Assessment of water resources carrying capacity based on fuzzy comprehensive evaluation – case study of Jinan, China

Yi Wu, Zhongyu Ma, Xiang Li, Li Sun, Shaohua Sun and Ruibao Jia

ABSTRACT

Jinan is a city that typifies the water resource shortage in North China. This study selected nine indices to evaluate the regional water resources carrying capacity (WRCC), which is an important constraining factor in relation to socioeconomic development and the ecological environment. The AHP-CRITIC weighting method was applied to determine the index weighting, and WRCC dynamics during 2011–2016 were analysed and evaluated quantitatively using the fuzzy comprehensive evaluation method. The results revealed the following. (1) During 2011–2016, the comprehensive score of the WRCC was <0.4, indicating poor WRCC. (2) The degree membership of the average evaluation results to V_1, V_2, and V_3 increased successively during 2011–2016. The degree membership of V_2 in 2011–2013 was greater than that of V_3; however, the situation was reversed during 2014–2016. (3) The indices of available amount of water resources per capita, utilization rate of water resources, water supply per capita, modulus of water supply, quota of domestic water demand, and population density were factors that affected the WRCC of Jinan unfavourably. Conversely, the indices of water demand per 10,000 Yuan industrial output value and water use rate of the ecological environment were factors that played positive roles in improving the WRCC.

Key words | carrying capacity, evaluation index, fuzzy comprehensive evaluation, water resource

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HIGHLIGHTS

- AHP-CRITIC weighting method is used to calculate the weight of evaluation index.
- Fuzzy comprehensive evaluation method is applied to evaluate the factor affecting the water resources carrying capacity.
- Multi factor comprehensive evaluation is made through the comprehensive evaluation matrix.

INTRODUCTION

The crisis regarding water resources is an environmental problem that affects many parts of the world. China is a country relatively short of water resources with a per capita water supply that is only 25% that of the world standard. Of around 600 cities in China, more than 400 are short of water supply, of which more than 100 have acute water shortage, with a water shortage of 6 billion cubic meters. Although China has vigorously promoted the construction of a water-saving society and implemented the most stringent water resources management system in the past decade, the South-to-North Water Diversion Project has also greatly improved the water shortage of cities along the route. However, with the rapid development of economy and society, the current water shortage has increased unabated compared to ten years ago, and the water resource problem is still one of the most important factors in terms of China's recent socioeconomic development (Zhang & Zhao 2020).

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Following increased prominence of the problem of water resources, the concept of the water resources carrying capacity (WRCC) was proposed in the 1980s in China (Duan & Luan 2014). The carrying capacity of water resources refers to the maximum capacity of the regional water resources to support a certain level of socioeconomic development based on predicted levels of technical and socioeconomic development, the principle of sustainable development, and the condition of maintaining a benign cycle of the ecological environment. The WRCC represents an important component in the sustainable development of a country or region that works as a constraining factor to balance the population, economy, and environment, especially in areas of water shortage. As a fundamental topic in the fields of sustainable development and water resource safety, the WRCC has become an area of active research in water resource science (Han *et al.* 2010; Wang *et al.* 2012; Liu *et al.* 2017).

The WRCC is one of the principal indices used to describe the scale of socioeconomic development that could be supported by a regional water resource. However, there has been a lack of specific studies on this topic outside of China. Most previous related studies have generally considered the fields of resource carrying capacity, sustainable development theory, and regional design, focusing primarily on water resource management and related policy. In China, study of the WRCC has developed rapidly (Feng & Liu 2006; Yang *et al.* 2016). In the 1990s, a number of studies focused on the WRCC of arid areas, such as in the Heihe River and Yellow River basins. In the 21st century, the research direction has changed from consideration of the large scale (i.e. large river basins and large regions) to focusing on small-scale areas and cities.

Generally, recent WRCC studies have applied conventional trend, background analysis, fuzzy comprehensive evaluation, multi-objective decision analysis, principal component analysis, and system dynamics methods (Wang & Pan 2014; Xie *et al.* 2014). For example, application of fuzzy comprehensive evaluation for assessment of WRCC has been reported in relation to several different locations in China; for example, river basins in the arid zone (Wang *et al.* 2005), Jiansanjiang Branch Bureau (Lv *et al.* 2008), and Shanxi Province (Liu *et al.* 2013). However, there are certain disadvantages inherent in the application of such methods to WRCC investigations. The independence among factors restricts the application of conventional trend and background analysis methods. Although principal component analysis has been used to study the spatial change of the WRCC within a certain year, the method is not suitable for investigating WRCC dynamics in different years owing to information loss. The system dynamics method has been used primarily in simulations of short- and medium-term developments because difficulties in handling parameters in long-term simulations could lead to unreasonable conclusions. The weightings applied to different factors are crucial elements in the multi-objective decision analysis method. As the weightings are usually determined based on subjective judgment (e.g. Klee, Delphi, and AHP methods) (Benson & Sun 2000), the results will be influenced by subjective criteria (Laura 2009). In this study, index weighting was calculated using the AHP-CRITIC subjective and objective composite weighting method. Then, the fuzzy comprehensive evaluation method was used to evaluate the WRCC based on single factor evaluation of the various factors that affect the carrying capacity of water resources. The adopted calculation method overcame the limitation of mutual independence between factors inherent in the background analysis and conventional trend methods, and avoided the drawbacks of using subjective and objective methods alone when determining the factor weights. We quantitatively analysed the WRCC during 2011–2016 in Jinan (China) to provide scientific support for water resource utilization, ecological protection, and related policy. The findings represent an important resource for scientific management of water resources and sustainable socioeconomic development.

