EVALUATION OF WATER RESOURCE'S CARRYING CAPACITY BASED ON THREE-ELEMENT CONNECTION NUMBER
A Case Study of Beijing-Tianjin-Hebei Region

by

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This study is to analyze the relationship between human settlements system and water resources, select the water resource's carrying capacity index, and construct a system based on the human settlements system theory for the water resource's carrying capacity index. The index weight is determined by the analytic hierarchy process, and the set pair analysis method is used to calculate the connection number and evaluation grade of samples in Beijing, Tianjin, and Hebei Province from 2016 to 2019. The results show that there are differences in water resources carrying capacity from the perspective of human settlements in Beijing, Tianjin, and Hebei Province, and the changing trend of water resources carrying capacity in the three regions is different. The introduction of human settlement theory into the construction of water resource's carrying capacity index system can better reflect the carrying capacity of water resources to human society and can provide a new perspective for other related research in the future.

Key words: *water resources carrying capacity, human settlements, set pair analysis, three-element connection number*

Introduction

Water is one of the most necessary resources for human survival, furthermore, the development of human society is inseparable from water. The water resources system will restrict the development of human society. If human beings use water resources blindly without restraint, it will also have transitional interference and adverse impact on the water resources system, resulting in serious consequences. Water resources and the ecological environment have been closely related to the development of the human economy and society. The imbalance of the water resources system will also lead to the imbalance of development and evolution between the *water resources, economy, society and ecological environment* comprehensive system [1]. Nowadays, water resources have become an important factor restricting the sustainable development of the social economy and maintaining the health of the ecological environment. Water resources are closely related to social development and people's daily life. On the one hand, water resources provide operating power for factories and enterprises,

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supplement human body water and support the normal operation of society. On the other hand, the change in society and the change in water use mode will be reflected in the change of water resources and affect the state of water resources.

To grasp the situation of water resources in a certain area and timely adjust the water resources supporting social operation or the source of pressure caused by water resources, it is necessary to measure the matching degree between water resources and the social and economic development of a certain area. The evaluation of water resources carrying capacity can quantitatively measure the carrying status of water resources in a certain area, and judge whether the water resources in a certain area are sufficient to continue to support the normal operation of society by integrating the characteristics of water resources such as water quality and quantity in a certain area and the overall situation of the area, and evaluating and analyzing different evaluation methods. Chinese scholars define water resources carrying capacity as the maximum population or socio-economic development scale that a region's water resources can continuously support in a certain period, under certain economic and technological conditions and living standards [2].

In the existing research on the evaluation of water resources carrying capacity, more consideration has been given to the quantity and quality of water resources, as well as the socio-economic situation, but there is a lack of subjective consideration of people and the combination of population and socio-economic development. Therefore, this study introduces the concept of the human settlement into the construction of the index system of water resources carrying capacity and takes more account of the water resources carrying capacity required by the human settlement by selecting indicators from the perspective of the human settlement. The human settlement system can be further divided into five systems: residential system, support system, human system, social system, and natural system. These five systems have the problem of how to face sustainable development [3]. The living system involves living material conditions, and water resources mainly support the consumption of ecological water. The support system involves the infrastructure of human settlements. The human system and social system are the main consumers of water resources. These two systems are the systems that cause pressure on the water resources system. The natural system covers the overall natural environment of the living environment, including the resource support and natural landscape provided by water resources.

Study area

Beijing, abbreviated as *Jing*, is the capital of the people's Republic of China and the political and cultural center of China. Tianjin hereinafter referred to as *Jin*, is one of the municipalities directly under the central government of the people's Republic of China. It is also a national central city and the first batch of coastal open cities. Hebei Province hereinafter referred to as *Ji*, Hebei, hereinafter referred to as *Ji*, is one of the provincial administrative regions of the people's Republic of China and the provincial capital Shijiazhuang.

Beijing, Tianjin, and Hebei Province are located in North China with dense populations and rapid social development. The research on water resources carrying capacity in Beijing, Tianjin, and Hebei is the basis of resource and environmental assessment in Beijing, Tianjin, and Hebei, which provides the scientific basis and decision support for water resources utilization and population development for Beijing, Tianjin, and Hebei metropolitan area planning [4].

