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Evaluation of Water Resources Carrying Capacity under High Urbanization Rate in Guangzhou, China

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ABSTRACT

Since the beginning of the 21st century, the process of urbanization has accelerated, and water resources have faced greater pressure due to economic and social development and human production activities. In this study, a comprehensive evaluation system of WRCC was constructed by selecting 17 indicators, and the evaluation and analysis of the WRCC of Guangzhou from 2011 to 2020 were carried out based on the TOPSIS method and the obstacle degree model. The results show that the WRCC of Guangzhou showed a downward trend from 2011 to 2015, and gradually recovered from 2016 to 2020. The main obstacle factors for individual indicators are water resources per capita, irrigation water consumption per unit area, COD emissions, ammonia nitrogen emissions and ecological environment water use rate, etc. The water environment subsystem is the main obstacle factor for classification index. Based on the evaluation and analysis results, relevant suggestions are put forward.

Keywords: *Water resources carrying capacity, TOPSIS method, Obstacle degree model, Guangzhou*

1. INTRODUCTION

The carrying capacity of water resources describes the ability of a region’s water resources to support the socio-economic environment and human life. Water resource carrying capacity is a comprehensive index concerning the internal characteristics and interrelations of population, water resource, social economy and ecological environment[1][2]. The concept of water carrying capacity was first proposed in the field of ecosystems in the 1970s[3]. Current popular research methods of water resources carrying capacity were developed, such as analytic hierarchy process[4], principal component analysis[5], fuzzy comprehensive evaluation[6], back Propagation Neural Network[7], or technique in order of preference by similarity to ideal solution[8], etc. The evaluation of WRCC provides both the assessment of the regional level of WRCC and the identification of the obstacle factors that affect WRCC. Obstacle degree refers to hindrances to the improvement of WRCC defined by indicators and can be quantified using the obstacle degree model. The main obstacle factors are identified according to the obstacle degree ranking, and the study area is further evaluated. To explore the current situation of water resources in Guangzhou, this paper establishes a comprehensive evaluation index system for WRCC, uses the entropy method for objective weighting, adopts the TOPSIS method and obstacle degree model to evaluate and analyze the WRCC and obstacle factors in Guangzhou from 2011 to 2020.

2. RESEARCH METHOD

2.1. Study Area

Guangzhou is located in the southern part of mainland China, the central and southern part of Guangdong Province, between 113° 17' E and 23° 8' N (Figure 1). It is the capital of Guangdong Province and the political, economic, technological, educational and cultural center of Guangdong Province. The third largest city in China and the largest city in southern China. Guangzhou has a developed water system. The city's water area is 74,400 hectares, accounting for 10.05% of the country's land area. In 2020, Guangzhou's GDP has exceeded 2.5 trillion, with a total population of 18.676605 million and an urbanization rate of 86.19%. The total annual water resources in Guangzhou is 7.365 billion cubic meters, and the per capita water resources are 514 cubic meters, accounting for only one third of the province's per capita water resources. According to the international water shortage standard, per capita water resources less than 1,000 cubic meters are seriously short of water, indicating that Guangzhou is seriously short of water resources.

