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Research on water resource carrying capacity of capital water conservation functional zone

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Water resources are important for supporting regional economic development. A scientific and reasonable evaluation of the carrying capacity of water resources is of high significance to regional sustainable development. Zhangjiakou City is China's first capital water conservation functional area, which plays a role in ensuring the safety of water resources and ecological environment in the capital. Considering Chicheng County, Zhangjiakou City, as a typical area, its water resource carrying capacity in the current year (2018) and the plan year (2025) is evaluated by constructing a water resource carrying capacity evaluation index system for the county, determining the threshold of the bearing capacity evaluation index, and using the single-factor evaluation method and cloud theory method. In addition, the main factors affecting the water resource carrying capacity of Chicheng County are analyzed. The results show that: Based on the single factor evaluation results, the critical state of water resources carrying capacity was evaluated comprehensively, and the factor carrying capacity of total water consumption in the predicted planning level year (38.0603 in normal water year and 41.3403 in dry water year) does not exceed the total water consumption index (51.14). Furthermore, The water resources carrying capacity level of the present level year (.45) and the planned level year (.46) belong to the third level of the evaluation index system. There is further scope for the carrying capacity of water resources in Chicheng County to satisfy its economic and social development. However, it is urgent to solve the problems affecting the water quality elements of rivers, such as heavy river water pollution, low sewage treatment capacity, and weak pollution monitoring and supervision. It is necessary to optimize the industrial economic structure of Chicheng County, accelerate the improvement of water resources management system and mechanism, and ensure the long-term safety of water resources and ecological environment in the capital.

KEYWORDS

capital water conservation functional zone, water carrying capacity, single-factor evaluation, cloud theory, Chicheng County

1 Introduction

As the most basic natural resource, water resources not only provide the necessary material basis for the socio-economic development of the region and the virtuous cycle of ecological environment, but also one of the places with the most serious pollution (Yang et al., 2016; Jin et al., 2018; Zhang, 2019). China confronts water shortages. The study of the carrying capacity of water resources is of high significance to the sustainable development of its social economy (Wang et al., 2021). A reasonable and complete evaluation index system for the carrying capacity of water resources can improve the accuracy of the evaluation results and provide guidance for decision makers to make more scientific decisions (Wan, 2015).

At present, the evaluation methods for water resource carrying capacity mainly include the fuzzy comprehensive evaluation method, gray correlation analysis method, principal component analysis method, and set pair analysis method. Zhou Yanmei used the fuzzy comprehensive evaluation model to predict the carrying capacity of water resources in Heze City from 2020 to 2030 (ZHOU et al., 2021). Tong Changfu used the grey correlation degree analysis method to evaluate the bearing capacity of water resources in Ordos City and each sub-district (Tong et al., 2009). Lumin used the principal component analysis method to comprehensively evaluate the bearing capacity of water resources in Linyi City (Lu et al., 2016). Tang Aizhu used the set pair analysis method to diagnose and identify the evolution characteristics and vulnerability indicators of the water resource carrying capacity in Guiyang City from 2005 to 2017 (Tang and He, 2021). The single factor evaluation method is rarely used in the evaluation of water resources carrying capacity. Li, (2006) used the fuzzy single factor evaluation method to carry out a case study on the current situation of water resources carrying capacity of Linjiang River basin and analyzed the water resources carrying capacity of the basin. According to the single factor evaluation standard, Zhang, (2018) evaluated the total surface water carrying capacity and the total groundwater extraction carrying capacity respectively in Jimusi City, and the comprehensive evaluation result was serious overload. The number of single factor evaluation indicators has a significant impact on the evaluation results. The more the number, the more reliable the comprehensive evaluation results. Cloud model can reveal the randomness and fuzziness of objective events and realize the quantitative expression and objective evaluation of indicators. With the deepening of research, cloud model has been widely applied. Su Yangyue (Su et al., 2017) took the fuzzy comprehensive evaluation method as the main framework of evaluation, used the cloud model to grasp the uncertainty of the index quantity, built the improved evaluation model based on the cloud model and the fuzzy comprehensive evaluation method, and evaluated the water resources management of Huizhou City. Yang Lizhi (Yang et al., 2014) introduced the research idea of "cloud model" and carried on the quantitative expression and objective evaluation of the potential risks of water resource disputes between our country and 4 countries on the southwest border.

Ji Feng used the fuzzy comprehensive evaluation model to evaluate the carrying capacity of water resources in Zhangjiakou City considering the relevant research (Ji et al., 2012). Liu Yijiang combined the entropy right method with the multi-level comprehensive fuzzy evaluation method to study and analyze the current situation of water resource carrying capacity and the development and transformation of water resources in Zhangjiakou City (Liu et al., 2020). Ma Zhengang et al. used the comprehensive index method to calculate the variations in the water resource carrying capacity of Zhangjiakou City in the past 5 years and analyzed the main influencing factors (Ma et al., 2018). The above research focused on the definition of water resource carrying capacity in Zhangjiakou City, construction of the water resource carrying capacity index system, and evaluation model for water resource carrying capacity. In January 2017, General Secretary Xi Jinping proposed that Zhangjiakou City would construct a capital water conservation functional area and an ecological environment support area (Wu and Fu, 2017). At present, with the capital water conservation functional area as the research object, no additional research is being conducted on the comparative analysis of water resources carrying capacity in Zhangjiakou City using multiple methods.

The National Development and Reform Commission and the People's Government of Hebei Province jointly issued the "Construction Plan for the Zhangjiakou Capital Water Conservation Functional Zone and the Ecological Environment Support Area (2019–2035)" (July 2019). It clarifies the functional positioning of the capital water conservation functional area; capital ecological environment support area; and development positioning, construction goals, spatial layout, and construction priorities of the "two districts" in the capital (People's Government of Hebei Province, 2019). The capital water conservation functional area is based on the water systems of important river basins such as the Yongding River and Chaobai River in Beijing as the starting point. It improves the carrying capacity of water resources through a series of water conservation projects such as hydrological regulation, comprehensive treatment of river basins, and reclaimed water utilization (Liu and Chen, 2018). Based on this, this study considers Chicheng County, Zhangjiakou City, as the research area, and analyzes and evaluates its water resource carrying capacity in the current year (2018) and plan year (2025) by constructing the water resources carrying capacity evaluation index system of the county and determining the threshold of the bearing capacity evaluation index. The single-factor evaluation method is used to analyze the water quantity elements and water quality elements of Chicheng County. The "driving force-pressure-state-response" assessment model of the county is constructed using the cloud theory method. The twelve evaluation indicators of Chicheng County are analyzed to determine its water resource carrying capacity level in the current year and plan year. This is to provide 1) technical support for utilizing and protecting water resources in the county's "14th Five-Year Plan" and 2) reference for the subsequent implementation of the sustainable development of the capital water conservation functional area and the water resources security capacity building in the coordinated development of Beijing–Tianjin–Hebei.