Methods

Construction of index system

According to the five systems of a residential system, support system, human system, social system, and natural system, combined with the connotation of water resources carrying capacity and considering the operability of evaluation, the indicators are selected. Based on the idea of five systems of human settlements and the relationship between water resources and these five systems, the evaluation index system of water resources carrying capacity is constructed. Water resources are a part of natural resources. For the natural system, the total amount of water resources and surface water resources are selected as representatives. The aspects related to water in the social system include socio-economic development and social welfare. This paper selects two indicators: regional GDP and investment in industrial pollution control to reflect the social support for water resource consumption. The human system needs to select the index that can reflect the water consumption of human life. The urban population density is selected as the representative of domestic water. This index is the index of pressure caused by the water supply resource system. The living system and support system respectively select the indicators of harmless treatment rate of domestic waste, greening coverage rate of built-up areas, and road area to reflect other conditions of human settlements and supplement the parts not involved in the above indicators. According to the above ideas, the evaluation index system of water resources carrying capacity based on the perspective of human settlements is constructed, as shown in fig. 1.

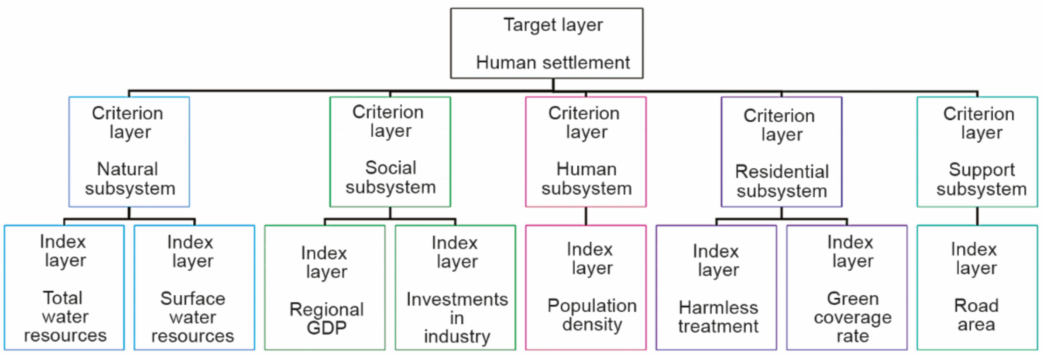

Figure 1. Evaluation index system of water resources carrying capacity based on the perspective of human settlement

Weight determination

There are two methods to determine the weight, subjective method and objective method. The subjective weight determination methods used in the evaluation of water resources carrying capacity mainly include the analytic hierarchy process. Due to the complex relationship between water resources and human settlements and the limitations of index selection, an analytic hierarchy process is used to determine the weight. When judging the relative importance between indicators, refer to the consistent matrix method proposed by Saaty *et al.* [5] and use the numbers 1-9 and their reciprocal as the scale.

Calculation steps of set pair analysis

Set pair analysis is a method to deal with the uncertainties in practical problems [6]. The set pair analysis method is used to calculate the connection coefficient, which can be further evaluated and analyzed according to the connection number. Referring to the dynamic evaluation method of water resources carrying capacity proposed by Li *et al.* [7], calculate the connection number of evaluation samples, three-element connection number, and evaluation index value respectively, and then calculate the average connection number and obtain the evaluation grade on this basis. The specific steps are:

– Calculate the three-element connection number of evaluation samples and judge the overall trend of samples:

$$u_{1i} = v_{1i1} + v_{1i2}I + v_{1i3}J \tag{1}$$

where u_{1i} is the connection number of evaluation samples, and v_{1i1}, v_{1i2}, and v_{1i3} – the identity, difference and opposition of set pairs, respectively, and I, J – the difference coefficient and opposition coefficient respectively.

– Calculate the three-element connection number and evaluation index value connection number, and analyze the cause of the general trend of the sample through the changing trend of a certain index of each sample:

$$u_{2i} = v_{2i1} + v_{2i2}I + v_{2i3}J \tag{2}$$

where u_{2i} is the connection number of the evaluation index value, and v_{2i1}, v_{2i2} and v_{2i3} – the identity, difference and opposition of set pairs respectively.