STUDY AREA

The city of Jinan is the capital of Shandong Province (China). Jinan is located in the central western part of the province, which has a warm temperate sub-humid monsoon climate. There are many rivers and springs in Jinan, including the Yellow and Xiaoqinghe rivers and the Baotu, Heihu, and Pearl springs. Since 2013, water transported from the Yangtze River via the East Line of South-to-North Water Diversion Project has become another important water resource for the city. The arrangement of the water system and the distribution of the springs in Jinan are shown in Figure 1. A population of 7.23 million is supported by 10 large- and medium-sized

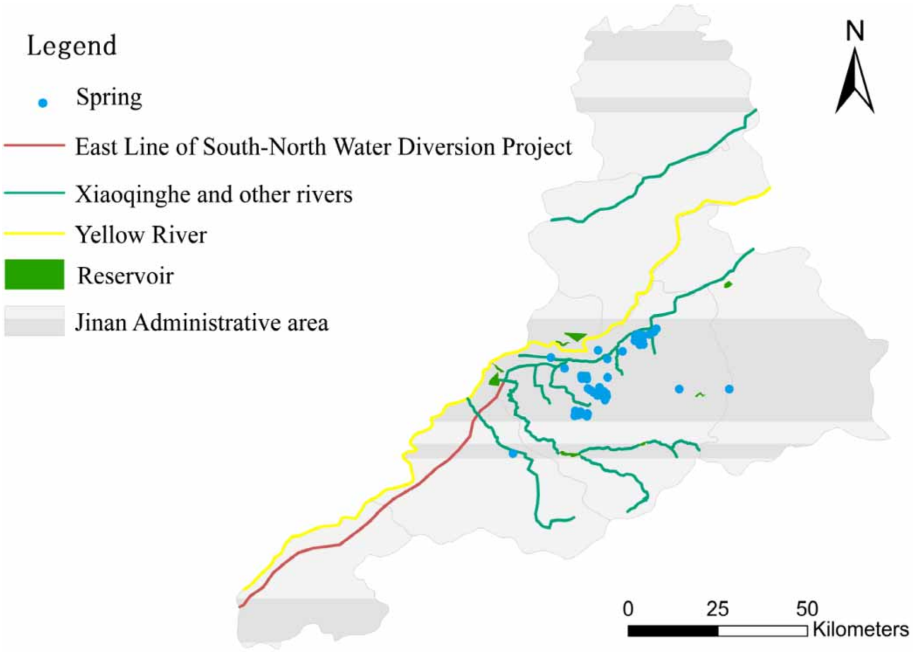

Figure 1 | Arrangement of the water system and distribution of springs in Jinan.

reservoirs, 182 small reservoirs, and more than 900 ponds. The multi-year average rainfall is 1.48 billion m^3 and the per capita water resource is 210 m^3, which is only 10% that of the national standard level and far lower than the world average threshold of 1,000 m^3 (Wang & Chen 2011). As a city that typifies the water resource shortages in North China, Jinan exhibits the features of insufficient total amount, non-uniform annual distribution, and heterogenous regional variation of its water resource. Moreover, the WRCC is the key factor constraining the regional socioeconomic development and the ecological environment. The rainfall in the rainy season (June–September) accounts for 75% of the annual total amount; however, there can be a four-fold variation in the actual amount of rainfall received among different years. The regional mountainous topography restricts water resource conservation and makes efficient water resource utilization difficult (Liu *et al*, 2011).

METHOD AND DATA SOURCES

Construction of evaluation index system

Based on the requirements of scientific, comprehensive and generalised, systematic and independent, and qualitative and quantitative principles, we selected nine indices that reflect the urban water resources condition, water supply facility, water demand, water usage and conservation, social development, and ecological environment (Wang & Chen 2011). The evaluation index system consisted of three levels: a target layer, criterion layer, and index layer, as shown in Figure 2. The target layer (A) represented the carrying capacity of the water resources, while the criterion layer (B) included the urban water conditions, water supply structure and engineering status, water demand structure and water saving level, social development status, and ecological environment status.

