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Study on the measurement and prediction of the ecological structure for water efficiency in China: from the perspective of "production-living-ecological" function

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Abstract

Countries are experiencing rapid social development under globalization, and it is a challenge to increase water efficiency and improve the ecological environment. This paper investigates the spatial and temporal changes of water efficiency in production-living-ecological function, which can help to improve the ecological environment and realize sustainable development. In this paper, Data Envelopment Analysis (DEA) is used to select evaluation indicators. The spatial directional distribution was analyzed using Standard Deviation Ellipse (SDE). The trend of spatial directional distribution was explored by choosing BP neural network model. The results show that: (1) There is a "stock-flow" link in the ecological structure of water resources. (2) The overall water efficiency of the production-living-ecological function indicates an oversupply. The main form is the exchange between ecological and production function. (3) Projections show that water used decreases from northeast to southwest and water efficiency increases from northeast to southwest. The production function occupies a large amount of water use. This paper establishes the theoretical framework of ecological structure of water efficiency and excavates the complex relationship and changing characteristics of production-life-ecological function and water efficiency. It provides a new perspective for the sustainable development of global water resources.

Keywords Ecological-production-living function · Water efficiency · Spatial and temporal variations · Standard deviation ellipse · BP neural network · Sustainable development

1 Introduction

It is well known that the amount of freshwater available for human use in the ecosystem is 1% of the water resources (Mishra, 2023). Water allocation and environmental degradation are one of the most pressing challenges facing the world in the twenty-first century (Padder & Bashir, 2023). Several measures have been taken globally to address this

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issue. For example, the United Nations 2023 High-Level Conference on Water Resources Management held in March 2023 introduced the Sustainable Development Goals (SDGs) (Khasraei et al., 2024). The conference emphasized the urgent need for rational allocation of water resources globally, especially in developing countries such as China, in order to cope with water scarcity (Hidayat et al., 2024). The sustainable development of water resources in developing countries such as China has been seriously affected due to inadequate infrastructure, weak policy implementation, and mismatch between supply and demand (Nugroho, 2021).

Water resources have long been often associated with ecology, production and livelihoods, respectively, and they are intricately linked (Feng et al., 2016). Improving water efficiency is one of the most effective and least costly ways to manage water resources (Algaba et al., 2024). Water efficiency effectively promotes ecologically supported agricultural and industrial production (Liu et al., 2023a; Tagne et al., 2021). People cannot live without ecological and productive support and even more so without water. Improvement in water efficiency is reflected in the use of less water to support the "production-living-ecological" function (Yu et al., 2024). Therefore, this study developed a theoretical framework for the ecological structure of water efficiency from the perspective of the "production-living-ecological" function to measure the spatial and temporal distribution of water efficiency. This framework can effectively improve water resources to realize sustainable development based on the constant total water resources.

The spatial and temporal distribution of water resources in China is seriously uneven. The distribution of water resources is often irrational, leading to mismatch of water resources across functions, which in turn generates water shortage (Wang & Wei, 2019). For example, the water resources of the Yangtze River basin and the areas south of it account for 81% of the country's total water resources (Liu et al., 2022). The South-to-North Water Diversion Project is difficult to solve the water shortage problem in the northern region. This paper explores the evolution of water efficiency in China based on the theoretical framework of water efficiency ecological structure. It aims to rationalize the allocation of water resources, reduce regional water conflicts, and realize the sustainable development of water resources in China.

The contributions of this paper are as follows: (1) A new theoretical framework of water efficiency ecological structure is established to analyze the complex relationship between production-living-ecological functions and water efficiency. (2) It reveals the changing characteristics of water efficiency in production-living-ecological functions and summarizes the changing rules of the ecological structure of water efficiency, which can provide reference for the water allocation problems in China and other developing countries. (3) Predicted the water resources situation in the next five years. Evaluate the differences in the spatio-temporal matching and coordinated development of water resources in the state of production-living-ecological differentiation, in order to seek the mechanism of the impact of the dynamic evolution of production-living-ecological functional differentiation on water efficiency. This will improve regional water efficiency and realize the sustainable development of global water resources.

Most literature analyzed water resources from regional differences and influencing factors. For example, some scholars have used the Tel index decomposition method to analyze China's regional differences in water resources. They found that the Tel index is trending upward, which means that the regional differences in China's water resources are increasing. With the advancement of spatial measurement technology, some scholars have pointed to a view. Under the background of ecological-production-living function differentiation, Water supply capacity, and water use efficiency are enhanced (Fu et al., 2022; Lin et al., 2022), with a clear spatial dependence. Water resources in areas with high water resource efficiency continue to overflow, leading to the gradual enhancement of water resources in the surrounding areas (Booker et al., 2012; Eggimann et al., 2017; Liu & Jensen, 2018). This can help alleviate the longstanding situation of uneven distribution of water resources (Angelakis et al., 1999; Deng & Zhao, 2015; Namara et al., 2010). However, these research objects only verify the existence of water resources spatial effects (Chen et al., 2021a, 2021b; Wang et al., 2019; Zou & Cong, 2021). It is difficult to reveal the dynamic association between water resources and space on a larger scale. Therefore, this paper measures the spatial and temporal distribution state of spatial water use in the ecological-production-life function to explore the evolution trend of spatial water use during the study period.

The influencing factors of water resources can be divided into four categories: industrial structure, climate change, economic development level, and water resource endowment (Liu et al., 2013; Cao et al., 2019; Zhang et al., 2016; Zhang et al., 2018; An et al., 2020). It is generally recognized that adjusting the industrial structure is an important way to reduce water demand. Extreme climate change increases the risk of a water crisis in China. Some scholars believe that rapid economic development will exacerbate the conflict between water use and economic growth. Water use efficiency is closely related to water resource endowment. Relevant scholars have carried out research on the degree of coupling with soil and water resources from various perspectives, including economic growth and development, urbanization, ecological environment, and integration (Du & Huang, 2017; Minnig et al., 2018; Salerno et al., 2018). These studies show that in economic activities, it is difficult to determine the ratio of water resources that maximizes economic, ecological and social benefits. However, it is possible to continuously adjust the water efficiency ratios of different intensities of eco-production-life functions, so as to realize the regulation of the eco-production-life function pattern. This paper evaluates the variability of water resources under the production-living-ecological differentiation state in terms of spatio-temporal matching and coordinated development of quantity. The purpose is to seek the mechanism of the influence of the dynamic evolution of production-living-ecological spatial differentiation on the utilization efficiency of water resources.

