Evaluation of water resource carrying capacity of two typical cities in northern China

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ABSTRACT

Global climate change and human activities are increasingly affecting the regional water resource carrying capacity (WRCC). For sustainable development, an important social challenge is understanding the carrying level of regional water resources. In this study, to assess the WRCC status, we used a fuzzy comprehensive evaluation model and combined the natural and social attributes of WRCC. Moreover, from the three dimensions of support force subsystem, pressure force subsystem (PFS), and regulation force subsystem (RFS), 12 evaluation indicators were selected. Furthermore, using the fuzzy comprehensive theory and natural and social comprehensive indicators, we constructed a WRCC-level evaluation model and used it to evaluate the carrying level of two typical cities in China, Shijiazhuang and Langfang, for the 2006–2015 period. The results demonstrate that the regional water-carrying status of each of these cities is slightly above that of WRCC and that carrying levels show an interannual increasing trend. Note that, in both cities, the primary reason for the low regional WRCC is water shortage, while PFS improvement, supported by an interannual PFS increasing trend during the same time period, is the primary reason for carrying-level improvement for both cities in the past 10 years. For the RFS dimension, evaluation scores were in the range of 2.14–2.98 for Shijiazhuang and 2.12–2.79 for Langfang. Furthermore, the evaluation model and the indicator system demonstrated complementary functionality; thus, our results have an important academic value, particularly with reference to evaluating the WRCC.

Key words | composite indicator system, fuzzy comprehensive evaluation model, level assessment, water resource carrying capacity

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HIGHLIGHTS

- This paper is a good initiative to provide a methodology to evaluate the water resource carrying capacity.
- For the regional management of water resources, our study provides both the theoretical basis and data support.

INTRODUCTION

Because of climate change, processes related to the water cycle have changed considerably. The spatiotemporal distribution and the available amount of water resources have been altered, which has affected the regional water resource carrying capacity (WRCC) (Brown *et al.* 2010; Wang *et al.* 2013). The United Nations Educational, Scientific, and Cultural Organization World Water Development Report reported that, with an increase in water demand

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and the influence of climate change, the amount of available water resources of multiple regions will continuously decrease (UNESCO 2003). Because of the influences of rapid economic and social development and climate change, the imbalance between demand and supply of water resources has increased, the water environment pollution has increased, and the natural ecosystem has been incrementally damaged (Cosgrove & Rijsberman 2014). Thus, for managers, investigating the WRCC has gradually become an urgent problem. In particular, under the influence of both climate change and human activity, the supply and demand of water resources in the basin is unbalanced, and natural disasters attributed to excessive water use are increasingly evident (Liu & Yang 2012), particularly in northern China. After the 1990s, large areas in Hebei Province, China, experienced groundwater overexploitation, which has caused disasters to occur from time to time in recent years.

The WRCC, which expands the concept of carrying capacity in the field of water resources, is a part of natural resource carrying capacity. In the late 1980s, the WRCC was proposed by Chinese researchers because of the increasingly prominent water problem. Internationally, to replace the WRCC, the concept of rationing the water supply to water demand or water availability is often used. For example, Falkenmark & Lundqvist (1998) used the concept of water availability to mean the same as the WRCC when they examined how to deal with water security issues for policy orientation and human adaptability. Similarly, in rural areas, during a study of key environmental indicators of sustainable development, Schultink (2000) discussed the definition of carrying capacity and the role of basic criteria. Ngana *et al.* (2004) reported the limitations of managing local water resources and the lack of sustainable water resource use in a strategic environmental assessment of managing water resources and development in Northeastern Tanzania. Note that the WRCC and its relationship with food, energy, and other systems and water security have become hot topics (Martinez-Hernandez *et al.* 2017; Helmstedt *et al.* 2018). Preliminary results initiated by the International Council of Scientific Unions (under the Future Earth Plan) address the sustainable development of water, energy, and food. The eighth phase of the International Hydrological Plan (IHP-VIII 2014–2021) considers water security as the third most important research direction. In its official documents of 2016–2018, the World Water Council clearly proposed the concept of water pressure balance under conditions of rapid economic growth (Jianhua *et al.* 2017).

Recently, many studies have focused on the concept, connotations, and evaluation of WRCC (Wei *et al.* 2009). Currently, the WRCC is considered to have three components: the theory of scaled water resource development, water resources supporting sustainable development capacity, and water resources supply to the largest population (Zhou *et al.* 2008). To address the scaled development of water resources, the focus is on the extent of water resource development and use that can nevertheless guarantee the coordinated development of the economy, society, and ecological environment under the current and foreseeable productivity, and the scientific level via allocation of water resources (Li *et al.* 2016; Yang *et al.* 2016). The key point is to ensure that the WRCC is at the maximum capacity that can still support sustainable economic and social development based on a certain level of science while still maintaining the ecological environment. The requirement for water resources to supply the largest population is related to the regional capacity of water supply to meet population size. Accordingly, the WRCC needs to address the maximum population capacity because of the current and expected regional economic and social development stage and reasonable allocation and efficient use of water resources, while maintaining healthy development of the ecological environment (Meng *et al.* 2009; Zuo & Zhang 2015). To summarize, although different researchers have different understandings of WRCC, there is no significant difference in points of view. Many researchers focused on the exploitable scale of water resources or the capacity of water resources to support the economy and society; therefore, studies on WRCC should focus on its evaluation and analysis of its application. The selection of a more effective method for scientific evaluation is a popular topic, particularly the evolution of water resource endowment because of climate change.