Based on the water resource condition of Jinan, the index layer (U) comprised the following: available amount of water resources per capita (U_1), utilization rate of water resources (U_2), water supply per capita (U_3), modulus of water supply (U_4), irrigation rate of cultivated land (U_5), quota of domestic water demand (U_6), population density (U_7), water demand per 10,000 Yuan industrial output value (U_8), and water use rate of the ecological environment (U_9). Index U_1 is the ratio of the available water resource to the total population. Index U_2 is the ratio of the water resource used to the total available water resource. Index U_3 is the ratio of the actual water supply to the total

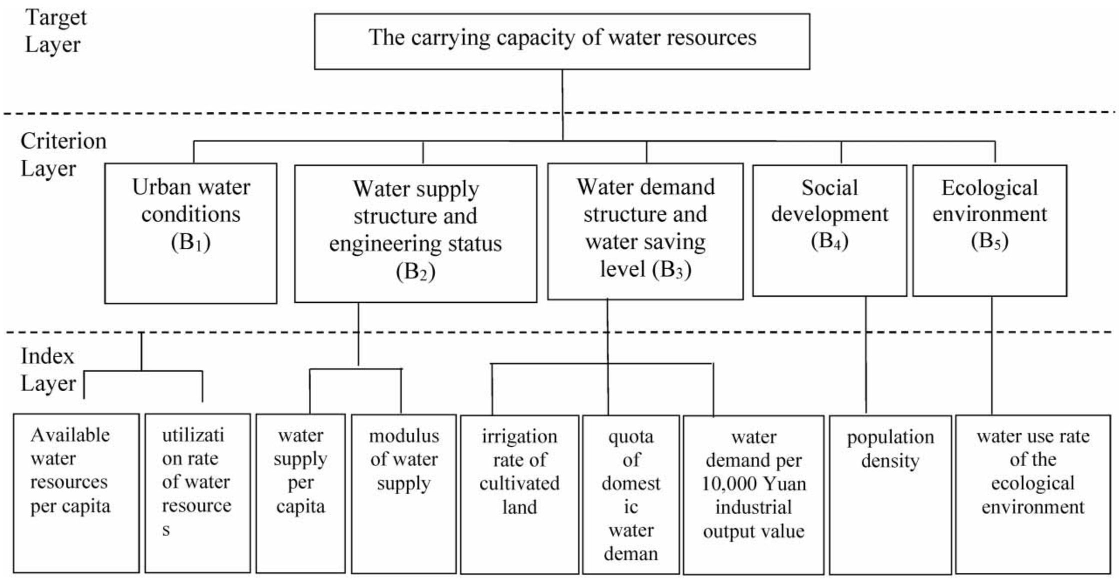

Figure 2 | Evaluation index system of water resources carrying capacity in Jinan.

population. Index U_4 is the ratio of the total water supply to the land area. Index U_5 is the ratio of the irrigation area to the total area of cultivated land. Index U_6 is the ratio of life-water to the total population. Index U_7 is the ratio of the total population to the land area. Index U_8 is the ratio of industry-water to total production. Index U_9 is the ratio of the ecological environment water to the total water usage. Of the above, U_1 and U_2 comprehensively reflect the water resources condition of urban development, and they are the two indicators most representative for determining the urban water resources condition and the degree of water shortage. U_3 reflects the capacity of the water supply system and the supporting capacity of the water resources for urban development, as well as the level of urban water consumption. U_4 partly reflects the capability of the urban water supply infrastructure to support regional socioeconomic development. U_5, U_6, and U_8 reflect the urban water demand, water use structure, water saving level, and industrial structure status. U_7 reflects the development of society and U_9 reflects the status of the ecological environment.

Calculation of evaluation index weighting

Methods for determination of index weighting can be divided into two categories: subjective weighting and objective weighting. The subjective weighting method requires that assessors give weights artificially depending on the importance of each index. This approach fully reflects the experience of experts and, currently, the AHP method and expert consultation method are the approaches used most widely. The objective weighting method determines index weighting based on actual data using objective information reflected by the index value. Typical objective weighting methods are the principal component analysis method and the CRITIC method (Yuan & Xin 2011). There are various deficiencies when using subjective and objective weighting methods in isolation; therefore, this study combined the advantages of both approaches to perform compound index weighting.

Subjective weight calculation – AHP method

The AHP method is an evaluation method based on the analytic hierarchy process. This approach uses data logical thinking to analyse multiple elements of target information, and certain information of the level above is used as a comparison criterion with which to calculate the relative importance of each element of information. For this, pairwise comparison judgment matrices are constructed and the weight of each element of information relative to the information of the previous level is calculated (Gao *et al.* 2014). In this study, the established index system and the AHP method were used to compare and rank each index layer. Then, the weight of each index in the evaluation index system of the WRCC of Jinan was calculated. After testing the consistency of each single layer and the general level, the subjective weighting (W_{AHP}) of each index was obtained (Table 1).

