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Spatial-Temporal Evaluation and Prediction of Water Resources Carrying Capacity in the Xiangjiang River Basin Using County Units and Entropy Weight TOPSIS-BP Neural Network

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Abstract: To improve the water resources carrying capacity of the Xiangjiang River Basin and achieve sustainable development, this article evaluates and predicts the Xiangjiang River Basin's water resources carrying capacity level based on county-level units. This article takes 44 county-level units in the Xiangjiang River Basin as the evaluation target, selects TOPSIS and the entropy weight method to determine weights, calculates the water resources carrying capacity level of the evaluation sample, uses a BP neural network model to calculate the predicted water resources carrying capacity level for the next 5 years, and adds the GIS method for spatiotemporal analysis.(1) The water resources carrying capacity of the Xiangjiang River Basin has remained relatively stable for a long period, with overloaded areas being the majority. (2) There are relatively significant spatial differences in the carrying capacity of water resources: Zixing City, located upstream of the tributary, is far ahead due to its possession of the Dongjiang Reservoir; the water resources carrying capacity in the middle and lower reaches (northern region) is generally higher than that in the upper reaches (southern region). (3) According to the BP neural network model prediction, the water resources carrying capacity of the Xiangjiang River Basin will maintain a stable development trend in 2022, while areas such as Changsha and Zixing City will be in a critical state, and other counties and cities will be in an overloaded state.This study has important references value for the evaluation and early warning work of the Xiangjiang River Basin and related research, providing a scientific and systematic evaluation method and providing strong support for water resource management and planning in Hunan Province and other regions.

Keywords: Xiangjiang River; water resources carrying capacity; TOPSIS model; entropy weighting method; BP neural network

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1. Introduction

The carrying capacity of water resources has always been a vital issue affecting a region's economic, social, and ecological environment. The "Outline of the National Water Network Construction Plan" proposes to build a national water network from 2021 to 2035 to solve the problems of water resources, water ecology, water environment, and water disasters [1]. Strengthening the rigid constraints of water resources carrying capacity is a crucial measure to ensure the construction of the national water network. At present, research on water resources carrying capacity is mostly focused on provincial, municipal, or administrative regions, with relatively few studies involving the water resources carrying capacity of complete river basins. For example, Xia Weijing et al. [2] used nine basins in Shaanxi as evaluation units and constructed a comprehensive evaluation model for water resources carrying capacity based on macro and comprehensive indicators; Ait Aoudia [3] assessed the population that can be supported in terms of water resources and household consumption patterns in Algeria, a country with scarce water resources.

At the level of research methodology, recent studies have shown a trend towards systematization, with a diverse array of tools being employed. For example, Zou Zonghua [4] evaluated the water resources carrying capacity of nine provinces and regions along the Yellow River through the construction of an indicator system. Yu Po [5] used the coupled water footprint theory and principal component analysis method to explore the water resources carrying capacity in the Xinjiang region based on water footprint. Liu Yan [6] used the system dynamics model to analyze the carrying capacity of water resources in Suibin County and solved the contradiction between supply and demand of water resources in Sanjiang Plain. Zuo et al. [7] evaluated the water resources carrying capacity of 15 regions in the Xinjiang Uygur Autonomous Region from 2004 to 2017 using the fuzzy comprehensive evaluation method. Although each of the above methods has its characteristics, for the Xiangjiang River Basin, the conventional trend method does not fully consider the interaction between factors affecting water resources carrying capacity, making it difficult to reflect the current situation. Principal component analysis can objectively determine the weights of indicators, but subjective factors also influence it in the grading criteria of evaluation parameters. The fuzzy comprehensive evaluation method can comprehensively process the discrete processes generated, but the information utilization rate is relatively low. The combination of the TOPSIS model and the entropy weight method can fully utilize indicator information to objectively and accurately evaluate the superiority and inferiority of different evaluation objects. Currently, it has been fully applied in research on water resources carrying capacity. Zhang Fan [8] evaluated the water resources carrying capacity of the Gansu section of the Yellow River Basin based on entropy weight TOPSIS, promoting economic development to match the water resources carrying capacity; Jiang Dejuan [9] quantitatively evaluated the water resources carrying capacity of 16 cities in Shandong Province from 2011 to 2020 based on comprehensive weighting and the TOPSIS model and proposed improvement suggestions. At the same time, choosing the BP neural network model as the prediction method is due to its strong self-learning ability, which can automatically extract features and patterns from data. In order to meet the needs of building a smart water network, the BP neural network model can achieve refined management and prediction of water resources, providing a scientific basis for the rational allocation and utilization of water resources. Xue Qing [10] conducted research on predicting and regulating the water resources carrying capacity in Jiangsu Province based on a BP neural network, providing a constructive basis for optimizing water resources regulation.

The Xiangjiang River is the largest in Hunan Province and is known as the “mother river” of Hunan. The basin is rich in mineral resources, and there are developed industries in the middle and lower reaches. Due to seasonal changes, the rainfall in the Xiangjiang River Basin fluctuates significantly throughout the year, resulting in varying degrees of droughts and floods throughout the basin. It is of great significance to evaluate and predict its water resources carrying capacity, which can better serve the basin’s economy and provide data to support the construction of Hunan’s smart water network.

2. Status of the Study Area

2.1. Research Modules

2.1.1. Selection of Research Units

This article evaluates the water resources carrying capacity of the Xiangjiang River Basin (Figure 1) at the county level, which can provide more detailed water resource data and facilitate the identification of specific water resource distribution and demand differences (Table 1). This detailed evaluation helps local governments formulate more effective water resource management policies, achieve rational allocation, and optimize resource utilization and thus improve the pertinence and operability of management.

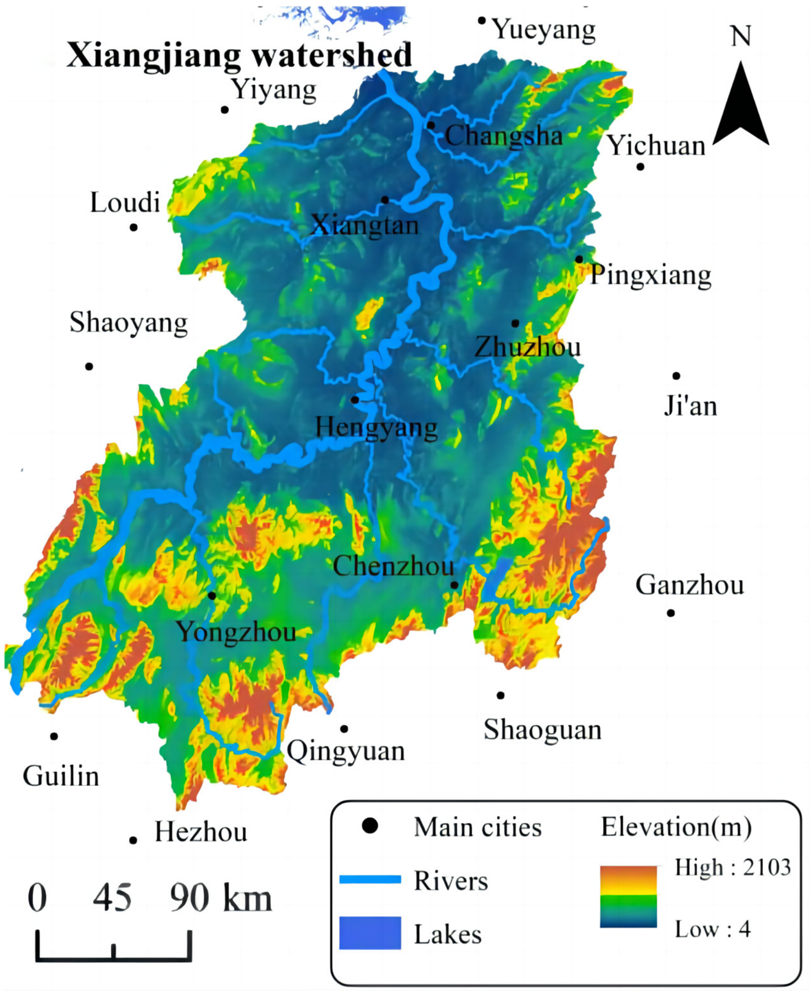

Figure 1. The Xiangjiang basin.

Table 1. The scales and their advantages.

Scale	Advantage
County scale	Data precision: Data at the county scale are more specific, reflecting local water conditions, water demand, and water management issues. Local features: able to identify local water resource issues in detail, such as overexploitation or pollution of water sources in a particular county. Management measures: The county scale is conducive to formulating targeted management measures and policies that adapt to the local situation.
Basin scale	Comprehensive: The basin scale can comprehensively consider the water resources situation in the whole basin, including the flow and utilization of water resources upstream and downstream. Regional collaboration: Considering upstream and downstream water use, the basin scale facilitates the development of transregional water management measures to address transboundary water issues.
Regional scale	Macro perspective: Regional scales often involve multiple basins, providing a more macro perspective to analyze water resources' spatial distribution and utilization. Trend analysis: suitable for identifying long-term trends in water resource changes and potential water scarcity issues within a region.
National scale	Overall trend: National-scale analysis can reveal the supply–demand imbalance and overall trend of water resources nationwide, such as the uneven distribution of water resources in different regions. Policymaking: It helps to formulate national-level water resource management policies and strategies, but may overlook specific local issues.

2.1.2. Overview of the Research Unit

The vast majority of the Xiang River is within Hunan Province, accounting for more than 95% of the basin area year-round, with upstream (southern) tributaries extending into

Guangxi Province. The source to the mainstream is in Hunan, with a basin covering nine prefecture-level cities (Changsha, Xiangtan, Zhuzhou, Hengyang, Chenzhou, Yongzhou, Loudi, Shaoyang, and Yueyang). According to the Xiangjiang River Flood Control Planning Report (HND/A1g-1-001) of the Hunan Provincial Institute of Water Resources, under the Ministry of Water Resources, in 1999, the Xiangjiang River involves 58 counties (cities and districts). However, the area of the counties covered by the basin varies considerably (Table 2).

Table 2. Distribution and drainage area ratio of counties (cities) in the Xiangjiang River Basin.

