Comprehensive Benefit Analysis of Water Resources in Guangzhou by AHP-TOPSIS Model

Jingwei Chen, Yueying Zhou*, Chuju Chen, Liyue Lan, Jiaxin Huang
School of Resources and Planning, Guangzhou Xinhua University, Guangzhou, Guangdong, China
**Corresponding Author*

Abstract: Water resources play a pivotal role in ensuring high-quality socio-economic development. Comprehensive benefit analysis of water resources is beneficial for enhancing the efficiency on water utilization, as well as realizing sustainable utilization of limited water. This paper constructs an index system, including four aspects: ecology, economy, society, and water resource development and utilization (WRDU). By employing the hierarchical analysis and improved TOPSIS model, we evaluate the characteristics and interfering factors of the comprehensive benefits on water resources in Guangzhou during 2012 and 2021. The results show: (1) The overall comprehensive benefit values of water resources in Guangzhou are between 0.318 and 0.500 , and exhibits a gradual upward trend, with the economic and social benefits increasing notably, while the ecological and WRDU benefits apparently significantly decline; (2) The growth rate of social benefits exceeds that of economic benefits; (3) Due to factors such as socio-economic development in Guangzhou, adjustments in water use structures, ecological environment management, population growth, and the various water resource management policies, the ecological benefits rise after its first declin, whereas the benefits from water resource development and utilization follow an initial rise then decrease pattern.

Keywords: TOPSIS Model; Temporal and Spatial Analysis of Comprehensive Water Resource Benefits; Subjective-Objective Weighting Method

1. Introduction

Water is the foundation and prerequisite for human survival and development [1]. Water resources embody both natural and societal attributes. Carrying out comprehensive benefit assessments of water resources is beneficial for enhancing the multiple uses of water resources, maximizing socio-economic and ecological benefits with limited investment in water resources [2]. The comprehensive benefit of water resources refers that water resource development and utilization (WRDU) generates combined benefits in the socio-economic and natural environment. As a result, analyzing the comprehensive benefits for water resources is both multi-level and multi-objective. Its influencing factors include geographical location, climate, environment, and economic development, etc. The intricate interactions among these factors make the study a significant challenge.

Numerous domestic and international researchers have conducted extensive work on the comprehensive benefit evaluation for water resources. For the aspect of various research methods, there are weighted summation method [3], principal component analysis [4], set pair analysis [5], fuzzy comprehensive evaluation method [6], etc. The TOPSIS model can comprehensively evaluate the discrepancy about various analysis schemes. In practical applications, the TOPSIS method, that fully utilize the raw data's information [7]. Considering the characteristics of Guangzhou city, a comprehensive benefit analysis index system of water resources is constructed in this study, and select AHP-TOPSIS model to analyze the comprehensive water resource benefits.

Regarding the weight of indicators, this paper uses the Analytic Hierarchy Process (AHP), which is highly practical. It can quantify human subjective judgments and make decision. It has notable effects on multi-indicator evaluation problems and multi-objective method optimization. He constructed an evaluation system from the technical and economic, ecological environment, and social benefit perspectives, analyzing the comprehensive benefits of water resource utilization in Weihai City [8]; Lu et al. used AHP to analyze the water environmental carrying capacity of a core city in the Huaihe River Basin, and combined the water environmental conditions of the Huaihe River Basin with its environmental and socio-economic characteristics. The evaluation results were satisfactory, demonstrating the practicality of this method [9].

This study builds an analysis index system for Guangzhou City, including 12 indicators such as per capita GDP, water consumption per 10,000 yuan GDP, and ecological environment water use rate, based on data from 2011 to 2021. By utilizing the TOPSIS model and the AHP method, this research identifies obstructive factors impacting Guangzhou's water resources benefits. It calculates relevant indices, determines the weights and closeness values of each indicator, and ultimately analyzes the synthetical benefits of water resources. The results can offer references for the future WRDU in Guangzhou.