Objective weight calculation – CRITIC method

The CRITIC method is an objective weight calculation method based on the strength of the contrast and conflict between evaluation indices. Contrast intensity is represented by the standard deviation (σ_j); the larger the standard deviation, the greater the amount of information reflected and the greater the weight. Conflict is based on the correlation between indices that is reflected in the form of the expression $R_j = \sum_{i=1}^{n}(1 - r_{ij})$, where r_{ij} is the correlation coefficient between evaluation indices i and j. If C_j denotes the amount of information contained in the j-th index, then $C_j = \sigma_j * \sum_{i=1}^{n}(1 - r_{ij}) = \sigma_j R_j$; the larger the value of C_j, the greater the amount of information contained in the index. After normalizing the information content of each index, the objective weight of the index can be obtained (Yuan & Xin 2011). After standardizing and regularizing the water resources evaluation index data of Jinan, and after calculating the standard deviation, correlation coefficient, and amount of information, the objective weightings of the nine indices were determined as $W_{CRITIC} = (0.0813, 0.0824, 0.1141, 0.1528, 0.1162, 0.0976, 0.0963, 0.1341, 0.1253)$.

Calculation of comprehensive weight of index

The AHP method is suitable for handling the subjective information of decision makers, while the CRITIC method is suitable for mining objective information in the sample data. This study combined the two methods to consider both subjectivity and objectivity. The AHP-CRITIC method was used to determine the comprehensive weightings of the indices:

$$W_j = W_{AHPj} * W_{CRITICj} / \sum_{j=1}^{m} W_{AHPj} * W_{CRITICj} \quad (1)$$

where W_j is the comprehensive weight of the j-th index to the target, and W_{AHPj} and $W_{CRITICj}$ are the weights of the j-th index to the target obtained by the AHP and CRITIC methods, respectively (Yuan & Xin 2011). After calculation, the comprehensive weightings of the nine indices were determined as $W = (0.125, 0.115, 0.120, 0.124, 0.091, 0.086, 0.100, 0.127, 0.112)$.

Table 1 | Weight of each index in the calculation of the water resources carrying capacity of Jinan

Target layer	Criterion layer	Weight of criterion layer	Index layer	Weight of index layer	W_{AHP}
A	B_1	0.311	U_1	0.523	0.163
			U_2	0.477	0.148
	B_2	0.198	U_3	0.563	0.111
			U_4	0.437	0.087
	B_3	0.256	U_5	0.325	0.083
			U_6	0.365	0.093
			U_8	0.31	0.079
	B_4	0.140	U_7	1	0.140
	B_5	0.095	U_9	1	0.095

Evaluation index classification and scoring

Using the national water resource standard and with reference to expert advice, we divided the indices into three grades: V_1, V_2, and V_3 (Huang & Ma 1990; Hou & Tang 2014), the details of which are shown in Table 2.

In Table 2, V_1 indicates satisfactory WRCC, i.e., the water resource is sufficient to guarantee the water supply and it has potential to support further socioeconomic development. Conversely, V_3 indicates poor WRCC; that is, the inadequate water resource restricts socioeconomic development. V_2 indicates that the WRCC is almost at saturation point; that is, the water resource can fulfil the current socioeconomic demands but it does not have potential to support further development (Yin *et al.* 2016; Wang *et al.* 2017).

To reflect the WRCC more precisely and to quantitatively evaluate the influence of grade on the WRCC, we assigned a score to each grade using a 1 cent scoring system, in which $a_1 = 0.95$, $a_2 = 0.5$, and $a_3 = 0.05$; the higher the score, the higher the potential for utilization of the water resource (Wang *et al.* 2017).

Membership degree calculation of evaluation index

Based on previous research on the membership degree function in the fuzzy comprehensive evaluation method, we

Table 2 | Grade of each index

Order	Evaluation index	Unit	V_1	V_2	V_3
1	Available amount of water resources per capita	m^3/person	>550	550–400	<400
2	Utilization rate of water resource	%	<50	50–80	>80
3	Water supply per capita	m^3/person	>330	330–240	<240
4	Modulus of water supply	10 k m^3/km^2	<1	1–15	>15
5	Irrigation rate of cultivated land	%	<40	40–80	>80
6	Quota of domestic water demand	L/person · day	<80	80–130	>130
7	Population density	Person /km^2	<300	300–800	>800
8	Water demand per 10, 000 Yuan industrial output value	m^3/10 k yuan (¥)	<20	20–100	>100
9	Water use rate of the ecological environment	%	>6	2–6	<2

calculated the membership function (U_{vi}) value (Ui) according to the real value of each index.

The evaluation grade was fuzzed to make clear the score gradient and the smooth transition of the membership degree function among the different grades. For V_2, we defined the membership degree as 1 when it fell on the middle point of an interval and 0.5 for data that fell on the end points on both sides. The membership degree decreased from the middle point to the end point. For V_1 and V_3, when the data fell on the threshold, we defined the membership as 0.5; the longer the distance from the threshold, the higher the membership score (Wang *et al.* 2017). Based on the above principles, we set the following membership degree formulas.