To address the challenges of sustainable water management and improve water efficiency within China's production-living-ecological framework, this study focuses on the following key research questions:

1. 1.How has water use efficiency evolved across China's production, living, and ecological functions over the past two decades, and what trends can be predicted for the future?
2. 2.What is the impact of the dynamic evolution of spatial differentiation in production, living, and ecological functions on water resource utilization efficiency across different regions of China?
3. 3.What will the state of water resources be over the next five years, and how will the coordinated development of water resources unfold under the differentiated functions of production, living, and ecology?

The remainder of the paper is summarized below. Section 2 describes the analytical framework, research methodology and data. Section 3 presents the results of the study. The spatial and temporal distribution of water use for production-living-ecological functions is discussed. Water resource projections for the next five years are presented. The main elements of the study framework are shown in Fig. 1. Section 4 reviews the results of previous studies in the literature and discusses the implications of this study for theory and practice

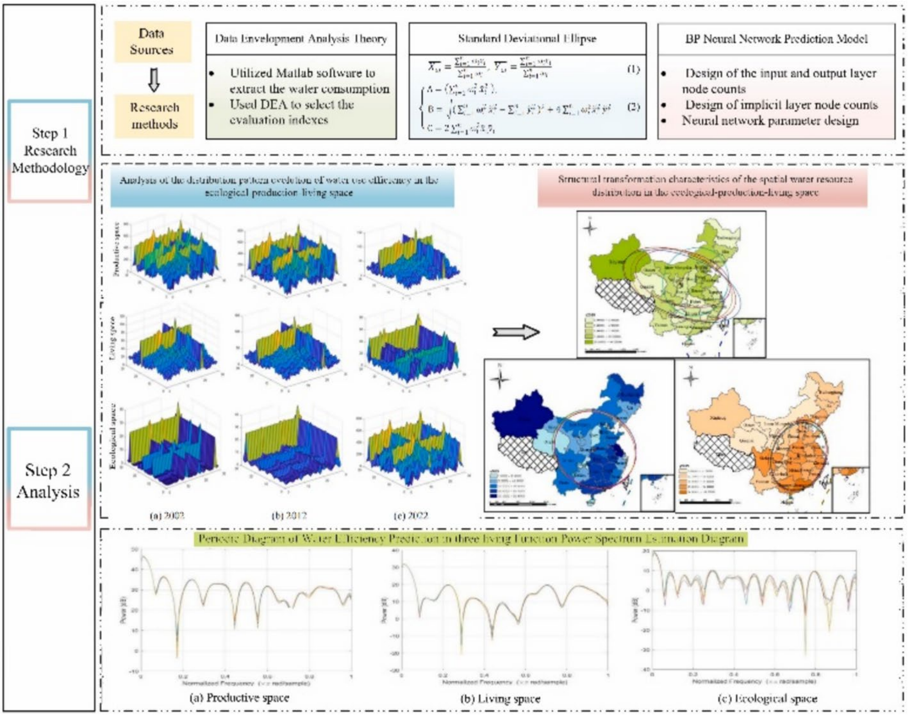


Fig. 1 The study framework

and research discrepancies. Section 5 summarizes the main conclusions of the study and makes recommendations.

2 Research methods and data

2.1 Data sources

This study mainly adopts the theory of the Data Envelopment Analysis (DEA), the weighted standard deviation ellipse model, and the BP neural network model. In view of the availability of data, the scope of this paper covers 30 provinces in China. Tibet, Hong Kong, Macau and Taiwan are excluded. The study period is 2002–2022.The latitude and longitude data of provincial and municipal cities in this paper are obtained from Sinomap press, and other data are mainly obtained from China Statistical Yearbook, China Water Statistical Yearbook, China Statistical Yearbook for Regional Economy, China Statistical Yearbook on Environment, and Statistical Yearbooks of provinces, municipalities and autonomous regions in the years 2003–2023. The study is mainly based on the ArcGIS10.2 platform to carry out relevant spatial calculations, using the WGS1984 UTM Zone 48N projected coordinate system as the spatial reference, and treating the 30 provinces as 30 elements under the given planar coordinates.

2.2 Research methods

2.2.1 Data envelopment analysis theory

Researchers mainly use Fuzzy Comprehensive Evaluation (FCE), water footprinting, Analytical Hierarchy Process (AHP), and Data Envelopment Analysis (DEA) to assess water efficiency (Wang et al., 2021; Sun et al., 2017; Mocholi-Arce et al., 2022). The AHP method and water footprinting method people's subjective decision-making influence the results greatly, and it is difficult to make rigorous mathematical arguments and explanations. On the contrary, DEA is based on Matlab software to analyze the results objectively, and has been widely used to evaluate the output efficiency of different regions with the same water inputs, to identify the causes of inefficiency, and to provide a basis for improvement measures (Le et al., 2022). The design of this study extracts the water consumption of 30 provinces in China from 2002 to 2022, and selects evaluation indicators in terms of both desired outputs (direct economic outputs) and undesired outputs (wastewater discharges) of water consumption. Therefore, DEA is applicable to this study and the next step is to select the specific model in DEA. In this study, the current popular DEA-SBM model was not selected, but the CCR and BCC models in DEA, considering that the purpose of the study focuses more on the ratio of inputs (water use) and outputs(economics), i.e., the results of water efficiency changes (Ding et al., 2022; Liu et al., 2024a, 2024b, 2024c).

