frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 01 October 2025
DOI 10.3389/fenvs.2025.1521769

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RECEIVED 04 November 2024
ACCEPTED 09 June 2025
PUBLISHED 01 October 2025

CITATION
Qianli X and Hongyao S (2025) Decoupling analysis of urban water resource utilization and economic development.
Front. Environ. Sci. 13:1521769.
doi: 10.3389/fenvs.2025.1521769

Decoupling analysis of urban water resource utilization and economic development

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The study constructs a decoupling evaluation model, taking Nanjing City as an example. It contributes to a deeper understanding of the sustainable utilization of water resources and the coordination between regional economic development and ecological preservation. In addition, Nanjing's water resource endowment, social background, economic foundation, and ecological environment have unique characteristics and significance. The results show that (1) the water resource ecological footprint tended to gradually decrease and level off. Water consumption in industry and agriculture was relatively high, and there were imbalances in the consumption and distribution of water resources across different social and economic sectors. (2) The carrying capacity of *per capita* water resources in Nanjing presented a gradual upward and downward trend, roughly resembling an "*M*" shape. (3) The average ecological deficit of *per capita* water resources over the recent 10 years was −0.53 hm^2/person. The average ecological pressure index was 4.54. Therefore, this suggests significant pressure on water resource utilization and ecological environment protection. (4) The decoupling rate between water resource utilization and economic development has reached approximately 100%, indicating that economic development can help a city reduce its dependence on water resources. However, the relationship between the development of industry and agriculture and water resource utilization was not well coordinated.

KEYWORDS

water resources, water ecological footprint, economy, decoupling, sustainable water resources utilization

1 Introduction

Water is regarded as the foundation of life and the basis of civilization (Kummu et al., 2016; Su et al., 2024; Vorosmarty et al., 2000). With the acceleration of global urbanization, water scarcity has become a critical bottleneck constraining sustainable urban development. According to the *United Nations World Water Development Report*, approximately 40% of the global population faces water scarcity (UNESCO, 2021), with urban areas being particularly affected. Currently, global water resource utilization exhibits two key characteristics: on one hand, continued growth in water consumption demonstrates a strong coupling relationship with economic development resources (Antonelli and Sartori, 2015; Peng et al., 2024); on the other hand, significant disparities in water-use efficiency exist across cities, with some developed cities having preliminarily achieved "decoupling" between economic growth and water consumption (Ansorge and Stejskalová, 2022). Compared to rural areas, cities rely more on water resources. It is crucial for a city to realize sustainable economic development with accurate calculation of the current status of water resources and achievement of the decoupling between scientific utilization of water resources and economic development (Liu et al., 2019; Wang et al., 2019). Current prominent issues in urban water resource utilization include the following: first, the excessive coupling between water use and economic development persists: most cities remain locked in the conventional paradigm where economic growth inevitably drives increased water consumption. Second, significant regional disparities exist: cities across different climatic zones and developmental stages face distinct decoupling challenges, yet tailored solutions remain inadequate. This study aims to systematically analyze the decoupling relationship between urban water resource utilization and economic development, elucidate its underlying mechanisms and spatiotemporal patterns, and provide scientific evidence for formulating differentiated water management strategies to promote urban green and low-carbon development.

Recently, scholars all over the world have studied the relationship between water resources and socio-economic development (Gao et al., 2024; Omer et al., 2020; Stoeglehner et al., 2011; Wang et al., 2019), mainly focusing on water footprint theory and decoupling elasticity theory. The water footprint theory was first proposed by Canadian ecological economist William (1992) and enriched by his student Wackenagel and William (1996) (William, 1996). It aimed to quantify the utilization of natural resources and the environmental pressure by calculating the dry land and water area of a region.

It is efficient for us to calculate and analyze the utilization of urban water resources and the current situation of water management using the Ecological Footprint Theory of Water Resources, which is one of the important indicators used to evaluate the sustainable development level of a city. Using this theory,Linnan et al. (2008) identified three key parameters for the calculation model of water resource ecological carrying capacity and water resource ecological footprint, namely, global average water resource yield, global equilibrium factor, and regional yield factor, which expanded the depth and breadth of water footprint theory in practical application.

The decoupling theory is proposed by OECD (2015), aiming to reveal the asynchronous process of economic growth and the decrease in resource consumption (Chen et al., 2022; Gong and Guo, 2024; Gong et al., 2021). When economic development comes at the cost of resource depletion and environmental pollution, certain measures should be taken to gradually reduce resource consumption and environmental pressure in order to achieve sustainable development. This process is defined as decoupling.

According to the decoupling theory, Tapio (2005) constructed the elasticity analysis coefficient of the decoupling theory, which was highly effective in the indication of economic development and the elastic process influencing the environment. This theory further discussed the degree of influence between different factors accurately. There are many studies that use decoupling theory. For example, Dai et al. (2019) constructed a three-dimensional footprint model and measured the use of land natural capital in Shanxi Province over two decades from the product–land class–region triple scale using the national hectare method in order to analyze its decoupling effect with economic development. Xiong et al. (2020) investigated the influence of socioeconomic factors on the transformation of water footprint. In addition, the results found that changes in demand structure and water intensity can save water. Zhang et al. (2024) studied the water trend of footprint historical evolution in the Yangtze River Delta and provided policy recommendations for optimizing water use.

Most of the studies on the relationship between the current utilization of water resources and economic development mainly involve evaluating the relationship between the utilization of water resources and economic development, recording the current status of water resources in specific regions, and balancing economic development and ecological environment protection. The current literature has the following limitations: first, it lacks sufficient dynamic analyses that capture the evolutionary trajectory of decoupling processes. Second, it predominantly focuses on macro-scale assessments, with inadequate attention to city-level dynamics. Finally, the majority of studies are unable to identify the state of economic development in different cities and the diversity in the endowment of water resources, which inevitably results in the inaccuracy of the obtained results of the relationship between the economic development of a single city and the ecological footprint of water resources. Through designating the particular city as the research object, it is convenient to eliminate the heterogeneity between different cities, which means that it can get access to the relationship between water resource utilization and economic growth in a specific region (city). Based on the existing literature, this study constructs a dynamic decoupling analytical framework at the urban scale. By integrating econometric modeling approaches, the article systematically investigate the driving mechanisms of water resource decoupling, thereby providing scientific evidence for sustainable urban development.