2. Overview of the Research Area and Data Source

2.1 General Description of the Study Area

Guangzhou City (longitude 112°57′ to 114°3′, latitude 22°26′ to 23°56′) is situated in the downstream Pearl River. It faces the South China Sea and comprises 11 administrative districts, as shown in Figure 1. Guangzhou has an intricate river system; the water area is totally 755 km². The surface water resources volume is 49.70 billion m³. With its maritime subtropical monsoon climate, the average annual temperature and precipitation are approximately 22°Cand 1736mm. As an international metropolis, global trade center, and international comprehensive transportation hub, the importance of water resources to Guangzhou is self-evident. For water resources, this study offers certain references for the reasonable allocation, conservation, and practical utilization.

2.2 Data Sources

The data selected for this study extract from the "Guangzhou Statistical Yearbook", "Guangzhou Water Resources Bulletin", and "Guangdong Statistical Yearbook" from 2012 to 2021. Some indicators were obtained after processing and calculation. In the process of data processing, because of a few missing data in several years, the average value of adjacent years has been used for supplementation.

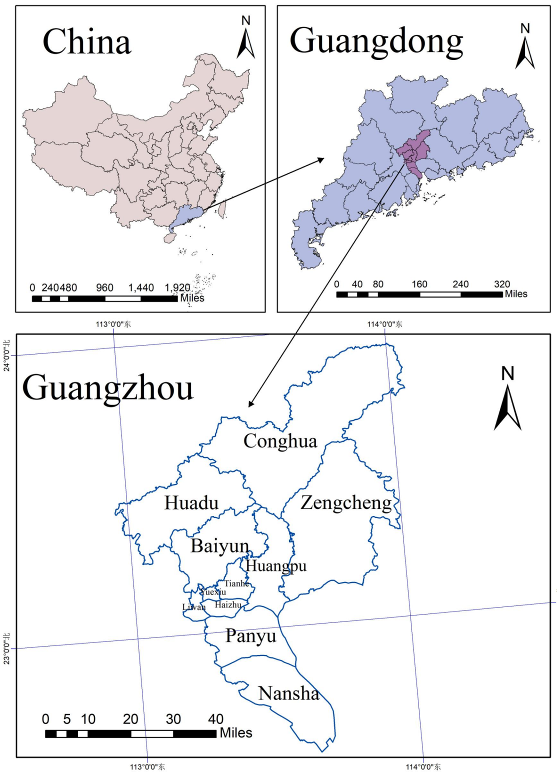

Figure 1. Geographical location map of Guangzhou

3. Research Methods

3.1 Construction of analysis Indicator System

Regional socio-economic development requires good water resources conditions. Sufficient financial support is required for the WRDU. A good ecological environment is the basic condition for water resource regeneration. Therefore, a multi-level analysis system should be established for the analysis of water resources benefits, comprehensively consider ecological, economic, and social benefits, and the WRDU. The established indicator system must have its emphasis and interconnectedness, and at the same time, it can comprehensively reflect the utilization of water. Due to the requirements for the independence, representativeness, quantifiability, and easy access of the analysis indicators, a comprehensive analysis of Guangzhou's ecological environment, economic and social water use level, and the status of WRDU was conducted, and relevant research results [10] were referred to choose the evaluation indicators of Guangzhou's comprehensive water resource benefits.

Ecological benefits usually refer to some benefits brought to humans by maintaining ecological balance and improving ecological conditions. However, in the process of production and life, people not only consume water resources but also discharge a large amount of polluted wastewater into nature, causing certain negative impacts on the ecological environment. Therefore, ecological benefits should be objectively evaluated from both positive and negative aspects. In terms of ecological benefits, three indicators were selected: ecological environment water use, ecological water structure ratio coefficient, and greening coverage rate.

The WRDU can bring direct or indirect economic benefits to human activities. Therefore, indicators selected for economic benefits mainly include per capita GDP, water consumption per 10,000 yuan GDP, and the proportion of the tertiary industry in GDP.

Social benefits mainly refer to the ability of WRDU measures for the socio-economic development and the impact on it. Indicators should consider the impact of water resource utilization on people's production, life, and society. Therefore, the following indicators were selected: population density, urbanization rate, and per capita comprehensive water use.

Water resource development and utilization capability refers to the current ability to use water resources. Therefore, water supply capacity, water supply pipeline density, and per capita water resources were selected as analysis indicators.