The difference between the CCR model and the BCC model is that the former assumes that returns to scale do not change when the size of the decision-making unit increases or decreases, while the latter assumes that returns to scale change. The efficiency calculated by the CCR model is the comprehensive efficiency, which is a comprehensive measure of the overall input and output efficiencies, while the BCC model adds a convexity assumption ($\sum \lambda_j = 1$) on the basis of the CCR model. $\sum \lambda_j = 1$ decomposes the comprehensive efficiency into pure technical efficiency and scale efficiency, in which pure technical efficiency refers to the output efficiency after excluding the scale factor under the current resource allocation and technical conditions, and scale efficiency is the production efficiency due to the influence of the input and output scale factors, which can reflect the actual input and output scales and the gap between the optimal scale structure and the combination of the scales. Therefore, this paper chooses to measure on the basis of the inputled BCC model, which can provide a more comprehensive understanding of the characteristics of water resource efficiency in various types of functions across the country. The BCC model is utilized to evaluate the water use efficiency of each function and calculate the gravitational value of it. In the process of calculating water use efficiency, the input indicators include agricultural water use, industrial water use, domestic water use, labor force and total investment in fixed assets, and the output indicators include total output value of agriculture, forestry, animal husbandry, fishery and industry, centralized treatment rate of domestic sewage, general budgetary income of the local financial sector, and the average salary of residents.

2.2.2 Standard deviational ellipse

Standard Deviational Ellipse (SDE) is a method to analyze the spatial directional distribution of geographic elements, which can accurately show the characteristics of the spatial distribution pattern of geographic elements, and is often used to analyze the spatial distribution trend of water resources (Zhou et al., 2023). In this study, SDE was used to analyze the spatial distribution characteristics of water efficiency, revealing the spatial aggregation characteristics of efficient and inefficient water use areas. An intuitive understanding of the spatial and temporal characteristics of water efficiency helps to identify the underlying causes and trends of changes. It consists of four basic elements: center of gravity coordinates, rotation angle, standard deviation (SDE) along the long axis, and standard deviation (SDE) along the short axis, which correspond to the relative position of the spatial distribution of the geographic elements, the trend of the main direction of development of the geographic elements, and the degree of discretization in the primary and secondary directions, respectively (Liu et al., 2023b). Specifically, this study critically assesses the spatial and temporal distribution of water efficiency through the four basic elements of SDE. Its calculation formula is as follows (Huang et al., 2022; Zhao et al., 2022).

Weighted mean center:

$$\overline{X_{\omega}} = \frac{\sum_{i=1}^{n} \omega_i x_i}{\sum_{i=1}^{n} \omega_i}, \overline{Y_{\omega}} = \frac{\sum_{i=1}^{n} \omega_i x_i}{\sum_{i=1}^{n} \omega_i} \tag{1}$$

Elliptical direction:

$$A = \left(\sum_{i=1}^{n} \omega_i^2 \tilde{x}_i^2 \right) \tag{2}$$

$$B = \sqrt{\left(\sum_{i=1}^{n} \omega_i^2 \tilde{x}_i^2 - \sum_{i=1}^{n} \tilde{y}_i^2 \right)^2 + 4 \sum_{i=1}^{n} \omega_i^2 \tilde{x}_i^2 \tilde{y}_i^2} \tag{3}$$

$$C = 2 \sum_{i=1}^{n} \omega_i^2 \tilde{x}_i \tilde{y}_i \tag{4}$$

where, (X_i, Y_i) are the spatial coordinates under the “production, living, ecology” function. ω_i denotes the weighted spatial element i.e. water efficiency in this paper. $(\overline{X}_{\omega}, \overline{Y}_{\omega})$ denotes the weighted average center of the spatial dataset under the function of “production, life, and ecology”. the $\tilde{x}_i$ and $\tilde{y}_i$ respectively denote the coordinate deviation from the spatial coordinates of the study object to the mean center (Guo & Luo, 2021).

2.2.3 BP neural network prediction model

A large number of studies have verified the existence of the spatial effect of water resources, but it is difficult to reveal the dynamic correlation between water resources and space on a larger scale (García-Ruiz et al., 2011; Wang et al., 2020). Therefore, in this paper, standard deviation ellipses are used to measure the spatial and temporal distribution state of water resources and explore the trend of water resources evolution. Then the changes are predicted for the next five years. Past researchers have predicted water efficiency through support vector machine (SVM), neural network method, and autoregressive moving average model (ARIMA) (Najwa Mohd Khozani et al., 2022; Palabıyık & Akkan, 2024; Rizal et al., 2022). Neural networks are currently the most widely used method to predict water efficiency due to their ability to learn complex nonlinear relationships. In this paper, a back-propagation (BP) neural network is used to predict changes over the next five years, dealing with multiple influencing factors under the “ecology-production-life” function.

The three-layer BP neural network model is chosen for this prediction, and the designed BP neural network is divided into three layers, which are the input layer, the hidden layer and the output layer.

2.2.3.1 Design of the input and output layer node counts The input layer is the total water use of the ecological production and living function space from 2002 to 2022, and the output layer is the projected water use of the ecological production and living function space from 2023 to 2027.

2.2.3.2 Design of implicit layer node counts The node counts in the hidden layer of the BP neural network affects the prediction accuracy of the BP neural network. Therefore, the optimal node counts in the hidden layer needs to be derived after some calculations, and the reference formula is as follows (Song et al., 2021):

$$\mathrm{l} < \mathrm{n} - 1,\ \mathrm{l} < \sqrt{(\mathrm{m} + \mathrm{n})} + \mathrm{a},\ \mathrm{l} = \log_2^{n} \tag{5}$$

n is the node counts in the input layer; l is the node counts in the implicit layer; m is the node counts in the output layer; a is a constant between (0, 10). In this paper, the predicted input variable n is 20 and the output variable m is 3. Combining the above formulas, the node counts in the implied layer can be taken as 5.

2.2.3.3 Neural network parameter design The BP neural network learning rate was set to 0.00001, the training accuracy to 0.000001, and the maximum number of training times to 1000, respectively.

3 Results and analysis

3.1 Analysis of the distribution pattern evolution of water use efficiency in the ecological-production-living function

In order to effectively analyze the spatial distribution of water resource in the ecological-production-living function, the spatial correlation of water use efficiency can be used to show the inter-regional water resource, and the gravitational value of water use efficiency reflects the spatial correlation of water use efficiency. Since water use efficiency is directly proportional to its gravitational value, it was decided to set the water use efficiency factor as the reciprocal of the water use index value in the process of calculating the gravitational value of water use efficiency. In order to more visually characterize the spatial and temporal evolution of water use efficiency correlations, the gravitational value data of water use efficiency for three years (2002, 2012 and 2022) were selected from 2002–2022 to make a gravitational surface diagram, and the results are shown in Fig. 2.