For the assessment factors of U_2, and U_4–U_8, the calculation equations for the relative membership function of each comment level are shown as Equations (2)–(4):

$$\mathrm{U_{V1}} = \begin{cases} 0.5\left[1+\dfrac{K_1-U_i}{K_2-U_i}\right] & U_i < K_1 \\ 0.5\left[1-\dfrac{U_i-K_1}{K_2-K_1}\right] & K_1 \le U_i < K_2 \\ 0 & U_i \ge K_2 \end{cases} \tag{2}$$

$$\mathrm{U_{v2}} = \begin{cases} 0.5\left[1-\dfrac{K_1-U_i}{K_2-U_i}\right] & U_i < K_1 \\ 0.5\left[1+\dfrac{U_i-K_1}{K_2-K_1}\right] & K_1 \le U_i < K_2 \\ 0.5\left[1+\dfrac{K_3-U_i}{K_3-K_2}\right] & K_2 \le U_i < K_3 \\ 0.5\left[1-\dfrac{K_3-U_i}{K_2-U_i}\right] & U_i \ge K_3 \end{cases} \tag{3}$$

$$\mathrm{U_{V3}} = \begin{cases} 0.5\left[1+\dfrac{K_3-U_i}{K_2-U_i}\right] & U_i \ge K_3 \\ 0.5\left[1-\dfrac{U_i-K_3}{K_2-K_3}\right] & K_2 \le U_i < K_3 \\ 0 & U_i \le K_2 \end{cases} \tag{4}$$

For the assessment factors of U_1, U_3, and U_9, the calculation equations for the relative membership function of each comment level are shown as Equations (5)–(7):

$$\mathrm{U_{V1}} = \begin{cases} 0.5\left[1+\dfrac{K_1-U_i}{K_2-U_i}\right] & U_i \ge K_1 \\ 0.5\left[1-\dfrac{U_i-K_1}{K_2-K_1}\right] & K_2 \le U_i < K_1 \\ 0 & U_i \le K_2 \end{cases} \tag{5}$$

$$\mathrm{U_{V2}} = \begin{cases} 0.5\left[1-\dfrac{K_1-U_i}{K2-U_i}\right] & U_i \ge K_1 \\ 0.5\left[1+\dfrac{U_i-K_1}{K_2-K_1}\right] & K_2 \le U_i < K_1 \\ 0.5\left[1+\dfrac{K_3-U_i}{K_3-K_2}\right] & K_3 \le U_i < K_2 \\ 0.5\left[1-\dfrac{K_3-U_i}{K_2-U_i}\right] & U_i \le K_3 \end{cases} \tag{6}$$

$$\mathrm{U_{V3}} = \begin{cases} 0.5\left[1+\dfrac{K_3-U_i}{K_2-U_i}\right] & U_i < K_3 \\ 0.5\left[1-\dfrac{U_i-K_3}{K_2-K_3}\right] & K_3 \le U_i < K_2 \\ 0 & U_i \ge K_2 \end{cases} \tag{7}$$

Setting the critical values of grades V_1 and V_2 as K_1 and of V_2 and V_3 as K_3, and the middle point of V_2 as K_2, we have $K_2 = (K_1+K_3)/2$. The critical value of each index to the grade is shown in Table 3.

Comprehensive evaluation

The final comprehensive evaluation score was calculated using Equation (8):

$$a = \frac{\sum_{i=1}^{3} b_i^k a_i}{\sum_{i=1}^{3} b_i^k} \tag{8}$$

in which a is the final comprehensive evaluation score for quantifying the WRCC; a higher value of a indicates stronger WRCC (Wang & Pan 2014). The value of k is set to emphasize the role of the dominant grade. In this study, it was set to 1 based on the actual situation in Jinan.

Data sources

The sources of data used in this study comprised the 'Jinan Water Resources Bulletin', 'Jinan Statistical Year Book', and 'Statistical Bulletin of Jinan's National Economic and Social Development' from the years 2011–2016. The final evaluation results are shown in Table 4.

Table 3 | Critical value of each index to the grade

Critical value	U_1	U_2	U_3	U_4	U_5	U_6	U_7	U_8	U_9
K_1	550	50	330	1	40	80	300	20	6
K_2	475	65	285	8	60	105	550	60	4
K_3	400	80	240	15	80	130	800	100	2

RESULTS AND DISCUSSION

Calculation of comprehensive evaluation score (*a*)

Based on the membership function, the membership degree (r_{ij}) of each index to each grade was calculated. Here, r_{ij} represents the membership degree of the i^{th} element to the j^{th} grade. Then, the comprehensive evaluation matrix R was calculated. Based on the comprehensive weight matrices W and R of each evaluation index, the final evaluation result (matrix B) was calculated using the equation $B = W \times R$. The results are shown in Equations (9)–(14):

$$R_{2011} = \begin{bmatrix} 0 & 0.155 & 0.845 \\ 0 & 0.170 & 0.830 \\ 0 & 0.667 & 0.333 \\ 0 & 0.251 & 0.749 \\ 0 & 0.919 & 0.081 \\ 0.400 & 0.600 & 0 \\ 0 & 0.402 & 0.598 \\ 0.624 & 0.376 & 0 \\ 0.576 & 0.424 & 0 \end{bmatrix} \tag{9}$$

$$R_{2012} = \begin{bmatrix} 0 & 0.150 & 0.850 \\ 0 & 0.160 & 0.840 \\ 0 & 0.633 & 0.367 \\ 0 & 0.252 & 0.748 \\ 0 & 0.918 & 0.082 \\ 0.314 & 0.686 & 0 \\ 0 & 0.392 & 0.608 \\ 0.632 & 0.368 & 0 \\ 0.258 & 0.743 & 0 \end{bmatrix} \tag{10}$$

