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Research article

Composite water value: A way forward to balance the development and protection of transboundary lakes

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ABSTRACT

Transboundary lakes are shared by multiple administrative regions. The key to balance the development and protection of transboundary lakes is to properly measure the value of water resources. Most of previous studies on the measurement of lake water resources value have not fully considered the ecosystem service function. This paper proposes a new concept “composite water value” to measure the value of transboundary lakes by integrating the external runoff value and the internal runoff value of water resources. The study constructs a composite water value measurement system for transboundary lakes, further analyzes its influencing factors,and applies the system to the case of Nansi Lake, a representative transboundary lake in eastern China. The results show that: (1) The composite water value of lakes is influenced by various factors, including industrial structure, water withdrawal, and water use methods, which impact the external runoff water value; meanwhile, the composite water quality and fluctuations in lake level are closely associated with the internal runoff water value. From 2008 to 2021, the average annual composite water value of Nansi Lake was 39.628 billion yuan, exhibiting a "rising-falling-fluctuating rising" trend due to pollution control policies, reduced precipitation, and enhanced water-saving technologies successively. (2) From a long-term perspective, it is necessary to focus on the internal runoff water use value of lakes. The internal runoff water value of Nansi Lake has been over 75% of the composite water value, and flood storage and water conservation are important manifestations of its ecosystem service value. (3) The external runoff water value of lake is closely related to the internal runoff water value, and relevant departments need to consider the balance between the water withdrawal of multiple cities along the lake and the retained water volume of the lake to achieve the maximum benefit of composite water value.

1. Introduction

Lakes are an essential part of the earth’s water cycle and, more broadly, the global ecosystem’s material cycle. As a space for water and air exchange between urban areas and the nature, lakes facilitate water storage and supply, climate regulation, biodiversity maintenance, etc. (Zhu et al., 2024; Spence D S et al., 2023). Since the 1980s, lake ecosystems have deteriorated, due to rapid economic development and global climate change, posing a prominent challenge for countries all over the world (Xu et al., 2023). The United Nations World Water Development Report 2021 highlights that water resources are often undervalued or wasted because we tend to focus only on their direct economic costs, overlooking their enormous value that is hard to be measured in monetary terms (UN-Water, 2021). The underestimation of the value of lakes also leads to short-sighted behaviors such as excessive extraction and pollution, resulting in severe damages to the natural structure and function of lakes. Consequently, the livelihoods and production activities become unsustainable in the communities dependent on lake resources, forming a vicious circle of ecological destruction and economic decline (Wen et al., 2021). Transboundary lakes, due to their geographic locations and cross-border interests, often involve more complicated issues and hence pose more serious challenges.

Measuring water value of transboundary lakes is critical to connecting water governance and regulation with water ecological protection and restoration, which has long been an international concern (Khajebelagh N R et al., 2022). However, the current mainstream methods for measuring water value focus on economic value, leading to the underestimation of lake water value. Therefore, the waste or

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shortage of water resources remains difficult to be corrected through water prices. In addition, the economic value does not fully reflect the comprehensive impact of water resources on the society and environment, resulting in frequent inter-regional water resources conflicts and the destruction of lake water ecology (Handmaker O et al., 2021). It is thus important to improve the methods of measuring water value especially in the presence of transboundary lakes. Leading scholars have also highlighted the importance of reassessing the value of water and integrating different values of water and their trade-offs into decision-making processes, which is essential for achieving sustainable and equitable water resource management (Garrick E D et al., 2017; Nature, 2021). Therefore, establishing a comprehensive assessment system for lake water value is crucial to identify all the benefits of transboundary lakes, and to provide data support for to balancing the development and protection of lake water resources.

2. Development of lake water value theory

The measurement of the value of water in early times mainly focused on the economic value of water resources and often regarded water as an inexhaustible natural resource (Carson R T and Mitchell R C, 1993). This concept leads to the distortion between supply and demand of water resources. Consequently, the shortage of water resources and the pollution of water environment are increasingly prominent as a global problem (Li et al., 2022a,b; Wang et al., 2022). Therefore, the environmental value of water resources has attracted much attention. The multiple values and complex uncertainty of water environment, the interaction between environmental change and water resources, and the measurement of water environmental value have become important topics. The ecological value theory based on natural resources has emerged (Li et al., 1999). The theory argues that water resources not only have consumption value, but also ecological value, which is an important factor for sustainable ecological and economic development (Pakalniete K et al., 2021; Yuan et al., 2024). However, the theory still stands on the productive and economic foundation, with water as only a means of production.

