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Evaluation of Water Resource Carrying Capacity in Sichuan Province Based on Principal Component Analysis

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ABSTRACT

This study explores the relationship between water resource carrying capacity and the coordinated development of the water-economy-ecosystem in Sichuan Province in the future. An assessment framework composed of four subsystems with a total of fourteen indicators is constructed, covering nearly fifteen years of data from 2008 to 2022. Principal component analysis is utilized for the analysis, and the results show that the principal components integrate key elements such as economy, efficiency, water resource systems, and population, revealing the importance of these factors in determining water resource carrying capacity. The water consumption per ten thousand GDP and per ten thousand industrial added value in Sichuan Province are significantly lower than the national average level, indicating an overall upward trend in water resource carrying capacity, reflecting Sichuan Province's high level of water resource utilization efficiency, which far exceeds the national average.

KEYWORDS

Water resource carrying capacity; Sichuan Province; Principal component analysis

1. INTRODUCTION

The carrying capacity of water resources, as a key component of the natural resource carrying capacity system, continuously evolves with the progression of society, economy, and technology, forming a dynamic and complex comprehensive indicator. General Secretary Xi Jinping pointed out at the Central Financial and Economic Leadership Group meeting that the carrying capacity of water resources is limited, which determines that the development methods and scales of water resources must be kept within reasonable limits to ensure sustainable economic and social development [1].

2. LITERATURE REVIEW AND THEORETICAL ANALYSIS

Wang Jianhua et al. [2] summarized the core issues in the current research on water resource carrying capacity, focusing on key scientific questions such as the four-dimensional dynamic evolution mechanism of "quantity-quality-space-flow" and the elastic boundaries of "water-economic society-ecology" system carrying capacity. Zhou Li et al. [3] assessed the water resource carrying capacity of Zhejiang Province using BP neural networks, revealing the critical impact of annual rainfall on the region's water resource carrying capacity. Yu Guobao [4] proposed an intelligent monitoring method for water resource ecological carrying capacity based on neural network algorithms. Cui Yi et al. [5] conducted an empirical analysis of various cities in Anhui Province using a dynamic differential coefficient, indicating that increasing water resource supply, enhancing vegetation coverage, optimizing water resource utilization and management, and strengthening ecological water demand can effectively enhance the water resource carrying capacity of Anhui Province. Zai Songmei et al. [6] established a corresponding water resource carrying capacity evaluation model based on support vector machine theory, finding that the water resource carrying capacity index of Xinxiang City could reach above 0.6 in 2015. Jiang Qiuxiang et al. [7] quantitatively evaluated the water resource carrying capacity of the Sanjiang Plain, discovering variations in the strength of water resource carrying capacity across different regions. The above literature collectively suggests that the evaluation of water resource carrying capacity must adapt to the characteristics of rapid changes in regional socio-economic conditions, employing scientific methods for assessment in a timely manner, and formulating reasonable water resource development and utilization strategies to ensure sustainable support for socio-economic activities. In light of this, this research adopts principal component analysis, selecting 14 indicators under 4 systems to comprehensively evaluate the water resource carrying capacity in Sichuan Province over the past 15 years, aiming to provide a reference for the high-quality development of water resources and socio-economics in Sichuan Province.

3. MODEL SETTING AND DATA DESCRIPTION

3.1. Principal Component Analysis

(1) Data standardization

Standardize the selected indicators using the Min-max normalization method. The formula for Min-max normalization is:

$$\boldsymbol{X_i^*} = \frac{\boldsymbol{X_i - min(X_i,\ \dots,\ X_n)}}{\boldsymbol{max(X_i,\ \dots,\ X_n) - min(X_i,\ \dots,\ X_n)}}$$

In the formula, $\boldsymbol{X_i^*}$ —— standardized value; $\boldsymbol{X_i^*}$—— original value; $\boldsymbol{i = 1, 2, 3, \dots, n;\ n = 10}$;

(2) Calculate the correlation coefficient matrix.

(3) Analyze the principal component factor loadings, eigenvalues, and variance contribution rates.

(4) Calculate scores and analyze the results.

3.2. Data Sources

The data in this article is sourced from the "Sichuan Provincial Water Resources Bulletin" (2013-2022), "Sichuan Provincial Economic and Social Development Statistical Bulletin" (2013-2022), and the "Sichuan Statistical Yearbook" (2013-2022).

3.3. Data Analysis

The evaluation indicators use data calculated with Microsoft Excel 2019 and principal component analysis conducted using SPSS Statistics 24 software.