As Table 1 shows, the comprehensive benefit analysis index system is constructed according to the above indicators.

Table 1. Comprehensive Benefit Analysis Indicators of Guangzhou's Water Resources

Target Layer (T)	Criteria Layer (C)	Indicator Layer (P)	Unit	Indicator Attribute
Comprehensive Benefits of Guangzhou Water Resources	Ecological Benefit (C_1)	Ecological Environment Water Use (P_1)	10,000 m³/year	+
		Ecological Water Structure Ratio Coefficient (P_2)	—	+
		Greening Coverage Rate (P_3)	%	+
	Economic Benefit (C_2)	Per Capita GDP (P_4)	10,000 yuan/person	+
		Water Consumption per 10,000 yuan GDP (P_5)	m³	-
		Proportion of Tertiary Industry in GDP (P_6)	—	+
	Social Benefit (C_3)	Population Density (P_7)	%	+
		Urbanization Rate (P_8)	%	+
		Per Capita Comprehensive Water Use (P_9)	10,000 people/km²	-
	Water Resource Development & Utilization Benefit (C_4)	Water Supply Capacity (P_{10})	10,000 m³/year	+
		Water Supply Pipeline Density (P_{11})	km/km²	+
		Per Capita Water Resources (P_{12})	%	+

3.2 Determining Weights Using Analytic Hierarchy Process

(1) Experts refer to Table 2, judging m indicators to construct the judgment matrix $C=(C_{ij})_{m\times m}$, wherein C_{ij} represents the comparative importance between indicator i and indicator j.

(2)Normalize the judgment matrix and then calculate all the indicators' weight, that is:

$$w_j=\frac{1}{m}\sum_{i=1}^{m}\frac{c_{ij}}{\sum_{j=1}^{m}c_{ij}},\ i,j=1,2,\dots,m \quad (1)$$

(3)To ensure the results are scientifically accurate and to avoid logical errors from multiple experts' scoring, a consistency test should be performed (Table 3). Based on the formula $CW = \lambda_{max}W$, determine the maximum eigenvalue λ_{max} and eigenvector W . Calculate the consistency index $\mathrm{CI} = \frac{1}{RI}(\lambda_{max} - n)$, introduce the random consistency index RI[10], calculate $\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}$, if $\mathrm{CR} < 0.1$, it indicates that the matrix satisfies the test, meaning the matrix allocation is reasonable; if not, the scores should be adjusted.

Table 2. Scale and Its Meanings in the Judgment Matrix

Scale	Description
1	When comparing factors C_i and C_j, C_i and C_j are of equal importance
3	Compared toC_j, C_i is slightly more important
5	Compared toC_j, C_i is significantly more important
7	Compared to C_j, C_i is much more important
9	Compared to C_j, C_i is extremely more important
2,4,6,8	When neither situation can describe the comparison between C_j *and* C_i, use for interpolation
Inverse of the above numbers	When C_i is less important than $C_j$as described above

3.3 Modified TOPSIS Model

The TOPSIS method can rank according to the distances of finite analysis objects to the idealized goal. It was first proposed by C.L. Hwang and K. Yoon in 1981. It's a relative assessment among existing objects. The TOPSIS method requires only that each utility function has a monotonic increase (or decrease). By measuring the distance from the analysis target to the best and worst solutions, it is the best when the evaluation object has the shortest distances to the best solution while longest to the worst solution; if not, the worst. The best solution has all indicator values reaching the optimal values for each analysis indicator. The worst solution has all indicator values reaching the worst values for each analysis indicator. The detailed calculation steps are:

(1) Normalize the data: Because of the different units, all indicators should not be directly calculated. Hence, for positive indicators, use the following standardization formula:

$$x_{ij} = \frac{x_{ij} - x_j^{min}}{x_j^{max} - x_j^{min}} \quad (2)$$

For negative indicators, the normalization formula is:

$$x_{ij} = \frac{x_j^{max} - x_{ij}}{x_j^{max} - x_j^{min}} \quad (3)$$

Where: x_{ij} are the original data of indicator j in year i; i=1, 2, …, n, j=1, 2, …, m.