Many methods are being developed to evaluate the WRCC: they can be divided into empirical estimation, index system evaluation, and complex system analysis. When searching for individual influencing factors, the empirical estimation method requires experienced researchers to estimate the regional WRCC. This type of method has a certain subjectivity because it does not consider a sufficient number of factors, e.g., based on the conditions in Israel. Walmsley *et al.* (2001) reported that the water resources in the Shiyang River Basin could supply to a larger population and economic scale. To calculate the water consumption of human beings, Hoekstra & Chapagain (2006) used water footprints, basically reflecting global water resources. To evaluate carrying capacity, the index system evaluation method uses several indices that influence the WRCC. This method's advantage is that there are no limitations on the characteristics of the study area, the application of a mathematical theory is more extensive, and the factors affecting the carrying capacity are considered. However, the selection of indices and the rationality of the weight of each index need to be examined. To evaluate the dynamic change of WRCC in Lanzhou, Gong & Jin (2009) used the fuzzy comprehensive evaluation method, and the results demonstrated that the carrying capacity in Lanzhou decreased on a year-on-year basis. Furthermore, to evaluate available and potential water resources of the Songhua River Basin in 2018, 2020, and 2030 and to provide the basis for the sustainable utilization of water resources, Yu & Lu (2018) coupled the fuzzy evaluation method and the grey wolf optimization method. To analyze the WRCC in terms of the connections among the economy, society, and water resources, this complex system analysis method uses different approaches or models. Because of the integrity, systematics, and multiobjective characteristics of water resources, this method can quantitatively analyze the internal relationship between the structure and function of water resources, the economy, the society, and the ecological environment system. This method does not simply have an upper limit for the population or economic scale that water resources in a basin contain; however, it clearly reflects the relationships among population, natural resources, the environment, and economic development. Because of the interrelation of various system components, two-way measures are used to generally improve the adaptability of water resources, other economic and social factors, and to test whether a regulatory scheme is sustainable considering regulation. Feng & Huang (2008) analyzed the WRCC of Jinhua City in Zhejiang Province using the system dynamics method by which they demonstrated that, compared to the traditional model, the method is dynamic and is more stable and efficient. Sun *et al.* (2016) systematically analyzed the local economic and social system and the water resource system by establishing the driver–pressure–state–impact–response model by which they assessed Bayannur, Inner Mongolia. The report claimed that its economic and social development is considerably restricted. Wang *et al.* (2013) analyzed the carrying capacity of Bosten Lake by combining system dynamics and analytic hierarchy processes; their research results provided a basis for a reasonable development pattern to protect the WRCC of Bosten Lake and the environment.

Thus, because of the recent increase in WRCC research, additional methods are being applied by many researchers. However, under various constraints, different methods have advantages and disadvantages, including the limitations of empirical estimation according to the requirements of researchers, the uncertainty of index thresholds of the index system evaluation, and the limitations of complex system analysis. Therefore, to summarize the advantages of different methods, Qiu *et al.* (2018) proposed a comprehensive WRCC evaluation model that combines system dynamics and fuzzy variable evaluation. The model analyzes the change of water use in Zoucheng City on the basis of system dynamics, proposes different water-use schemes that address local requirements, and then analyzes the level based on the fuzzy variable set. Furthermore, by integrating multiple requirements, the final recommended scheme is obtained (Qiu *et al.* 2018). Based on an original model combined with the regional water resource change and differences in regional water use and accommodating the changing environment, we chose to study Shijiazhuang and Langfang, two typical cities in northern China. Furthermore, we aimed to analyze and evaluate the WRCC, study the contribution of water resource change to the carrying capacity under climate change, investigate the regional WRCC because of different future development modes, predict the WRCC and the degree of overload in different years, and evaluate local reasons for overload. For the regional management of water resources, our study provides both the theoretical basis and data support.

METHODS

Fuzzy comprehensive evaluation model

The WRCC scheme is affected by multiple indices. Although each index is known to exert mutual influence, the degree is unclear and thus cannot be quantitatively expressed. Factors affecting water-carrying capacity restrict each other and are affected by each other; certain influences are positive, while others are negative. To quantify the performance evaluation of different results, we applied fuzzy comprehensive evaluation (Shouyu & Yu 2006; Forio *et al.* 2017). This method combines clear relationships among indices and the fuzzy relationship among index intervals in the scheme. Furthermore, it establishes the scheme evaluation model, which considers water resources as goals, sustainability optimization, social economy, and an ecological environment system (Deng *et al.* 2015). This method can quantitatively evaluate the comprehensive level of each scheme and clarify the degree of coordination of the scheme and the changing trend of the scheme set (Cakmak *et al.* 2013). If U is set as the scheme of the system dynamics model construction, the opposite fuzzy attributes of any index u are A and A^c. A pair of opposite measure values $\mu_A(u)$ and $\mu_A^c(u)$ determined in continuum are its relative membership and $\mu_A(u)+\mu_A^c(u)=1$. If the optimal scheme set is $U=\{u_1, u_2, \ldots, u_n\}=\{u_j\}$ $(j=1, 2, \ldots, n)$; $X=(x_{ij})$ $(i=1, 2, \ldots, m)$, it is the characteristic value of each index of scheme j. Moreover, X is the scheme set of WRCC; x_{ij} is the value of index i of the scheme j; and the interval range of single index i of the scheme set is determined as $I_{ij}=[\{\max(a_{ij})\}, \{\min(b_{ij})\}]$ or $I_{ij}=[\{\min(a_{ij})\}, \{\max(b_{ij})\}]$, where I_{ij} is the optimal interval of index i in scheme j, and the upper and lower limits of the optimal interval are the extreme values of index i in the scheme set or the interval range of the internationally recognized index is considered. Based on the evolution of the relative difference degree of variable sets, the optimal interval I_{ij} is divided into c level, and the interval matrix of index eigenvalues of c level is given by $I=[a_{ih},b_{ih}]$, where $(h=1,2, \ldots,c)$ in which a_{ih} and b_{ih} are the upper and lower limits of index I in the h-level standard, respectively. According to the unity-of-opposites theorem of variable sets, there must be a gradual mass change point of index i in the h- and $(h+1)$-level characteristic value range. Furthermore, the two sides of the mass change point correspond to two levels of opposition, as is known from formula (1), $\mu_A^c(u)=1$, i.e., the point k_{ih} with the corresponding level h membership degree of 1.