2 Overview of study area

Located in the north of Hebei Province and southwest of Beijing, Zhangjiakou City belongs to the same natural ecosystem as Beijing. It plays an essential role in ensuring the safety of the capital's water resources and ecological environment (Su et al., 2017). Chicheng County is located in the southwest of Beijing, and the county's center is at a distance of 180 km from Beijing, with a straight-line distance of 110 km. Chicheng County is 95 km long from north to south, and 88.75 km wide from east to west. It has a total area of 5287 km^2. Its jurisdiction area is the fourth in Hebei Province. Chicheng County is one of the 14 ring capital counties in Hebei Province. It has four townships bordering Beijing, with a bordering mileage of 153 km. The geographical location of Chicheng County is shown in Figure 1.

Chicheng County is located in the western branch of Yanshan. It is surrounded by high mountains. The medium and low mountainous areas account for approximately 90% of the county area, and the mountain valley area and basin area account for approximately 10% of the county area. The entire terrain slopes from northwest to southeast, with an average altitude of 1000 m. The landform types of Chicheng County can be divided into tectonic and ablative landforms, and river

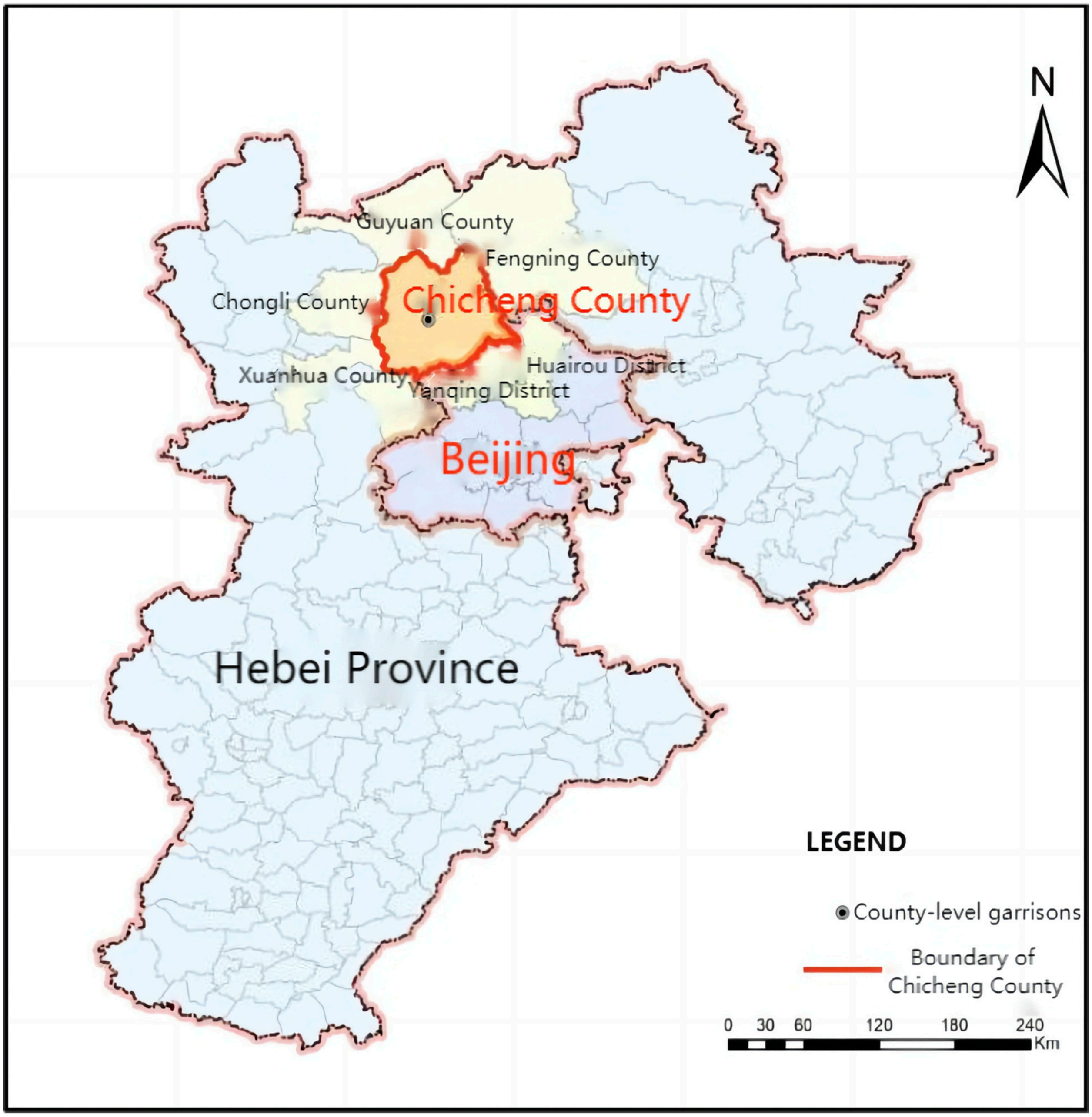

FIGURE 1
Geographical map of Chicheng county.

erosion and accumulation landforms according to the genesis. It can be divided into three forms according to the morphology: Zhongshan area, low mountainous area, and river valley area. Chicheng County mainly has the Heihe River, and the Bai River and its tributaries (the Three Rivers of the Red River). All these belong to the Bai River basin of the Chaobai River system. Of this, the Red River flows into the White River in the territory. Furthermore, the two main rivers Heihe River and White River run through the county from north to south, and flow into the Miyun Reservoir in Beijing. Approximately 200 million m^3 of water enters the reservoir annually. This accounts for 53% of the annual amount of water, which is an important source of drinking water in Beijing.