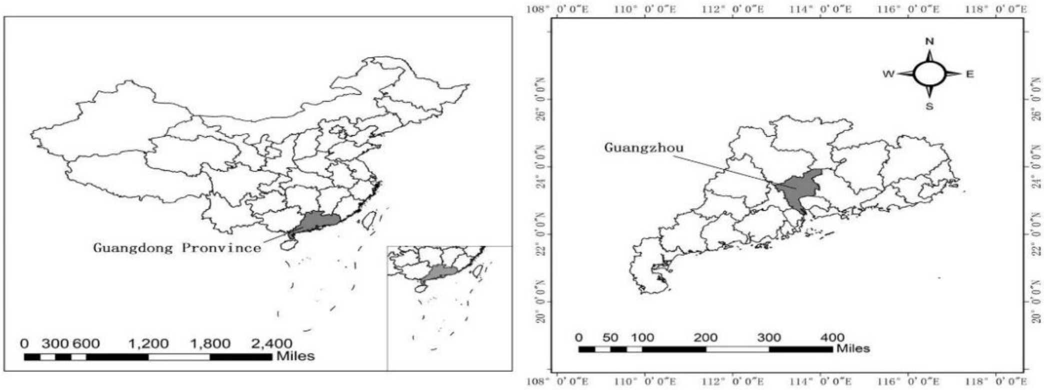

Figure 1 Administrative map of Guangzhou

2.2. Analysis Methods

2.2.1. Establishment of evaluation index system

The establishment of a comprehensive evaluation index system is fundamental for completing the study of WRCC[9]. Water resources maintain the development of economy and society, and the development of economy and society increases the pressure of water resources to a certain extent and destroys the state of water environment, indicating that there is a correlation effect between them. Therefore, this paper combines the characteristics of the current situation of water resources in Guangzhou, refers to the research success of domestic and foreign scholars[10][11][12][13], taking into account the mutual influence and restriction of water resources, population, environment, society, and economy, as well as the availability and ease of quantification of index data. The WRCC comprehensive evaluation system as shown in Table 1 is constructed.

Table 1. Comprehensive evaluation index system of WRCC in Guangzhou

Object hierarchy	Rule hierarchy	Index hierarchy	Index nature	The weight
WRCC *A*	Water resources subsystem B_1	Water resources per capita C_1 (m^3/people)	+	0.0821
		Modulus of water resources supply C_2 ($10^4 m^3/km^2$)	-	0.0351
		Rate of water resources development and utilization C_3 (%)	-	0.0261
		Percentage of surface water resources C_4 (%)	+	0.0393
		Water resources per unit area C_5 ($10^4 m^3/km^2$)	+	0.0368
	Social subsystem B_2	Population density C_6 (people/km^2)	-	0.0770
		Urbanization rate C_7 (%)	-	0.0280
		Per capita comprehensive water consumption C_8 (m^3/people)	-	0.0548
	Economic subsystem B_3	GDP per capita C_9 (yuan)	+	0.0572
		Water consumption per 10^4 yuan GDP C_{10} (m^3)	-	0.0366
		Water consumption per 10^4 yuan primary industry C_{11} (m^3)	-	0.0342
		Water consumption per unit area of farmland irrigation C_{12} (m^3/km^2)	-	0.0656

Water environment subsystem B_4	Rate of urban sewage treatment C_{13} (%)	+	0.0359
	COD emissions C_{14} (t)	-	0.0778
	Ammonia nitrogen emissions C_{15} (t)	-	0.1205
	Rate of vegetation coverage C_{16} (%)	+	0.0378
	Rate of ecological water consumption C_{17} (%)	+	0.1550

2.2.2. Determination of the weight

(1) To facilitate the analysis and comparison between indicators, the extreme value method is used to standardize the original data of positive and negative indicators. The specific calculation formula is as Eq.(1) through Eq.(3):

Construct original data matrix :

$$X = \left|X_{ij}\right|_{n\times m} \tag{1}$$

Standardized calculation of positive indicators :

$$X'_{ij} = \frac{\left(X_{ij} - X_{imin}\right)}{\left(X_{imax} - X_{imin}\right)} \tag{2}$$

Standardized calculation of negative indicators :

$$X'_{ij} = \frac{\left(X_{imax} - X_{ij}\right)}{\left(X_{imax} - X_{imin}\right)} \tag{3}$$

Where i=1,2⋯n is the number of evaluation indexes, j=1,2⋯m is the number of evaluation years, X_{imax} and X_{imin} respectively represent the maximum and minimum values of the ith evaluation indexes in the original data of all years.

Meanwhile, since the normalized treatment X′ij may be zero, further treatment is required according to Eq. (4) :

$$R_{ij} = X'_{ij} + 0.01 \tag{4}$$

The standardized matrix is obtained by calculating the above formulas:

$$R = \left|R_{ij}\right|_{n\times m} \tag{5}$$

(2) The entropy weight method is adopted to determine the weight of the evaluation index, and the specific calculation formula is as Eq.(6) through Eq.(9):