$$K_{ih}=\frac{c-h}{c-1}a_{ih}+\frac{h-1}{c-1}b_{ih} \tag{1}$$

where k_{ih} is the point with the subordination degree of h level corresponding to index i in the optimal interval, and c is the index evaluation level; other variables are defined above. From Equation (1) and matrix I, to obtain matrix K: $K=[k_{ih}, b_{ih}]$, if the eigenvalue of the scheme set index x_{ij} is in the interval between two adjacent levels h and $(h+1)$ of matrix K, the relative membership degree of x_{ij} to level h is then calculated as follows:

$$\mu_{ih}(u_j)=0.5\times\left(1+\frac{b_{ih}-x_{ij}}{b_{ih}-k_{ih}}\right) \quad x_{ij}\in[k_{ih}, b_{ih}] \tag{2}$$

$$\mu_{ih}(u_j)=0.5\times\left(1-\frac{b_{ih}-x_{ij}}{b_{ih}-k_{ih}}\right) \quad x_{ij}\in[b_{ih}, k_{i(h+1)}] \tag{3}$$

where $\mu_{ij}(u_j)$ is the relative membership degree of index i of scheme j to level h and other variables are defined above. Note that the relative membership degree of x_{ij} is 0 when it is less than h and greater than $(h+1)$. Similarly, the relative membership matrix μ_h (u_{ij}) of each index of u_i is obtained, and the comprehensive relative membership vector of each scheme to level h is then calculated as follows:

$$V_h(u_j)=\frac{1}{1+\left\{\dfrac{\sum_{i=1}^{m}[w_i(1-\mu_{ih}(u_j))]^p}{\sum_{i=1}^{m}[w_i\mu_{ih}(u_j)]^p}\right\}} \tag{4}$$

where $V_h(u_j)$ is the relative membership degree of each index of scheme j to level h; w_i is the weight of index i; and $w_1+w_2+\ldots+w_m=1$; $\alpha=1$ with p as the distance parameter. In our analyses, we consider the Haiming distance $p=1$ (Qui *et al.* 2018) as the linear model of the comprehensive relative membership degree of the scheme to level h:

$$V_h(u_j) = \sum_{i=1}^{m} w_i \mu_{ih}(u_j) \tag{5}$$

The characteristic value in the corresponding level of scheme j is derived as follows:

$$H(u_j) = \sum_{h=1}^{c} v_h^0(u_j) \cdot h \tag{6}$$

where $v_h^0(u_j)$ is the normalized vector $(v_h(u_j))$. In this study, to form the evaluation system, we established the primary indicators affecting the WRCC. Because of certain complicated influence indicators, many factors are involved, and we used multivariate membership functions for judgment. Thus, we based the building of the evaluation indicator system on previous studies and the fuzzy mathematical theory.

Evaluation indicators for WRCC

The traditional concept of WRCC emphasized that water resources could afford the freshwater requirements of human activities, which should not affect the laws of nature; however, because of the development of various WRCC theories, the WRCC concept embraces a wider understanding such as allowance for maintaining the original natural state of the water cycle and the effect of climate change and human activities. Note that climate change affects the amount of water resources available regionally and determines the primitive carrying capacity of regional water resources (Zhang *et al.* 2017). Both water use and its efficiency are directly related to the level of regional economic and social development. Therefore, the primary point for evaluating the regional WRCC is to ensure that water use does not alter the natural water cycle and that the capacity of limited water resources can afford social uses of water (Chi *et al.* 2019; Zhang *et al.* 2019). In particular, the WRCC must first ensure that water resources are available and that water use is efficient. Second, the water resources should be sufficient to meet the requirements of human activities. Third, the management of water resources should be efficient in ensuring the normal waterbody function. Finally, water-based ecosystems should be considered a limited resource to meet human requirements. Based on the current description of WRCC, the concept of force subsystems is fundamental to its evaluation. For determining the regional WRCC, water resource is a critical element, but both water abundance and use must be considered. In particular, in densely populated areas, such as Shijiazhuang and Langfang, the social service function of water resources is quite competitive; therefore, water use is considered to be the utilization level of water resources. Furthermore, both regional population and economic scale are considered. For studying water management, all known or possible factors should be considered because the regional WRCC is limited. The study of WRCC indicators helps realize socially and ecologically sustainable development of water resources. Therefore, we established a water-carrying capacity evaluation indicator system with three dimensions, i.e., the support, pressure, and regulation force subsystems (SFS, PFS, and RFS), and four indicators for each criterion layer (Tables 1 and 2).

As demonstrated by the selected evaluation indicators, three dimensions can truly reflect the overall WRCC. Furthermore, the weight of the selected indicators is an important part of the evaluation system and is the basis for establishing the mathematical evaluation model. Between the evaluation system and factual data, the indicator weight of the comprehensive evaluation is in quantitative agreement. In this study, we used prior-published research results and experts' comprehensive analyses, as shown in Table 3 (Zhang *et al.* 2017).

Based on the relativity and uncertainty of the WRCC, as shown in Table 4, we divided the performance standard into five levels: carrying surplus, capable of carrying, moderate-carrying, slight over-carrying, and severe over-carrying (Cheng *et al.* 2016). The carrying-surplus level indicates that water use has little influence on the natural water cycle, and water resources can support both optimal social and ecological development of a region. Furthermore, the capable of carrying level indicates that the water use agrees with the natural water cycle, as coordinated development is maintained between them. The moderate-carrying level indicates that the natural water cycle has been affected by the water use and has exerted certain influence on the ecological environment of the region; however, the extent

Table 1 | Definitions of selected evaluation indicators

Index	Definition	Description	Notes
I1: Per capita GDP	GPDp = GDP/pou	GDP, the total GDp; pou, population	Unit: 10 thousand Yuan
I2: Water consumption per unit value added in industry	Wwai = Wind/Vind	Wind, water used by industry; Vind, added value in industry	Unit: m^3
I3: Water consumption rate	Rcon = Wcon/Wuse	Wcon, water consumption; Wuse, water used	Unit: %
I4: Average water resource amount per Mu	WApM = WA/Pagr	WA, agricultural water supplement; Pagr, total agricultural area	Unit: m^3; bearing capacity of water resources (for agricultural irrigation)
I5: Utilization ratio of water resources	Ruti = (Wsur + Wgrd)/Wtol	Wsur, surface water supply; Wgrd, groundwater supply; Wtol, total water resources	Unit: %
I6: Per capita water resources	Wper = Wtol/pou	Wtol, total water resources; pou, population	Unit: m^3
I7: Rate of groundwater supply	Rgrd = Wgrd/Wtol-sup	Wtol-sup, total water resource supply	
I8: Attainment rate of water function zone	Numstand/Num	Numstand, standard number; Num, total number of water function zones	
I9: Guarantee rate of ecological water demand	REco = Wrep/Wde	Wrep, ecological water supplement; Wde, ecological water demand	Unit: %; supply of ecological water
I10: Quantified rate of water quality	Rquan = Wquan/Wtoa	Wquan, quality water resources; Wtoa, total water resources	Unit: %
I11: Rate of standard river length	Rsr = Std/S	Std, standard river length; S, river length	Unit: %; quality of rivers
I12: Water consumption per unit value added	Wvau = Wvau/Vvau	Wvau, water used; Vvau, added value	Unit: m^3