Unlike the "engineering water shortage" in canyon areas and the "resource-based water shortage" in the most northern part of China, Nanjing, located in the lower reaches of the Yangtze River, faces serious pressure on *per capita* water resources due to rapid economic development and population growth. Although it has abundant water resources from the Yangtze River and Qinhuai River, Nanjing is one of the "quality-based water shortage" cities. Thus, based on the historical water resource data in Nanjing, this article calculates the average water consumption and ecological footprint to describe the trend of the ecological footprint of water resources. Furthermore, it is meant to provide the local government with the support of data to solve the problem of coordination between urban water resource utilization and economic development.

2 Data and methods

2.1 Data sources and definitions

This article tracks and statistically studies the use of water resources and the economic growth in the recent 10 years in Nanjing. The data used include the total water resources of Nanjing from 2013 to 2022, water consumption of different types of water, and economic indicators (a total of three first-level indicators and 11 second-level indicators, which are derived from the *Nanjing Statistical Yearbook*[1] and *Nanjing Water Resources Bulletin*[2] from 2013 to 2022). In the calculation of the water resource footprint, water used in agriculture, forestry, animal husbandry, and fishery (primary industry) refers to the water resources used for various needs, such as farmland irrigation, forestry irrigation, livestock breeding, and sanitation. It is represented by agricultural water consumption as reported in the Water Resources Bulletin. In the *Nanjing Water Resources Bulletin* from 2013 to 2016, the water used in agriculture and the water used in the forestry and fishery industries are listed separately. The former is almost six times greater than the latter. However, in this article, both are collectively defined as agricultural water. Water used in the industry refers to various types of water consumed in industrial production processes. This article directly quotes the total amount of industrial water consumption from the *Nanjing Water Resources Bulletin*. Ecological water consumption is represented by the water consumption of the ecological environment in the *Water Resources Bulletin*. Domestic water consumption includes water for living in both urban and rural areas. This article summarizes the data on the consumption of urban public domestic water and residential domestic water in *the Water Resources Bulletin*. Population and socio-economic development are defined as relevant data such as the gross domestic product of Nanjing, agricultural (primary industry) output value, industrial output value, and the population of year-end residents in Nanjing. According to WWF2002 (*World Wide Fund for Nature Earth Report 2002*), γ_w is the factor of global water equalization, taking a value of 5.19 (dimensionless) (Li et al., 2020; Sun and Zhang, 2017). ψ is the factor of water resource production, a region-specific data standardized by prior research. According to the research of Linnan et al. (2008), Nanjing city's ψ is 1.02 (dimensionless). p_w is the average production capacity of global water resources, taking a value of 3140 m^3 hm^{-2} (Li et al., 2020; Wackernagel et al., 2004).

2.2 Ecological footprint of water resources

The ecological footprint of water resources refers to the metabolic intensity of water resources in an area. It includes not only the consumption of water resources by human beings in daily life and production but also the maintenance of the natural environment. The calculation formula is provided in Equation 1:

$$EF_w = ef_w \times N = \gamma_w \times \left(\frac{W}{P_w}\right). \tag{1}$$

Here, EF_w is the ecological footprint of water resources. ef_w is the *per capita* ecological footprint of water resources (hm^2/person). N is the number of the resident population at the end of the year. γ_w is the global equilibrium factor of water resources. W is the regional water consumption (m^3). P_w is the average capacity of global production of water resources.

1 See http://tjj.nanjing.gov.cn/for further details.

2 See http://shuiwu.nanjing.gov.cn/for further details.

2.3 Calculation and evaluation model for the sustainable development of water resources

2.3.1 Per capita ecological carrying capacity model

The ecological footprint theory suggests that the ecological carrying capacity of water resources reflects the ability of these resources to support the healthy development of the regional ecosystem and economic system in the region under current management and technological conditions. It has natural, spatial, and social attributes. It is necessary to comprehensively consider the current situation of the ecological environment and the water resources needed for social production, ecological production, and life (Gao et al., 2024). The formula is provided in Equation 2:

$$ec_w = \frac{0.4 \times \psi \times \gamma_w \times \left(\frac{Q}{P_w}\right)}{N}. \tag{2}$$

Here, ec_w refers to the *per capita* ecological carrying capacity (hm^2/person). According to the research of Linnan et al. (2008), it is identified that 60% of the water resources in a certain region are usually used to maintain the ecosystem, and 40% are used to meet the development needs of human society. Therefore, the coefficient is multiplied by 0.4. Q indicates the total amount of regional water resources in the study area.

2.3.2 Index of water resource ecological stress and the *per capita* ecological surplus/deficit of water resources

The water resource ecological stress index refers to the relative pressure intensity of the socio-economic system on regional water resources, reflecting the scarcity of water resources. Moreover, it quantifies the dependence of human production on water resources. The larger it is, the more safety issues in water resource utilization there will be. The *per capita* ecological surplus/deficit of water resources is an indicator that quantitatively reflects the natural capital relationship between human and water systems. It is also the result of comparing the human load and ecological capacity of the region, explaining the sustainability level laterally. The formulas are provided in Equations 3, 4:

$$s_w = \frac{ef_w}{ec_w}, \tag{3}$$

$$eb_w = ec_w - ef_w. \tag{4}$$

When $eb_w = 0$, $s_w = 1$. Here, the water resource ecology is roughly balanced. If $eb_w > 0$ ($s_w < 1$), it indicates that the water resources in the region are sufficient to support its development of economy, environment, and society. Moreover, it is believed that we can further optimize the use of water resources. However, if $eb_w < 0$ ($s_w > 1$), water resources are in a state of ecological deficit, representing that the water resource ecology in the region has been damaged and the water resources are insufficient to support the sustainable development of the regional economy.