Table 4 | Evaluation results for Jinan during 2011–2016

Year	Available amount of water resources per capita (m^3/person)	Utilization rate of water resources (%)	Water supply per capita (m^3/person)	Modulus of water supply (10 k m^3/km^2)	Irrigation rate of cultivated land (%)	Quota of domestic water demand (L/person · day)	Population density (person/km^2)	Water demand per 10, 000 Yuan industrial output value (m^3/10 k yuan(¥))	Water use rate of the ecological environment (%)
2011	233.7	109.1	255	21.95	63.23	85	860.9	6.84	6.36
2012	224.6	112	252	21.91	63.30	89.3	868.9	5.71	5.03
2013	298.1	82.2	245	21.43	69.50	93.7	875.1	4.92	4.94
2014	111.9	213.6	239	21.13	67.77	98.3	883.6	4.75	4.69
2015	162.4	138.6	225	20.07	67.67	103.3	891.7	4.21	8.96
2016	231.5	97.1	225	20.33	68.68	108.4	904.4	3.85	12.01

$$R_{2013} = \begin{bmatrix} 0 & 0.212 & 0.788 \\ 0 & 0.436 & 0.564 \\ 0 & 0.556 & 0.444 \\ 0 & 0.261 & 0.739 \\ 0 & 0.763 & 0.238 \\ 0.226 & 0.774 & 0 \\ 0 & 0.384 & 0.616 \\ 0.637 & 0.363 & 0 \\ 0.235 & 0.765 & 0 \end{bmatrix} \quad (11)$$

$$R_{2014} = \begin{bmatrix} 0 & 0.103 & 0.897 \\ 0 & 0.050 & 0.950 \\ 0 & 0.489 & 0.511 \\ 0 & 0.267 & 0.733 \\ 0 & 0.806 & 0.194 \\ 0.134 & 0.866 & 0 \\ 0 & 0.375 & 0.625 \\ 0.638 & 0.362 & 0 \\ 0.173 & 0.828 & 0 \end{bmatrix} \quad (12)$$

$$R_{2015} = \begin{bmatrix} 0 & 0.120 & 0.880 \\ 0 & 0.102 & 0.898 \\ 0 & 0.375 & 0.625 \\ 0 & 0.290 & 0.710 \\ 0 & 0.808 & 0.192 \\ 0.034 & 0.966 & 0 \\ 0 & 0.366 & 0.634 \\ 0.642 & 0.358 & 0 \\ 0.798 & 0.202 & 0 \end{bmatrix} \quad (13)$$

$$R_{2016} = \begin{bmatrix} 0 & 0.154 & 0.846 \\ 0 & 0.234 & 0.766 \\ 0 & 0.375 & 0.625 \\ 0 & 0.284 & 0.716 \\ 0 & 0.783 & 0.217 \\ 0 & 0.932 & 0.068 \\ 0 & 0.353 & 0.647 \\ 0.644 & 0.356 & 0 \\ 0.875 & 0.125 & 0 \end{bmatrix} \quad (14)$$

Taking 2011 as an example in Equation (15),

$$B = W \times R = (0.125, 0.115, 0.120, 0.124, 0.091, 0.086, 0.100, 0.127, 0.112) \times \begin{bmatrix} 0 & 0.155 & 0.845 \\ 0 & 0.170 & 0.830 \\ 0 & 0.667 & 0.333 \\ 0 & 0.251 & 0.749 \\ 0 & 0.919 & 0.081 \\ 0.400 & 0.600 & 0 \\ 0 & 0.402 & 0.598 \\ 0.624 & 0.376 & 0 \\ 0.576 & 0.424 & 0 \end{bmatrix} = (0.1782, 0.4208, 0.4011) \quad (15)$$

The comprehensive evaluation score of the WRCC was calculated using Equation (16):

$$a = \frac{\sum_{i=1}^{3} b_i^k a_i}{\sum_{i=1}^{3} b_i^k} = (a_1, a_2, a_3) \times (b_1, b_2, b_3)^T = (0.95, 0.5, 0.05) \times (0.1782, 0.4208, 0.4011)^T = 0.3997. \quad (16)$$

The final WRCC comprehensive evaluation results are shown in Table 5.