Table 2 | Index system used for WRCC evaluation

Layer	Index		
Target layer	Water resource comprehensive carrying capacity		
Criterion layer	SFS	PFS	RFS
Indicator layer	I5, I6, I8, and I11	I1, I3, I9, and I12	I2, I4, I7, and I10

of influence is controllable. The slight over-carrying level indicates that the influence of water use has already threatened the natural water cycle, and the WRCC has reached an alert state. The severe over-carrying level indicates that the regional water resource demand has considerably exceeded the carrying range of the natural water cycle because of actual water use, and the natural water cycle has entered a vicious circle. The flowchart of this method can be seen in Figure 1.

Table 3 | Summary of index weights

Target layer	Criterion layer	Indicator layer	Total weight
Level of regional water-carrying capacity (100%)	SFS (37%)	I5	0.08
		I6	0.18
		I8	0.10
		I11	0.11
	PFS (32%)	I1	0.11
		I3	0.06
		I9	0.04
		I12	0.06
	RFS (31%)	I2	0.08
		I4	0.07
		I7	0.03
		I10	0.08

Study area

Shijiazhuang and Langfang are located in Hebei Province in northern China (Figure 2). Shijiazhuang (113°30′–115°29′E;

Table 4 | Carrying levels for evaluation indicators

Level	Carrying surplus	Capable of carrying	Moderate carrying	Slight over-carrying	Severe over-carrying
Carrying scores	5	4–5	3–4	2–3	1–2

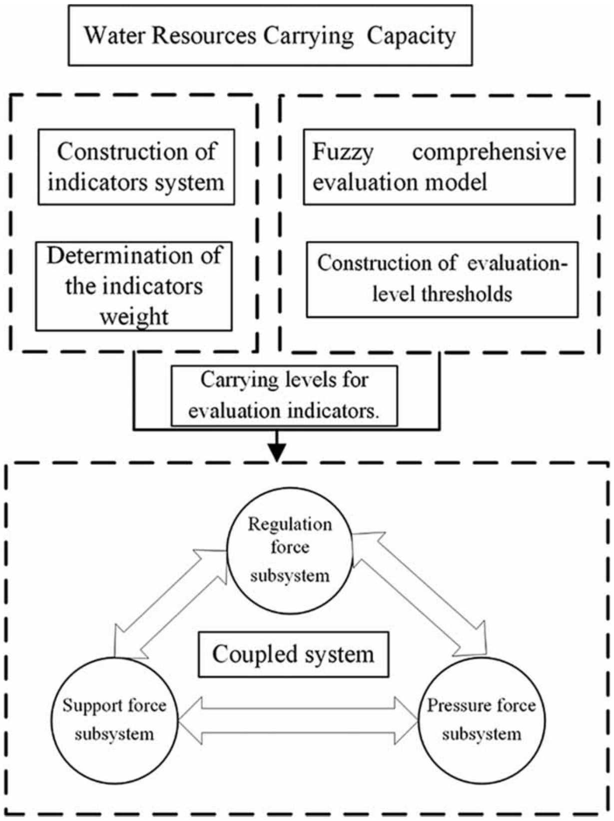

Figure 1 | Thoughts and flow chart of the methods.

37°27′–38°45′N), the capital of Hebei Province, is in the south central part of the province, on the western edge of the North China Plain, and toward the east of the Taihang Mountains. With an area of 13,126 km^2, Shijiazhuang had a permanent population of 10.07 million in 2015, and its gross domestic product (GDP) reached 544.06 billion RMB. After 1980, the socioeconomic development of Shijiazhuang has been in the leading position in the province with industrial capacity as its primary means of economic growth. However, the overexploitation of water resources in Shijiazhuang has recently been significant, and the amount of water resources in the region has significantly decreased. Furthermore, water resources show a significant downward trend in Langfang; the misalignment between water resource supply and demand is significant. Langfang (116°07′–117°15′E; 38°30′–40°05′N) has an urban area of 6,429 km^2. By the end of 2015, the population was 4.61 million, and the GDP reached 247.38 billion RMB. Precipitation records for 1981–2015 show that the annual average precipitation of Langfang is 509.2 mm, i.e., 3.274 billion m^3.

RESULTS AND DISCUSSION

Based on prior methods and our index evaluation system, we established two series of application schemes for regional water-carrying capacity for Shijiazhuang and Langfang. Data for the actual years 2006–2015 were collected and taken to be the evaluation object, and the carrying levels for all layers were evaluated. Then, for the requisite evaluation of future WRCC, the planning year 2016 was used as the benchmark year.

Evaluation of previous 10 years based on the indicator system

For the WRCC evaluation, the first step was to determine threshold levels for each indicator and to set the threshold range for features. Based on the relevant research results and government standards, the thresholds were set for various indicators (Table 5). Subsequently, the current values of all evaluation indicators for Shijiazhuang and Langfang were obtained from water-resource bulletins, various investigations, and measurements. In a recent period of 10 years, based on the water resources, water supply, and water-use statistics of these two typical cities (2006–2015), the above calculations were performed for each year. Figures 3 and 4 show detailed water-use and other relevant information for Shijiazhuang and Langfang. Because of the obtained eigenvalues for each scheme level, we determined that the better schemes were associated with larger levels. We could then compute a specific numeric value within the status assessment yield using which we could improve our understanding of the connection between the level degree and the three dimensions (SFS, PFS, and RFS).