2.4 Decoupling evaluation model of water resource ecological footprint and economic development

The Tapio decoupling index (Fu et al., 2024; Wu et al., 2019) is a ratio that compares the rate of change between water environmental

TABLE 1 Decoupling index, decoupling state, and evaluation criteria.

State		T	ΔEF_w	ΔGDP	Main meaning
Decoupling	Strong decoupling (SD)	(−∝, 0]	≤0	>0	GDP increases, while EF_w decreases
	Weak decoupling (WD)	(0, 0.8]	>0	>0	GDP increases at a faster rate than EF_w
	Recessive decoupling (RD)	[1.2, ∝)	<0	<0	GDP decreases at a slower rate than EF_w
Link	Expansive coupling (EC)	(0.8, 1.2]	>0	>0	GDP increases, while EF_w shows medium-speed growth
	Recessive coupling (RC)	(0.8, 1.2]	<0	<0	GDP decreases, while EF_w decreases at a medium speed
Negative decoupling	Expansive negative decoupling (END)	[1.2, ∝)	>0	>0	GDP increases at a slower rate than EF_w
	Weak negative decoupling (WND)	(0, 0.8)	<0	<0	GDP decreases at a faster rate than EF_w
	Strong negative decoupling (SND)	(−∝, 0]	≥0	≤0	EF_w recesses, while GDP decreases slowly

pressure and economic drivers. It is used to analyze the relationship between the ecological footprint of water resources and economic development, ultimately determining their decoupling status. Based on previous research, the formula is provided in Equation 5:

$$T = \frac{\Delta EF_w}{\Delta GDP} = \frac{(EF_{w_t} - EF_{w_{t-1}})/EF_{w_{t-1}}}{(GDP_t - GDP_{t-1})/GDP_{t-1}}. \quad (5)$$

Here, T is the decoupling index between the ecological footprint of regional water resources and economic development. ΔGDP is the growth rate of the gross domestic product (GDP) in year t. ΔEF_w is the rate of change in the ecological footprint of water resources in year t. GDP_t and GDP_{t-1} are the GDP of the region in the *t*th and t−1th years, respectively. EF_{w_t} and $EF_{w_{t-1}}$ are the ecological footprints of water resources in the *t*th and t−1th years, respectively.

Based on Tapio's explanation of index determination and standard definitions (Fang Kai, 2015), this article illustrates the decoupling state and its representational connotation, as shown in Table 1.

Tapio divides the decoupling elastic index into eight categories, with 1.2, 0.8, and 0 as critical values:

(1) When T < 0, ΔEF_w ≤0, and ΔGDP > 0, the ecological footprint of water resources is strongly decoupled from economic development. In this state, the economy increases, while the rate of water resource consumption decreases, achieving maximum economic growth with minimal water resource consumption. This is defined to be the most ideal state.
(2) When 0 < T ≤ 0.8, ΔEF_w >0, and ΔGDP > 0, it is in a weak decoupling state. By this time, the increase in water footprint will lag behind the rate of economic growth, and economic growth will also be accompanied by a slow increase in water footprint. Thus, it is necessary to increase control over the rational use of water resources and raise water conservation awareness.
(3) When T > 1.2, ΔEF_w <0, and ΔGDP < 0, it indicates a decoupling of recession. Under this state, economic development decreases, and the water footprint also rapidly decreases. It is important to adjust the industrial structure to promote economic recovery and ensure the sustainable use of water resources.
(4) When 0.8 < T ≤ 1.2, ΔEF_w >0, and ΔGDP > 0, it is in a growth-connected state, indicating that while the economy is developing, the water footprint will also increase. This is a typical state that requires the authority to take comprehensive steps to promote reasonable coordination between economic growth and water resource consumption.
(5) When 0.8 < T ≤ 1.2, ΔEF_w <0, and ΔGDP < 0, it is in a decreasing connection state. There is a decrease in both the water footprint and economic development. Continuous improvement in the pricing mechanism of water resources can be adopted to stimulate green technology innovation and promote sustainable economic recovery.
(6) When T > 1.2, ΔEF_w >0, and ΔGDP > 0, it is in a negative decoupling state of growth. The rate of water footprint increases faster than that of economic development. To address this, a system of total water use needs to be established, and the investment in water-saving technology should be increased for the sake of the comprehensive optimization of water resource utilization. It is necessary to carry out cross-sectoral and cross-industry water resource management and planning.
(7) When 0 < T < 0.8, ΔEF_w <0, and ΔGDP < 0, it is in a weak negative decoupling state. At this time, both economic growth and water footprint decrease. The rate of economic recession decreases faster than that of water footprint. The government can increase support for water-saving projects, encourage investment in the green industry, and raise awareness about environmental protection.
(8) When T ≤ 0, ΔEF_w ≥0, and ΔGDP ≤ 0, it is in a strong negative decoupling state, and the water footprint increases, while economic development is in a decreasing stage, indicating that the ecological footprint of water resources and economic development are in the most unfavorable state. Immediate steps must be taken, like the resetting of water resource allocation, the improvement in water resource management, and the popularization of efficient water-saving equipment, to achieve a virtuous cycle of economic development, environmental protection, and social stability.