The annual average total water resources of Chicheng County amount to 247 million m^3. Of this, the total surface water resources amount to 241 million m^3, the total groundwater resources amount to 122 million m^3 (mineralization ≤ 2 g/L), and the amount of double calculation is 116 million m^3. The water quality of rivers throughout the year belongs to Class III. water quality, and the water quality is in Category II throughout the year, and the non-flood season is Class III. Water resources vary considerably during the year and between years, the spatial distribution is non-uniform, there is a contradiction between supply and demand, the total amount of water resources in the county is inadequate, and the amount of water resources *per capita* is highly insufficient. The total annual average water resources

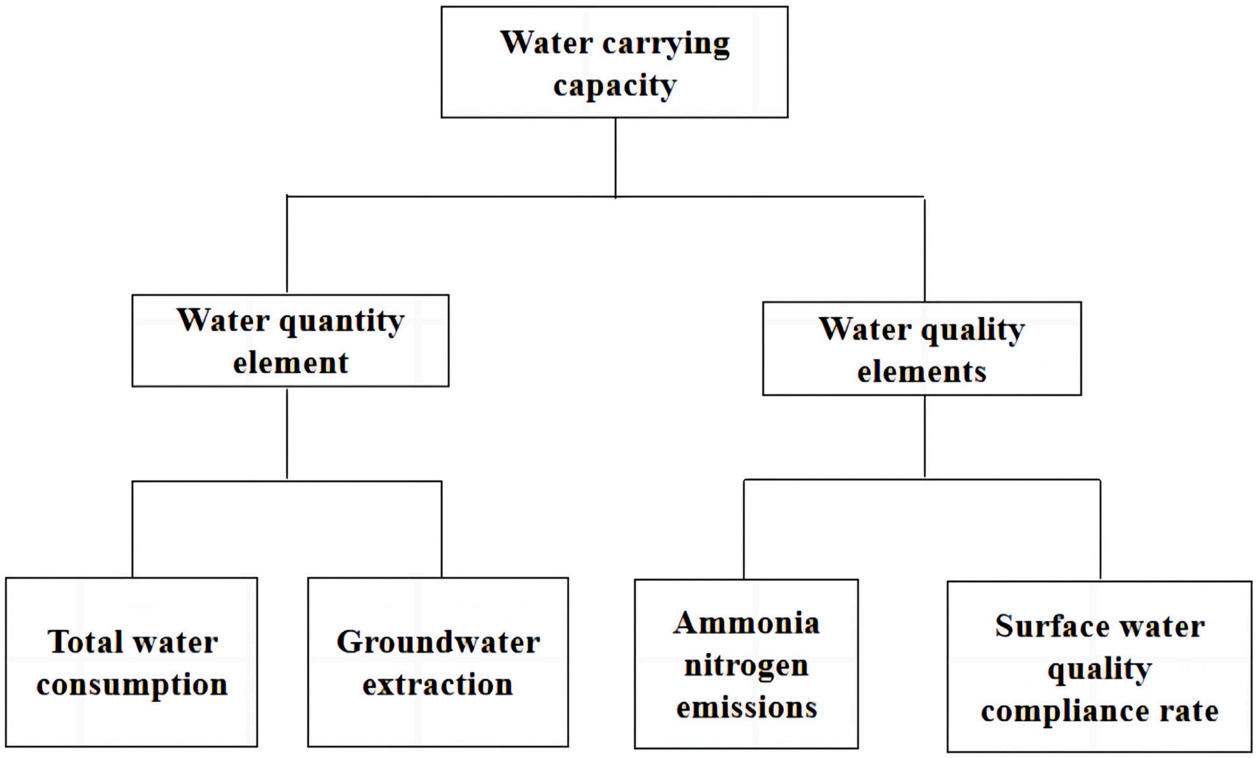

FIGURE 2
One-factor evaluation method index system.

of Chicheng County amount to 247 million m^3. The *per capita* water resources in 2018 amount to 839.28 m^3, which is less than half of the national *per capita* water resources of 2007.57 m^3 in that year.

3 Evaluation of the carrying capacity of water resources

The carrying capacity of water resources refers to the maximum level of sustainable development that a certain area of water ecosystems can carry when water management and social economy are optimized under a certain time period and technology level (Wang and Dan, 2012). The establishment of an appropriate evaluation model for the carrying capacity of regional water resources has important theoretical and practical significance for regional economic development, ecological environmental protection, and sustainable utilization of water resources (Zheng and Li, 2021).

In this study, the water resources carrying capacity of Chicheng County in 2018 (current year) and 2025 (plan year) are analyzed and evaluated by constructing its water carrying capacity evaluation index system, determining the threshold of the bearing capacity evaluation index, and using the one-factor evaluation method and cloud theory method.

3.1 One-factor evaluation method

3.1.1 Introduction to univariate evaluation

The single-factor evaluation method refers to the analysis and evaluation of a single index separately. Furthermore, the bearing status of each index is assessed directly according to the measurement standard of each index (Wu et al., 2015).

Combined with the actual situation of Chicheng County and the analysis requirements of single-factor evaluation methods, an evaluation index system is constructed as shown in Figure 2. The evaluation of water quantity elements is carried out according to the current total annual water consumption W and groundwater extraction amount G. In addition, the regional scope of severe overload, overload, critical state, and non-overload is divided. The pollutant discharge emission P and surface water quality compliance rate Q are evaluated according to the water quality element evaluation standards. In addition, the water quality elements are delineated as severe overload, critical state, and non-overload.

The evaluation index level threshold table is established as shown in Table 1 according to the "Technical Guidelines for the Work of the National Population Development Functional Zone" and the actual situation of Chicheng County.

The criteria for assessing the bearing status of resources according to the evaluation results of water quantity and water quality elements are as follows:

(1) Severe overload: any of the water quantity and water quality elements is overloaded severely;
(2) Overload: any of the water quantity and water quality elements is overloaded;
(3) Critical state: any of the water quantity and water quality elements is in a critical state;
(4) No overloading: Water quantity and water quality elements are not overloaded.

TABLE 1 Evaluation level threshold of one-factor evaluation method for water resource carrying capacity in Chicheng County.