Name of Place or City	County and City Name and Percentage (%)										
	1	2	3	4	5	6	7	8	9	10	11
Changsha	100.0 Changsha	100.0 Urban, suburban	100.0 Wangcheng	91.5 Ningxiang	100.0 Liuyang						
Zhuzhou	100.0 Zhuzhou	100.0 Liling	100.0 Youxian	100.0 Chaling	100.0 Yanling	100.0 Urban, suburban					
Xiangtan	100.0 Xiangtan	100.0 Urban, suburban	100.0 Xiangxiang	100.0 Shaoshan							
Hengyang	100.0 Hennan	100.0 Hengyang	100.0 Hengshan	100.0 Hengdong	100.0 Leiyang	100.0 Changning	100.0 Qidong	100.0 Urban, suburban			
Shaoyang	6.3 Xinshao	47.5 Shaodong	2.0 Shaoyang								
Yueyang	3.5 Xiangyin	14.0 Miluo									
Loudi	100.0 Shuangfeng	100.0 Lianyuan	26.8 Lengshuijiang								
Chenzhou	100.0 Anren	100.0 Yongxing	100.0 Zixing	91.0 Guidong	79.0 Rucheng	100.0 Jiahe	98.5 Guiyang	100.0 urban area	25.0 Linwu	5.5 Yizhang	
Yongzhou	100.0 Urban area	100.0 Shuangpai	57.0 Jiang yong	95.5 Jianghua	100.0 Daoxian	100.0 Lanshan	100.0 Qiyang	100.0 Xintian	100.0 Ningyuan	100.0 Dongan	100.0 Jindong Forest Farm

In order to assess the water resources carrying capacity of the Xiangjiang River in a more in-depth and precise manner, this study is the first to refine its analysis to the level of county units. However, the land area belonging to the Xiangjiang River varies among the county units. Combining the previous studies [11–14] with the actual situation of the Xiangjiang River, more than 50% of the area where the Xiangjiang River flows through is considered the "county unit" in this study. The urban area of a prefecture-level city within the assessment scope may be less than the land area of a county or township in relation to the basin area; therefore, it is more accurate and objective to combine prefecture-level cities' urban areas into a "county unit", which was verified in the earlier pre-study; Changsha's Tianxin and Yuhua Districts and Chenzhou's Suxian and Beihu Districts were taken as a separate "county unit". In this regard, the earlier pre-study has verified that the evaluation of Changsha's Tianxin District and Yuhua District and Chenzhou's Suxian District and Beihu District as separate "county units" basically makes no difference. Accordingly, this study involves seven prefecture-level cities' urban areas and 37 counties (cities), or 44 "county units" (Table 3).

Table 3. County-level units in the research area.

Prefecture-Level City	County Level Unit
Changsha City	Changsha City District, Wangcheng District, Ningxiang County, Liuyang City, Changsha County
Xiangtan City	Xiangtan City District, Xiangxiang City, Shaoshan City, Xiangtan County
Zhuzhou City	Zhuzhou City District, Zhuzhou County, Liling City, You County, Chaling County, Yiling County
Hengyang City	Hengyang City District, Leiyang City, Changning City, Qidong County, Hengyang County, Hengdong County, Hengshan County, Hengnan County
Chenzhou City	Chenzhou City District, Zixing City, Anren County, Guiyang County, Rucheng County, Jiahe County, Guidong County, Yongxing County
Yongzhou City	Yongzhou City District, Qiyang City, Lanshan County, Xintian County, Jiangyong County, Shuangpai County, Ningyuan County, Dong'an County, Daocheng County, Jianghua Yao Autonomous County.
Loudi City	Loudi City District, Shuangfeng County, Lianyuan County

2.2. *Regional Water Resources*

2.2.1. Hydrological Water Resources

The Xiangjiang River is the largest in the Dongting Lake system of the Yangtze River Basin. It originates from Ziliang Yao Autonomous Township in Lanshan County, Hunan Province, and its mainstream runs from south to north through cities such as Yongzhou, Hengyang, Zhuzhou, Xiangtan, and Changsha before flowing into Dongting Lake at Lulintan in Xiangyin County (Figure 2). The main stream is 670 km long, with a drainage area of 85,225 km^2 and an annual runoff of 106 billion m^3, making it the largest river in Hunan. The Xiangjiang River has a developed water system and numerous reservoirs, with 124 primary tributaries and 16 main tributaries and a drainage area greater than 1000 km^2. Among them, Xiaoshui has a drainage area of 12,000 km^2, followed by Leishui and Yishui. Eleven controlled water conservancy hub projects have been built on the Xiangjiang River, including large-scale reservoirs with a storage capacity of over 100 million cubic meters, such as Centian River, Shuangpai, Ouyang Sea, Taoshui, Dongjiang, Qingshanlong, Jiubu River, Shuifu Temple, Zhushu Bridge, Guanzhuang, and Huangcai. The largest reservoir, Dongjiang Lake, is located in Zixing City, with a total storage capacity of 9.15 billion cubic meters and a catchment area of 26,000 square kilometers.

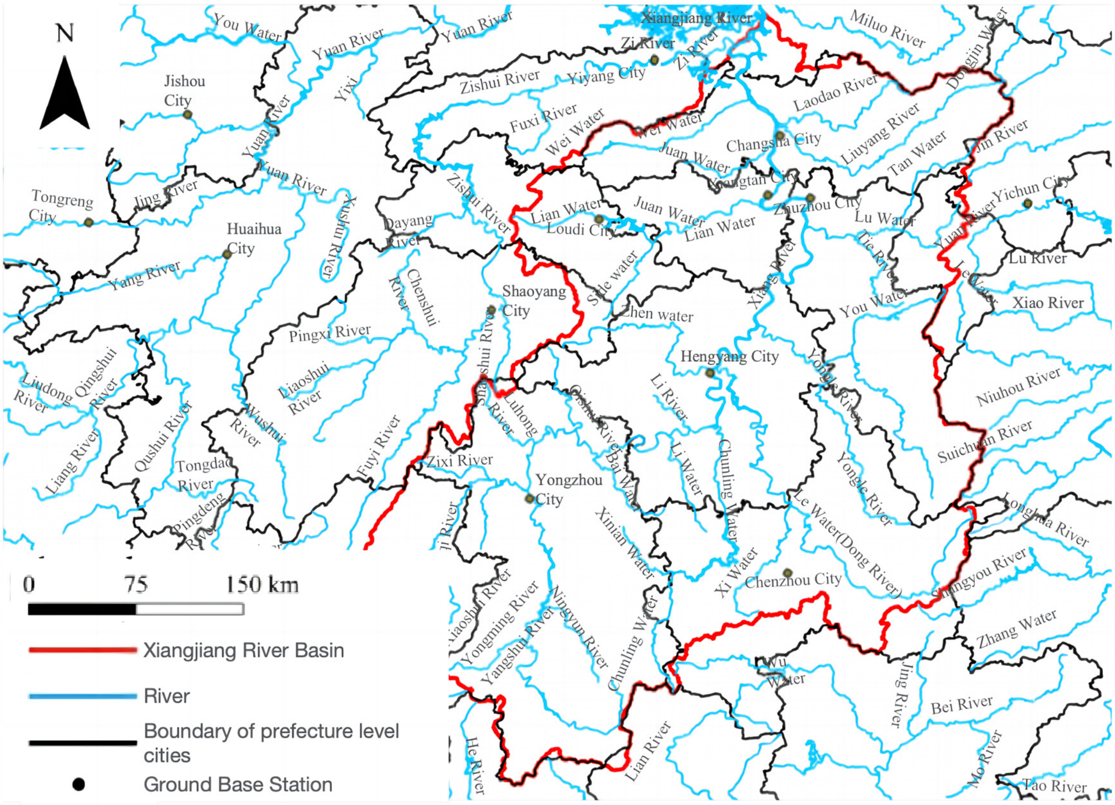

Figure 2. Branches of the Xiangjiang River Basin.

2.2.2. Water Quality and Environment

The Xiangjiang River has abundant mineral resources, with agriculture as the main upstream activity and industry as the main midstream and downstream activity; this poses hidden dangers to the water quality of the Xiangjiang River. The rainstorms in spring and summer wash the ground, pollutants are carried into the river through surface runoff, and total nitrogen and phosphorus gradually increase from upstream to downstream. Since 2012, efforts to improve the ecological environment have continuously increased, with over 90% of the Xiangjiang River's sections under national and provincial control having water quality above Class III (Figure 3).

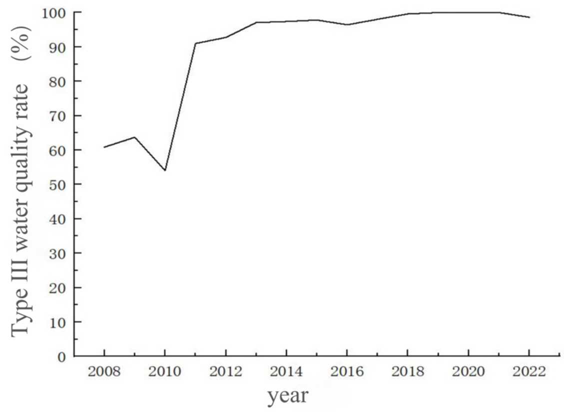

Figure 3. Proportion of water quality above Class III in the Xiangjiang River.

2.2.3. Economic and Social Conditions

The population of Xiangjiang increased from 32.6559 million in 2008 to 36.3745 million in 2022, accounting for approximately 55% of the province's population. The urbanization process is accelerating, and the urban population share has increased from 41.94% in 2008 to 57.05% in 2022. GDP has shown remarkable growth, increasing from CNY 714.087 billion in 2008 to CNY 3061.655 billion in 2022, and per capita GDP has increased from CNY 18,637.26 in 2008 to CNY 70,886.43 in 2022, demonstrating a sustained upward trend.

3. Evaluation and Forecasting Methods

3.1. Evaluation Models and Methods

3.1.1. Evaluation Modelling Framework

The model architecture is defined as having three layers: the target layer, the criterion layer, and the indicator layer (Figure 4). The target layer is the water resources carrying capacity of the Xiangjiang River, which includes five interrelated and constrained criterion layers: resource support, economic support, social support, environmental support, and management support (Figure 5). Resource support is the most direct water resources endowment system, economic and social conditions are the most direct results of the basin water resources carrying capacity, the environmental status reflects the sustainable development level of "green water and green mountains are golden silver mountains", and the management capacity reflects the potential and soft power of the water resources carrying capacity, which provides support for the intelligent water network. The criterion layer is evaluated by approximating the ideal solution ranking (TOPSIS). The method has a clear and explicit model structure, is widely used, has mature calculation methods, and is highly adaptable.