4. EVALUATION OF WATER RESOURCE CARRYING CAPACITY IN SICHUAN PROVINCE

4.1. Selection of Indicators

This article fully integrates the concept of water resource carrying capacity and the research experiences of other scholars [8-10], resulting in a system of 14 indicators (A1-A14) across 4 subsystems that constitutes the evaluation index system for the water resource carrying capacity of Sichuan Province, as shown in Table 1.

Table 1. Rating Indicator System

Target layer	System layer	Indicator layer
Water resource carrying capacity	Economic system	GDP(A1), The proportion of the tertiary industry in GDP (A2), the effective irrigated area (A3), and the grain yield per unit area (A4)
	Water Resource System	Average rainfall in the whole province (A5), total water resources (A6), total water consumption (A7), industrial water consumption (A8), agricultural water consumption (A9), net water consumption (A10)
	Efficiency System	Water consumption per ten thousand yuan of GDP (A11), water consumption per ten thousand yuan of industrial added value (A12)
	Population system	Total population (A13), urban population proportion (A14)

4.2. Correlation Analysis

A correlation analysis was conducted on the selected and processed standardized indicators, and the results are shown in Figure 1. The KMO value is 0.689, and most of the indicator correlation coefficients are above 0.600, indicating a strong correlation among the selected indicators. Therefore, the above-selected indicators can be used for the analysis of water resource carrying capacity in Sichuan Province.

4.3. Principal Component Factor Loadings, Eigenvalues, and Variance Contribution Rates

The principal component loading matrix, eigenvalues, and variance contribution rates are shown in Table 2.

Two principal components with eigenvalues > 1 were extracted, with variance contribution rates of 75.484% and 12.187%, respectively, resulting in a cumulative contribution rate of 87.671%. This indicates that these two principal components contain the main information of the 14 indicators.

In Principal Component 1, the significant factors include GDP, the proportion of the tertiary industry to GDP, the area of irrigated effective arable land, grain yield per unit area, total water usage, agricultural water usage, net water consumption, water usage per 10,000 GDP, water usage per 10,000 industrial added value, total population, and the proportion of urban population, totaling 10 indicators. Among them, GDP, the proportion of the tertiary industry to GDP, the area of irrigated effective arable land, and grain yield per unit area reflect the economic system's impact on the carrying capacity of water resources, indicating that there is a negative correlation between economic volume and the pressure on water resource carrying capacity: the larger the former, the greater the pressure on the latter. Total water usage, agricultural water usage, and net water consumption demonstrate the impact of the water resource system on its carrying capacity; water usage per 10,000 GDP and water usage per 10,000 industrial added value reflect the efficiency system's influence on the carrying capacity of water resources, while total population and urban population proportion illustrate the pressure of the population system on water resource carrying capacity.

The major factors in principal component 2 are the average rainfall in the province and the total water resources. However, the variance contribution rate of principal component 2 is only 12.187, indicating that the main factors affecting the water resource carrying capacity in Sichuan Province are not the industrial water usage, the average rainfall in the province, or the total water resources.

Table 2. Principal component eigenvalues and variance contribution rate

Component	Factor loadings	
	Principal Component 1	Principal Component 2
GDP	0.920	0.283
The proportion of the tertiary industry in GDP	0.943	0.222
Effective irrigated area	0.930	0.323
Unit area grain yield	0.895	0.391
Average rainfall in the province	0.111	0.904
Total water resources	0.186	0.964
Total water usage	0.767	-0.102
Industrial water usage	-0.760	-0.475
Agricultural water usage	0.913	0.081
Net water consumption	0.959	-0.420
Water consumption per ten thousand yuan of GDP	-0.908	-0.311
Water consumption per ten thousand yuan of industrial added value	-0.931	-0.295
Total population	0.810	0.163
Proportion of urban population	0.936	0.306
Eigenvalue	10.568	1.706
Variance contribution rate / %	75.484	12.187
Cumulative variance contribution rate /%	75.484	87.671

4.4. Comprehensive Score and Evaluation

The principal component scores and comprehensive scores are shown in Table 3 and Figure 1 below.As can be seen from Figure 1, in recent years, the overall water resource carrying capacity of Sichuan Province has shown an upward trend, indicating that the regional water resource carrying capacity has been continuously improving, with a slowdown in growth in 2020. In 2022, the water consumption per ten thousand GDP in Sichuan Province was 44.3 m3, slightly higher than the national average of 49.6 m3; in 2022, the water consumption per ten thousand industrial added value in Sichuan Province was 12.9 m3, significantly lower than the national average of 24.1 m3, indicating that the overall water consumption level in Sichuan Province is higher than the national average, and the efficiency of water resource utilization is relatively high.