– Calculate the average connection number, determine the evaluation grade, and judge the state of sample water resources carrying capacity through the sample evaluation grade and evaluation index grade value:

$$v_{ik} = \frac{(v_{1ik}v_{2ik})^{0.5}}{\sum_{k=1}^{3}(v_{1ik}v_{2ik})^{0.5}}, \quad u_i = v_{i1} + v_{i2}I + v_{i3}J \ (i = 1, 2, \cdots, n_i) \tag{3}$$

where v_{ik} refers to the geometric average of the coefficient of connection number of evaluation index value and u_i is the average number of contacts, k = 1, 2, 3.

Study case

Data description

According to the indicators determined according to the previous ideas, the corresponding index data of Beijing, Tianjin, and Hebei Province from 2016 to 2019 are obtained from the data query system of the National Bureau of statistics.

Index system and weight

Considering the relative importance of each index, obtained judgment matrix. After calculation, Cr = 0.099286, which passed the consistency test. The calculated weight vectors are {0.33748, 0.150776, 0.203327, 0.078148, 0.037444, 0.060379, 0.102849, 0.029597}.

Set classification for indicators, distinguish the bigger the better type and the smaller the better type, and set three levels and four dividing points S0, S1, S2, and S3, where S1 is the dividing point between the optimal level and the intermediate level, S2 is the dividing point between the intermediate level and the worst level, and S0 and S3 are the boundary points of sample data.

Results and discussion

Calculate the index data according to the above calculation steps of the set pair analysis method. According to the calculation of the connection number of evaluation samples, tab. 1, it can be seen that there is polarization in different sample indicators in Beijing and Tianjin. For example, there are indicators with values at level 1 and level 3 in 2017 and 2019, but there are no indicators at level 2.

Table 1. Sample connection number for evaluation of water resources carrying capacity in Beijing, Tianjin, and Hebei in the Beijing-Tianjin-Hebei region

Area	2016	2017	2018	2019
Beijing	0.2788 + 0.6916I + 0.0296J	0.4821 + 0I + 0.5179J	0.4821 + 0.4883I + 0.0296J	0.4040 + 0I + 0.5960J
Tianjin	0.0781 + 0.1508I + 0.7711J	0.0781 + 0I + 0.9219J	0.0781 + 0I + 0.9219J	0.1385 + 0I + 0.8615J
Hebei	0.7993 + 0.2007I + 0J	0.8597 + 0.1403I + 0J	0.8597 + 0.1028I + 0.0374J	0.8597 + 0.1028I + 0.0374J

The connection numbers of index values of each sample in Beijing, Tianjin, and Hebei Province are calculated respectively. The calculation results take the data of Beijing as an example (see tab. 2), and the status of specific index values can be judged from each link number.

Table 2. Connection number of evaluation index of water resources carrying capacity in Beijing

Indicators	2016	2017	2018	2019
The total amount of water resources	0 + 0I + 1J	0.0393 + 0.5I + 0.4607J	0 + 0I + 1J	0.0364 + 0.5I + 0.4636J
Surface water resources	0 + 0I + 1J	0.0176 + 0.5I + 0.4824J	0 + 0I + 1J	0.0135 + 0.5I + 0.4865J
Regional gross domestic product	1 + 0I + 0J	0.7609 + 0.2391I + 0J	0.5724 + 0.4276I + 0J	0.4401 + 0.5I + 0.0599J
Complete investment in industrial pollution control	0 + 0I + 1J	0.5493 + 0.4507I + 0J	0.6163 + 0.3837I + 0J	0.5591 + 0.4409I + 0J
Urban population density	0.8795 + 0.1205I + 0J	0.8803 + 0.1197I + 0J	0.8741 + 0.1259I + 0J	0.8734 + 0.1266I + 0J
Harmless treatment rate of municipal solid waste	1 + 0I + 0J	1 + 0I + 0J	0.9524 + 0.0476I + 0J	0.9091 + 0.0909I + 0J
Green coverage rate in built-up area	0.7692 + 0.2308I + 0J	0.7576 + 0.2424I + 0J	0.7576 + 0.2424I + 0J	0.7576 + 0.2424I + 0J
Road area	0 + 0I + 1J	0 + 0I + 1J	0 + 0I + 1J	0 + 0I + 1J

By calculating the connection number and average connection number of the evaluation index value, the comprehensive evaluation grade value can be obtained, tab. 3, and the comprehensive evaluation grade value can be visualized by using ArcGIS software, fig. 2. It can be seen that the evaluation grade values in Tianjin in the past four years are high, while those in Hebei Province are low, and the fluctuation in Beijing is obvious.