From 2002 to 2022, in the spatial distribution pattern of the ecological-production-living function, only the ecological function is decreasing, while all other functions are increasing, and the living function is growing at the fastest rate. The spatial correlation of water use efficiency by spatial type shows the following characteristics:

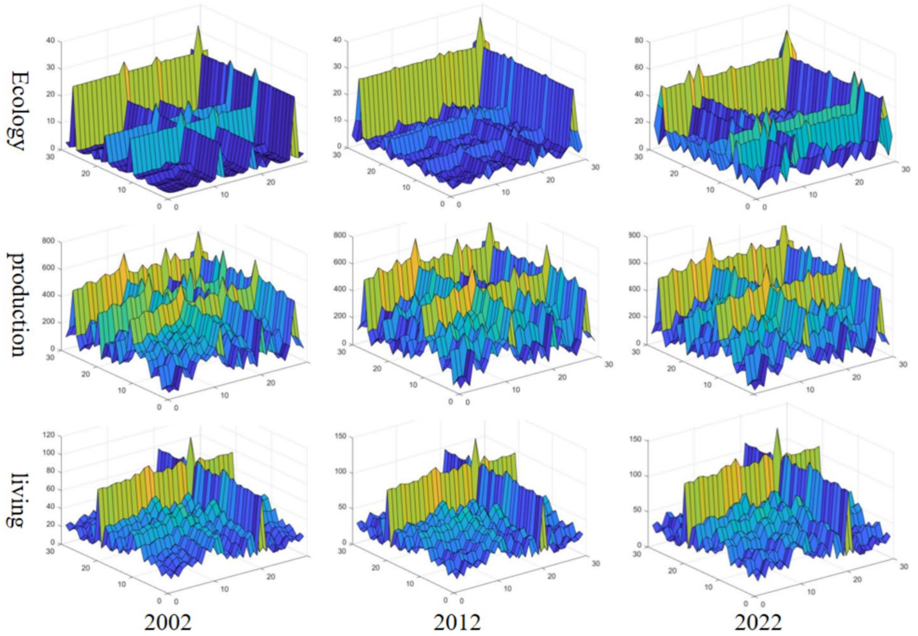


Fig. 2 Gravity surface diagram of water use efficiency in production-life-ecological function. Horizontal and vertical coordinates 0–30 for Beijing, Chongqing, Tianjin, Anhui, Fujian, Guizhou, Hebei, Heilongjiang, Henan, Hubei, Hunan, Jiangsu, Jiangxi, Liaoning, Shaanxi, Shandong, Shanxi, Sichuan, Zhejiang, Hainan, Guangdong Gansu, Guangxi, Jilin, Ningxia, Qinghai, Yunnan, Xinjiang, Inner Mongoria, Shanghai

The spatial correlation of production water use efficiency rises and diverges significantly over time. The production function roughly coincides with the main origins of China's grain crops, which are mainly distributed in the provinces east of the Hu Line, including mainly Hubei, Shanxi, Hebei, eastern Sichuan, and the Huaihe River Basin of Shandong, Jiangsu, Henan, and Anhui, as well as the northeastern part of China, such as Jilin, Heilongjiang, and Liaoning. Overall, the spatial correlation between production function and water efficiency gradually increases.

Quality and distance directly affect the correlation strength of living water efficiency. The living function is mainly distributed east of the Hu Line, which is closely connected with the production function. Agricultural production land generally has better natural conditions, which is suitable for human life, therefore, living function is gradually formed. The quality of water use efficiency and the spatial distance between provinces and cities directly affect the correlation strength between provinces and cities in terms of water use efficiency, in which the industrial structure, the location of provinces and cities and the level of economic development will affect the quality of water use efficiency.

The variability in the correlation strength of ecological water use efficiency with environmental change is high. The ecological function is roughly categorized into four types: grassland, water, woodland and other ecological function, which are mainly distributed in the southeast and west of the Hu Line. Most of the grassland ecological function is in the arid and semi-arid regions and alpine areas of Qinghai, Tibet, Xinjiang and Inner Mongolia in the west. The woodland ecological function is mainly distributed in northeastern China and south of the Yangtze River, the other ecological function is in the northwestern region, which is dominated by the arid and semi-arid regions and alpine areas of Qinghai, Xinjiang, west of Inner Mongolia, and northwestern Gansu; and the area of water ecological function is the smallest, which is affected by climate and topography more than the other three types. Compared with the other three ecological function, the ecological function of water area is the smallest, and is greatly affected by climate and topography. Therefore, the ecological function of water area is concentrated in the western area and the lower terrain area like the east and the south.

3.2 Structural transformation characteristics of the spatial water resource distribution in the ecological-production-living function

Based on the standard deviation ellipse model to measure the spatial water resource layout of the ecological-production-living function, the standard deviation ellipse diagram of China's spatial water supply and water consumption of the ecological-production-living function from 2002 to 2022 is drawn, as shown in Fig. 3, and its parameters and standard distances are shown in Table 1. By comparing and analyzing the parameters and changes of water supply and consumption in the ecological-production-living function in 30 provinces, autonomous regions and municipalities directly under the central government from

