulnerability of the Heihe River Basin in 2003, 2010, and the A1 and B1 scenarios. The result indicates that between 2003

and 2010, the change trend of water resource vulnerability is relatively slow, and the change trend of vulnerability is aggravating. Mild vulnerability and moderate vulnerability and severe vulnerability in 2003 and 2010 are higher than in Scenarios A1 and B1. And for the extreme vulnerability in 2003 and 2010, it is between that of Scenarios A1 and B1. Through the result, it can be seen that applying the attribute identification method to calculate the water resource vulnerability set value is more in line with the actual situation, which provides a new measure of thinking about the evaluation of water resource vulnerability.

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