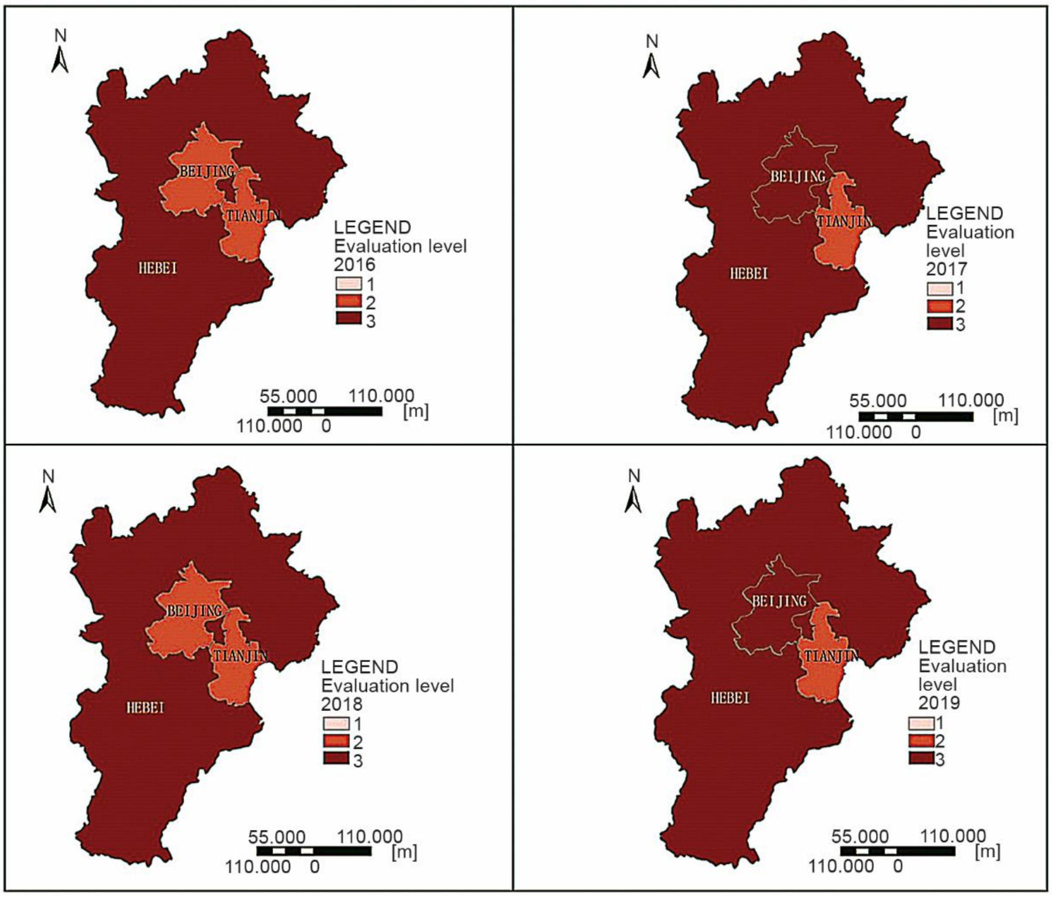

Figure 2. Comprehensive evaluation grade of water resources carrying capacity in the Beijing-Tianjin-Hebei region

Table 3. Comprehensive evaluation grade of water resources carrying capacity in the Beijing-Tianjin-Hebei region

Area	2016	2017	2018	2019
Beijing	1.7766	2.1278	1.6331	2.2094
Tianjin	2.7501	2.8826	2.8804	2.7533
Hebei	1.2222	1.2442	1.2786	1.2899

Single index evaluation is carried out through the evaluation index grade value, The main factors affecting the bearing capacity of the overall water resources group in an area are analyzed, tab. 4. It can be seen that except for the amount of surface water resources, the investment in industrial pollution control, and the harmless treatment rate of domestic waste, other indicators in Tianjin are at the worst level, which is also the reason for the high evaluation level values of Tianjin in the past four years. Except for the urban population density, Hebei Province is at the worst level, which is the same as the evaluation level of Hebei Province in the past four years. The values are consistent with the lower results. The road area, total water resources, surface water resources, and investment in industrial pollution control in Beijing have samples at the worst level, of which more in 2017 and 2019 are the reasons for the fluctuation of the evaluation grade value.