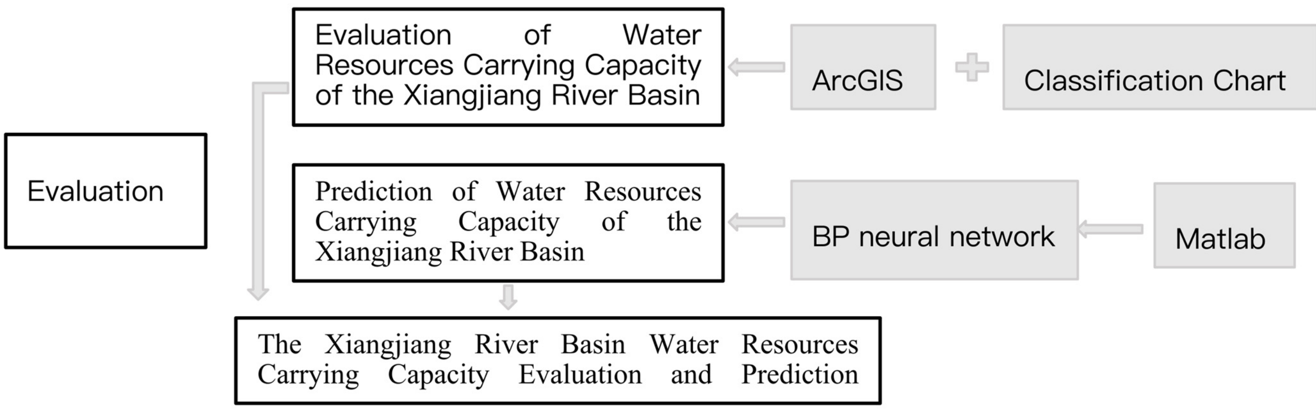

Figure 4. Figure technological route.

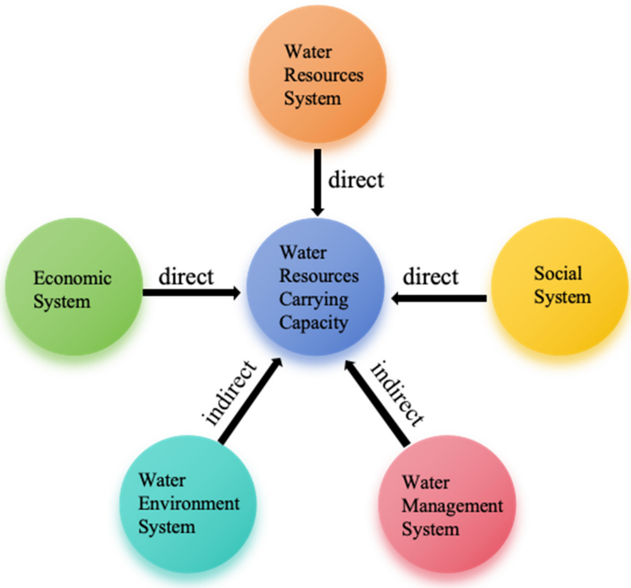

Figure 5. Guideline layer framework.

3.1.2. TOPSIS Method

TOPSIS (technique for order preference by similarity to an ideal solution), also known as the "ideal solution ranking method", is a method that ranks multiple evaluation objects by comparing their similarity to the ideal solution and determines their relative superiority or inferiority. This method has the advantages of a flexible and convenient calculation process, accurate and reasonable evaluation results, etc.

To improve the application of the TOPSIS model in water resources carrying capacity evaluation, many scholars have conducted in-depth research. For example, Du Xuefang et al. [15] combined subjective and objective weighting methods with the TOPSIS model to evaluate the water resources carrying capacity of Zhengzhou City from 2010 to 2019; Ma Jimin et al. [16] combined the entropy weight method and the CRITIC (criteria importance through intercriteria correlation) method and applied them to the improved grey relational approximation solution ranking (GRA-TOPSIS) model. Deng Quancheng et al. [17] used a TOPSIS model combining the entropy value method and the analytic hierarchy process to comprehensively evaluate the water resources carrying capacity of Xinxiang City from 2006 to 2018 and conducted obstacle analysis on the evaluation results. However, Xu Zhenghua [18] cited an improved entropy weight TOPSIS model evaluation method, using information entropy to calculate the weights of each evaluation indicator and using the optimal solution of Euclidean distance to evaluate the water resources carrying capacity.

In these studies, analysis was conducted based on the proximity of the evaluation values C_i. The closer C_i is to 1, the closer the evaluation object is to the optimal solution, indicating that the object is relatively better. Finally, the water resources carrying capacity levels are classified based on the proximity of each object in descending order. Through the research on the improvement and application of the TOPSIS method in the evaluation of water resources carrying capacity, it can be seen that in the actual evaluation process, combining other weight determination methods can improve the accuracy and reliability of the evaluation results. The introduction of these methods makes the evaluation process more comprehensive and scientific, providing decision-makers with more in-depth and actionable information.

Based on TOPSIS and the entropy weight method to calculate the evaluation value of the water resources carrying capacity of the Xiangjiang River, the steps of the TOPSIS calculation are as follows:

1. A set of data with a sample size of m and a number of indicators of n is processed with the same trend, and then the data are dimensionless according to the following formula, i.e., a dimensionless decision matrix:

$$Z = (z_{ij})_{m \times n},\ z_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}}} \tag{1}$$

2. Determine the optimal solution z_j^+ and the worst solution z_j^- for each indicator:

$$z_j^+ = \max\{z_{1j}, z_{2j}, \cdots, z_{mj}\} \tag{2}$$

$$z_j^- = \min\{z_{1j}, z_{2j}, \cdots, z_{mj}\} \tag{3}$$

3. Determine the weighted Euclidean distance between each evaluation object and the optimal and worst solutions D_i^+ and D_i^-:

$$D_i^+ = \sqrt{\sum_{j=1}^{n} [w_j(z_{ij} - z_j^+)]^2} \tag{4}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} [w_j(z_{ij} - z_j^-)]^2} \tag{5}$$

where w_j is the combination weight of indicator j.

4. Determine the proximity C_i:

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{6}$$

Finally, according to the degree of C_i's closeness to 1, the closer C_i is to 1, the closer the object is to the best solution, i.e., the object is relatively better, and ultimately, the objects are ranked according to the degree of proximity of each object from the largest to the smallest and divided into water resources carrying capacity classes.

3.2. BP Neural Network Prediction Method

The accurate prediction of the evolution trend of the water resources carrying capacity in the Xiangjiang River Basin is of great significance for promoting the construction of a smart water network in the region and achieving sustainable development strategies. Therefore, based on the established evaluation index system for water resources carrying capacity, an effective prediction model is adopted to predict the water resources carrying capacity of the Xiangjiang River Basin. In terms of selecting prediction models, both grey prediction models and neural network models can be used to predict water resources carrying capacity. Among them, the BP neural network is a widely used artificial neural network model which has the advantages of simple structure and strong operability. By adjusting the network structure and parameters, a BP neural network can solve most of the problems faced by neural networks, providing an innovative approach and way to enhance the carrying capacity of regional water resources. Therefore, selecting a BP neural network as the model for predicting the water resources carrying capacity of the Xiangjiang River Basin and applying a BP neural network to predict the water resources carrying capacity of the Xiangjiang River Basin can provide a scientific basis for the construction of a smart water network in the region and provide practical and effective analysis methods for the planning and decision-making of relevant government departments.

In this study, with a 15-year dataset of 26 indicators of 44 county units in the Xiangjiang River, 16,160 pieces of data were collected, which is a large amount of data, and the BP neural model was selected for prediction. The specific steps were performed as follows:

First, the network structure was determined. A three-layer BP neural network containing one hidden layer (i.e., input layer, hidden layer, and output layer) was used to predict the risk of the water carrying capacity of the Xiangjiang River.

Second, the number of neurons in each layer was determined. The water resources carrying capacity system of the 44 county units of the Xiangjiang River and the 5 subsystems of resources, economy, society, water environment, and water management carrying capacity assessment value served as the input part, and the number of nodes in the input layer was 5; the prediction part of the model was trained many times. We determined the training set for the assessment value of the data samples of 2008–2015, the prediction set for the assessment value of the data samples of 2016–2022, and the predicted water resources carrying capacity assessment value for 2023–2027. In this study, the output is the carrying capacity value of each system in the 44 county units of the Xiangjiang River, and the number of nodes in the output layer was determined to be 1. Through substitution and repeated tests, the number of nodes in the implied layer stratification of 6 was finally selected.

Third, the allowable error and learning rate were selected. Usually, the value of the learning rate (η) ranges from 0.01 to 0.80. In this study, we used a variable adaptive learning rate so that the network training in different phases of the network automatically set the sizes of the different learning rates; the initial learning rate was 0.01. The maximum number of training iterations was 1000 times.

Fourth was data processing and Matlab implementation design. There are some differences in the magnitudes of the sample data, and the sample data are mapped to $[-1, 1]$ for normalization, allowing us to input data in Matlab to repeatedly train to obtain a suitable model before substituting the values to obtain the predicted water resources carrying capacity of 44 county units of the Xiangjiang River in the next 5 years.

3.3. Screening the Indicator System

The selection of the indicator system adopts a combination of "universal" and "special" methods. This study is based on previous research and relevant literature to determine an evaluation index system for the actual situation of the Xiangjiang River. Firstly, 15 literature indicators closely related to the water resources carrying capacity of the basin were statistically analyzed [19–33]. The classification and frequency of the indicators were compared and analyzed, and 19 indicators with a frequency greater than 4, such as precipitation, per capita water resources, water production modulus, and population density, were directly selected into the indicator system (universal indicators). Based on field research and in-depth interviews with experts, a total of 26 evaluation indicators for the carrying capacity of water resources in the Xiangjiang River were selected, including seven specific indicators such as agricultural potential indicators, first-tier water prices, pesticide and fertilizer usage, and water conservancy practitioners (Table 4). It should be noted that the natural population growth rate is a negative indicator in other literature, following the idea of "family planning" to suppress population growth. Based on the current fertility situation and policies to encourage fertility, this study has determined it as a positive indicator.

Table 4. The Xiangjiang River Water Resources Carrying Capacity Index System.