Evaluation indicators	Evaluation of carrying status			
	Severe overload	Overload	Critical	No overloading
Total water consumption W	$W \geq 1.2\times W_0$	$W_0 \leq W \leq 1.2\times W_0$	$.9\times W_0 \leq W \leq W_0$	$W < .9\times W_0$
Amount of groundwater used G	$G \geq 1.2\times G_0$ or The over-exploitation coefficient of shallow groundwater in the over-exploitation area ≥.3 or there is a deep pressure water extraction or there is excessive groundwater exploitation in mountainous areas	$G_0 \leq G \leq 1.2\times G_0$ or Shallow groundwater overexement coefficient in over-exploitation areas is between (0,0.3] or there is over-exploitation of groundwater in hilly areas	$.9\times G_0 \leq G \leq G_0$	$G < .9\times G_0$
Pollutant emissions P	$p \geq 3\times P_0$	$1.2\times P_0 \leq p < 3\times P_0$	$1.1\times P_0 \leq p < 1.2\times P_0$	$p < 1.1\times P_0$
Surface water quality compliance rate Q	$Q \leq .4\times Q_0$	$.4\times Q_0 < Q \leq .6\times Q_0$	$.6\times Q_0 < Q \leq .8\times Q_0$	$.8\times Q_0 \leq Q$

TABLE 2 Data acquisition and sources.

Serial number	Index	Numerical and categorical	Data sources
1	total annual water consumption of Chicheng County (million m^3)	33.8074	the results of the 2018 Chicheng County Water Resources Bulletin
2	groundwater extraction volume (million m^3)	23.6074	
3	red line index of total water use control in Chicheng County in the current year (million m^3)	51.14	Zhangjiakou City Implementation of the Strictest Water Resources Management System 2016–2020 Control Target Decomposition Plan
4	groundwater exploitation control index in Chicheng County in the current year (million m^3)	26.29	
5	water quality targets in important water functional areas	Class II	
6	Water quality compliance rate	100%	In 2016, 8 of the provincial water function area compliance evaluation results participated in the evaluation results
7	Water quality compliance rate control indicators	100%	
8	COD limit the amount of discharge into the river (t/a)	177.7	Adopt the 2015 COD and ammonia nitrogen emission limits in Chicheng Prefecture
9	COD emissions (t/a)	28.1	
10	Limits of ammonia nitrogen into the river (t/a)	5.9	
11	Ammonia nitrogen emissions (t/a)	6.6	

The water resources carrying status of Chicheng County are analyzed sequentially according to the above evaluation method. Furthermore, the rationality of the evaluation results is analyzed in combination with the regional water resource conditions, development and utilization conditions, and economic and social development and trends.

3.1.2 Results of the single-factor evaluation method

3.1.2.1 Data acquisition

According to the results of the 2018 Chicheng County Water Resources Bulletin, the total annual water consumption of Chicheng County is 33.8074 million m^3. Of this, the groundwater extraction volume is 23.6074 million m^3. According to the "Zhangjiakou City Implementation of the Strictest Water Resources Management System 2016–2020 Control Target Decomposition Plan", the red line index of total water use control in Chicheng County in the current year is 51.14 million m^3, the groundwater exploitation control index in Chicheng County in the current year is 26.29 million m^3, and the water quality targets in important water functional areas are Class II.

According to the results of the 2016 provincial water function zone standard evaluation, eight water function areas in Chicheng County participated in the water quality compliance rate of 100%. Furthermore, Water quality compliance rate control indicators was 100%.

The 2015 COD and ammonia nitrogen emission limits of Chicheng County were used rather than the current annual pollutant discharge limits. Among these, the COD emission limit, river entry, ammonia nitrogen emission limit, and river entry are 177.7 t/a, 28.1 t/a, 5.9 t/a, and 6.6 t/a, respectively.

The above results are summarized in the following Table2.

3.1.2.2 The carrying capacity of water resources

First, the single-factor evaluation of water quantity factors and water quality elements is carried out. Furthermore, the four evaluation

TABLE 3 Evaluation table of the total water consumption capacity of the current year (2018).

Administrative	Evaluation indicators	Metrics	The carrying capacity of the water quantity element	
	Total water consumption (Ten thousand m^3)	Total water consumption target (Ten thousand m^3)	W/W_0	Load level
Chicheng County	3380.74	5114	.66	No overloading

TABLE 4 Groundwater carrying status evaluation table for the current year (2018).

Administrative	Evaluation indicators	Metrics	The carrying capacity of the water quantity element	
	Groundwater extraction (Ten thousand m^3)	Groundwater extraction indicators (Ten thousand m^3)	G/G_0	Load level
Chicheng County	2360.74	2629	.89	No overloading

TABLE 5 Status quo year (2018) water quality compliance rate element evaluation results table.

Administrative	Evaluate the number of water functional areas	Evaluation indicators	Metrics	The carrying capacity of the water quantity element	
		Water quality compliance rate Q (%)	Water quality compliance rate control indicators Q_0 (%)	Q/Q_0	Load level
Chicheng County	8	100	100	1	No overloading

levels of severe overload, overload, critical state, and non-overload are delineated and then, evaluated comprehensively according to the evaluation results of water quantity factors and water quality elements. The evaluation table of the total water consumption capacity of the current year (2018) and Groundwater Carrying Status Evaluation Table for the current year (2018) are presented in Tables 3, 4.

As is evident from Table 2, the current annual total water consumption in Chicheng County is not overloaded.

As is evident from Table 3, the current annual groundwater bearing status of Chicheng County is not overloaded.

The water quality elements are evaluated according to the current annual water quality compliance rate of the water functional area, the amount of pollutants entering the river, etc. The annual compliance rate of Chicheng County from the evaluation of the water function area is 87.5%, Q/Q0 is one, and the water quality compliance rate element of the water function area is not overloaded. The evaluation results of the water quality compliance rate element of the water function area are detailed in Table 5.

The average emission degree of COD and ammonia nitrogen in the water functional area of Chicheng County is calculated according to the current annual discharge of major pollutants and the limit of pollutants entering the river in Chicheng County, respectively (see Table 6).

A comprehensive evaluation of the current annual water resources carrying status is carried out based on the above water quantity and water quality analysis results (see Table 7). The comprehensive evaluation results are critical.

3.1.2.3 Forecast of the bearing capacity of the total annual water consumption element at the planning level

The total amount of water used includes five categories: domestic water; industrial water; agricultural water; forestry, animal husbandry, fishing, and livestock water demand; and ecological water demand. It is predicted separately by means of quota forecasting, and trend analysis and prediction.