In practice, in 1975, there occurred a serious conflict between Los Angeles water use and Mono Lake ecological protection, that is, the well-known Mono Lake case. In this case, the courts and administrative agencies fully recognized the value of "internal runoff water" of lakes, and considered environmental value of lakes (Wang, 2016).Since then, people have increasingly shifted their awareness of lake water value from a single dimension to a comprehensive of ecosystem (Guo et al., 2021; Sabater S et al., 2021). The key to the comprehensive value assessment is to explicitly measure the value of "internal runoff water", which was overlooked and underestimated. In 1997, Costanza et al. studied the concept of "Ecosystem Services" and defined it as various products and services obtained directly or indirectly by human beings from the ecosystem (Costanza R et al., 1997). Ouyang et al. proposed the concept of Gross Ecosystem Product, which can monetize various ecosystem services (Ouyang et al., 2013). the United Nations proposed the Millennium Ecosystem Assessment Framework by in 2000 to quantify the water value of rivers and lakes from the ecosystems perspective (MEA, 2000; Gou et al., 2021). This method provides a theoretical basis for measuring the service value of lake water resources ecosystem, and also provides a scientific basis for the allocation of common resources, the payment of ecological services and the compensation of ecological value (Sterner W R et al., 2020). Therefore, incorporating ecosystem service value into lake water value is important to cope with long-term water security challenges.

To sum up, the current studies on lake water value mostly focus on quantitative analysis of the economic value of lakes and wetlands, and do not fully consider the ecosystem service, and rarely explores the correlation between the economic value and the ecological value of lake water resources. This paper proposes a theoretical framework to conceptualize the composite water value of transboundary lakes by considering the external runoff and internal runoff water value, and constructs an effective measurement system of composite water value of transboundary lakes from an Ecosystem Services perspective.

3. Framework and methods

3.1. Theoretical framework of composite water value of transboundary lakes

Consumptive water use typically requires separating water resources from waterways, groundwater, or other water sources, which is referred to the "external runoff use mode ". However, the flow of water resources in waterways, streams or lakes not only ensures water quality, but also improve their recreational, aesthetic and ecological value. The way of keeping water resources in waters is known as the "internal runoff use mode". While the "external runoff water" of lakes is indispensable for human life and economic development, the "internal runoff water" is crucial for ecological and environmental protection. How to optimally balance water use "between internal and external" requires a full understanding of all the benefits that humans derive from lakes. This paper proposes a theoretical framework of the composite water value of transboundary lakes (Fig. 1), which is divided into external runoff water value and internal runoff water value. The water value of external runoff is mainly reflected by the economic value of water used for production, household and ecological purposes, while the water value of internal runoff mainly refers to the value of ecosystem services generated by lake water, including ecological and cultural value. The core is to conduct a comprehensive benefit assessment on the composite value of transboundary lake water resources, including key indicators and driving factors. This approach aims to promote optimal allocation of lake water resources by integrating the water value of external runoff and the water value of internal runoff.

3.2. Case study

Nansi Lake is the largest freshwater lake in northern China and one of the most important transboundary lakes in China. It consists of four connected lakes: Weishan, Zhaoyang, Dushan and Nanyang (Fig. 2). The lake is located in the plain area of the Yangtze River at the junction of Shandong and Jiangsu provinces in China. The lake is an important water source for industrial production and ecosystems in coastal areas. It also facilitates water supply and serves as a storage reservoir for the South-to-North Water Diversion project. There are abundant natural resources, and the region is dominated by fishing and industry and agriculture. Nansi Lake plays an important strategic role in promoting regional economic development and maintaining regional ecosystems.

However, the use of water resources in Nansi Lake has had problems for a long time. Without enough awareness of the value of the ecosystem, people discharge wastewater from agricultural and industrial production to the lakes, which deteriorate water quality and damage the water ecological environment. This in turn has negative impacts on local social and economic development (Feng et al., 2022). The unclear rights, responsibilities and interests across multiple regions is the source of cross-border conflicts in relation to water resources allocation (Zhang et al., 2023). Due to the particularity of the geographical location and the typicality of water problems, the management and protection of water resources in Nansi Lake have attracted wide attention in recent years. Therefore, this paper takes Nansi Lake as an example to construct a composite water value measurement method for transboundary lakes, which provides a basis for the optimal allocation of transboundary lake water resources and provides a reference for the management of other lakes.