Target Level	System Level	Indicator Layer	Unit (of Measure)	Characteristic
Water Resources Carrying Capacity of the Xiangjiang River	Resource supportability	Precipitation	mm	Positive
		Average per capita water resources	m^3/person	Positive
		Coefficient of Storage	10^4 m^3/km^2	Positive
		Wodule of water supply	10^4 m^3/km^2	Positive
		Eco-environment water consumption	10^4 m^3	Negative
	Economic support	GDP per capita	10^4 CNY	Positive
		Effective irrigation area	%	Positive
		Agricultural potential index	ton	Positive
		Water consumption per 10,000 CNY GDP	m^3/10^4 CNY	Negative
		The output value of agriculture, forestry, animal husbandry, and fishery	10^4 CNY	Positive
		Sewage discharge per 10,000 CNY of GDP	m^3/10^4 CNY	Negative
	Social support	Density of population	Persons/km^{-2}	Negative
		Urbanization rate	%	Positive
		Natural population growth rate	%	Positive
		First-tier water price	CNY	Negative
		Per capita water demand	m^3	Negative
	Environmental support	Per capita domestic water consumption	m^3/person	Negative
		consumption of pesticide and fertilize	kg	Negative
		Proportion of Class III or above water	%	Positive
		Wastewater treatment rate	%	Positive
		Forest cover	%	greater than zero
	Management support	Water Utilization	%	Negative
		Dam length	m	Positive
		impoundage	m^3	Positive
		water conservation practitioner	person	Positive
		Rural garbage management rate	%	Positive

3.4. Data Sources and Pre-Processing

3.4.1. Data Sources

The evaluation period for the carrying capacity of water resources in the Xiangjiang River is from 2008 to 2022. The data sources for this period include the China Statistical Yearbook, Hunan Provincial Statistical Yearbook, Hunan Provincial Water Resources Bulletin, Yongzhou City Water Resources Bulletin, Chenzhou City Water Resources Bulletin, Hengyang City Water Resources Bulletin, Zhuzhou City Water Resources Bulletin, Xiangtan City Water Resources Bulletin, Changsha City Water Resources Bulletin, and Loudi City Water Resources Bulletin, as well as various county-level units' National Economic Statistics Bulletins and the EPS data platform. Due to the low level of openness of county-level unit data, some data sources were obtained through on-site consultation and telephone interviews. Very few missing data were imputed.

3.4.2. Data Processing

1. Standardized treatment

The polar deviation method was chosen to standardize the data. After standardization, the values may have 0 values to ensure that the assigned weights are meaningful. The standardized values were summed with 0.001, thus obtaining Z_{ij} as a positive indicator:

Positive indicators:

$$z_{ij} = \frac{x_{ij}(\max) - x_{ij}}{x_{ij}(\min) - x_{ij}(\min)} + 0.001 \tag{7}$$

Negative indicators:

$$z_{ij} = \frac{x_{ij} - x_{ij}(\min)}{x_{ij}(\max) - x_{ij}(\min)} + 0.001 \tag{8}$$

2. Weight calculation method

In this study, the entropy weighting method is used to determine the weights, which is classical and objective in dealing with multiple indicators.

$$S_{ij} = \frac{Z_{ij}}{\sum_{i=1}^{n} Z_{ij}} \tag{9}$$

Calculate the entropy value of the jth indicator H_j:

$$H_j = -\frac{1}{\ln n}\sum_{i=1}^{n} S_{ij} \ln S_{ij} \tag{10}$$

Calculate the value of the coefficient of variation E_j from the entropy value H_j:

$$E_j = 1 - H_j \tag{11}$$

Calculation of indicator weights W_j:

$$W_j = \frac{E_j}{\sum_{j=1}^{m} E_j} \tag{12}$$

4. Measurement and Analysis of Water Carrying Capacity

4.1. Measurement of Water Carrying Capacity

4.1.1. Weighting Values

This article calculates the weights of indicators for the Xiangjiang River from 2008 to 2022 using the entropy weight method. Due to the complexity of analyzing data spanning 15 years, in order to simplify the process and facilitate analysis, a 5-year interval is set to calculate the weight ratio of each criterion layer indicator (Table 5). The results indicate that the weight of management support has the highest proportion, while the rest of the system is relatively balanced. Each indicator showed fluctuating changes during the research period.

Table 5. Weight ratio of the criterion layer (%).

Normative Layer	2008	2013	2018	2022	On Average
Resource support	13.39	15.13	19.83	20.23	17.14
Economic support	15.00	17.16	16.72	18.19	16.77
Social support	8.27	9.87	10.18	7.92	9.06
Environmental support	10.73	9.53	11.98	9.36	10.40
Management support	52.61	48.39	41.30	44.31	46.65

4.1.2. Evaluation of Water Resources Carrying Capacity

Due to the long time span of this study, centralized analysis may overlook the details of year-by-year changes, resulting in scattered information. Therefore, three "five-year stages" are set up, from the first five-year stage to the third five-year stage, to analyze the comprehensive evaluation results regarding the water resources carrying capacity of the Xiangjiang River with a moderate time span. The comprehensive evaluation values of the water resources carrying capacity for each "five-year stage" during the research period are shown in (Table 6).

Table 6. Evaluation values and rankings of water resources carrying capacity of each county unit in the Xiangjiang River.

County Unit	2008–2012	2013–2017	2018–2022	On Average	Rankings
Changsha City District	0.407	0.382	0.378	0.389	5
Wangcheng District	0.371	0.362	0.394	0.376	7
Changsha County	0.393	0.395	0.400	0.396	4
Liuyang City	0.409	0.441	0.457	0.436	2
Ningxiang County	0.394	0.452	0.452	0.433	3
Zhuzhou City District	0.364	0.360	0.358	0.360	8
Zhuzhou County	0.300	0.285	0.264	0.283	41
Liling City	0.303	0.374	0.364	0.347	12
Youxian County	0.306	0.329	0.309	0.314	25
Chaling County	0.287	0.317	0.306	0.303	30
Yanling County	0.314	0.337	0.338	0.330	17
Xiangtan City District	0.363	0.398	0.378	0.380	6
Xiangxiang City	0.303	0.356	0.359	0.339	14
Shaoshan City	0.267	0.288	0.301	0.285	40
Xiangtan County	0.343	0.311	0.311	0.321	20
Hengyang City District	0.368	0.358	0.337	0.354	10
Leiyang City	0.320	0.328	0.283	0.310	27
Changning City	0.289	0.342	0.333	0.321	21
Qidong County	0.298	0.386	0.359	0.348	11
Hengyang County	0.322	0.356	0.320	0.333	15
Hengdong County	0.295	0.300	0.277	0.291	36
Hengshan County	0.280	0.333	0.310	0.308	28
Hengnan County	0.321	0.330	0.302	0.318	23
Loudi City District	0.307	0.337	0.339	0.328	18
Shuangfeng County	0.283	0.295	0.289	0.289	39
Lianyuan County	0.274	0.299	0.295	0.289	38
Chenzhou City	0.327	0.364	0.374	0.355	9
Zixing City	0.516	0.520	0.510	0.515	1
Anreng County	0.271	0.281	0.290	0.281	43
Guiyang County	0.279	0.306	0.309	0.298	33
Rucheng County	0.281	0.325	0.355	0.320	22
Jiahe County	0.276	0.299	0.295	0.290	37
Guidong County	0.293	0.312	0.343	0.316	24
Yongxing County	0.282	0.305	0.300	0.296	35
Yongzhou County	0.348	0.345	0.344	0.346	13
Qiyang City	0.294	0.302	0.313	0.303	31
Lanshan County	0.278	0.309	0.337	0.308	29
Xintian County	0.247	0.279	0.288	0.271	44
Jiangyong County	0.284	0.310	0.348	0.314	26
Shuangpai County	0.304	0.321	0.342	0.322	19
Ningyuan County	0.248	0.289	0.306	0.281	42
Dongan County	0.266	0.310	0.314	0.297	34
Daoxian County	0.274	0.304	0.318	0.299	32
Jianghua County	0.311	0.335	0.350	0.332	16

4.2. Water Carrying Capacity Analysis

The water resources carrying capacity of the Xiangjiang River Basin has shown a relatively stable growth trend from 2008 to 2022, with an overall carrying capacity level of level II. The carrying capacity of water resources is at a poor level, especially in the county units of Changsha City. The water resources carrying capacity has shown a continuous upward trend. In 2022, four county-level units reached level III, with a medium level of water resources carrying capacity. However, after the water resources carrying capacities of Changsha City, Xiangtan City, and Qidong County briefly remained at a medium level in 2008, 2009, and 2016, the water resources carrying capacities returned to a relatively poor level. The water resources carrying capacities of county-level units in Chenzhou and Yongzhou City have shown an upward trend, while Xiangtan City, Hengyang City, and Loudi City have lesser water resources carrying capacities. The upward trend of the carrying capacity is not obvious, and it fluctuates at the level of poor water resources carrying capacity.

4.2.1. Time Trends

1. Changsha

The water resources carrying capacity of five county-level units in Changsha City is higher than the average level of the Xiangjiang River. Among them, Liuyang City and Ningxiang County have had a medium level of water resources carrying capacity for many years, and there is a fluctuating upward trend; Wangcheng District and Changsha County are at a moderate level and maintain relative stability. The carrying capacity of urban water resources has been fluctuating and declining since reaching its highest level in the city in 2008 (Figure 6), possibly due to the continuous influx of a large population and limited water supply capacity.

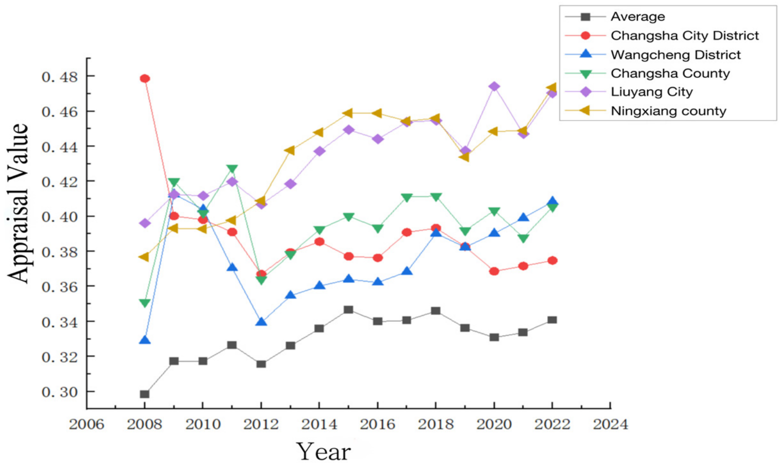

Figure 6. Trend Chart of Water Resources Carrying Capacity in Various County Units of Changsha City.