The county's urban population is predicted to attain 102,100 in 2025, and the rural population would attain 189,600. The comprehensive water consumption index of urban residents is taken from 120 L/personday. The quota method is used to predict that the domestic water consumption of urban residents would be 4.472 million m^3 in 2025. The comprehensive water consumption index of rural residents would be 65 L/personday. The quota method is used

TABLE 6 Results of the evaluation of the elements of the river into the river in the current year (2018).

Administrative	Evaluation indicators	Metrics	Bearing conditions of water quality elements				
	COD emissions P_1 (t/a)	Ammonia nitrogen emissions P_2 (t/a)	COD limit the amount of discharge into the river P_{10} (t/a)	Limits of ammonia nitrogen into the river P_{20} (t/a)	P_1/P_{10}	P_1/P_{20}	Load level
Chicheng County	28.1	6.6	177.7	5.9	.158	1.12	Critical

TABLE 7 Current status year (2018) water carrying capacity evaluation table.

Administrative	The bearing status of the water quantity element			Bearing status of water quality elements			Comprehensive evaluation
	Elements of total water consumption	Groundwater Mining elements	Evaluation results of water quantity elements	Water quality compliance rate elements	Contaminant River entry features	Evaluation results of water quality elements	
Chicheng County	No overloading	No overloading	No overloading	No overloading	Critical	Critical	Critical

to predict the water consumption of rural residents in 2025 to be 4.4983 million m^3.

According to the average annual growth rate of industrial added value above the designated size in Zhangjiakou City during the "13th Five-Year Plan" period, it is predicted that the industrial added value of Chicheng County in 2025 would be CNY 2.53 billion. The water consumption of industrial added value of CNY 10,000 is 10 m^3, and the total industrial water demand of Chicheng County in 2025 is predicted to be 2.53 million m^3.

According to the "Five-year Implementation Plan for the Comprehensive Treatment of Groundwater Over-exploitation in Hebei Province (2018–2022)" and the "Opinions on the Guarantee of Surface Water Supply in Zhangjiakou City" (Zhang Zhengcheng [2019] No. 115), the effective irrigation area of the county would continue to maintain 192,800 mu in 2025. The irrigation water demand of farmland is predicted by the irrigation quota method. The analysis shows that the irrigation water demand of farmland in Chicheng County would be 22.43 million m^3 (50% flat water year) and 25.71 million m^3 (75% dry water year).

After calculating the current quotas for irrigation of forest fruit fields, the water demand for grassland, and the water replenishment of fish ponds, the water demand for forestry, animal husbandry, and fishery would be 650,000 m^3 in 2025, and that for livestock would be 1.9 million m^3.

Combined with the requirements of the Zhangjiakou Surface Water Allocation and Utilization Plan (2020), the ecological water demand forecast predicts that the ecological water demand of Chicheng County would be 1.58 million m^3 by 2025.

According to the above analysis, the total water demand in Chicheng County in 2025 would 38.0603 million m^3 (50% flat water year) and 41.3403 million m^3 (75% dry water year). The results are shown in Table 8.

The bearing capacity of the total water consumption elements of Chicheng County in 2025 (plan year) of the flat water year and dry water year is predicted based on the total water consumption control index of Chicheng County in the current year (2018). The results are shown in Table 9.

As is evident from Tables 3–8, the bearing conditions of the total water consumption elements under the conditions of the plan year (2025) for Chicheng County are predicted to be non-overloaded.

3.2 Evaluation method of water carrying capacity based on cloud theory

3.2.1 Cloud model theory

Cloud models can scientifically and effectively describe the ambiguity and randomness of things, quantitatively characterize the qualitative language that exists in life, and strengthen the quantitative analysis and data operability of uncertain things (Hu, 2008). In this study, a comprehensive evaluation model based on the cloud theory is established, and the carrying capacity of water resources in Chicheng County is analyzed and evaluated.

3.2.1.1 The digital characteristics of the cloud are determined.

Let U be a domain of the theory for the formation of an exact set of numbers, A be a qualitative concept on U, and x be a qualitative language value on U. x corresponds to the membership degree of A, y ($0 \le y \le 1$), is a random number with a stable trend, the distribution of y on U is called the subordinate cloud (referred to as the cloud), and each group (x, y) becomes a cloud droplet. Clouds are mappings from the domain U to the interval [0,1] (Wang et al., 2021).

The cloud is a mapping from the domain U to the interval [0,1] using numerical features such as expectation (Ex), entropy (En), and superentropy (He) to represent its concept of uncertainty.

Ex is a numerical value of a qualitative concept that determines the center of gravity of the cloud:

$$\mathbf{E_x} = (\mathbf{B}_{\min} + \mathbf{B}_{\max})/2$$

TABLE 8 Forecast results of water demand for chicheng county in the planning level year (2025).

Domestic water consumption		Industrial water demand	Agricultural irrigation Water requirements		Water requirements for forestry, herding, fishing and livestock	Ecology Water requirements	Total water demand	
Domestic water for urban residents	Rural residents use water comprehensively		50% Flat water year	75% Dry years			50% Flat water year	75% Dry years
447.20	449.83	253	2243	2571	255	158	3806.03	4134.03

TABLE 9 Evaluation table of the total water consumption capacity of Chicheng County in the planning level year (2025).

Domestic water consumption	Evaluation indicators	Metrics	The carrying capacity of the water quantity element	
	Total water consumption (Ten thousand m^3)	Total water consumption target (Ten thousand m^3)	W/W_0	Load level
Chicheng County (50% Flat water year)	3806.03	5114	.69	No overloading
Chicheng County (75% Dry years)	4134.03	5114	.81	No overloading

Entropy En is a measure of uncertainty in qualitative concepts:

$$\exp\left|-\frac{(B_{max} - B_{min})^2}{8E_n^2}\right| \approx 0.5$$

$$E_n = \frac{|B_{max} - B_{min}|}{2.355}$$

Superentropy (He) is a measure of ambiguity of entropy that determines the thickness of the cloud.

Here, the minimum and maximum boundaries of an evaluation level are represented with k as the constant.