Figure 5 shows the evaluation scores for each of the three dimensions of the evaluation indicator system and

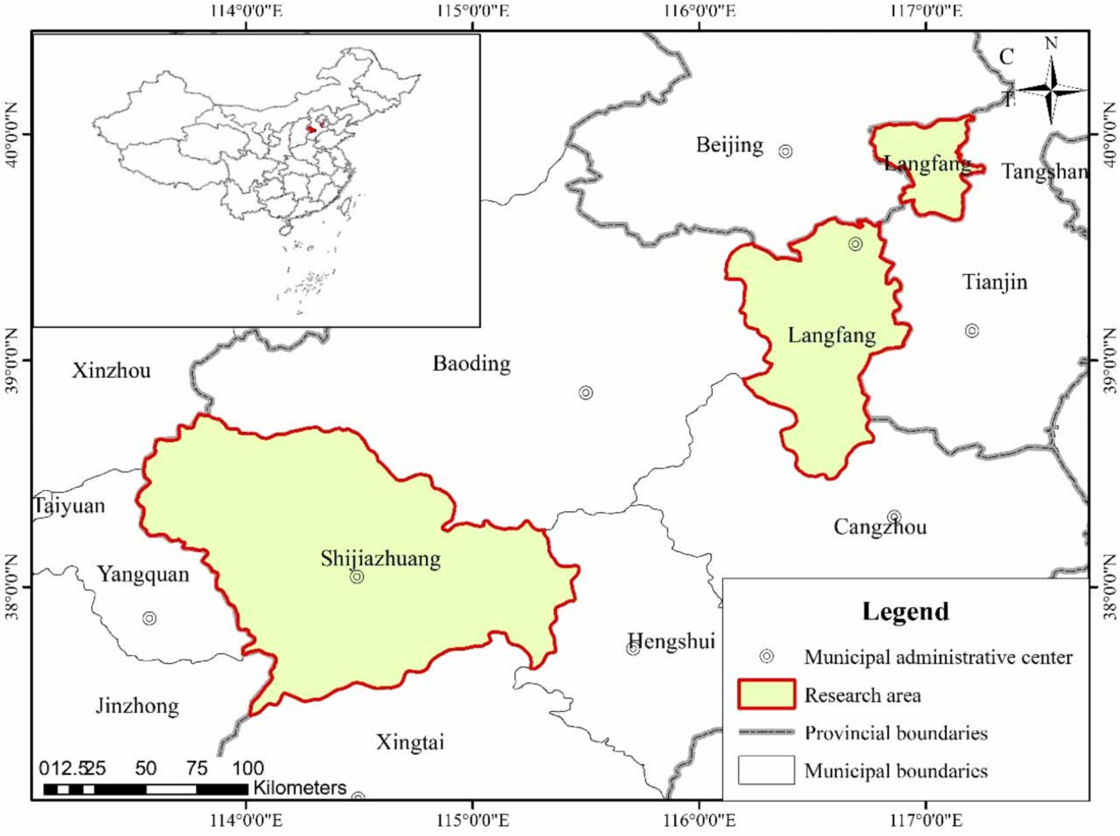

Figure 2 | Locations of Shijiazhuang and Langfang in China.

Table 5 | Evaluation-level thresholds and corresponding score interval for indicators

Indicator	**Unit**	**Carrying surplus 5**	**Capable of carrying (5, 4)**	**Moderate carrying (4, 3)**	**Slight over-carrying (3, 2)**	**Severe over-carrying (2, 1)**
I1	%	≤3	(3, 6)	(6, 9)	(9, 14)	>14
I2	m^3	≤300	(300, 500)	(500, 800)	(800, 1,000)	>1,000
I3	%	100	(100, 80)	(80, 50)	(50, 30)	(30, 0)
I4	m^3	≥1,500	(1,500, 1,000)	(1,000, 800)	(800, 500)	(500, 0)
I5	%	≤30	(30, 50)	(50, 70)	(70, 90)	(90, 200)
I6	m^3	>500	(500, 400)	(400, 200)	(200, 100)	≤100
I7	%	≤15	(15, 25)	(25, 40)	(40, 50)	>50
I8	%	100	(100, 80)	(80, 50)	(50, 30)	(30, 0)
I9	%	>100	(100, 90)	(90, 50)	(50, 30)	≤30
I10	%	100	(100, 98)	(98, 95)	(95, 90)	(90, 0)
I11	%	100	(100, 80)	(80, 50)	(50, 30)	(30, 0)
I12	m^3	≤10	(10, 20)	(20, 35)	(35, 50)	>50

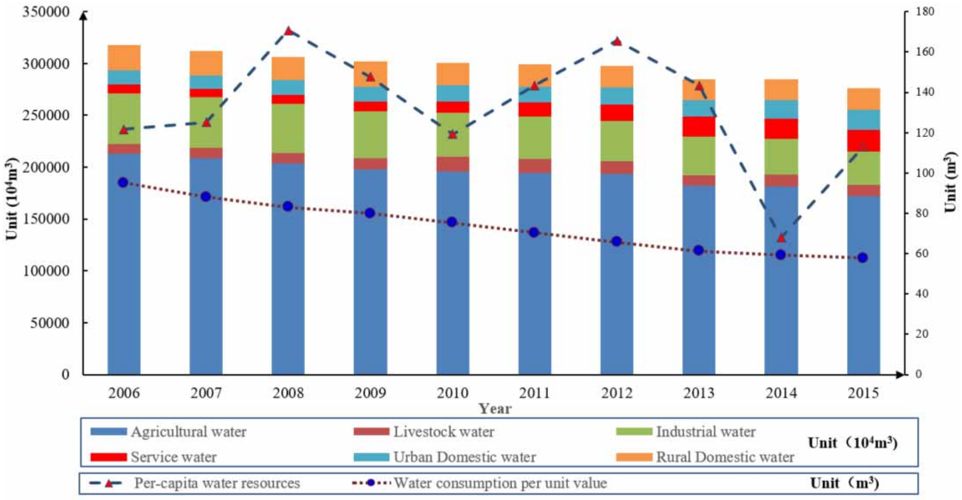

Figure 3 | Water use during 2006–2015 in Shijiazhuang, China.