Calculated the proportion of the sample value of the ith index in the jth year:

$$p_{ij} = \frac{R_{ij}}{\sum_{j=1}^{m} R_{ij}} \tag{6}$$

Calculate the entropy of the ith index:

$$e_i = -k\sum_{j=1}^{m} p_{ij}\ln p_{ij} \tag{7}$$

When $e_i > 0, k > 0$, let $k = 1/\ln m$, the entropy reaches the maximum value:

$$e_i = -\frac{1}{\ln m}\sum_{j=1}^{m} p_{ij}\ln p_{ij} \tag{8}$$

Calculate the weight of the ith evaluation index:

$$w_i = \frac{(1 - e_i)}{\sum_{i=1}^{n}(1 - e_i)} \tag{9}$$

2.2.3. TOPSIS model

TOPSIS orders the criteria according to the distances from the object to the ideal and the negative solutions[14]. After the reference related literature at home and abroad[15], combined with the actual situation of Guangzhou, the grade of WRCC is shown in Table 2. The specific calculation equation is as Eq. (10) through Eq.(15):

Construct weighted normalization matrix:

$$Z = \left|z_{ij}\right|_{n\times m} = R_{ij} \times w_i \tag{10}$$

Confirm positive and negative ideal values:

$$z^+ = \left\{\max_{1\leqslant i\leqslant n} z_{ij} \mid i = 1,2,\cdots,n\right\} = \{z_1^+, z_2^+, \cdots, z_n^+\} \tag{11}$$

$$z^- = \left\{\min_{1\leqslant i\leqslant n} z_{ij} \mid i = 1,2,\cdots,n\right\} = \{z_1^-, z_2^-, \cdots, z_n^-\} \tag{12}$$

Calculate the distance between the index and the positive and negative ideal values:

$$D_j^+ = \sqrt{\sum_{i=1}^{n}\left(z_i^+ - z_{ij}\right)^2} \tag{13}$$

$$D_j^- = \sqrt{\sum_{i=1}^{n}\left(z_i^- - z_{ij}\right)^2} \tag{14}$$

Calculate the proximity between the evaluation object and the ideal value:

$$T_j = \frac{D_j^-}{D_j^+ + D_j^-} \tag{15}$$

where the smaller D_j^+ is, the closer the evaluation index is to the positive ideal solution, the better the condition of water resources is. The smaller D_j^- is, the closer the evaluation index is to the negative ideal solution, the worse the water resources condition will be. T_j is the comprehensive evaluation value of WRCC in jth year. The larger the value of T_j, the higher the WRCC score.

Table 2. The grade of the WRCC in Guangzhou

WRCC score*(Tj)*	Carrying grade
[0.6, 1)	Excellent
[0.5, 0.6)	Positive
[0.4, 0.5)	Normal
[0.3, 0.4)	Poor
[0,0.3)	Weak

2.2.4. Obstacle degree model

The obstacle degree model was used to calculate the obstacle degree of each index and identify the single and classified obstacle factors that restrict the carrying capacity of water resources.The factor contribution degree(F_{ij}) refers to the contribution of a single index to the overall goal, which is generally expressed by the weight of each index; the index deviation degree(I_{ij}) refers to the actual value of each index and the gap between the optimal target value that can be expressed by the difference between 1 and the standardized value of each index; the degree of obstacle(P_{ij},p_{ij})can indicate the degree of influence of each index on the WRCC. The specific calculation formula is as Eq.(16) through Eq.(19):

$$F_{ij} = w_{ij} \times w_i \tag{16}$$

$$I_{ij} = 1 - R_{ij}\# \tag{17}$$

$$p_{ij} = \frac{F_{ij} \times I_{ij}}{\sum_{i=1}^{n} \left(F_{ij} \times I_{ij}\right)} \times 100\% \tag{18}$$

$$P_{ij} = \sum p_{ij} \tag{19}$$

where w_{ij} is the weight of the j th evaluation index, w_i is the weight of the criterion layer to which index j belongs, and R_{ij} is the standard value of the jth evaluation index.

2.2.5. Data sources

The evaluation index data used in this study mainly comes from the "Guangzhou Statistical Yearbook" (2012–2021), "Guangzhou City Water Resources Bulletin"(2011-2020).

3. RESULTS AND DISCUSSION

3.1. Evaluation and analysis of WRCC in Guangzhou

Based on the above research methods, this paper calculates the WRCC in Guangzhou from 2011 to 2020, and the results are shown in Figure 2 and Figure 3.