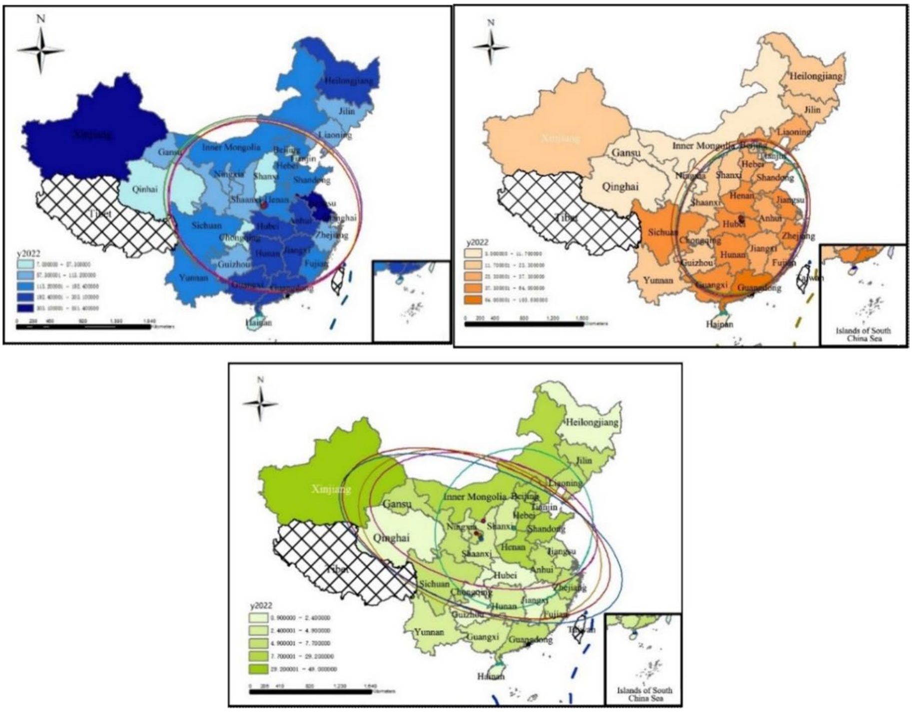


Fig. 3 Ellipse diagram of standard deviation of water supply and consumption. The map is produced based on the standard map with review number GS (2019)1822 downloaded from the standard map service website of the State Administration of Surveying, Mapping and Geographic Information, with no modifications to the base map

Table 1 Standard deviation ellipse parameters and standard distance of water supply and consumption in three living spaces

Year	Fuction in water	CenterX	CenterY	XStdDist	YStdDist	Rotation
2002	Production	1,120,233	3,749,544	1,337,757	1,154,379	112.7296
	Living	1,285,831	3,552,159	915,581.8	1,100,922	24.5473
	Ecological	794,475.9	3,945,873	2,035,677	957,381.1	111.1674
2007	Production	1,112,889	3,740,650	1,355,026	1,152,389	112.7749
	Living	1,304,478	3,536,851	824,565.7	1,138,732	23.51901
	Ecological	734,351.7	4,015,840	1,927,677	992,870.1	111.7517
2012	Production	1,134,351	3,764,214	1,349,556	1,169,249	110.1237
	Living	1,303,557	3,535,379	842,846.8	1,113,586	24.83444
	Ecological	783,004.6	3,987,134	1,738,079	1,047,393	112.1217
2017	Production	1,102,049	3,793,281	1,393,390	1,187,149	108.0617
	Living	1,304,684	3,509,005	843,114.7	1,064,309	25.32754
	Ecological	1,249,549	4,082,636	1,045,313	1,119,227	40.96626
2022	Production	1,100,610	3,778,832	1,387,577	1,163,693	108.6325
	Living	1,289,815	3,514,839	858,705.6	1,046,445	26.36131
	Ecological	833,755.1	4,184,230	1,585,057	874,648.9	104.253

2002 to 2022, the evolution process of the distribution of water resource in the ecological-production-living function in China is summarized as follows:

3.2.1 The trajectory of the water use gravity center in the ecological-production-living function spatial distribution:

From 2002 to 2012, the water use gravity center in production function (mainly in Henan Province) moving inland, and this trend became more significant after 2006. The water use gravity center in living function (mainly in Hubei Province) generally migrated eastward, with a spatial distance of 214 km. The water use gravity center of ecological function spatial distribution (mainly in Gansu and Shaanxi Provinces) generally migrated west-northward, with a significant shift from southeastern Gansu Province to central Shanxi Province in 2006, and then back to Gansu Province in 2007.

3.2.2 Trends in of water use structures in the ecological-production-living function:

For production function, the main transfer in route is the transformation of grassland ecological function and forest ecological function to agricultural production function, while the main transfer in route for industrial production function is the transformation of forest ecological function, grassland ecological function and agricultural production function. In terms of living function, the conversion of woodland ecological function, grassland ecological function and agricultural production function forms a new rural living function, while woodland ecological function, agricultural production function and rural living function are gradually converted into urban living function. In terms of ecological function, the main transfer in route is the conversion of grassland ecological function and agricultural production function to woodland ecological function, while the conversion of woodland ecological function, other ecological function and agricultural production function can form grassland ecological function. Finally, the transfer in route of the watershed ecological function is not only from the agricultural production function and the grassland ecological function, but also from other ecological functions.

3.2.3 Trends out of water use structures in the ecological-production-living function:

In terms of production function, most of the agricultural production function will become grassland ecological function and woodland ecological function, and the transfer out of industrial production function will mainly include agricultural production function and water ecological function. In terms of living function, the main type of agricultural production function will be rural living function, and urban living function will be transferred out to water ecological function and agricultural production function. In terms of ecological function, the transfer out of woodland ecological function mainly contains grassland ecological function and agricultural production function. The transfer out of grassland ecological function contains woodland ecological function and other ecological function, and water ecological function will become agricultural production function, grassland ecological function, and other ecological function. The other ecological function and grassland ecological function show the trend of transferring out to each other. This is also consistent with the results of other researchers (Hao et al., 2019).

3.2.4 Projections of water use trends in ecological-production-living function

In this paper, the BP neural network is used to assess the degree of impact on the three types of function, and the water use trend in the next five years of the ecological-production-living function is predicted by setting the impact factor to ensure the accuracy of the data computation, and the results of the calculations are shown in Table 2. The periodogram is estimated according to the prediction results of water use in the ecological-production-living function from 2023 to 2027, as shown in Fig. 4 below. From the table and the figure, it is easy to see that the predicted results of water use efficiency in the ecological-production-living function from 2023 to 2027 basically show a steady increase.