(2)Vector normalization of indicator data:

The transformation formula is:

$$b_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad (4)$$

After normalization, the most significant feature of the improved method is thatthe squared sum of the same attribute values for each scheme is 1.. Then, the weight is multiplied by the normalized matrix to acquire the weighted normalized matrix.

$$C_{ij} = \omega_j b_{ij} \quad (5)$$

(3)Calculate the positive and the negative ideal solution $C^+$and C^-

Positive ideal solution: $C^+ = (C_1^+, C_2^+, ..., C_j^+) C_j^+ = \max\{C_{1j}, C_{2j}, ..., C_{ij}\}$(6)

Negative ideal solution: $C^- = (C_1^-, C_2^-, ..., C_j^-)$

$$C_j^- = \min\{C_{1j}, C_{2j}, ..., C_{ij}\} \quad (7)$$

(4)Determine the Euclidean distance from each scheme to the positive ideal point and the negative ideal point, d_i^+ and d_i^-:

use the following formulas:

$$d_i^+ = \sqrt{\left[\sum_{j=1}^{n} \left(C_{ij} - C_j^+\right)^2\right]} \quad (8)$$

$$d_i^- = \sqrt{\left[\sum_{j=1}^{n} \left(C_{ij} - C_j^-\right)^2\right]} \quad (9)$$

For each evaluation object i, determine the comprehensive analysisvalue S_i:

$$S_i = \frac{d_i^-}{d_i^- + d_i^+} \quad (10)$$

4. Comprehensive Benefit Evaluation of Water Resources in Guangzhou

4.1 Indicator Weight

Based on the pairwise comparison results of experts on the importance of each elements, a scoring matrix is obtained. As in Table 3, through the AHP, determine each criterion's weight to its target. The comprehensive weight results are shown in Table 4. The random consistency ratios of the four criteria layers are 0.0079, 0.0048, 0.0158, and 0.0122, respectively. All results meet the consistency inspection.

Table 3. Comprehensive Benefit Analysis Index Weight of Water Resources in Guangzhou City

Judgement Matrix						Weight	Consistency Test		
							λ_{max}	CI	CR
A-C_i	A	C_1	C_2	C_3	C_4		4.0311	0.0104	0.0115
	C_1	1	1/2	2	3	0.280			
	C_2	2	1	3	4	0.469			
	C_3	1/2	1/3	1	1	0.136			
	C_4	1/3	1/4	1	1	0.115			
C_1-P_i	C_1	P_1	P_2	P_3			3.0092	0.0046	0.0079
	P_1	1	3	2		0.539			
	P_2	1/3	1	1/2		0.164			
	P_3	1/2	2	1		0.297			
C_2-P_i	C_2	P_4	P_5	P_6			3.0055	0.0028	0.0048
	P_4	1	2	5		0.595			
	P_5	1/2	1	2		0.277			
	P_6	1/5	1/2	1		0.128			
C_3-P_i	C_3	P_7	P_8	P_9			3.0183	0.0092	0.0158
	P_7	1	1/2	1/4		0.137			
	P_8	2	1	1/3		0.240			
	P_9	4	3	1		0.623			
C_4-P_i	C_4	P_{10}	P_{11}	P_{12}			3.0142	0.0071	0.0122
	P_{10}	1	2	1/5		0.168			
	P_{11}	1/2	1	1/7		0.094			
	P_{12}	5	7	1		0.738			

Table 4. Comprehensive Benefit Analysis Index Weights

Criterion Layer	Weight	Evaluation Indicator	Weight	Comprehensive Weight
Ecological Benefit	0.280	Ecological Environment Water Consumption (P_1)	0.539	0.151
		Ecological Water Structure Coefficient (P_2)	0.164	0.046
		Green Cover Rate (P_3)	0.297	0.083
Economic Benefit	0.469	Per Capita GDP (P_4)	0.595	0.279
		Water Consumption per Ten Thousand GDP (P_5)	0.277	0.130
		Tertiary Industry Proportion in GDP (P_6)	0.128	0.060
Social Benefit	0.136	Population Density (P_7)	0.137	0.019
		Urbanization Rate (P_8)	0.240	0.033
		Per Capita Comprehensive Water Consumption (P_9)	0.623	0.085
Water Resource Development and Utilization Benefit	0.115	Water Supply Capability (P_{10})	0.168	0.019
		Water Supply Pipeline Density (P_{11})	0.094	0.011
		Per Capita Water Resources (P_{12})	0.738	0.085