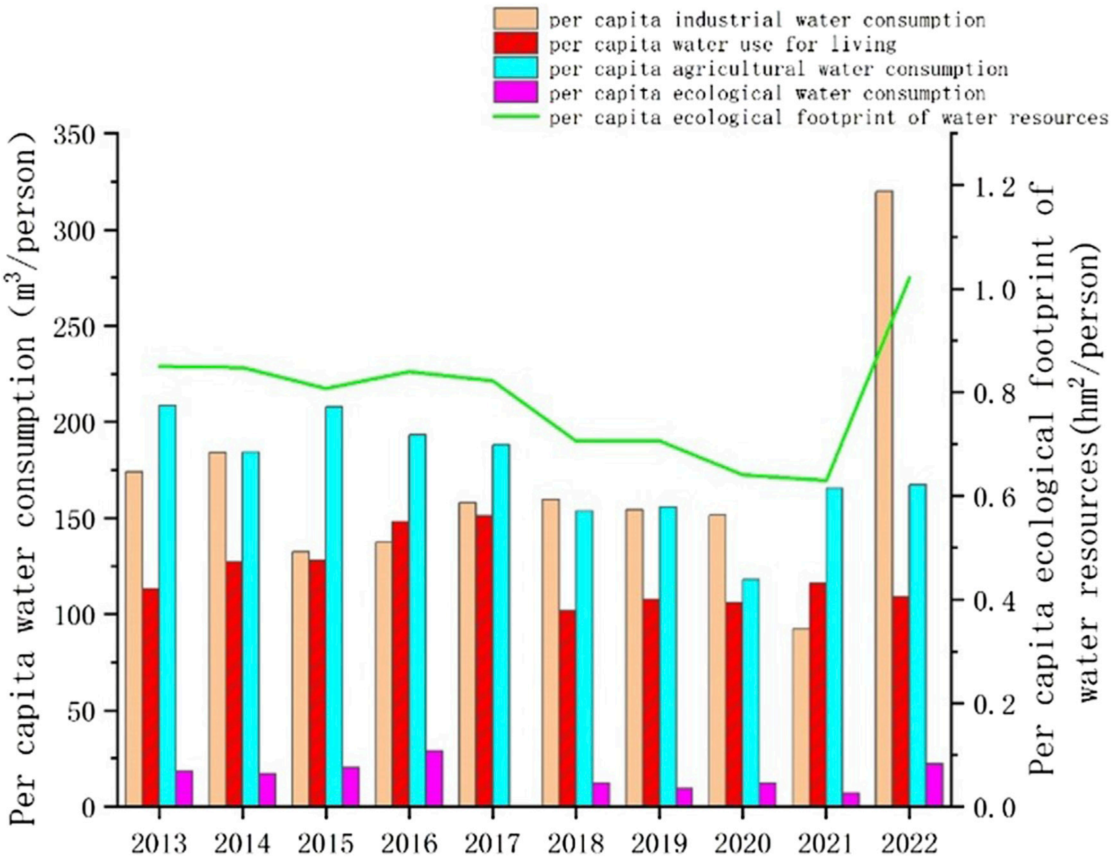

FIGURE 1
Per capita water consumption and *per capita* ecological footprint of water resources in Nanjing, 2013–2022.

3 Results

3.1 Results and analysis of water footprint composition in Nanjing

Based on the data of *Nanjing Water Resources Bulletin* from 2013 to 2022, we calculate the ecological footprint of water resources, as shown in Figure 1. According to the type of industry, the agricultural water consumption of the primary industry is the highest, accounting for an average of 40%. The industrial water consumption of the secondary industry consists of 30%, which is the second-highest water usage, followed by residents' daily life at 25%. Moreover, ecological environment water consumption ranks last, accounting for an average of 5%.

During the allocation of water resources, less attention is often paid to water used for public welfare, such as the ecological environment. As a result, most cities suffer from a shortage of water resources due to accelerating urbanization and population growth, which restricts water available for the ecological environment.

The *per capita* domestic water consumption in Nanjing has remained relatively stable at approximately 100 m^3/person for 10 years, suggesting the reasonable development and management of water resources in Nanjing. This is conducive to ensuring the normal life of residents and the long-term development of urban public industries, which further promotes the stable development of the industrial economy and drives the optimization and upgrading of the industrial structure.

We analyzed the ecological footprint of *per capita* water resources in Nanjing from 2013 to 2022 and found that it remained stable overall, decreasing from a high point of 0.85 hm^2/person in 2013 to a low point of 0.63 hm^2/person in 2021. Although it increased to 1.02 hm^2/person in 2022, social and economic developments, as well as people's quality of life, have continued to improve, which is essential for the sustainable development of a city.

3.2 Sustainable development status of water resources

3.2.1 Change trend of *per capita* water resource ecological carrying capacity

According to Figure 2, the *per capita* ecological carrying capacity of water resources in Nanjing showed a gradual increase and then a decrease in an *M*-shaped pattern from 2013 to 2022. It came to the lowest point of 0.07 hm^2/person and 0.08 hm^2/person in 2019 and 2022, respectively. The value was at its peak in 2016 and 2020, with 0.38 hm^2/person and 0.35 hm^2/person, respectively. The peak value is more than five times the valley value. In 2022, the industrial water