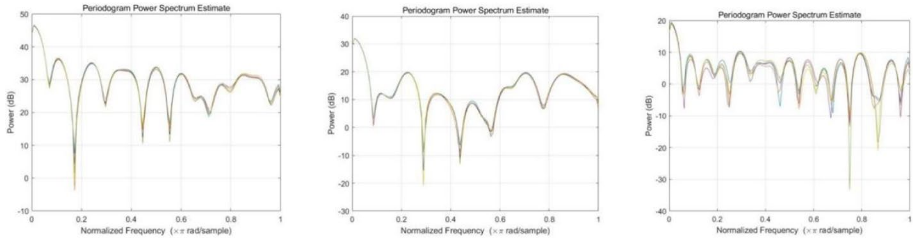
Earlier statisticians had used the periodogram estimation to find the hidden periodicity from a large amount of data, and the resulting periodogram varies with the length of the signal sequence taken, which was known as random fluctuation (Springford et al., 2020). From the Fig. 3, it can be clearly seen that the power of the predicted periodogram of water resource in the production function fluctuates gently between 20 and 40, the power of the predicted periodogram of water resource in the living function fluctuates gently between 0 and 20, and the power of the predicted periodogram of water resource in the ecological function fluctuates violently up and down around the vertical coordinate 0, and all of them have no obvious cyclic changes. In terms of water resource and the proportion of water use efficiency in each region, the southern region of China is the main distribution area of high value of water use efficiency from 2002 to 2022, and the northern region is the main distribution area of low value, which is basically consistent with the distribution of inter-provincial annual precipitation and the production-living function pattern in China (Tao et al., 2022). Due to the frequent interchange of production-living function, the fluctuation trend of (a) (b) prediction result is very similar and shows the result of approximate nudging, which indicates that its water resource is corresponding to the regular change, and the cycle power indicates that the water resource of production function is almost twice as much as those of living function. The predicted results of (c) fluctuates drastically, and

Table 2 Development trend of water use efficiency of three living functions from 2023 to 2027

Vintages	Production function					Living function					Ecological function				
	2023	2024	2025	2026	2027	2023	2024	2025	2026	2027	2023	2024	2025	2026	2027
Beijing	7.10	7.21	6.00	6.06	5.94	17.17	15.80	18.14	16.74	17.56	16.31	16.31	14.79	14.99	14.22
Chongqing	48.25	45.98	48.07	49.17	52.44	21.48	22.41	21.53	22.54	20.47	1.66	1.79	1.78	1.49	1.52
Tianjin	15.54	13.97	15.79	14.11	15.86	6.71	6.53	6.22	6.27	6.47	6.65	6.70	6.85	5.77	6.81
Anhui	217.50	210.63	214.19	199.59	208.23	35.37	35.99	35.81	35.78	36.32	8.49	9.65	8.75	7.15	9.28
Fujian	139.09	137.93	136.99	139.39	142.43	34.11	34.10	33.05	33.87	33.58	6.07	4.72	5.33	3.72	3.38
Guizhou	69.63	59.01	61.18	57.34	70.56	18.67	18.41	19.27	20.07	20.32	1.04	1.19	1.26	1.38	1.15
Hebei	138.48	128.58	132.30	121.68	134.34	27.13	27.27	27.46	26.96	27.34	8.20	8.79	10.27	8.67	10.36
Heilongjiang river forms the border between northeast China and Russia	294.09	281.10	269.76	280.14	285.25	14.77	15.08	14.72	14.00	14.47	2.34	3.93	1.36	5.02	2.04
Henan	157.58	157.94	146.56	149.09	160.32	44.20	43.74	42.47	41.72	44.49	16.11	17.71	17.39	17.97	15.45
Hubei	209.38	213.37	206.34	219.87	215.32	51.81	51.46	51.68	51.98	50.61	1.47	1.49	1.53	1.90	1.42
Hunan	258.38	258.67	257.13	265.31	253.72	44.68	42.87	44.53	43.83	47.67	4.04	4.17	3.54	3.64	3.96
Jiangsu	502.75	500.65	493.33	468.33	488.89	64.41	63.26	63.82	63.52	63.39	3.55	4.71	3.89	5.56	4.23
Jiangxi	214.61	216.27	222.60	223.09	213.08	28.58	28.94	28.69	29.04	28.92	4.73	3.43	3.15	2.15	2.55
Liao ning	97.30	98.18	98.67	98.79	99.01	25.36	25.56	25.26	25.31	25.26	7.40	6.68	6.94	7.04	8.56
Shanxi Western	66.24	56.43	69.19	56.86	68.39	18.66	18.95	18.62	18.81	19.01	3.13	4.27	5.01	6.58	3.51
Shandong	167.88	161.85	165.73	160.09	159.39	37.30	37.34	36.72	35.41	34.91	8.64	11.26	12.11	10.20	10.46
Shanxi	56.94	53.36	56.24	49.41	60.49	14.76	15.30	14.78	14.45	15.00	4.71	5.29	3.14	2.55	3.76
Sichuan	178.78	174.61	168.63	177.22	165.91	53.38	51.50	51.04	51.23	50.07	7.04	6.92	6.81	6.80	6.76
Zhejiang	108.01	116.24	112.66	116.26	114.86	47.59	47.24	47.42	46.90	47.02	7.04	6.53	6.79	6.60	7.00
Hainan	34.08	34.64	34.55	34.11	34.56	8.18	8.08	8.25	8.71	8.24	0.71	0.70	0.70	0.70	0.70
Guangdong	293.35	303.41	311.06	315.12	320.18	108.85	105.93	105.90	105.46	105.30	7.30	7.42	6.52	6.57	5.97

Table 2 (continued)