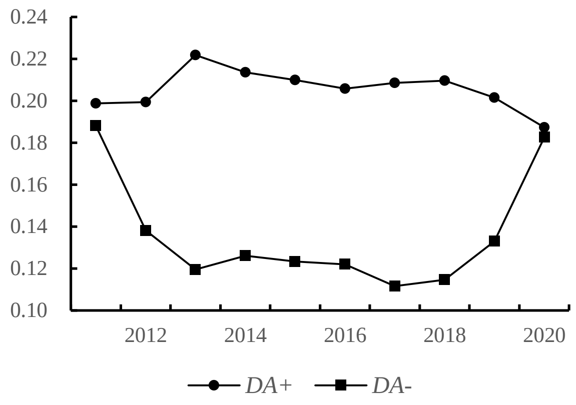

Figure 2 Dynamic trend of D^+, D^- in the comprehensive evaluation of WRCC in Guangzhou

Figure 3 Dynamic trend of WRCC from 2011 to 2020 in Guangzhou

On the whole, the WRCC in Guangzhou is at the poor level. In recent 10 years, the WRCC of Guangzhou firstly decreased and then increased, and fluctuated significantly from 2013 to 2017. Concretely, the grade of WRCC decreased significantly from the normal level to the poor level between 2011-2013. From 2014 to 2016, the grade of WRCC began to rise, basically maintaining in the range of 0.35-0.4. In 2017, it declined again, reaching the lowest value of 0.3487 in the decade. From 2018 to 2020, the grade of WRCC began to rise steadily and recovered to the normal level, reaching the highest value of 0.4927 in ten years and expected to reach the positive level.

In 2011, the Guangzhou Municipal People's Government issued the Outline of the 12th Five-year Plan for National Economic and Social Development of Guangzhou (2011-2015), which detailed the social and economic development plan of Guangzhou in the next five years. In 2015, Guangzhou's GDP reached 1.81 trillion yuan, with an average annual growth rate of 10.1% during the 12th Five-Year Plan period, and a net increase of 735.213 billion yuan compared with 2010. However, with the rapid improvement of social economy, the city is also facing great downward pressure. The overall extensive economic development mode and large population concentration lead to the rapid expansion of the total urban population. Resources and environment constraints are becoming tighter, pollution control and environmental protection are becoming more and more serious, resulting in a significant decline of WRCC in Guangzhou.

Since 2016, the contradiction between water resources, social and economic development has attracted extensive attention from the whole society. At the beginning of the 13th Five-Year Plan, Guangzhou Municipal People's Government has issued the Outline of the 13th Five-year Plan for National Economic and Social Development of Guangzhou (2016-2020). The outline makes detailed plans for ecological civilization construction, resource utilization, population strategy and urban development layout. The city actively promotes water environment improvement projects, comprehensively promotes efficient and economical utilization of water resources, implements dual control over the total amount and intensity of water resources consumption, and implements the strictest water resources management system. Water Conservation Plan of Guangzhou municipality (2018-2035) was released by Water Resources Bureau of Guangzhou Municipality in 2017, which systematically analyzed water resources conditions and water-saving status quo of Guangzhou municipality, and established general goals and specific measures for water conservation. The city has achieved good results in water-saving action, marking a new height in the construction of water-saving city, and the WRCC shows a steady upward trend.

3.2. Analysis of obstacles to WRCC in Guangzhou

3.2.1. Factor analysis of obstacle degree of single index

Through the calculation of obstacle degree model, the obstacle degree of single index of WRCC in Guangzhou from 2011 to 2020 is calculated, and the top five indicators are selected according to the value, as shown in Table 3.

Table 3. The obstacle degree of single index of WRCC in Guangzhou from 2011 to 2020