2. Zhuzhou

Among the six county units in Zhuzhou City, the water resources carrying capacity of Zhuzhou City District and Liling City is higher than the average level of the basin. Yiling and Youxian Counties fluctuate above and below the average level, while Zhuzhou and Chaling Counties have a lower-than-average water resources carrying capacity and a poorer level of water resources carrying capacity, respectively (Figure 7). As far as the current situation is concerned, the fluctuation in water resources carrying capacity of the six county units in Zhuzhou City is very significant. The government needs to increase investment and strengthen management to gradually improve the water resources carrying capacity level.

3. Xiangtan

The water resources carrying capacity of Xiangtan City is at a moderate level. Among the four county-level units in Xiangtan City, the water resources carrying capacity values of the urban area and Xiangxiang City are higher than the average level. Xiangtan County has only been above the average level for four years, while Shaoshan City has been consistently below the average level (Figure 8). The fluctuation trend of the water resources carrying capacity in Xiangxiang City and Shaoshan City is similar.

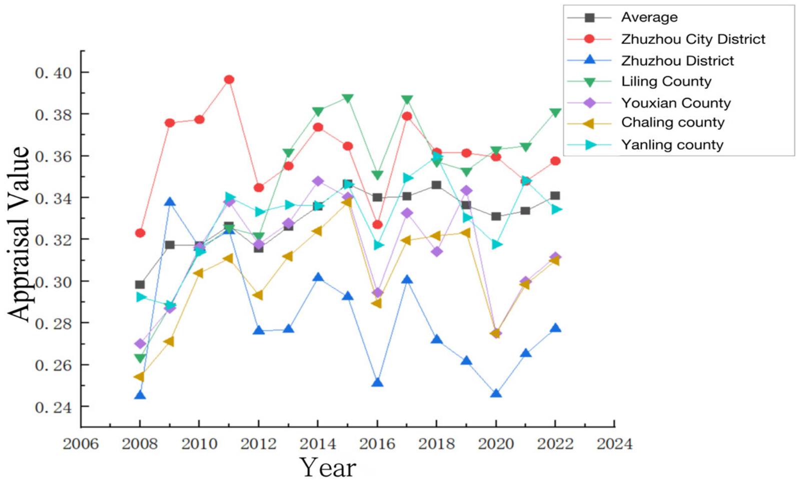

Figure 7. Trend Chart of Water Resources Carrying Capacity in Various County Units of Zhuzhou City.

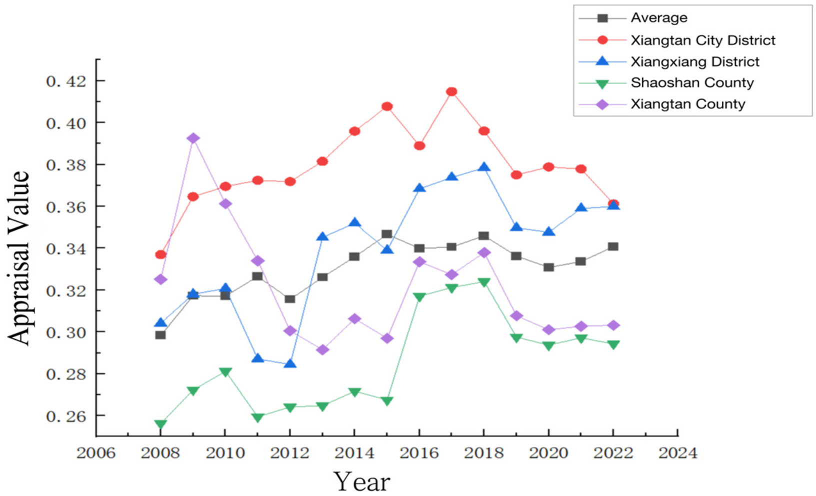

Figure 8. Trend Chart of Water Resources Carrying Capacity in Various County Units of Xiangtan City.

4. Hengyang

The overall performance of water resources carrying capacity in various county-level units of Hengyang City is relatively stable, but it still needs to be improved. Among the eight county-level units in Hengyang City, the water resources carrying capacity of the urban area and Qidong County is higher than the average level. Changning City has been above average for several years, while Leiyang City, Hengdong County, Hengshan County, and Hengnan County have been consistently below average (Figure 9). Qidong County has steadily improved since 2011 and reached a moderate level in 2016. The overall water resources carrying capacities of other county-level units have not fluctuated significantly.

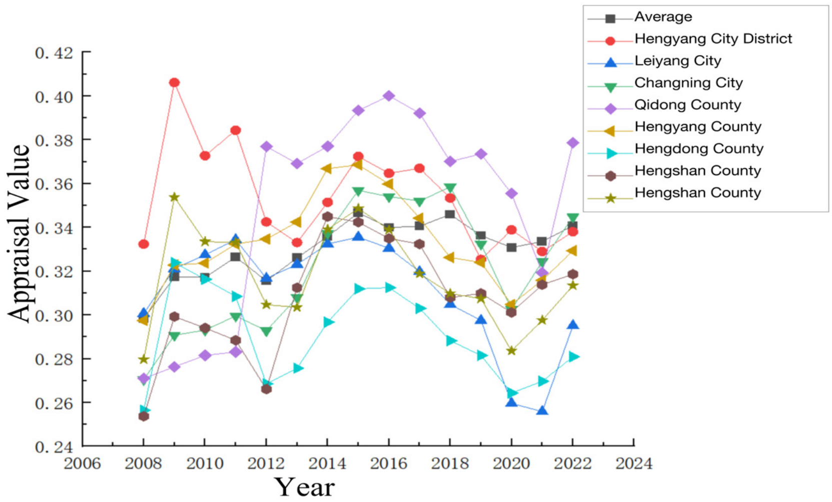

Figure 9. Trend Chart of Water Resources Carrying Capacity in Various County Units of Hengyang City.

5. Loudi

The overall water resources carrying capacity of Loudi City is at a poor level and fluctuates little (Figure 10). The water resources carrying capacity of the Loudi City area hovers at the average level all year round (Figure 10). Shuangfeng County and Lianyuan County, on the other hand, have water resources carrying capacities that are always below the average level, which may be mainly due to insufficient water resources supply.

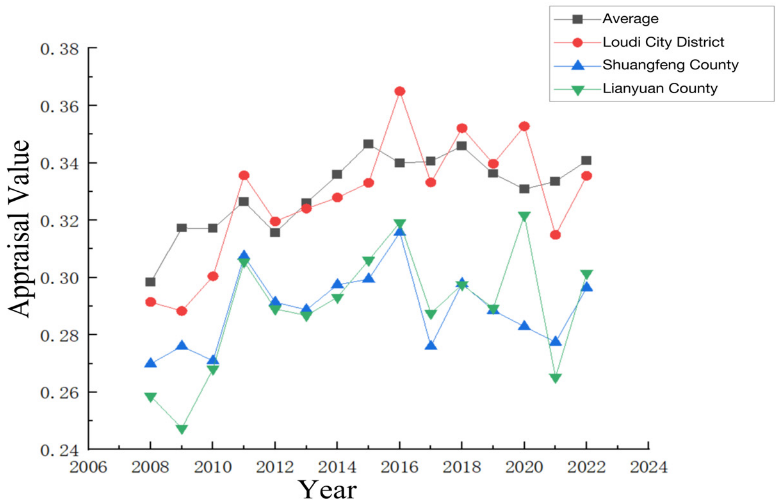

Figure 10. Trend Chart of Water Resources Carrying Capacity in Various County Units of Loudi City.

6. Chenzhou

Chenzhou City has a medium level of water resources carrying capacity. Zixing City has the highest water resources carrying capacity among the county units of the Xiangjiang River, mainly due to its Dongjiang Reservoir, the largest reservoir in Hunan. The Dongjiang Reservoir has a perennial water storage capacity dozens of times larger than other reservoirs, equivalent to 1/2 of the water demand of Dongting Lake. The water resources carrying capacity of the Chenzhou City area is always above average, while the rest of the county units are always below average. The carrying capacities of water resources in the seven county units of Chenzhou City reflect an overall stable state (Figure 11).

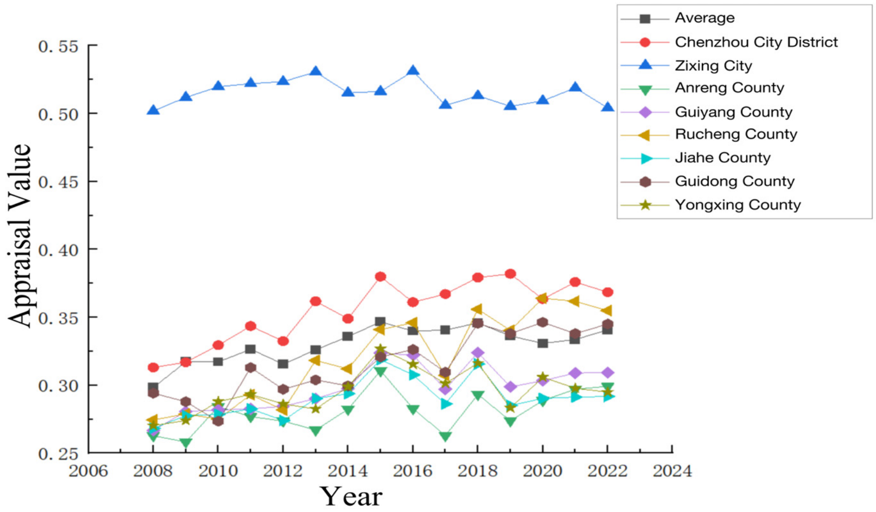

Figure 11. Trend Chart of Water Resources Carrying Capacity in Various County Units of Chenzhou City.

7. Yongzhou

Yongzhou City is the source of the Xiangjiang River, but its water resources carrying capacity is generally low. The water resources carrying capacity of the urban area of Yongzhou City is always higher than the average level, while Jianghua County fluctuates around the average level. The water resources carrying capacities of other county units are lower than the average level, but the water resources carrying capacities of most county units show a steady upward trend (Figure 12).