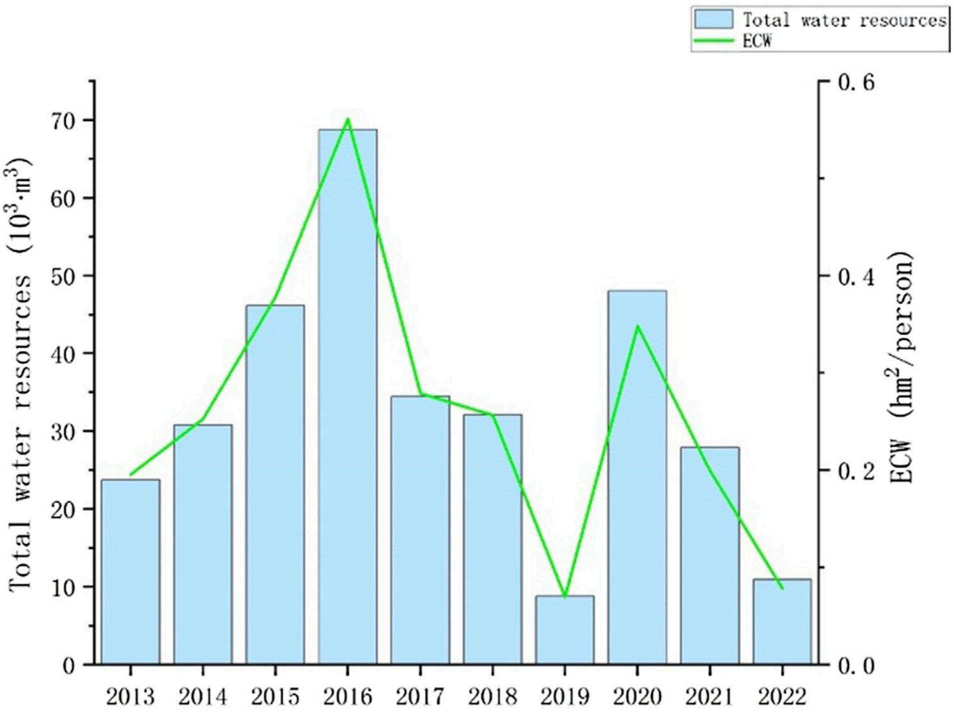

FIGURE 2
Changes in *per capita* ecological carrying capacity and total water resources in Nanjing, 2013–2022.

consumption in Nanjing increased sharply, reaching 30.36 billion m^3. It results in the abnormal data on *per capita* industrial water consumption and *per capita* water resource ecological footprint shown in Figure 1. The possible reasons are as follows: first, the total industrial output value of the city's above-scale industries exceeded 1.5 trillion yuan, which showed an increase of 5.9% over the previous year. The expansion of industrial production will inevitably lead to an increase in industrial water consumption. Second, the climate in Nanjing was seriously abnormal in 2022. The average temperature reached the highest record in the same period since 1961. The number of high-temperature days broke the record for high-temperature days in summer. The reservoir water storage capacity set the lowest record in the same period, and the water level of the Yangtze River, Shuiyang River, and Shijiu Lake set the lowest record at the same time. High-temperature weather and drought lead to a significant increase in the consumption of cooling water by industrial enterprises, such as thermal power, steel, chemical, and other industries, needing more water to cool equipment. Finally, some enterprises have made slow progress in the implementation of water-saving measures and the construction of repeated water-use systems and have not made full use of unconventional water sources, such as reclaimed water and rainwater, which may also lead to an increase in industrial water consumption.

The trend of change has shifted from a slow decrease to a sharp decrease, and the ecological carrying capacity of water resources in Nanjing has shown a fluctuating trend. In April 2015, the State Council issued *the Action Plan for Water Pollution Prevention and Control (Ten Measures for Water*), which marked the important planning and determination of the Chinese government toward water environment governance. After the policy was promulgated, Nanjing has achieved some progress in the utilization of water resources and the protection of the ecological environment. However, water resource treatment still needs to be given great importance to ensure that the ecological carrying capacity of water resources can be continuously improved to meet the needs of urban sustainable development. There is a close relationship between the ecological carrying capacity of water resources and the total amount of water resources, but it is not a linear relationship. The total amount of water resources is one of the important factors affecting the ecological carrying capacity of water resources, but it is not the only factor. Further analysis is needed on relevant conditions, such as forest cover, water bodies, population size, and geological landforms in the region.

3.2.2 Change trend of ecological surplus and deficit in water resources

As shown in Figure 3, the *per capita* water resources in Nanjing have been in a state of ecological deficit for 10 years, with an *M*-shaped trend of change. Decreasing from −0.67 hm^2/person in 2013 to −0.28 hm^2/person in 2016, the ecological deficit then increased from −0.64 hm^2/person in 2019 to the peak of −0.94 hm^2/person in 2022. The average *per capita* ecological deficit over the past 10 years is −0.53 hm^2/person, which indicates that the ecological deficit is still relatively large and places significant pressure on the environment.

Nanjing, a rapidly developing city in the Yangtze River Delta Economic Belt, is an important economic center and a densely populated area in China. The high demand from primary and secondary industries, as well as for domestic water, has led to a prominent contradiction between water supply and demand. The

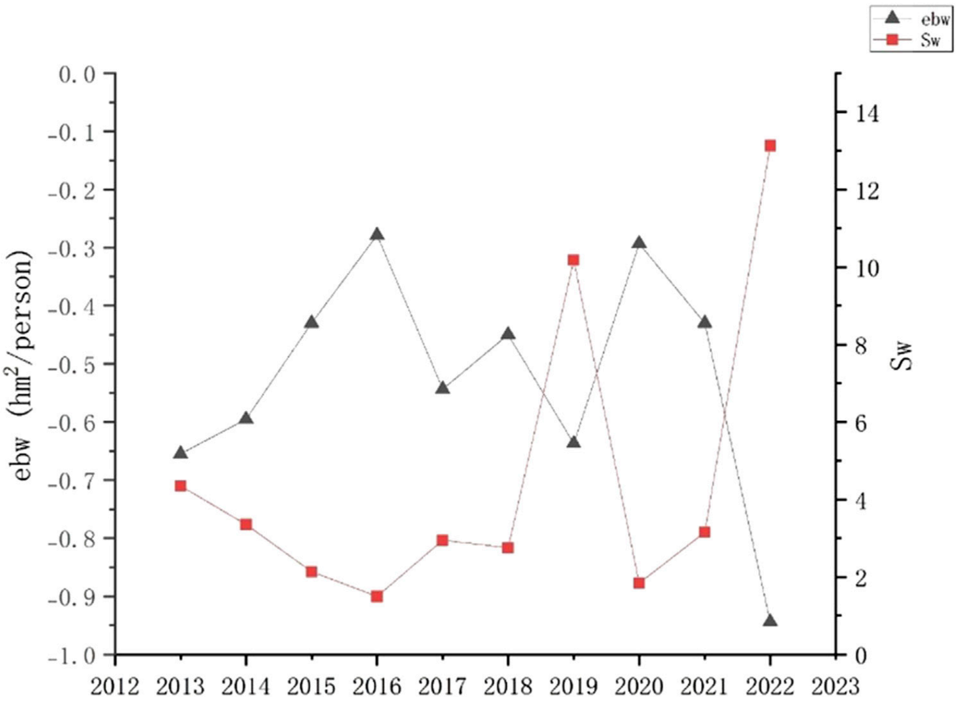

FIGURE 3
Trends in ecological pressure, ecological surplus, and ecological deficit of *per capita* water resources in Nanjing, 2013–2022.