4.2 Analysis of Water Resources Benefits

The study for comprehensive benefit of water resources is an integrated study of evaluation, planning, and forecasting. Table 5 lists the values of the comprehensive benefit analysis of water resources in Guangzhou during 2012 and 2021. The value of 2021 was the highest at 0.500, and 2013 has the lowest at 0.3183. The overall values trended slightly upward during the decade, but the temporal trends of each index layers were different.

From 2012 to 2021, with the support of policies, Guangzhou actively cooperated with Hong Kong and Macao, attracting a large number of migrant workers to Guangdong, which promoted urban construction and economic development, and the growth of social benefits was the most significant. Due to the impact of the epidemic from 2019 to 2020, consumer enthusiasm decreased, fiscal expenditure on epidemic prevention increased, and economic benefits decreased. However, it rebounded in 2020. The growing of the socio-economy drove yearly increase in the construction of international shipping hub projects and large-scale projects like "IAB" strategic projects. The increase in water consumption for daily life and industry led to a reduction in water allocated for ecological environments, thereby affecting the decrease in the ecological water structure ratio. Both the ecological benefit and the benefit from water resource development and utilization trended downwards, while the ecological benefits sharply declined after 2012, and even though they have rebounded under multiple environmental protection policies, they have not yet reached the original level. From 2012 to 2016, Guangzhou implemented the strictest water resource management system, strengthened controls on WRDU, water efficiency controls, and pollution intake management in water function areas. Urban water-saving levels improved, and the benefits of water resource development and utilization grew, reaching 0.879. However, influenced by the increasing population, per capita water resources decreased, leading to a gradual decline in the benefits of WRDU.

Compared with other first tier cities in China, the economic development of Guangzhou is slightly backward. It is necessary to further improve the talent introduction policy, and attach importance to high-quality development. At the same time, it is important to achieve harmony between people and water, avoiding rough water resource development and sacrificing the ecological environment. Allocating water resources with forward-looking perspective, which can also help to improve the water resources benefits in multiple aspects.

Table 5. Benefit Analysis Values of Water Resource in Guangzhou City

Year	Ecological	Economic	Social	Water Resource Development and Utilization Benefit	Comprehensive analysis Index	Comprehensive Rating
2012	0.672	0.374	0.074	0.640	0.474	III
2013	0.041	0.448	0.095	0.680	0.318	IV
2014	0.069	0.512	0.133	0.675	0.352	IV
2015	0.074	0.580	0.189	0.767	0.394	IV
2016	0.087	0.607	0.275	0.876	0.429	III
2017	0.133	0.647	0.313	0.545	0.464	III
2018	0.245	0.653	0.393	0.499	0.493	III
2019	0.265	0.467	0.504	0.819	0.401	III
2020	0.297	0.491	0.963	0.342	0.447	III
2021	0.295	0.592	0.956	0.217	0.500	III

5. Conclusion

This article has constructed an analysis index system covering ecological environment, economy, society, and water resources. By using the AHP-TOPSIS method, an analysis of the water benefits of Guangzhou City during 2012 and 2021 over 10 years has been carried out, leading to the following conclusions:

(1)In 2021, Guangzhou City reached its peak in terms of comprehensive benefits of water resources at 0.500, while the lowest was in 2013 at 0.3183. The overall trend is a slow rise.

(2)From 2012 to 2021, the growth rate of social benefits in Guangzhou City was the highest, followed by economic benefits. Ecological benefits and the benefits from water resource development and utilization showed fluctuations due to factors like Guangzhou's economic and social development, uneven water distribution, population growth, and the various water resource management policies.

(3)Using the AHP and the improved TOPSIS method to respectively calculate the weights of each index and the benefits of water resources has made the results more in line with reality. This can provide a scientifically reasonable reference value for improving the efficiency of WRDU in Guangzhou City and promoting harmony between humans and water.

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