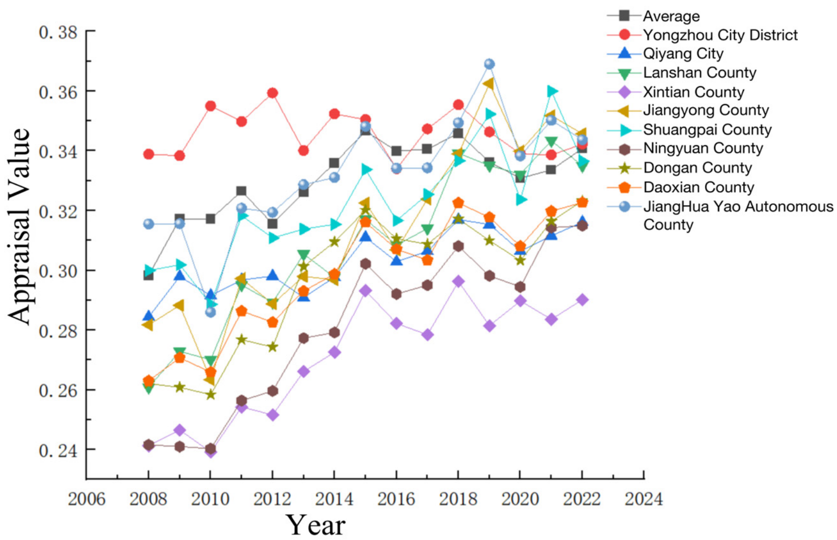

Figure 12. Trend Chart of Water Resources Carrying Capacity in Various County Units of Yongzhou City.

4.2.2. Spatial Evolution

The study imports the aforementioned evaluation values of the Xiangjiang River water resources carrying capacity into the ArcGIS PRO 10.6 software and uses the interval grading method to divide the water resources carrying capacity scores into five levels: poor (red), relatively poor (orange), moderate (yellow), relatively strong (blue), and strong (green) (Table 7), which are more convenient for internal comparison and trend analysis [34–38]. A software drawing was produced of a spatial evolution distribution map of the Xiangjiang River water resources carrying capacity based on long-term evaluation values (Figure 13).

Table 7. Evaluation Grading Table.

Carrying Capacity Class	Appraise Value	Rating Color	Water Carrying Capacity
I	[0, 0.2]	red	Poor water carrying capacity
II	(0.2, 0.4]	orange	Relatively poor water carrying capacity
III	(0.4, 0.6]	yellow	Medium water carrying capacity
IV	(0.6, 0.8]	blue	Relatively strong water carrying capacity
V	(0.8, 1]	green	Strong water carrying capacity