Analysis of results of comprehensive evaluation score (*a*)

Qualitative analysis of the comprehensive score value (*a*) refers to the grading standard of similar methods in related literature. Here, we divided the range of values of *a* based on two critical values. Values of *a* of <0.4 and >0.7 indicate overload and light load of the WRCC, respectively; intermediate values indicate a suitable load (Chen *et al.* 2004). It can be seen from Table 5 that the comprehensive score values of the WRCC in Jinan during 2011–2016 are all <0.4. This indicates that the outlook regarding the WRCC is not optimistic. The WRCC, which is in an overload state, has declined in general and water resources have become a constraint on socioeconomic development. The lowest *a* value was 0.3462 in 2014. According to the original data of water resources in Jinan, combined with the calculation formula and principle of fuzzy comprehensive evaluation, the main reason is that 2014 was a dry year and that the total amount of water resources available in Jinan was seriously short (the lowest value of all evaluated

Table 5 | Final WRCC comprehensive evaluation results

Year	V_1	V_2	V_3	*a*
2011	0.178 2	0.420 8	0.401 1	0.399 7
2012	0.136 2	0.456 0	0.407 9	0.377 8
2013	0.126 7	0.481 9	0.391 5	0.380 8
2014	0.111 9	0.434 4	0.453 7	0.346 2
2015	0.173 8	0.369 0	0.457 2	0.372 5
2016	0.179 8	0.372 3	0.447 9	0.379 3
Mean	0.151 1	0.422 4	0.426 6	0.376 1

years). Overall, the comprehensive evaluation results of each year are reasonably stable with little fluctuation; however, the a values of 2011–2013 were higher than those of 2014–2016. Although the a value increased annually during 2014–2016, it was only slightly higher than the six-year average in 2016, which shows that with the rapid level of socioeconomic development in Jinan, the form of the water resources shortage has become even more serious. Even though a series of positive measures such as industrial water use, water saving, and ecological environment protection have been taken to produce the rise in the a value during 2014–2016, additional measures should be implemented to improve the WRCC of Jinan.

Analysis of membership degree of evaluation results to each evaluation grade

Analysis of the membership degree of the evaluation results presented in Table 5 to the three evaluation levels revealed that the average evaluation results during 2011–2016 in descending order were V_3, V_2, and V_1. Among them, the membership degree of V_2 during 2011–2013 was higher than that of V_3, while it was the opposite during 2014–2016. This is the direct reason for the decline in the comprehensive evaluation results of the WRCC of Jinan in the evaluation years.

Analysis of membership degree of each index to different evaluation grades

From the membership matrix R of each evaluation index in Jinan during 2011–2016, it can be seen that six (seven) of the nine evaluation indicators of 2011–2015 (2016) have a membership degree of zero to V_1, indicating that the evaluation indicators of the WRCC are not optimistic. Further analysis of the membership degree of each evaluation index to each grade revealed that U_1 and U_2 have the highest membership degree to V_3, which is generally >0.8 (except in 2013). In 2014, the membership degree of U_2 to V_3 was as high as 0.950, indicating that U_1 and U_2 are the factors that affect the WRCC of Jinan most unfavourably, and that the high membership degree of V_3 is the main reason for the low WRCC. The reason is that Jinan is a city that typifies the water shortages in North China. The total amount of water resources is limited and the population is large. Therefore, the per capita water resource is low (only 10% that of the national average), which is also the reason for the high utilization rate of water resources. The U_1 and U_2 index values are closely related to the total water resources; the larger the total water resources, the higher the membership degree of U_1 and U_2 indicators to V_3. Therefore, increasing the total amount of water resources is particularly important for enhancement of the WRCC. According to statistics, the amount of water introduced to Jinan in recent years from the Yellow River and the Yangtze River has been approximately 580 and 100 million m^3 per year, respectively. In the future, water resources in Jinan could be augmented by increased transfer of water from the Yellow and Yangtze rivers (with the implementation of the second and third phases of the East Route Project of the South-to-North Diversion Project), and through increased utilization of unconventional water sources such as rain floodwater, reclaimed water, and spring water. In addition, the relationship between spring protection and the development and utilization of groundwater resources could be examined, and increased development and utilization of groundwater resources could be combined with the implementation of the Surface Water to Groundwater Project in Jinan.

The subordination degree of U_3 to V_2 decreased annually (from 0.667 in 2011 to 0.375 in 2016), while the membership degree of V_3 increased annually (from 0.333 in 2011 to 0.625). It indicates that U_3 is also a factor that adversely affects the WRCC of Jinan. The annual change of this index value caused the WRCC to decrease because the rate of increase of the actual water supply was lower than that of the population. From the perspective of inter-annual change, the membership degree of U_4 to each grade was largely unchanged and its membership degree to V_3 was >0.7. Therefore, U_4 is another principal reason for the low WRCC of Jinan; that is, limited by the lack of water resources in the city, the total water supply and the index value are both reduced. According to statistics, the total water supply in 2014 and 2015 was greater than the total water resources, indicating that water resources transferred from outside the region were utilized in Jinan. With continued expansion of both the urban area and the size of the population, the shortage of the total water supply in Jinan could become increasingly prominent.