3.2.1.2 Forward normal cloud generator

A normal random number is generated with En as the expectation and He2 as the variance. Second, a normal random number xi is generated with Ex as the expectation and variance. Finally, the corresponding membership value yi, (xi, yi) is calculated to form any cloud drop in the number field. The above process is repeated until n cloud droplets are generated. The yi calculation formula is as follows:

$$y_i = \exp\left[\frac{-(x_i - E_x)^2}{2(E_{ni})^2}\right]$$

3.2.1.3 Membership matrix

The corresponding membership R of each evaluation index is calculated by the above steps related to the forward cloud generator.

$$R = \begin{pmatrix} r_{11} & \cdots & r_{1m} \\ \vdots & \cdots & \vdots \\ r_{n1} & \cdots & r_{nm} \end{pmatrix}$$

3.2.1.4 The evaluation grade value of the carrying capacity of water resources

The evaluation grade value of the carrying capacity of water resources is calculated as follows:

$$P = W^T \times R$$

where W is the weight of each metric.

3.2.2 Evaluation index system

An evaluation model of "driving force-pressure-state-response" is established. Furthermore, an evaluation index system for the carrying capacity of water resources in Chicheng County is constructed (see Figure 3).

According to the actual scenario of the existing indicators, the evaluation threshold is divided into five levels with reference to the average status of various indicator systems worldwide. Among these, the first level indicates that the bearing capacity in the state is exceptionally strong, and that the potential for development and utilization is high. The second level indicates that the bearing capacity in the state is relatively strong, and that the potential for development and utilization is high. The third level indicates that the carrying capacity in the state matches the economic development. The fourth level indicates that the bearing capacity in the state is relatively weak, and that there is a marginal overload of water resources. The fifth level indicates that the bearing capacity in the state is exceptionally weak, and that the overload of water resources is severe. The thresholds for the specific grade division are shown in Table 10:

The values of the annual evaluation indexes of the current year and plan year for Chicheng County are shown in Table 11:

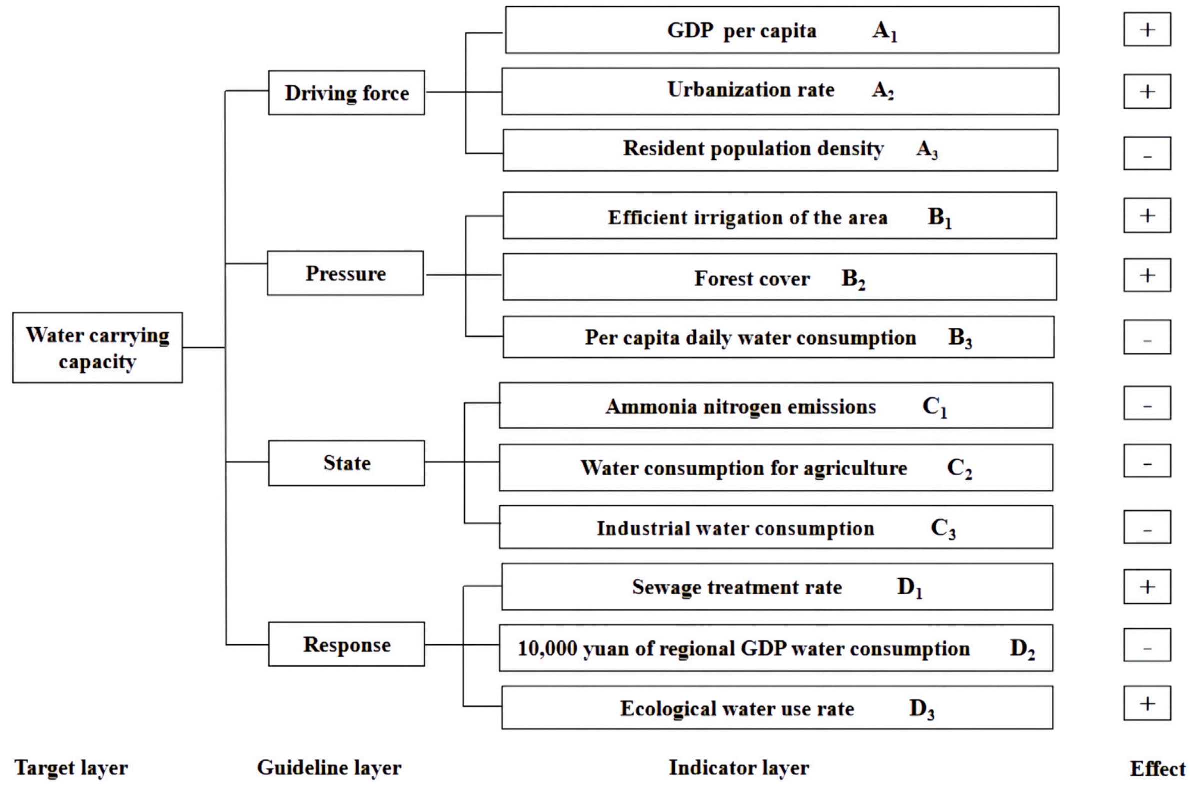

FIGURE 3
Evaluation index system of water resource carrying capacity in Chicheng County.

TABLE 10 The threshold of water resource carrying capacity evaluation level based on cloud theory in Chicheng County.

Grade			Class I	Class II	Class III	Class IV	Class V
Driving force A	GDP per capita A_1	Million yuan/person	5–10	2.5–5	1.5–2.5	.5–1.5	0–0.5
	Urbanization rate A_2	%	80–100	60–80	40–60	20–40	0–20
	Resident population density A_3	person/km^2	100–300	300–500	500–800	800–1200	1200–1400
Pressure B	Efficient irrigation of the area B_1	10,000 acres	50–100	30–50	20–30	10–20	0–10
	Forest cover B_2	%	60–100	50–60	40–50	30–40	8–30
	Per capita daily water consumption B_3	L/(person*year)	40–80	80–140	140–180	180–200	200–220
State C	Ammonia nitrogen emissions C_1	Tons/year	0–20	20–60	60–120	120–200	200–500
	Water consumption for agriculture C_2	%	0–20	20–30	30–50	50–70	70–100
	Industrial water consumption C_3	%	0–15	15–20	20–30	30–40	40–60
Response	Sewage treatment rate D_1	%	95–100	90–95	85–90	60–85	0–60
D	10,000 yuan of regional GDP water consumption D_2	m^3/10,000 yuan	10–50	50–150	150–250	250–300	300–400
	Ecological water use rate D_3	%	45–100	30–45	15–30	5–15	0–5

3.2.3 Evaluation and analysis results of water resource carrying capacity of cloud theory

The numerical characteristics of the cloud are obtained by calculating and analyzing the bearing capacity of water resources in Chicheng County according to the cloud theoretical algorithm based on the "driving force-pressure-state-response" indicator model. The results are shown in Table 12.