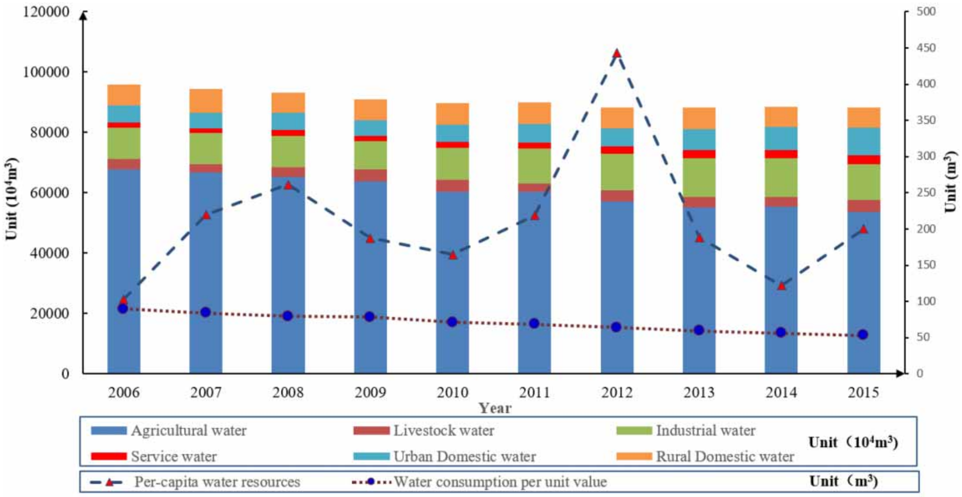

Figure 4 | Water use during 2006–2015 in Langfang, China.

the carrying level for both Shijiazhuang and Langfang for each year during 2006–2015. In Figure 5, the black dotted line means severe over-carrying, the red dotted line means slight over-carrying, the violet dotted line means moderate carrying, the blue dotted line means capable of carrying, and the green dotted line means carrying surplus. Figure 5 shows the carrying-level performance of each dimension and city. In this figure, the carrying level of each dimension means the accumulation of the carrying level of these indicators in this dimension, and the level is the water resource carrying level based on the three dimensions and indicator weight system. Figures 6 and 7 show the trends of each dimension and carrying level for both Shijiazhuang and Langfang. During 2006–2015, the status of the regional water-carrying capacity for both cities was all slightly over-carrying, and the carrying levels show an interannual increasing trend.

For the SFS dimension, the lower evaluation scores are the primary reason for the lower carrying levels (apart from 2012). During the 10-year study period (except for 2012) for Langfang, the water-use shortage was met by groundwater exploitation, and the coefficient of groundwater was >1.0. In 2012, the abundant rainfall obviously enhanced certain indicators for Langfang. SFS evaluation scores were in the range of 1.89–2.67 for Shijiazhuang and 1.98–3.46 for Langfang, which show a slight over-carrying state because both cities were experiencing considerable water shortage, a

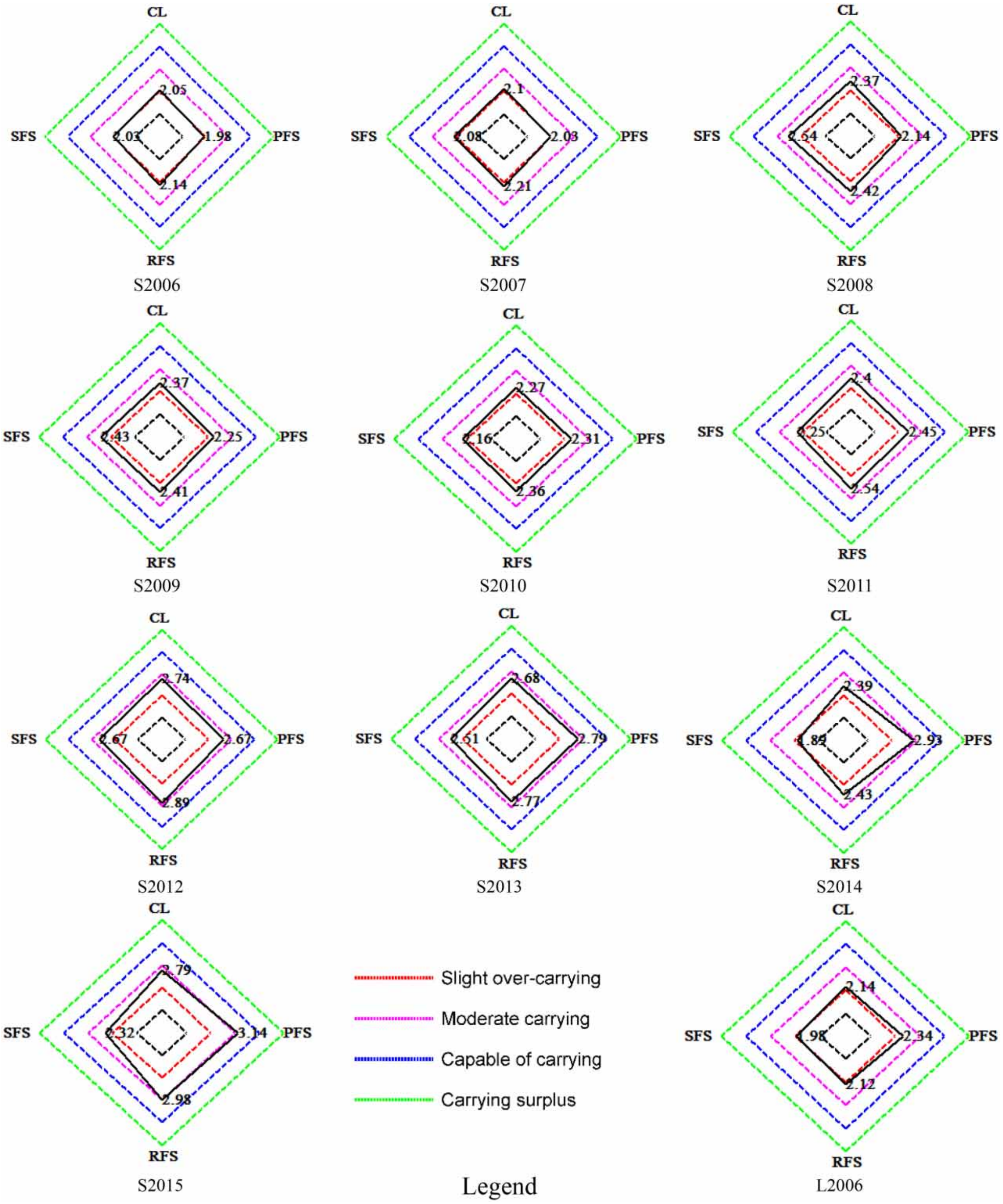

Figure 5 | Carrying scores for three dimensions and carrying levels for Shijiazhuang (S) and Langfang (L), China, during 2006–2015. CL, carrying level (in red color); PFS, pressure force subsystem; RFS, regulation force subsystem; SFS, support force subsystem. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wcc.2021.203. *(continued.)*.