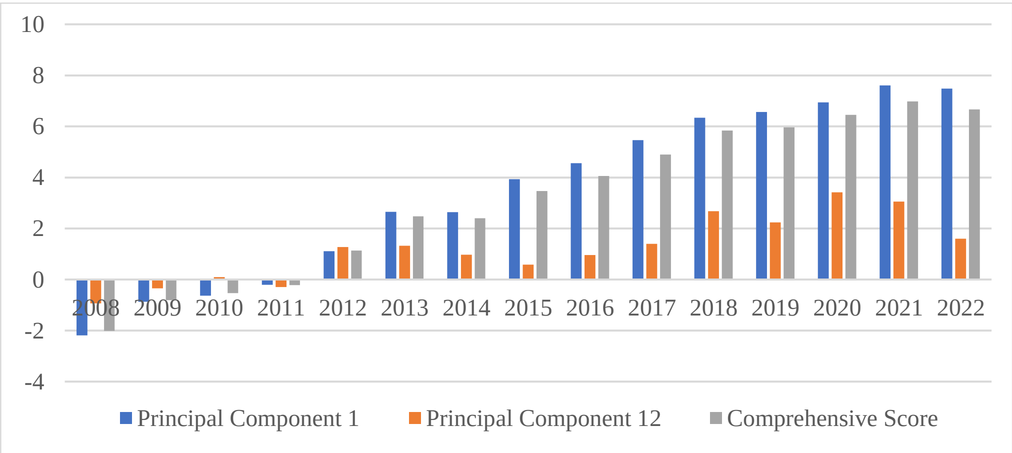

Figure 1. Principal component scores and composite scores

Table 3. Principal component scores and composite scores

Year	Principal Component 1	Principal Component 2	Year	Principal Component 1	Principal Component 2
2008	-2.189	-0.939	2016	4.563	0.963
2009	-0.877	-0.344	2017	5.465	1.399
2010	-0.633	0.098	2018	6.345	2.678
2011	-0.205	-0.290	2019	6.562	2.242
2012	1.110	1.268	2020	6.941	3.412
2013	2.658	1.326	2021	7.608	3.052
2014	2.635	0.973	2022	7.483	1.596
2015	3.927	0.582			

5. CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

(1) Through the analysis of the principal components of water resource carrying capacity in Sichuan Province over the past 15 years (2008-2022), it has been found that GDP, effective irrigated farmland area, grain output per unit area, total water consumption, industrial water consumption, agricultural water consumption, water consumption per ten thousand yuan of GDP, water consumption per ten thousand yuan of industrial added value, and the proportion of urban population are the main factors affecting the water resource carrying capacity of Sichuan Province.

(2) A comprehensive evaluation shows that the water resource carrying capacity in Sichuan Province has shown an overall upward trend in recent years, and the efficiency of water resource utilization is above the national average level, which can be further stably improved.

5.2. Recommendations

(1) Promote water-saving technologies and measures. Encourage industrial enterprises to adopt advanced water-saving equipment and processes, such as closed-loop water recycling systems, to increase the reuse rate of industrial water. For example, a large chemical company improved its water reuse rate from 50% to 80% through process modifications, reducing water consumption per ten thousand yuan of industrial output. In agriculture, promote efficient irrigation technologies such as drip irrigation and sprinkler irrigation to replace traditional flood irrigation. For instance, an agricultural demonstration park adopted drip irrigation technology, saving more than 30% of water compared to flood irrigation, while also increasing grain yield per unit area.

(2) Advance water ecological restoration projects to restore the ecological functions of rivers and lakes and enhance the water resource conservation capacity. For example, an ecologically polluted river was treated through measures such as planting aquatic plants and introducing microorganisms, which improved water quality and increased the availability of water resources.

(3) Optimize water resource allocation. Strengthen inter-regional water resource allocation by constructing water conservancy projects to achieve reasonable distribution of water resources. Prioritize ensuring residents' domestic water consumption and ecological water use, while reasonably arranging industrial and agricultural water usage.

(4) Develop a water resource recycling industry. Encourage and support sewage treatment companies to improve sewage treatment levels and reuse the treated gray water. Promote the construction of rainwater harvesting and utilization systems for urban greening and landscape replenishment.

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