According to the corresponding index values, weights, and numerical characteristics, the membership matrix of the positive cloud generator algorithm is generated, the randomness and uncertainty in the cloud model membership calculation are considered, the mean value of the 1000 program operation results is used as the final membership degree in this study,

TABLE 11 The annual evaluation index values of the current situation and planning level of Chicheng County.

Evaluation indicators	unit	2018(Status quo year)	2025(Planning level year)
GDP per capita A_1	Million yuan/person	3.8	4.5
Urbanization rate A_2	%	33.2	35
Resident population density A_3	person/km^2	48	55
Efficient irrigation of the area B_1	10,000 acres	19.28	19.28
Forest cover B_2	%	54.37	59
Per capita daily water consumption B_3	L/(person*year)	47450	41975
Ammonia nitrogen emissions C_1	Tons/year	5.9	5.9
Water consumption for agriculture C_2	%	71	58.9
Industrial water consumption C_3	%	8	6.6
Sewage treatment rate D_1	%	90	95
10,000 yuan of regional GDP water consumption D_2	m^3/10,000 yuan	11.8	10
Ecological water use rate D_3	%	3	4.2

TABLE 12 The digital characteristics of the cloud.

Index	Grade	A_1	A_2	A_3	B_1	B_2	B_3	C_1	C_2	C_3	D_1	D_2	D_3
Ex	I	7.5	90	200	75	80	60	10	10	7.5	97.5	30	72.5
	II	3.75	70	400	40	55	110	40	25	17.5	92.5	100	37.5
	III	2	50	650	25	45	160	90	40	25	87.5	200	22.5
	IV	1	30	1000	15	35	190	160	60	35	72.5	300	10
	V	.25	10	1300	5	19	210	350	85	50	30	375	2.5
En	I	2.12	8.49	84.93	21.23	16.99	16.99	8.49	8.49	6.37	2.12	16.99	23.35
	II	1.06	8.49	84.93	8.49	4.25	25.48	16.99	4.25	2.12	2.12	42.46	6.37
	III	.42	8.49	127.39	4.25	4.25	16.99	25.48	8.49	4.25	2.12	42.46	6.37
	IV	.42	8.49	169.85	4.25	4.25	8.49	33.97	8.49	4.25	10.62	21.23	4.25
	V	.21	8.49	84.93	4.25	9.34	8.49	127.39	12.74	8.49	25.48	42.46	2.12

TABLE 13 Evaluation results of cloud model of water resource carrying capacity game.

Year of evaluation	Evaluation values of water resource carrying capacity in different grades					Final rating
	I	II	III	IV	V	
Status quo year (2018)	.12	.03	.45	.29	.14	III
Planning level year (2025)	.09	.07	.46	.27	.11	III

and the membership matrix R1–R12 of 12 evaluation indicators is constructed. It is illustrated using R1 as an example:

$$R_1 = \begin{matrix} \textbf{year} \\ \textbf{2018} \\ \textbf{2025} \end{matrix} \begin{bmatrix} \text{I} & \text{II} & \text{III} & \text{IV} & \text{V} \\ 0 & 0.134 & 0.750 & 0.116 & 0 \\ 0 & 0.012 & 0.685 & 0.279 & 0 \end{bmatrix}$$

The entropy weight method is used to calculate the weights of the 12 evaluation indicators. The maximum eigenvectors and eigenvalues of the matrix are calculated with the help of MATLAB software and by normalizing the formula : $\mathbf{W_i} = \frac{M_i}{\sum_{i=1}^{n} M_i}$, i = 1,2, … … 12. The characteristic vector components of each evaluation index (i.e., the weights W) are calculated.

$$\mathbf{Wi} = (.\mathbf{039}, \mathbf{0.044}, \mathbf{0.066}, \mathbf{0.105}, \mathbf{0.028}, \mathbf{0.078}, \mathbf{0.029}, \mathbf{0.044}, \mathbf{0.066}, \mathbf{0.029}, \mathbf{0.037}, \mathbf{0.025}).$$

The evaluation value of the carrying capacity of water resources under different grades is calculated by the affiliation matrix R and weight W. The water resource carrying capacity levels of Chicheng County in 2018 (*status quo* year) and 2025 (plan year) are determined by the principle of maximum affiliation (see Table 13).

The above table shows that the carrying capacity level of water resources in Chicheng County in 2018 belongs to the third level in the evaluation index system. The water resource carrying capacity level of the county in 2025 based on the predicted values of the indicators also belongs to the third level in the evaluation index system.

4 Analysis of influencing factors of water carrying capacity

The above two analysis and evaluation results show that the water resource carrying capacity of Chicheng County in the current year (2018) and plan year (2025) matches the economic development. Furthermore, in the future period, the water resource carrying capacity of Chicheng County would have more scope for satisfying its economic and social development.

The implementation of documents such as the "Hebei Provincial Water Resources Protection Plan" and "Zhangjiakou City Implementation of the Strictest Water Resources Management System 2016–2020 Control Target Decomposition Plan" has further strengthened the water resources protection of Chicheng County. The county has steadily promoted water resources protection and treatment projects and the efficient operation of sewage treatment and reclaimed water utilization, continuously strengthened the protection management of water resources, improved the construction of water conservancy informatization, and implemented policies such as total water withdrawal control. This has substantially improved the water security capacity for Chicheng County's economic and social development, and promoted the adaptation of economic and social development to the carrying capacity of water resources and water environment.

Meanwhile, the single-factor evaluation method shows that the water quality factors in Chicheng County are in a critical state, and that the problems of water resource utilization and protection are prominent. This is owing to the low water quality of certain rivers in the county. The capacity to absorb pollution is low. A large amount of sewage such as urban domestic sewage, rural livestock and poultry manure, and agricultural fertilizers is discharged directly into the river. This causes surface water pollution. Coupled with the deficiency of water in small and medium-sized rivers, the task of river water ecological restoration and governance is highly challenging. To a certain extent, it lags behind the improvement of the carrying capacity of water resources in Chicheng County.