Vintages	Production function					Living function						Ecological function			
	2023	2024	2025	2026	2027	2023	2024	2025	2026	2027	2023	2024	2025	2026	2027
Gan shu	89.51	84.10	92.03	90.67	87.94	9.22	9.40	9.00	9.16	9.55	8.43	7.85	2.23	5.63	4.45
Guangxi	223.69	220.43	223.63	230.47	242.42	36.99	39.17	39.31	36.68	36.30	4.96	5.17	4.96	4.94	4.33
Jilin	93.20	92.34	89.72	92.31	98.18	13.14	13.23	13.88	14.17	14.51	6.87	8.23	10.35	9.40	10.20
Ningxia	62.78	62.35	62.78	62.42	62.18	3.24	3.56	3.42	3.30	3.55	3.02	3.93	2.34	3.80	2.53
Qinghai	20.09	19.33	20.40	20.01	21.19	3.12	2.68	2.85	3.29	2.93	1.30	1.35	1.31	1.25	1.46
Yunnan	125.39	124.13	122.96	122.09	122.37	25.06	25.65	24.13	25.45	25.73	4.60	3.65	2.45	1.50	1.42
Xinjiang	508.09	505.61	483.29	501.66	523.24	16.53	17.06	16.86	16.50	17.54	12.61	11.67	12.28	8.06	14.53
Neimeng	152.05	145.11	148.71	148.38	147.48	11.64	12.18	11.53	10.32	10.98	33.71	31.56	30.42	31.92	31.18
Shanghai	71.48	73.88	73.65	73.32	73.41	23.40	22.76	23.26	23.60	23.28	0.77	0.88	0.89	0.88	0.99



(a) Productive function (b) Living function (c) Ecological function

Fig. 4 Periodic diagram of water efficiency prediction in three living function power spectrum estimation diagram. **a** Productive function, **b** Living function and **c** Ecological function

show different power changes in different years, which is related to the low carrying capacity of water resource due to severe water scarcity in many areas of the ecological function and poorly constructed basic water facilities, for instance, in the case of relatively low annual precipitation, the per capita water resource of the northwestern and northern China regions (such as Ningxia, Hebei, Tianjin, etc.) are low. Especially in Ningxia, which is located in the inland northwest, has an extreme lack of water resource, leading to the coexistence of pollution induced water shortage, water shortage of resource and engineering water shortage.

4 Discussion

In this paper, we embarked on a comprehensive exploration of the spatial and temporal dynamics of water use within the distinct contexts of ecological, productive, and living functions across China. Through an extensive analysis spanning two decades (2002 to 2022), we delineated the patterns of water efficiency across 30 provinces, autonomous regions, and municipalities. Our findings unearth significant regional differentiations in water use efficiency and reveal a nuanced interaction between water resources and the 'production-living-ecological' functions. Most notably, the study forecasts a promising trend of steadily increasing water use efficiency from 2023 to 2027, amidst the complexities of China's evolving ecological structure and sustainable development goals. The implications of these findings are explored in depth in the following section, which examines the functional relevance and transformation of the ecological structure of water efficiency.

4.1 Functional relevance of water efficiency

The spatial correlation of production water use efficiency shows regional differentiation. In line with Chen's findings (Chen et al., 2021a, 2021b), the Huaihe River Basin, centered on Anhui and Jiangsu, and the Northeast region, centered on Jilin, form regions with high correlation values for productive water use efficiency. In contrast, the Beijing-Tianjin-Hebei region and Pearl River Delta region are areas with low values. From an intra-regional perspective, there is significant polarization within the Northeast region, Jilin's production water use efficiency correlation with Liaoning and Heilongjiang is significantly greater than that with other cities in the Northeast region, while the Huaihe River Basin does not show any polarization. However, the Beijing-Tianjin-Hebei region and the Pearl River Delta region always have low values of production water use efficiency correlation. The factors directly affecting the strength of production water use efficiency correlation are quality and distance. From previous research literature, it was found that the factors that directly affect the strength of the correlation between water efficiency in production are the level of water efficiency and distance (Zhang et al., 2021). As a special economic zone, the quality of living water use efficiency in Guangdong is the maximum value, while the quality of it in Jiangxi, Fujian, and Hunan provinces follows. In terms of spatial distance, the spatial correlation of water use efficiency is also larger in the neighboring provinces of Guangdong, Jiangxi, Fujian, and Hunan. In contrast, Shanxi, Gansu, Qinghai, and Ningxia provinces are more backward in terms of economic development level, with correspondingly lower quality of water use efficiency, and relatively larger spatial distances from high-value cities such as Guangdong, so the spatial correlation of water use efficiency is also relatively weak. Overall, the ecological-production-living function has decreased to different degrees over time. According to previous studies, the trend of population growth has led to an increase in the demand for residential functions, and it is more common to only build houses without demolishing them (González-Torres et al., 2022), expanding the living function. The implementation of the agricultural production subsidy system and the strict regulation of land transfer (Huang et al., 2024; Pan et al., 2024) have expanded the production function. The implementation of ecological restoration and maintenance policies and corresponding programs increased ecological functions (Klaus & Kiehl, 2021). With rapid economic development, a series of problems such as sewage discharge (Shi et al., 2021; Zhang et al., 2024), climate deterioration (Surendran et al., 2021), and desertification (Kirkby, 2021) have led to serious impacts on the ecological structure of water efficiency.

4.2 Functional transformation of water efficiency

The evolution of water supply and consumption patterns across China is not just a matter of resource distribution; it fundamentally influences regional water security, agricultural productivity, and economic sustainability (Deng et al., 2022). Our analysis not only reveals the spatial and temporal trends in water resources, but also needs to explain the broader implications of these changes. As the Bruns study shows (Bruns et al., 2022), changes in water supply and use foreshadow deeper socioeconomic transformations such as urbanization, industrialization, and even the effects of climate change. These changes have far-reaching implications for regional water resources and water efficiency, from agricultural productivity to urban water supply systems (Rathee & Mishra, 2023).

Patterns of water use and management in China are changing in response to urban sprawl, economic development, and changing climate patterns (Younan et al., 2023; Zhai et al., 2024). The movement of the centers of gravity for water use efficiency from 2002 to 2022 underscores significant regional transformations in water demand and supply mechanisms. Initially centered in Henan Province, the gravitational shift towards the west by 2012 reflects not just changing agricultural practices but also the impact of national policies like the South-to-North Water Diversion Project. In addition, China is undergoing a phase of rapid industrialization and urban development (Song et al., 2024; Yang et al., 2024), the same shift observed in the "production-life" water use ellipse across Henan and Hubei to the western provinces. This westward expansion is intertwined with efforts to balance economic growth and environmental sustainability, challenging regions to adapt to new water use patterns. Over the years, adjustments in the long and short axes of these ellipses have further demonstrated the scarcity of water resources and the growing need for efficient management strategies to cope with climate variability and anthropogenic pressures (Davamani et al., 2024).