scarcity that originated from the unique regional climate. Both the lower guarantee rates of ecologically sustainable water supply and excessive groundwater exploitation were the primary reasons that led to the assessment of water ecology as inadequate. Furthermore, the actual situation revealed that the poor quality of natural rivers is a common problem for both cities and demonstrated the gap that had to be closed to attain the best level from the

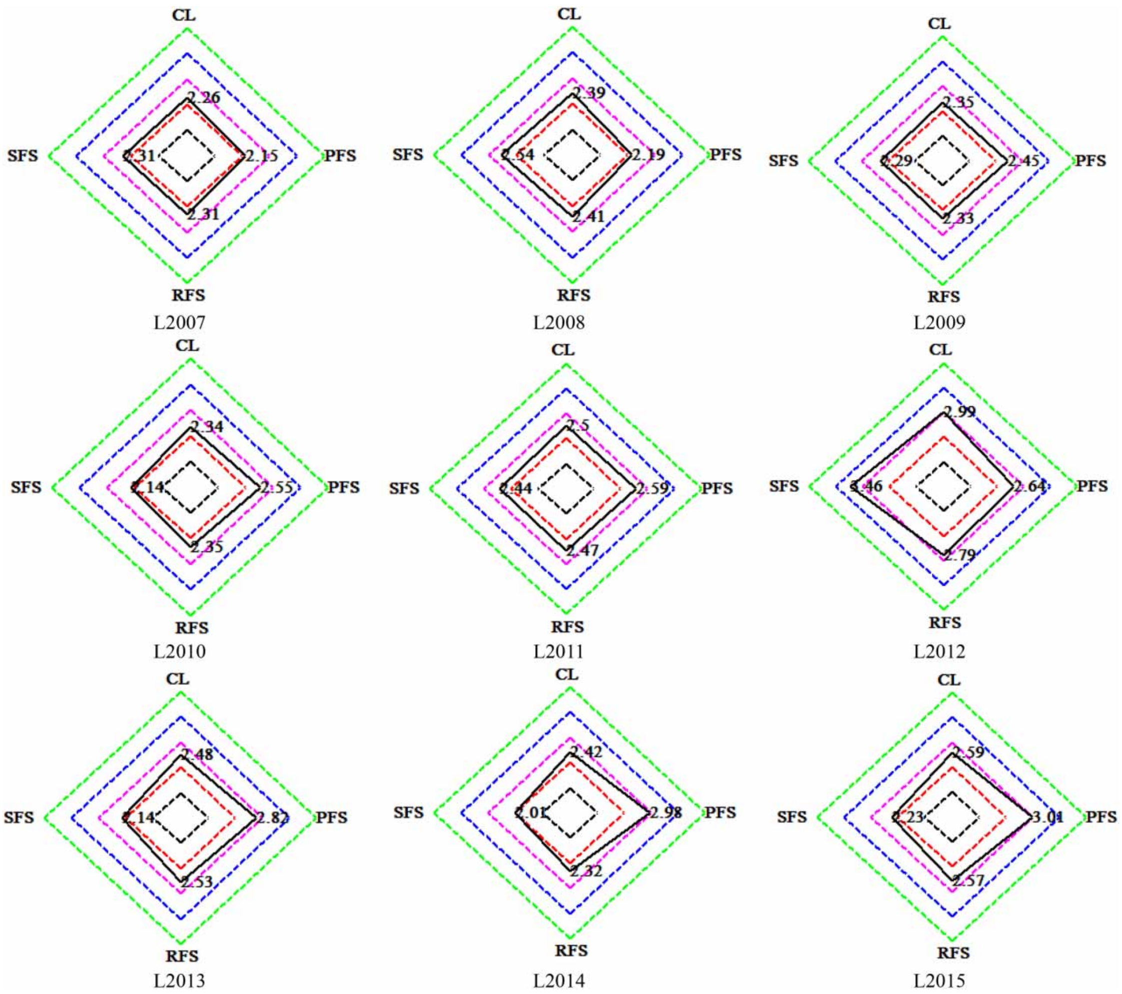

Figure 5 | Continued.

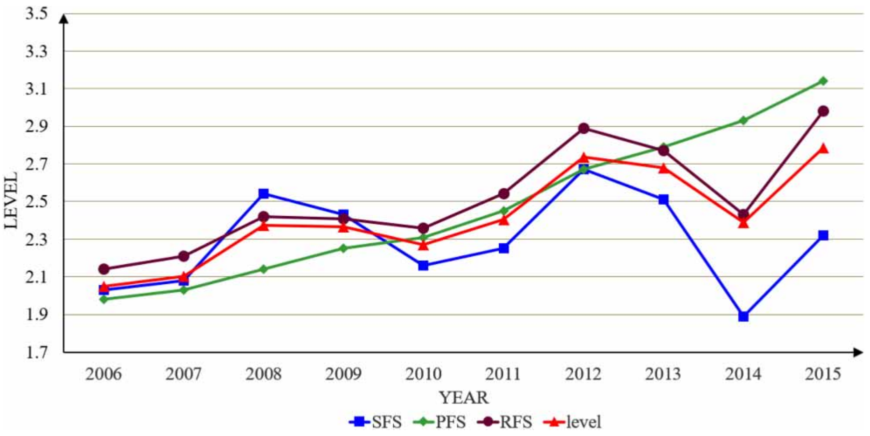

Figure 6 | Trend of each dimension and carrying level in Shijiazhuang, China. PFS, pressure force subsystem; RFS, regulation force subsystem; SFS, support force subsystem.