The membership degree of U_5 to each grade showed little interannual change. The membership degree to V_1 was zero; the membership degree to V_2 in the range of 0.763–0.919 was the highest, and the membership degree of V_3 was 0.081–0.238. This index is close to the bearing capacity limit and the degree of sustainable utilization. According to the data of the Jinan Water Resources Bulletin, agriculture is the major water user in Jinan and farmland irrigation accounts for approximately 45% of the total water use. However, in many areas of Jinan, the mode of flood irrigation is still used and the effective utilization rate of agricultural irrigation is approximately only 45%. Advanced water-saving irrigation methods such as sprinkler irrigation and drip irrigation have not been realized in a large area of Jinan and outdated irrigation methods result in low irrigation efficiency. Therefore, promotion of advanced water-saving irrigation methods should be strengthened in the future.

The membership degree of U_6 to V_1 decreased annually from 0.4 in 2011 to 0, while the membership degree to V_2 was the largest and increased annually. The membership degree of U_7 to V_2 was less than that of V_3. The membership degree of V_2 decreased annually, while the membership degree of V_3 increased annually, indicating that the carrying capacity reflected by the U_6 and U_7 indices decreased. Following recent improvements in living standards, the domestic water demand quota has increased. In addition, socioeconomic development has led to expansion of the urban scale of Jinan and to increased population density. Therefore, it will be necessary to raise public awareness regarding water-saving measures and to accelerate the promotion of water-saving appliances to end the waste of domestic water.

The subordination degree of U_8 to each grade showed little interannual change. The membership degree of V_1 was >0.6, indicating that U_8 is a factor that affects the WRCC of Jinan favourably. It suggests that the degree of water resources development and utilization is optimistic and that it has certain development potential. The reason is that with optimization and adjustment of the industrial structure, promotion of advanced water-saving technologies, and improvement in the rates of water reuse and reclaimed water utilization, the water demand of 10,000 yuan industrial output value is decreasing. Furthermore, since 2011, Jinan has vigorously implemented the 'Shandong Province Water Consumption Control and Management Measures', vigorously promoted the construction of a water-saving society, strictly implemented the 'Three Red Lines' assessment system for water use, and shut down enterprises with large water consumption, low output, and severe water pollution. Currently, the water reuse rate of large- and medium-sized enterprises in Jinan is high and some enterprises have even reached zero discharge. However, the water reuse rate of small-sized enterprises (especially township enterprises) remains low and industrial water saving is not balanced. Therefore, the next step should focus on improving the water reuse rate of small enterprises, adjusting and optimizing the industrial structure, vigorously developing high-tech industries, and adjusting and transforming traditional industries to fully exploit the development potential of the available water resources.

The membership degree of U_9 to V_3 was zero during 2011–2014; the membership degree to V_1 decreased from 0.576 to 0.173, and the membership degree to V_2 increased continuously. However, the membership degree of U_9 to V_1 rebounded significantly from 2015 to 2016 (highest value: 0.875 in 2016), which was the main reason for the improvement of the WRCC in 2015 and 2016. The reason is that increased public attention on the ecological environment and the construction of a water ecological city in Jinan have increased the water consumption rate of the ecological environment and produced results regarding protection of the water environment.

CONCLUSIONS

In this study, the WRCC of Jinan was evaluated based on nine indicators: the available amount of water resources per capita, utilization rate of water resources, water supply per capita, modulus of water supply, irrigation rate of cultivated land, quota of domestic water demand, population density, water demand per 10,000 Yuan industrial output value, and water use rate of the ecological environment.

The AHP-CRITIC subjective and objective composite weighting method was used to determine the weighting of each evaluation index. This approach was adopted because the two methods complement each other, while maintaining the stability of the weighting coefficient, which leads to improved extraction of information from the data. Based on evaluation and classification of each evaluation index, the dynamic changes of the WRCC of Jinan during 2011–2016 were analysed quantitatively using the fuzzy comprehensive evaluation method. From this, the underlying reasons were analysed and corresponding countermeasures and suggestions were proposed.

During 2011–2016, the WRCC of Jinan was in a state of overload. The comprehensive score a was <0.4 and it presented a general downward trend. This means that the outlook regarding water resources in Jinan is not optimistic, and that water resources have become a constraint on further socioeconomic development. Given the recent rapid socioeconomic development and continuous expansion of the urban scale of Jinan, the situation regarding the shortage of water resources could become increasingly serious. It is imperative that effective measures be adopted urgently to improve the WRCC of Jinan.

The membership degree of the mean value of the evaluation results during 2011–2016 to the three levels in descending order was V_3, V_2, and V_1. Analysis revealed that U_1, U_2, U_3, U_4, U_6, and U_7 were factors that affected the WRCC of Jinan unfavourably, whereas U_8 and U_9 were factors that played positive roles in improving the WRCC.

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DATA AVAILABILITY STATEMENT

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

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