4.3 Further discussion

The increase in China's per capita water resources and the improvement in water use efficiency for ecological, productive and domestic functions signal a move towards more sustainable management. However, the anticipated transition from a negative to a positive water use deficit from 2023 to 2027 casts a shadow over the future sustainability of these resources. This shift reflects the complex interplay between water supply and demand and underscores the critical need for adaptable strategies that can maintain ecological equilibrium and safeguard water resource sustainability (Lako & Çomo, 2024).

Initially remaining below 1.0, the water stress index signifies a period of comparative security in water availability for China's productive sectors. Nevertheless, as this index nudges and eventually exceeds 1.0 in the coming years, it marks a critical threshold, signaling a pivot towards unsustainable exploitation of water. This emerging trend points to the looming challenge of satisfying escalating water demands while preserving the integrity of our water resources.

Fluctuations in water stress in the provinces and municipalities show the different challenges faced by regions in the sustainable management of water resources. Regions with water stress indices consistently exceeding 10 are approaching the tipping point of unsustainable water efficiency ecological structures and must radically change their management strategies to improve efficiency, promote conservation and ensure equitable distribution of resources to avoid deterioration of water quality and supply.

Furthermore, the encroachment of living and production activities into natural habitats exacerbates the vulnerability of ecological functions, signifying a wider environmental predicament (Radić & Gavrilovic, 2021; Liu et al., 2024b). This encroachment, leading to the fragmentation of ecological functions and loss of biodiversity, poses an imminent threat to the resilience of ecosystems, calling for immediate intervention to protect these vital resources.

The significance of our findings reaches beyond China, resonating with nations across Africa and parts of Asia that are confronting similar challenges of water scarcity (Hejnowicz et al., 2022; Liu et al., 2024c). These countries can glean valuable lessons from China's experience to navigate their own water resource dilemmas. The general applicability of this study lies in its use of a holistic and integrated approach to water resources management that combines sustainable practices, strong governance and active community participation to increase resilience in the face of the complex challenges posed by water scarcity.

In summary, our research emphasizes the critical need for prompt and strategic reforms in water resource management. Cultivating a deeper comprehension of the intricate relationships between ecological, productive, and living functions is crucial in steering us towards a future where water resources are managed more sustainably, equitably, and resiliently on a global scale.

5 Conclusions and policy recommendations

5.1 Conclusions

In this paper, the evolution of the ecological structure of water efficiency for production-living-ecological functions in China is explored using data envelopment analysis, weighted standard deviation ellipse model and BP neural network model. In addition, the ecological structure for the next five years was predicted based on the water efficiency characteristics of the production-living-ecological functional areas. The conclusions are as follows:(1) The DEA results show that there is a complex "stock-flow" relationship between production-living-ecological functions and water efficiency. They are characterized by intricate nonlinear feedback mechanisms, multidimensional interactions, multiple coupling and direct causality. (2) This paper uses SDE model to analyze the ecological structure change of water efficiency from 2002 to 2022. The results show that water use decreases from the northeast to the southwest, but water use efficiency increases and overall sustainability decreases. The interconversion of production function and ecological function is the main form of change. In addition, the range of ecological functions gradually shrinks with economic development. (3) The BP neural network prediction results show that the water consumption of the production function is almost twice as much as the water consumption of the living function. The ecological function is highly susceptible to fluctuations in water use. The expansion of living and production functions leads to a decline in the quality of the ecological environment, which must be protected immediately.

5.2 Policy recommendations

China's water resources are strictly managed by the State Council, and a radical improvement in the ecological structure of water efficiency must rely on policy support. Therefore, we suggest that the government should build a strict regulatory system. Delineate the living functional areas, production functional areas and ecological functional areas to strengthen the functional area control measures. At the same time, it is also necessary to innovate the institutional mechanism, through timely and strategic reforms, to build a water rights trading market with the coexistence of multiple living and production subjects. Measures will be taken separately for the status quo of each region. South China has a large potential to improve water efficiency and should strengthen the construction of basic water conservancy facilities. Southwest, Northeast, and East China should appropriately improve the quality of labor and the utility of capital investment to prevent wasteful behavior of resources. Northwest and North China should strictly control industrial water use, strengthen industrial sewage management, and encourage enterprises to recycle water resources. Overall for the coordination of sustainable development of water resources and economic and social development, to reach a "win–win" game pattern.

5.3 Limitation and future research

We acknowledge several limitations in this study that could be addressed in future research. Firstly, the data used excludes regions such as Tibet, Hong Kong, Macau, and Taiwan, potentially limiting the representativeness of the findings for all of China. Additionally, while the study employs robust methodologies such as Data Envelopment Analysis (DEA), the Standard Deviational Ellipse (SDE) model, and the BP neural network model, these methods may not fully capture the complex, nonlinear interactions between water use and socio-economic factors. The predictive accuracy of the BP neural network could also be constrained by the exclusion of variables like unexpected policy changes and climate variability, which significantly impact water use trends. Moreover, the findings are mainly applicable within the Chinese context, which may limit their generalizability to other regions with different environmental and socio-economic conditions.

To address these shortcomings, future research could expand the geographical scope to include the previously excluded regions and explore comparative studies with other countries facing similar water management challenges. It would be beneficial to incorporate additional variables, such as climate change projections and socio-economic development scenarios, to provide a more comprehensive understanding of water efficiency dynamics. Moreover, adopting more advanced predictive models, such as deep learning algorithms or hybrid approaches, could enhance the accuracy of predictions. Conducting longitudinal studies to monitor the long-term impacts of policies and practices on water efficiency would provide valuable insights, supporting the development of targeted strategies for sustainable water management. Finally, future research should aim to translate these findings into practical policy recommendations to effectively improve water resource management.

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Declarations

Conflict of interest The author declared no potential conflicts of interest with respect to the research, author ship, and/or publication of this article.

Data availability The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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