TABLE 2 Ecological stress of water resources in Nanjing from 2013 to 2022.

Year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Average
SW	4.35	3.36	2.14	1.50	2.95	2.75	10.18	1.84	3.16	13.13	4.54

significant ecological deficit of water resources proves that Nanjing is facing challenges in water resource development, management, and utilization. The protection of water resources must be accelerated to realize sustainable utilization and ecological balance of water resources. Based on Figures 2, 3, it can be concluded that the *per capita* ecological carrying capacity and *per capita* ecological deficit have shown a roughly *M*-shaped trend over the past 10 years, and they were similar.

3.2.3 Trends in the ecological pressure index of water resources

During the research period, the overall ecological pressure on water resources in Nanjing presented a *W*-shaped pattern, as shown in Table 2 and Figure 3. The ecological pressure index of water resources was approximately 4.54, which is much higher than 1, indicating the exploitation and utilization of water resources were in a difficult situation. The change in *per capita* water resources' ecological carrying capacity in Nanjing was opposite to that of the water resource ecological pressure value. The change in the *per capita* ecological deficit of water resources was opposite to that of the ecological pressure value of water resources. The total amount of water resources in Nanjing was opposite to the ecological pressure index of water resources. These asynchronous changes had a certain impact on the ecological pressure of water resources.

Although the total amount of water resources is high, the water resources are relatively abundant, and the demand for water resources from human production activities can be met, which leads to a relatively small ecological pressure on water resources. Under the circumstances, both the water environment and ecosystem can be well protected and maintained. The ecological balance is also maintained. In contrast, water resources in short supply certainly result in a significant growth in ecological pressure on water resources. Accordingly, through effective management and protection of ecological resources, the *per capita* ecological carrying capacity of a region will be enhanced. Nevertheless, due to population growth or unreasonable use of resources, the *per capita* ecological deficit may still increase uncontrollably.

3.3 Evaluation of decoupling between the utilization of water resources and the economic growth

3.3.1 Overall analysis of the decoupling between the water resource ecological footprint and economic growth

The results of the calculation and analysis of water resource consumption and economic development in Nanjing from

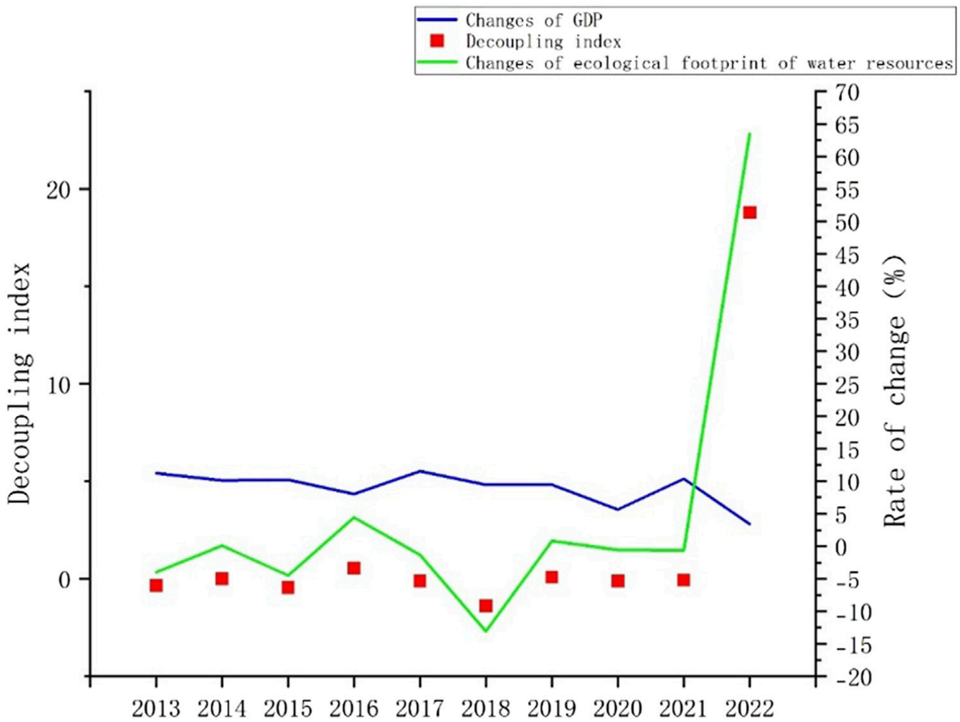

FIGURE 4
Dynamic decoupling index of water use and economic development in Nanjing from 2013 to 2022.

2013 to 2022 are shown in Figure 4. From this, we can conclude the following: (1) over the past 10 years, the ecological footprint of water resources in Nanjing generally showed a consistent trend with economic growth. (2) There were six instances of strong decoupling, three of weak decoupling, and one recession of decoupling between GDP growth and the water resource ecological footprint in Nanjing. It cannot be ignored that every year decoupling occurred, with strong decoupling accounting for 60%. Except for the highly discrete data in 2022, the decoupling index was mostly stable. This indicates that the economic growth and water resource consumption in Nanjing were generally decoupled. Although the economic growth was at a high level, the use of water resources decreased, and the economic growth did not exert excessive pressure on water resources. The high proportion of strong decoupling suggests that Nanjing has achieved great achievements in water resource management, environmental protection, and sustainable development, which is conducive to healthy development. However, there have been three instances of weak decoupling, reminding us that the ecological footprint of water resources and economic development are still in a state of incongruity. Economic growth still comes at the cost of consuming water resources, and benign development is not stable enough. The problems of economic increase at the cost of consuming water resources and the lack of stable development still exist. It may be a result of various factors, such as economic restructuring, changes in water-saving policies, and urbanization in Nanjing. Regarding these problems, further measures are needed to promote the sustainable utilization of water resources and the sustainable development of the economy.