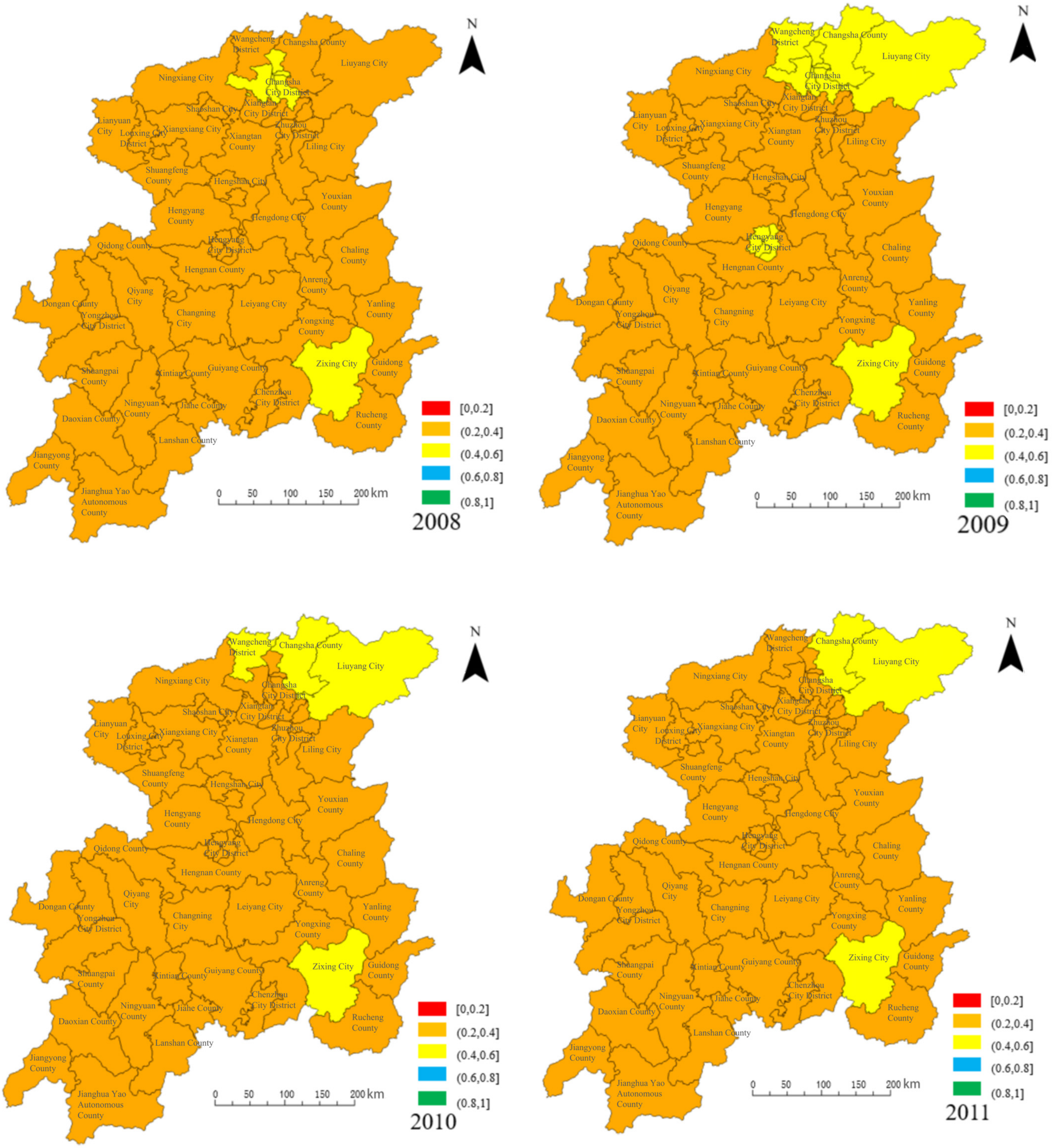

Figure 13. *Cont.*

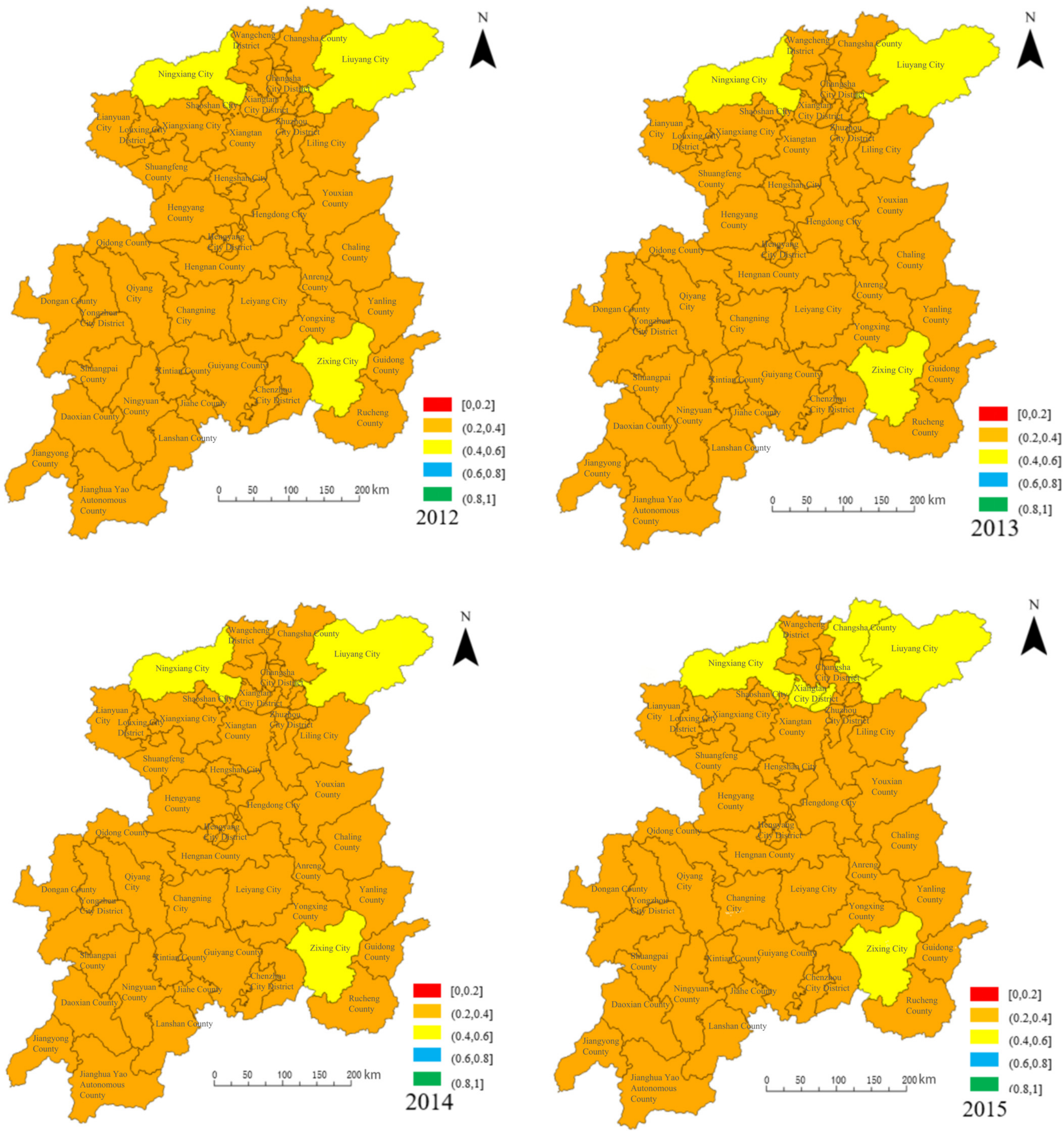

Figure 13. *Cont.*

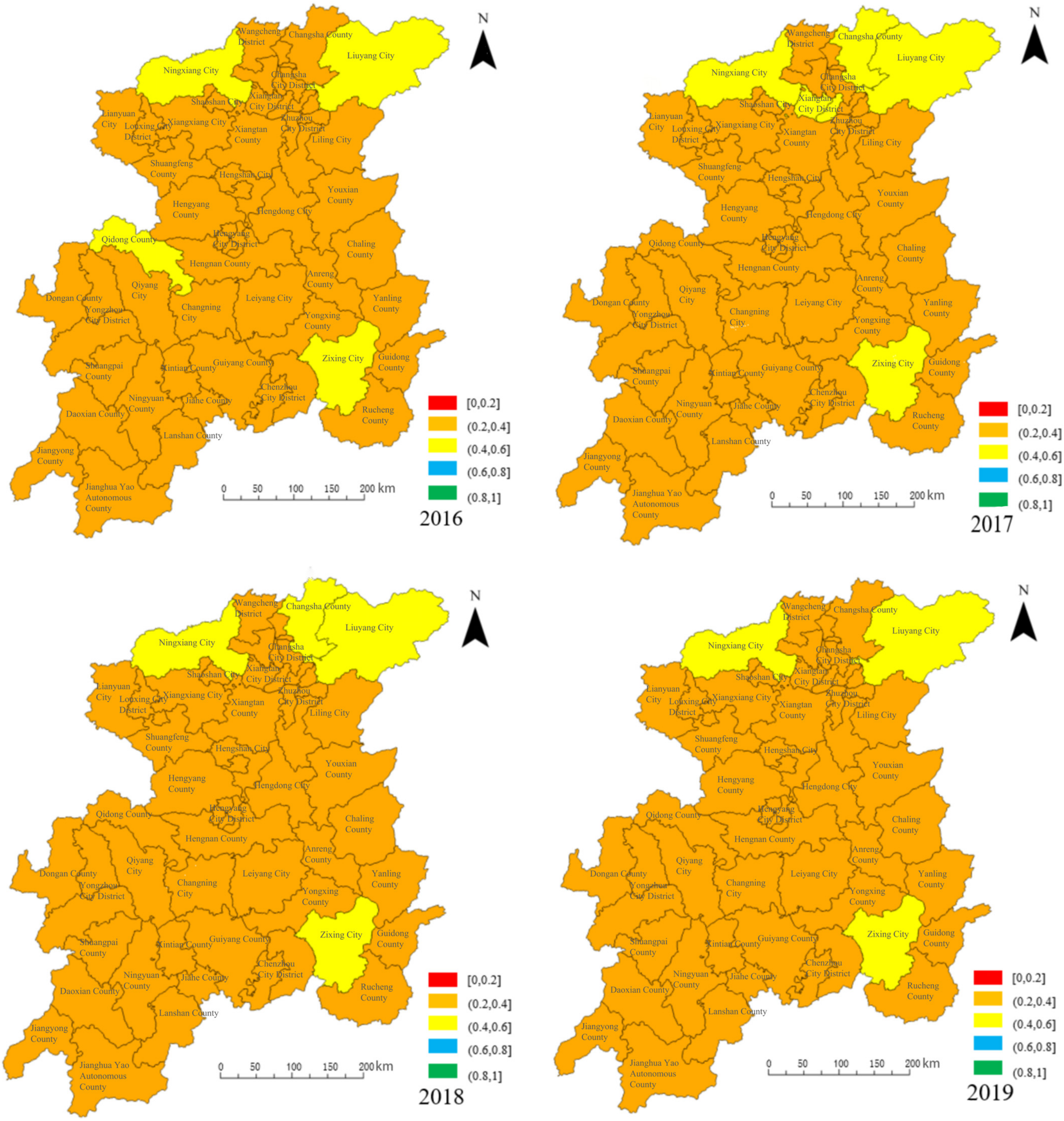

Figure 13. *Cont.*

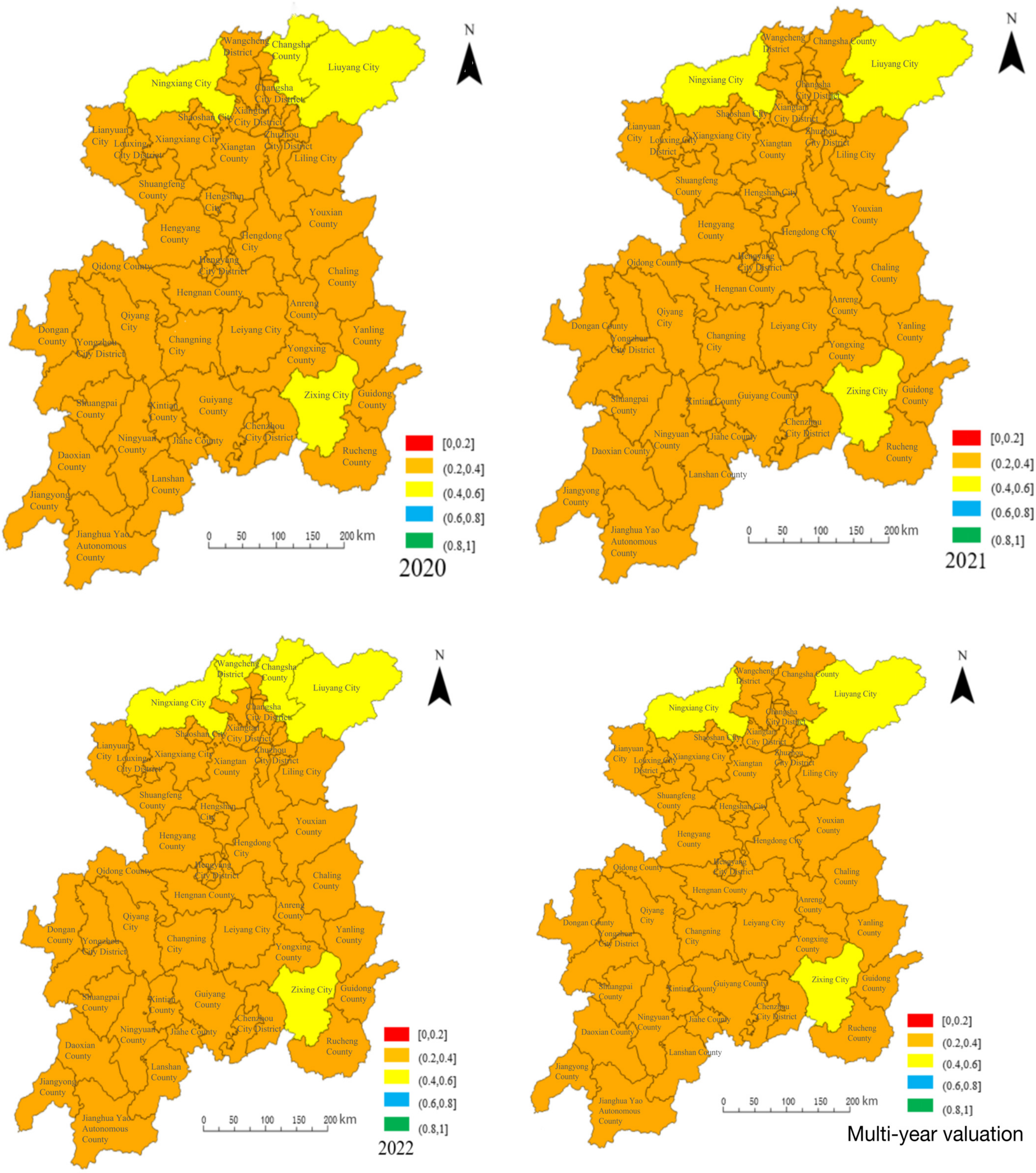

Figure 13. Spatial distribution map of 15-year average water resources carrying capacity of the Xiangjiang River.

From the above figure, it can be seen that there is a significant correlation between the spatial distribution of the water resources carrying capacity and the regional advantages in water resources during the evaluation period. The water resources carrying capacities of the five county-level units in Changsha City, the northernmost part of the Xiangjiang River, have fluctuated at a moderate level for many years. The water resources carrying capacities of Ningxiang County and Liuyang City have been at a moderate level all year round, while Zixing City has been above the moderate level due to the Dongjiang Reservoir. The areas with good water resources carrying capacities are mainly distributed in the lower reaches of the Xiang River, presenting an overall pattern of "high in the north and low in the south, low in the upstream and high in the downstream". The water resources carrying capacity of each urban area is basically higher than those of the counties and districts.

4.2.3. Guideline Layer Analysis

The contribution of the water resources carrying capacity criterion layer to water resources carrying capacity varies year by year. In the indicator radar chart, the contribution of each subsystem to the carrying capacity of water resources in the Xiangjiang River and the differences between regions can be obtained from the five criterion layer dimensions. We use the radar chart comparison method to analyze the advantages and disadvantages of the criterion layer system. Based on the weight values of the five criterion layers, due to space limitations, only the radar chart of the average weight of the water resources carrying capacity criterion layers for seven prefecture-level city units from 2008 to 2022 was exported (Figure 14).

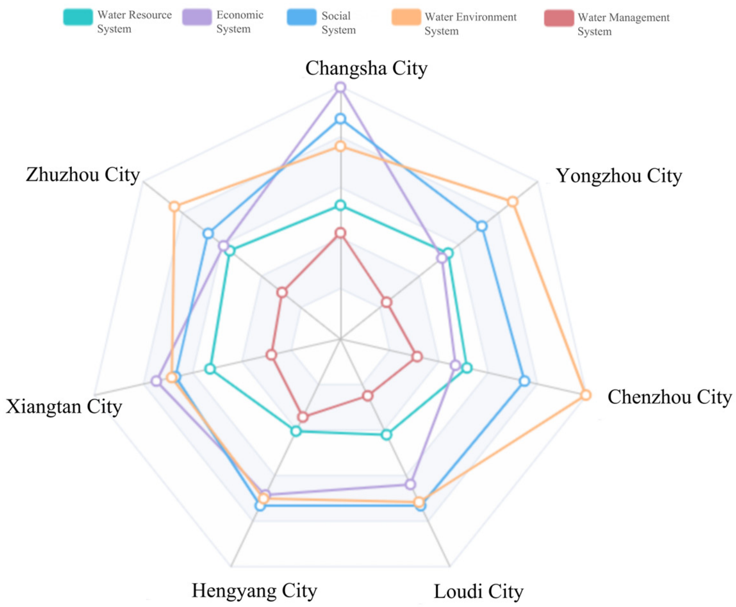

Figure 14. Radar chart of average evaluation value at the criterion level.