4.1 Analysis of influencing factors

According to the analysis, the main factors affecting the carrying capacity of water resources in Chicheng County are as follows.

4.1.1 The total amount of water resources and the degree of development and utilization

The total amount of water resources is the fundamental data for the study of the carrying capacity of water resources. It is also one of the key factors that determine the carrying capacity of water resources in the basin. In addition, the carrying capacity of water resources is based on a certain level of development and utilization of water resources. The current development and utilization of water resources is also one of the main factors affecting the carrying capacity of water resources. Therefore, the amount of groundwater resources, average annual total amount of water resources, irrigation rate of cultivated land, and amount of groundwater extraction in Chicheng County are important indicators affecting the carrying capacity of water resources in it.

4.1.2 The state of economic and social development

Economic development factors are the main drivers of the variation in the water resource carrying capacity in Chicheng County. These also impose the highest demands on the carrying capacity of water resources. The proportion of industrial and agricultural water consumption, per capita water consumption, and ecological environment water consumption has increased continuously with the rapid development of the economy and the population increase. This places significant demands on the carrying capacity of water resources. The urbanization rate of Chicheng County, proportion of tertiary industry in the GDP, and reuse rate of industrial water are the most important sensitive factors for the dynamic transformation of water resources.

4.1.3 Degree of water pollution and ecological damage

Water pollution is the main factor influencing the decrease in carrying capacity of water resources. Insufficient attention is paid to the treatment of water used in the industry, agriculture, and daily production. This aggravates the degree of water pollution, results in the continuous deterioration of water quality, and makes the limited water resources more scarce. To a certain extent, water pollution would accelerate the process of ecological destruction, result in the shrinkage of drinking water sources, and restrict the development of water resource carrying capacity in Chicheng County to a certain extent.

4.1.4 Construction of water-saving management system

The construction of a water-saving management system can effectively improve the carrying capacity of regional water resources. With the gradual implementation of relevant plans, the protection of water resources in Chicheng County has been developed further, the construction of a water-saving society has been promoted vigorously, the protection and management of water resources have been strengthened, the rational development and conservation and utilization of water resources have been improved considerably, and the carrying capacity of water resources in Chicheng County has been improved to a certain extent.

4.2 Suggestions and measures

At this stage, the overall carrying capacity level of water resources in Chicheng County is optimistic. This indicates that the management and protection of water resources in Chicheng County have achieved remarkable results. However, there is a substantial scope for improvement. At present, the significant problems of river water pollution, low sewage treatment capacity, weak pollution monitoring and supervision, etc., severely affect the carrying capacity of water resources in Chicheng County. Therefore, this study puts forward the following four recommendations:

4.2.1 Implement documentation requirements

Stringently execute the Opinions of the State Council on implementing the Strictest Water Resources Management System. Chicheng County should clarify the "three red lines" of water resources management, and stringently implement the "four systems" of total water-use control, water-use efficiency control, water function area restriction, and water resource management responsibility and assessment according to the requirements of the document.

4.2.2 Optimize the industrial structure

Optimize the industrial economic structure of Chicheng County. Stringently limit industries with high water consumption and high pollution, and reduce the consumption of water resources and sewage discharge. Relevant departments should formulate development and reform policies for the above industries. These should be clarified in documents such as medium- and long-term development plans to improve the utilization rate of water resources.

4.2.3 Improve wastewater treatment capacity

Improve the sewage treatment capacity of Chicheng County. The industrial wastewater, agricultural wastewater, and domestic wastewater in Chicheng County would be rectified effectively by improving the construction of urban sewage pipe network and the daily treatment capacity of existing sewage treatment plants, or adding an appropriate number of new sewage treatment plants. Furthermore, "100% sewage treatment" would be realized, and the carrying capacity of water resources would no longer be restricted.

4.2.4 Improve relevant systems

Accelerate the improvement of water resources management systems and mechanisms, and strengthen the supervision of water resources. Install equipment for monitoring water quality and water quantity in the main sections of reservoirs and rivers, the control sections of rivers in townships and towns, water function areas, drinking water sources, groundwater intake points, medium and large irrigation areas, groundwater over-exploitation areas, etc. Ensure real-time monitoring and supervision. Strengthen the formulation, implementation, and publicity of relevant laws, regulations, and policies.

5 Conclusion

This study considered Chicheng County, Zhangjiakou City, Hebei Province, as the research object and constructed the water resource carrying capacity evaluation index system of the county, determined the threshold of the bearing capacity evaluation index, and used the one-factor evaluation method and cloud theory method to analyze and evaluate the water resource carrying capacity of the county in the current year (2018) and plan year (2025). The main conclusions are as follows:

(1) The carrying capacity of water resources in Chicheng County was analyzed using the one-factor evaluation method. The total annual water consumption and groundwater bearing status of Chicheng County are not overloaded. The evaluation result of the water quantity element is not overloaded, the water quality compliance rate element is not overloaded, and the pollutant entry factor is critical. Thus, the water quality element evaluation result and the comprehensive evaluation status of Chicheng County water resources carrying capacity level are in critical states. According to the current annual total water consumption control index, the bearing situation of the total water consumption element of Chicheng County's planning level in the year is not overloaded.

(2) The evaluation and analysis of the carrying capacity of water resources in Chicheng County based on the cloud theory algorithm of the "driving force-pressure-state-response" index model revealed that the water resource carrying capacity of Chicheng County in both current year and plan year belongs to the third level in the evaluation index system.

(3) The results of both analyses and evaluations show that the water resource carrying capacity of Chicheng County in the current year matches the economic development. These also show that the water resource carrying capacity of the plan year of Chicheng County would match the economic development. Furthermore, in the next time period, the water resources carrying capacity of Akagi County would have more scope for satisfying its economic and social development.

(4) The water security capacity of Chicheng County's economic and social development has been improved considerably. However, there are still problems of low river-water quality and pollution absorption capacity. Chicheng County should speed up the improvement of the water resources management system and mechanism, improve the capacity of sewage treatment, and provide a long-term sustainable assurance for the security of the capital's water resources and ecological environment.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

JN and WN were employed by Engineering Design and Research Center, Beijing IWHR Corporation

The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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