Year	1		2		3		4		5	
	Index	Obstacle degree	Index	Obstacle degree	Index	Obstacle degree	Index	Obstacle degree	Index	Obstacle degree
2011	C15	27.03%	C14	14.84%	C16	8.58%	C13	8.16%	C1	8.02%
2012	C15	26.29%	C14	16.97%	C17	15.12%	C13	6.49%	C7	3.84%
2013	C17	30.36%	C15	24.36%	C14	15.53%	C12	4.80%	C7	3.53%
2014	C17	33.14%	C15	24.75%	C14	14.99%	C12	5.38%	C7	3.50%
2015	C17	34.73%	C15	23.80%	C14	13.74%	C12	4.71%	C6	3.56%
2016	C17	39.37%	C15	24.46%	C1	5.04%	C6	4.93%	C12	4.86%
2017	C17	34.26%	C15	23.35%	C1	9.78%	C12	5.69%	C6	5.60%
2018	C17	33.99%	C15	21.95%	C1	10.29%	C6	6.25%	C12	6.10%
2019	C17	41.28%	C15	23.21%	C6	7.40%	C1	6.67%	C14	6.36%
2020	C17	43.78%	C1	14.47%	C16	10.10%	C6	9.88%	C12	8.48%

Table 4. The obstacle degree of classification index of WRCC in Guangzhou from 2011 to 2020

Year	Obstacle degree			
	B1	B2	B3	B4
2011	24.05%	4.57%	13.13%	58.25%
2012	9.53%	3.93%	17.07%	69.48%
2013	7.84%	3.74%	12.69%	75.73%
2014	7.74%	3.98%	12.57%	75.71%
2015	4.57%	7.09%	11.07%	77.28%
2016	8.49%	8.31%	10.75%	72.46%
2017	17.36%	8.78%	10.52%	63.34%
2018	19.93%	9.55%	10.21%	60.30%
2019	9.63%	10.95%	7.77%	71.64%
2020	24.73%	13.41%	8.28%	53.59%

The results show that the main obstacles affecting WRCC in Guangzhou include water resources per capita, population density, comprehensive water consumption per capita, irrigation water consumption per unit area, COD emissions, ammonia nitrogen emissions and ecological environment water consumption rate, etc. Comprehensive changes in guangzhou city water resources carrying capacity in 2011-2020, although Guangzhou notice to implement various water resources management and protection measures, however, as the city of rapid economic development and population explosion, the speeding up of urbanization makes the effect of existing measures is limited. Guangzhou water situation is still grim, the main problem with task needs to improve system of water saving, water environment governance, water consumption and the intensity of dual control management pressure, lack of urban water supply facilities upgrading and professional maintenance, unconventional water utilization rate is low, and the social public water saving awareness is relatively weak.

3.2.2. Analysis of classification index obstacle factors

According to the obstacle degree results of single index, the obstacle degree of classification index of WRCC in Guangzhou City from 2011 to 2020 is further calculated, and the results are shown in Table 4.

Overall, during the study period, the main classification obstacle factor of WRCC is the water environment subsystem in Guangzhou, and its obstacle degree is greater than 50%, the rest of the three subsystems in the different stages of the influence degree is different, from the concrete numerical water resources subsystem to fluctuations rise, present a tendency of increasing overall social subsystem, economic subsystem general decline. Therefore, under the background of rapid economic development and increasing pressure on water resources in Guangzhou, attention should be paid to making decision-making adjustments from the water environment subsystem, taking into account the water resources system and social system, continuing to optimize the economic subsystem, increasing water resources management and control, imporving the intensity of water control, water efficiency, and reducing the pollutants in wastewater. Finally, the sustainable development of the city and the improvement of the environmental carrying capacity of water resources will be realized.

4. CONCLUSION

According to the evaluation results of WRCC, during 2011-2015, the urbanization process of Guangzhou accelerated, water resources problems became increasingly prominent, and the WRCC showed a downward trend. After 2017, the WRCC recovered and showed a steady upward trend. From the point of obstacle factors measuring the results of the analysis, specific indicators in each subsystem, and the main obstacle factors for individual indicators are water resources per capita, irrigation water consumption per unit area, COD emissions, ammonia nitrogen emissions and ecological environment water use rate, etc. The water environment subsystem is the main obstacle factor for classification index.

The main suggestions to improve the WRCC in Guangzhou are as follows. First, through effective subsidy policies to encourage water-saving technology innovation, accelerate the research and development of agricultural efficient water-saving technology. Sceond, the sewage treatment plant can be upgraded scientifically to control the COD and ammonia nitrogen emission standards in the sewage, and the treated sewage can be used to enrich the reclaimed water. Third, it can establish and improve the scientific water price system and promote the maintenance and transformation of water facilities to regulate the water use of urban residents.

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