3.3.2 Analysis of the decoupling relationship between the water resource ecological footprint and economic growth in the industrial and agricultural parts

The sections with the highest water consumption in Nanjing are industry and agriculture, as shown in Figures 5, 6, from which we can learn the following: (1) the coordination between the ecological footprint of water resources and economic growth in agriculture was superior to that in the industry. (2) The evaluation of the industrial decoupling index shows that there were three instances of strong decoupling, four of weak decoupling, and three of growth connectivity. For the industry sector specifically, there were seven instances of strong decoupling, one of weak decoupling, and two of growth connectivity. The differences showed that the development of industrial sectors in Nanjing relied more on water resources than agriculture but demonstrated more sustainability in protecting the environment. For the utilization of agricultural water resources, there were 7 years of negative decoupling, with strong decoupling accounting for 50%, and weak decoupling and growth decoupling accounting for 10% each. In 2020, there was even a decrease in decoupling. Overall, although the economic development of agriculture decreases, it is also accompanied by an increase in environmental pressure and an excessive dependence on water resource utilization.

The higher dependence of industry on water resources than that of agriculture may be attributed to the following four reasons: (1) industrial structure differences: as a key industrial city in the Yangtze River Delta, Nanjing hosts water-intensive industries, such as petrochemicals, steel, and electronics (e.g., Yangzi Petrochemical and Nanjing Iron & Steel Group).

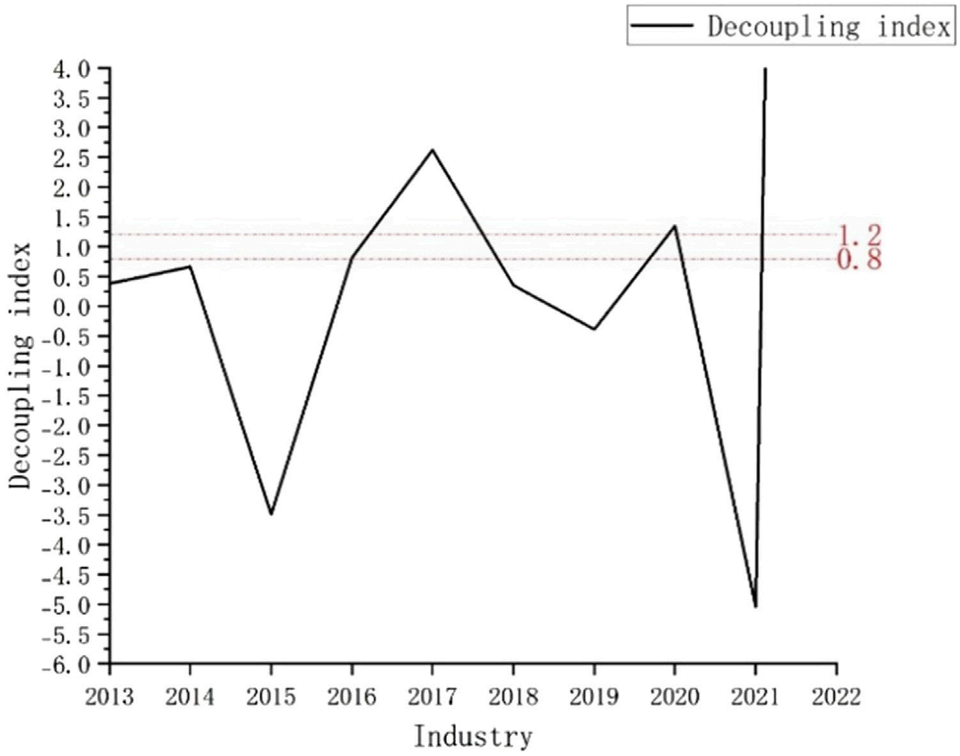

FIGURE 5
Changes in the decoupling relationship between the ecological footprint of water resources and economic development in industrial sectors, 2013–2022.

Production processes require substantial cooling and washing water, making water consumption relatively inflexible. Nanjing's agriculture primarily focuses on rice and vegetable cultivation. Although irrigation is necessary, water usage can be reduced through water-saving technologies (e.g., drip irrigation and mulching) and crop structure adjustments (e.g., drought-resistant crops). Additionally, some areas rely on natural rainfall. (2) Technical and management levels: some traditional enterprises still rely on outdated equipment, resulting in low water recycling rates (e.g., direct discharge of cooling water). The high cost of water-saving technological upgrades has weakened corporate motivation for improvement. The government promotes efficient water-saving irrigation (e.g., water-saving demonstration zones in the Gaochun District) and precision fertilization technologies. Policy subsidies have reduced the cost of water conservation for farmers. (3) Policy regulatory intensity: despite the implementation of water resource taxes and pollutant discharge permit systems, enforcement challenges persist, including incidents of unauthorized emissions and data manipulation by enterprises, resulting in significant regulatory difficulties. Ecological compensation mechanisms (e.g., rewards for water-saving farmers) and environmental awareness campaigns have proven highly effective, with farmers demonstrating strong environmental consciousness. (4) Characteristics of water resource utilization: industrial parts (e.g., electronics manufacturing) require high-quality water (e.g., ultrapure water), leading to elevated treatment costs. Agriculture's flexible water quality needs enable large-scale reclaimed water applications.