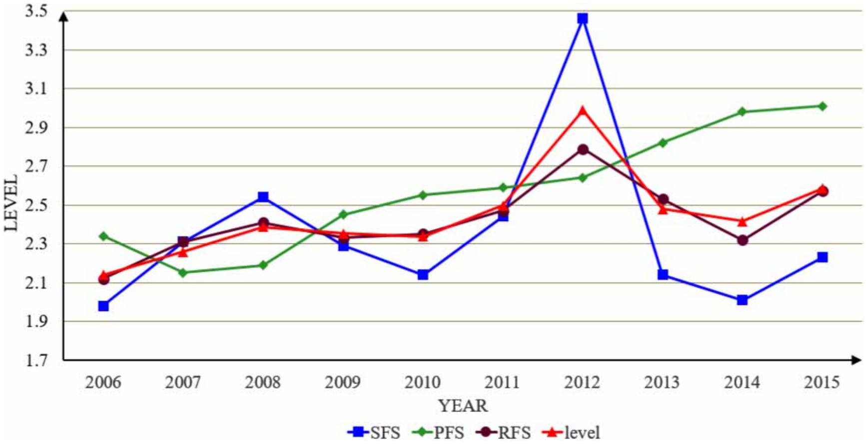

Figure 7 | Trend of each dimension and carrying level in Langfang, China. PFS, pressure force subsystem; RFS, regulation force subsystem; SFS, support force subsystem.

worst level. For both cities, the evaluation results for the PFS dimension (Figures 6 and 7) clearly show an interannual increasing trend in the recent 10-year period from 2006 to 2015. Owing to limited water resources, water use in both cities has reached a relatively critical level. In particular, in Shijiazhuang, industrial structure upgrades and the reduction of the elevated water consumption have led to reduced pressure on water resources, which in turn has improved the levels in the PFS dimension, thus reflecting a stage improvement from severe over-carrying to moderate carrying. For both cities, a higher efficiency of agricultural water use has benefited the limited capacity of regional water resources. The evaluation recognition results indicate that the carrying level has attained a relatively significant improvement across PFS, which has shown the greatest improvement among the three dimensions. Overall, the improvement in PFS is the primary reason for carrying-level improvement for both cities in the studied 10-year period. For the RFS dimension, owing to the water shortage in both cities, the management of water resources has reached a relatively high level. RFS evaluation scores, in the range of 2.14–2.98 for Shijiazhuang and 2.12–2.79 for Langfang, have shown an interannual increasing trend. In both cities, the water-use level has significantly influenced the balance between water demand and supply, which is the primary approach to govern the use of water resources. For both cities, the calculations involving RFS reveal considerable differences in relation to regional industries. Thus, to optimize the management of water resources, it is necessary to foster and strengthen interregional exchanges and cooperation.

Discussion

During 2006–2015, the overall status of WRCC in Shijiazhuang and Langfang is that of slight over-carrying. Note that, in both cities, the scarcity of water resources has been the primary impetus for achieving higher carrying levels. Furthermore, to enhance regional water–resource-carrying levels, improvements in water quality and quantity have been essential approaches. The higher water-use efficiency in Shijiazhuang (compared to Langfang) is the primary reason for better performance in the carrying evaluation. Interbasin water transfer might meet the land uneven distribution of water resources; however, because of the development of the regional economy, industry restructuring must match the regional WRCC to ensure compatibility between development and water resources. Furthermore, for selected cities in northern China, the health status of the regional water ecology should not be ignored. To date, in both Shijiazhuang and Langfang, the overexploitation of groundwater is the most significant challenge for enhancing the regional WRCC. To improve the carrying level for the two cities, the groundwater exploitation should be rational, and the requirement for ecologically sustainable water use must be met. In this study, we determined that the improvement of available water quantity and the efficiency of its use are the primary ways to enhance the regional WRCC level. Considering the limitations of objective conditions, regionally sustainable development must ensure the efficient use within the carrying capacity. Considering major regional differences between the two cities, local governments should upgrade the levels of water use via optimization and industrial adjustments, while certain industries should be relocated to areas with greater water resources. To assess the carrying levels of Shijiazhuang and Langfang within the context of the regional WRCC, we used the fuzzy comprehensive evaluation model and the composite indicator evaluation system. The evaluation model and indicator system offered complementary functions; moreover, the composite indicator evaluation system assessment provided carrying scores for various dimensions, and the fuzzy comprehensive evaluation model revealed relative membership to reflect carrying status. Using a combination of the two methods, we established an indicator-based formation and evaluation system to assess the carrying status of the regional WRCC.

CONCLUSION

In this study, the methods used were comprehensive and practical evaluation while addressing several dimensions of regional WRCC. For evaluating carrying levels of a recent 10-year period, their application in the cities of Shijiazhuanag and Langfang is shown to be effective. Because of theoretical development using the fuzzy evaluation model, we managed to quantify the relationship between limited water resources and water use. By allocating evaluation indicators and assigning relative weights, the existing problems could be diagnosed when these methods were applied for evaluating the regional WRCC for different areas. The results of evaluation methods used demonstrated that the status of regional water-carrying capacity for Shijiazhuang and Langfang is slight over-carrying, and the carrying levels showed an interannual increasing trend. Based on the derived values of indicator performance, we determined that, for both cities, limited water resources may be the primary reason for the low regional WRCC. In the recent 10-year period of 2006–2015, the improvement in the PFS dimension is the primary reason for carrying-level improvement for both cities, within which an interannual increasing trend was seen. For the RFS dimension, evaluation scores were in the range of 2.14–2.98 for Shijiazhuang and 2.12–2.79 for Langfang. Moreover, the continuing trend of increasing RFS can improve the regional WRCC. Overall, we provided a regional development strategy by the evaluation of the two cities. A simulation of regional WRCC demonstrating how to meet the water shortage in relation to the regional population could assist in forming a sustainable regional development strategy; however, the evaluation process is complicated. Furthermore, in this study, the methods that we used have certain limitations related to the compilation of various data, regional policies, and social challenges. For the evaluation process, the thresholds of selected indicators should realistically reflect all dimensions or characteristics of regional water supply and demand.

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DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories (http://slt.hebei.gov.cn/a/2019/09/16/2019091638248.html).

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