Table 4. Evaluation grade of the single index of water resources carrying capacity in the Beijing-Tianjin-Hebei region

Area	Indicators	2016	2017	2018	2019
Beijing	The total amount of water resources	2.4271	3.0000	2.4214	3.0000
	Surface water resources	2.4730	3.0000	2.4649	3.0000
	Regional gross domestic product	1.6199	1.4276	1.2391	1.0000
	Complete investment in industrial pollution control	1.4409	1.3837	1.4507	3.0000
	Urban population density	1.1266	1.1259	1.1197	1.1205
	Harmless treatment rate of municipal solid waste	1.0909	1.0476	1.0000	1.0000
	Green coverage rate in the built-up area	1.2424	1.2424	1.2424	1.2308
	Road area	3.0000	3.0000	3.0000	3.0000
Tianjin	The total amount of water resources	3.0000	3.0000	3.0000	3.0000
	Surface water resources	2.4703	3.0000	3.0000	3.0000
	Regional gross domestic product	3.0000	3.0000	3.0000	3.0000
	Complete investment in industrial pollution control	1.4365	1.4586	1.4374	1.4154
	Urban population density	3.0000	3.0000	3.0000	3.0000
	Harmless treatment rate of municipal solid waste	3.0000	3.0000	3.0000	1.0000
	Green coverage rate in the built-up area	3.0000	3.0000	3.0000	3.0000
	Road area	3.0000	3.0000	3.0000	3.0000
Hebei	The total amount of water resources	1.0000	1.3926	1.2898	1.4668
	Surface water resources	1.0000	1.4509	1.2693	1.4937
	Regional gross domestic product	1.4836	1.3922	1.2838	1.0590
	Complete investment in industrial pollution control	1.2644	1.0819	1.1301	1.0000
	Urban population density	2.1590	2.1750	3.0000	3.0000
	Harmless treatment rate of municipal solid waste	1.5667	1.0909	1.0909	1.2308
	Green coverage rate in the built-up area	2.3400	2.1400	2.1800	2.0400
	Road area	1.4029	1.3383	1.1932	1.1269

Conclusions

By introducing the theory of the human settlements system, this paper constructs the evaluation index system of water resources carrying capacity considering human settlements. The preliminary judgment of regional water resources carrying capacity state is carried out through the overall connection number of samples and evaluation grade value, and then the determinants or influencing factors of regional water resources carrying capacity state are analyzed through the connection number component of sample index value and single index evaluation grade value. Overall, there are obvious differences in water resources carrying capacity from the perspective of human settlements in Beijing, Tianjin, and Hebei Province. The water resources carrying capacity of Hebei Province is good, followed by Beijing and Tianjin. In addition, the changing trend of water resources carrying capacity in the three regions is different, which is mainly reflected in the trend that the water resources carrying capacity of Tianjin increase first and then decreases slightly, the water resources carrying capacity of Hebei Province increases slowly, while the water resources carrying capacity of Beijing fluctuates greatly.

Compared with other research results on the evaluation of water resources carrying capacity in Beijing, Tianjin, and Hebei, this result is more consistent with the result [2] of using the load index value through the carrying population of water resources and is less consistent with the result [8] of the measurement method based on quantity quality domain flow. The reason may be that the latter split cities in Hebei Province in the evaluation process of Hebei Province, the state of water resources carrying capacity in a small area can be compared in more detail. The evaluation method used in this paper can also further collect data, refine the evaluation results in a smaller regional scope, and find more influencing factors by adding evaluation indicators, which can be further studied and discussed in the future, additionally the effect of the mountain-river structure [9] and uncertainties [10, 11] on water resource is another topic in future, and thermal science will play an important role [12, 13].

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