The radar chart clearly shows that the management support evaluation values of the seven prefecture-level cities in Xiangjiang have been lagging behind other systems for many years, indicating that the water management capacity of Xiangjiang is generally weak and needs to be further strengthened. In contrast, the resource support is only stronger than the management support, indicating that the endowment of water resources to the Xiangjiang River does not have many advantages. In terms of environmental support, the evaluation values of Yongzhou City, Chenzhou City, and Zhuzhou City are consistently better than those of other cities, possibly due to relatively fewer industries and the construction of water conservation forests. This indicates that good contributions have been made to protecting water sources, controlling water pollution, and protecting water resources for the Xiangjiang River. The economic system of Changsha has made the greatest contribution, but the water environment is not cause for optimism.

5. Water Carrying Capacity Projections

5.1. Forecasting Criteria

This article refers to the relevant literature on the risk warning of the water resources carrying capacity and the classification standard [39–44]. The risk warning level of the water resources environmental carrying capacity is divided into five levels (Table 8), which reflect the risk status of the water resources carrying capacity of the Xiangjiang River.

Table 8. Classification criteria for early warning results of water resources carrying capacity in the Xiangjiang River.

Carrying Capacity Class	Appraise Value	State of Affairs	Early Warning Signal Signs
I	[0, 0.2]	Grossly overloaded	red
II	(0.2, 0.4]	Overloading	orange
III	(0.4, 0.6]	Boundary	yellow
IV	(0.6, 0.8]	Weak bearing	blue
V	(0.8, 1]	Can bear	green

5.2. Projected Results

Overall, the water resources carrying capacity of the Xiangjiang River will increase slightly to a stable level, and the risk level will still be "overloaded" (Figure 15). From 2023 to 2027, the risk of the water resources carrying capacity of the Xiangjiang River will remain unchanged, and there will be a slight downward trend in the prediction interval, i.e., it is predicted that the carrying capacity of the water resources in the study area will decrease. Therefore, we should remain vigilant.

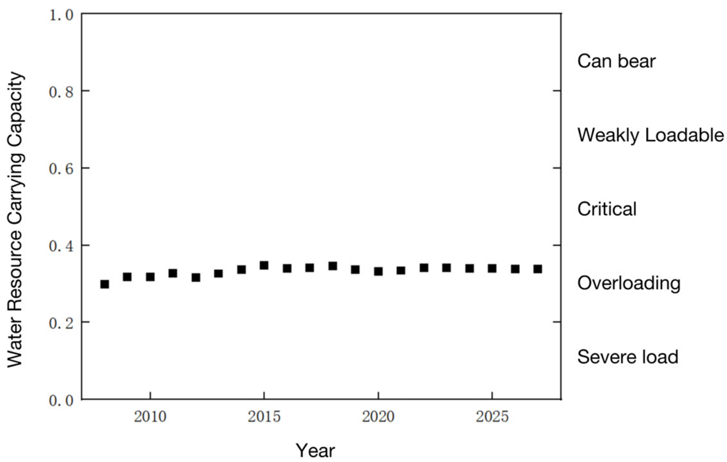

Figure 15. Prediction of the water resources carrying capacity of the Xiangjiang River by BP neural network.

Based on the predicted results, in-depth analysis shows that the sustained "overload" risk level in the Xiangjiang River Basin may be related to population migration and rapid economic development.

5.3. Spatial Distribution of Forecast Results

In 2022, the water resources carrying capacities of Changsha County, Wangcheng District, Ningxiang City, Liuyang City, and Zixing City were in the critical state, which is better than the other county units, which were classified under the overloaded state. Based on the aforementioned BP neural network prediction, in the next five years, the abovementioned five county units will continue to maintain their critical state, and the rest of the county units will remain in the overloaded state. In the predicted trend, the water resources carrying capacities of the Changsha urban area and Liling City will reach more than 0.39 in 2027, which is expected to be in the critical state later, and a specific spatial distribution is shown in Figure 16.

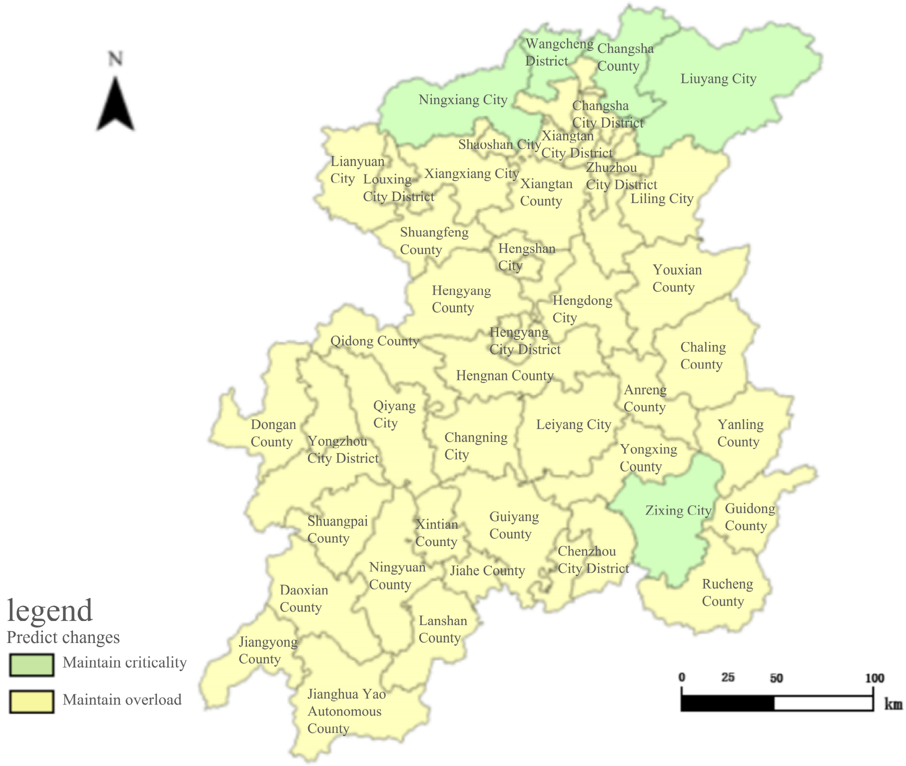

Figure 16. Forecast spatial distribution of water resources carrying capacity in the next 5 years.

6. Discussion

This article draws on Xiaohua Fu's [45] discussion of various algorithms' applications in water resource management, protection, and ecology, proposing future research directions and prospects. Xiaohua Fu [46] demonstrated that the particle-swarm-optimized support vector regression (PSO-SVR) model achieves high accuracy and broad applicability for predicting water quality; Honglei Chen [47] developed a model incorporating long short-term memory (LSTM) and attention mechanisms, enhancing the accuracy of water quality prediction for Australia's Burnett River. These papers have significantly aided our research regarding methodology and evaluation metric selection. Additionally, this article's evaluation and prediction of the Xiangjiang River Basin's water resources carrying capacity also incorporates Shengxin Lan's [48] early warning assessment and trend analysis of the resource and environmental carrying capacity in Altay, Xinjiang. These achievements strongly support our research conclusions, corroborating each other.

Based on the warning results, in-depth analysis shows that although the total amount of water resources in the Xiangjiang River Basin is relatively sufficient, factors such as population growth, economic development, and industrialization still exert severe pressure on water resources, especially in the middle and lower reaches. Changsha County and Wangcheng District in Changsha City are facing the risk of approaching the critical point of water resources carrying capacity, and the warning range is approaching the 0.4 warning line. This means that these two county-level units may enter an overloaded state at any time, which may be caused by the decline in the carrying capacity of the social system and water resources system due to future population inflows. Meanwhile, the water resources carrying capacities of Liuyang City, Ningxiang County, and Zixing City have also shown downward trends, which may be closely related to population migration and changes in economic activities. In contrast, other county-level units may achieve a steady increase in water resources carrying capacity in the future due to population outflow and optimization of water resource management.

For areas such as Changsha City, Wangcheng District, Ningxiang City, Liuyang City, and Zixing City that may continue to have critical water resources carrying capacities in the next five years, it is necessary to strengthen water resource management, such as by building or upgrading water supply systems, sewage treatment facilities, and water resource monitoring systems, to improve water resource utilization efficiency, reduce waste, and prevent further deterioration into an overloaded state. In addition, as these regions are in a critical state, local governments need to formulate and adjust policies based on the predicted results, with a focus on the sustainable use of water resources. Especially in Changsha, due to the increasing demand for water resources caused by population inflow and economic development, it is urgent to take measures to optimize water resource allocation to ensure sustainable development in the future. For areas like Zixing City, although that area is temporarily ahead of other regions due to the existence of Dongjiang Reservoir, it is still necessary to pay attention to ecological environment protection to avoid irreversible impacts on the environment caused by excessive resource development.

This article uses the TOPSIS model and entropy weight method to determine the water resources carrying capacities of 44 county-level units in the Xiangjiang River Basin and predicts the water resources carrying capacities for the next five years through a BP neural network model. This method mainly considers the specific situation of the Xiangjiang River Basin, involving details such as water resource distribution, economic development status, and environmental management, and provides scientific tools and methods for evaluating and predicting the water resources carrying capacity of the basin. However, for practical applications, adjustments and optimizations need to be made according to local conditions. Different basins may face different problems and challenges, such as water resource abundance and scarcity, differences in management capabilities, various types of pollution sources, and so on. Therefore, when applied to other watersheds, adjustments may need to be made based on local hydrological, economic, and social conditions, as well as environmental factors.

7. Conclusions

1. Based on 15 years of observation and research in the Xiangjiang River Basin, it was found that the water resources carrying capacity in the region maintained a relatively slow growth and then tended to flatten out during this period. However, the water resources carrying capacities of each county unit are not completely consistent, reflecting the differences and inconsistencies in local development trends, mainly due to various factors such as economic development, technological progress, and the implementation of water resource management policies.
2. In terms of spatial distribution, there are relatively significant differences in the carrying capacities of water resources in the area of the Xiangjiang River. The southern (upstream) counties of Chenzhou and Yongzhou have abundant water resources and a good ecological environment, but their water resources carrying capacities are generally lower than those of the northern (middle and downstream) counties, which may be closely related to the economic development levels of Changsha, Zhuzhou, and Xiangtan. The level of water resources carrying capacity is a comprehensive issue that goes beyond the endowment of water resources.
3. According to the BP neural network model, it is predicted that the water resources carrying capacity of the Xiangjiang River Basin in the coming years will continue the steady development trend of 2022. Changsha County, Wangcheng District, Ningxiang City, Liuyang City, Zixing City, and other areas will be in a critical state that is better than other counties and cities. Most county-level units are overloaded, indicating that the carrying capacity of water resources in the Xiangjiang River needs to be monitored vigilantly.

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