Given the distinct water resource demands of industry and agriculture, the following strategies can be implemented: (1) spatial optimization of industrial distribution: traditional heavy industries should be phased out (e.g., relocating some production capacity of Nanjing Iron & Steel), and emerging water-efficient industries (e.g., software & IT services and biopharmaceuticals) should be developed. Integrated rice–fish farming should be promoted in Luhe District to reduce water consumption associated with monoculture rice cultivation. (2) Deep water conservation in the industrial sector: technological upgrades should be mandated, and water-use quotas per unit output value should be enforced in water-intensive industries (petrochemicals and steel), while obsolete production capacities are phased out. Closed-loop water recycling systems should be promoted (e.g., a 30% reduction in cooling water was achieved through circulation systems at an electronics manufacturer in the Nanjing Economic Development Zone). Economic incentive mechanisms should be, implemented, including tiered water pricing with punitive tariffs and elevated water resource taxes imposed on enterprises that exceed quotas. Industrial park should be optimized through the development of park-wide reclaimed water systems (e.g., Jiangbei New Area Project), enabling cascading water reuse among enterprises through intensive resource management. (4) Innovative policy and regulatory mechanisms: precision industrial supervision should be ensured by requiring the installation of real-time online monitoring devices, with data directly linked to

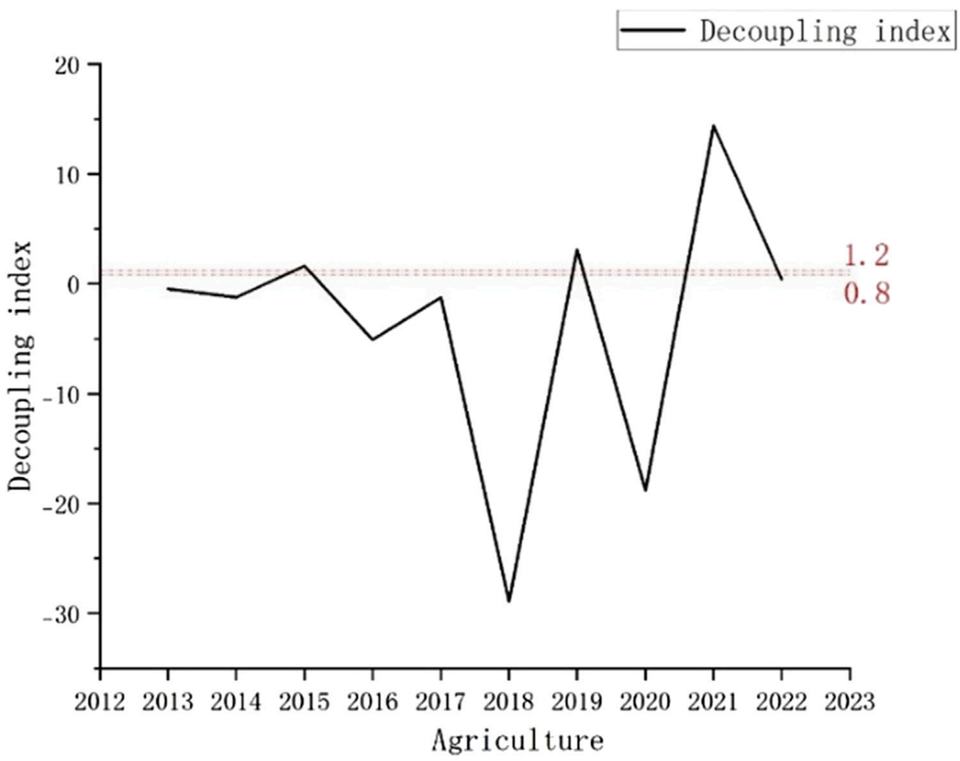

FIGURE 6
Changes in the decoupling relationship between the ecological footprint of water resources and economic development in agricultural sectors, 2013–2022.

environmental protection agencies. Stringent penalties should be applied for data fraud (e.g., automatic fines triggered by abnormal discharge data patterns); inter-departmental coordination mechanisms should be established (e.g., joint Water Affairs Bureau/Agriculture Bureau initiatives) to develop spatially differentiated management protocols like Nanjing's *"Three-Zone Water Resource Management System"* (red/yellow/blue zoning), under which strict location restrictions are imposed on water-intensive projects.

4 Conclusion

This article pays attention to the pressure caused by water resource consumption on human social production and life. Based on the water resource bulletin and socio-economic statistical data, the water resource ecological footprint and water carrying capacity of Nanjing from 2013 to 2022 are calculated using the theory and method of the water footprint. The relationship between the water resource ecological footprint and economic development is analyzed using the Tapio decoupling model to reveal the balance between water resource utilization and economic development. The following conclusions are drawn: (1) the water footprint of Nanjing shows a downward trend, continuously tending toward a positive development, which is essential for the sustainable utilization of water resources. However, the water consumption was mainly for industrial and agricultural uses, indicating that the allocation of water resources was not sufficiently reasonable. This must be closely related to the structure of industry in Nanjing. The next step should be industries' cooperation to improve the efficiency of the water use. (2) The *per capita* ecological carrying capacity of water resources and the *per capita* ecological deficit in Nanjing have shown a continuous trend of improvement. Nevertheless, the average *per capita* ecological deficit in Nanjing for many years was –0.53 hm^2/person, and the average ecological pressure index of water resources was 4.54, far more than 1, suggesting an imbalance between water supply and demand. As a large city, Nanjing has experienced rapid economic development, a large population, and large water resource consumption. Government should strengthen water resource management, advocate for water conservation, increase investment in science and technology, and gradually promote ecological restoration. (3) According to the analysis of the decoupling between the ecological footprint of water resources and economic development, the decoupling rate is 100%, and strong decoupling is 60%. All in all, it developed coordinately, providing a relatively environmentally friendly and stable support for future economic development. (4) Compared to the water consumption of the industrial and agricultural sectors, the dependence of industrial development on water resources is still evident. The Nanjing government should actively adjust and improve its industrial structure, enhance the efficiency of water resource utilization and the development of a green economy, address excessive consumption of water resources in industrial production, gradually achieve a strong decoupling between water resource utilization and economic growth, and contribute to sustainable socio-economic development. As a result, we still need to accelerate the environmentally friendly upgrading of industrial structures and the improvement of the water environment.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding author.

Author contributions

XQ: Writing – original draft, Writing – review and editing, Data curation, Formal analysis, Investigation. SH: Formal analysis, Methodology, Project administration, Resources, Writing – review and editing.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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