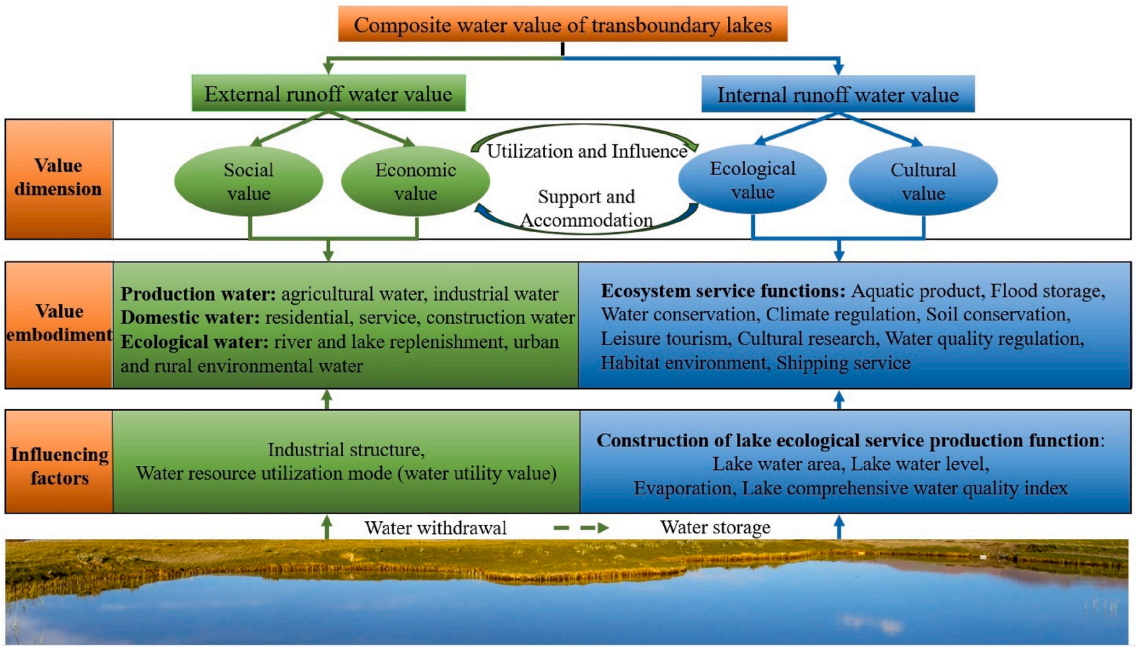

Fig. 1. Theoretical framework of composite water value of transboundary lakes.

Fig. 2. Water area diagram of Nansi Lake.

3.3. Construction of composite water value measurement system for transboundary lakes

Currently, the measurement of the transboundary lake water resources value focuses on two aspects. One is to use economic methods to measure the economic value of water resources itself, reflecting the utility that water brings to users (Buttinelli R et al., 2024; Yu et al., 2023); the other is to use geographical methods to measure the ecosystem service value of lake wetlands (Liu et al., 2023; Long et al., 2022). This paper uses the residual value method, benefit allocation coefficient method, and function value method to calculate the value of outflow water use and inflow water use of lakes. The measurement of the value of outflow water use is based on the principle of contribution allocation of production factors and uses an improved benefit allocation coefficient method to allocate benefits according to the proportion of production factor contributions. The agricultural irrigation benefit allocation coefficient is determined using the residual value method, and the supply benefit allocation coefficient for other water activities is determined using the total added value of industrial profits and costs. The advantage of this method is that it can distinguish the differences and causes of the water use mode and water efficiency of urban economic development in lake areas and provide scientific basis for efficient water resources allocation. The value of inflow water use is calculated from the ecological function volume and ecological economic value volume using the function value method. The function value method emphasizes service functions, considering not only the material products provided by ecosystems but also the value of regulating services (such as climate regulation and water source recharge) and cultural services (such as leisure and tourism, aesthetic experience). The advantage of this method is that it can simulate the monetary value of ecosystem functions and quality of goods through the production equation, and convert the monetary value of different ecosystem goods into monetary value based on the shadow engineering method, alternative cost method, etc., so that these services can be compared with the value generated by traditional economic activities, thereby enhancing the importance of ecosystem services in economic decision-making(Ouyang et al., 2013).

This paper selects a set of key indicators for composite water value of transboundary lakes, and constructs the measurement system (Table 1). The formula of composite water value of transboundary lakes is:

$$CWV = \sum^{n} {}_{i}V_i \ (i = 1, 2, 3\ldots, n = 13) \quad (1)$$

Where CWV represents the composite water value of transboundary lakes, V_i represents the value of three industries of major cities and the value of ten ecosystem services of lakes.

After calculating the external runoff water value of the three industries in the upper and lower reaches of the transboundary lake basin, the total external runoff water value of the transboundary lake can be derived as follows:

$$LERV = \sum_{i}^{n} (v_{ij}Q_{ij}) \ (i = 1, 2, 3, j = 1, 2, 3\ldots, n = 3) \quad (2)$$

Where $LERV$ represents the total water value of external runoff, v_{ij} represents the water utility coefficient of industry i in city j, and Q_{ij} represents the external runoff consumption of industry i in city j. The plant industry in the primary industry accounts for a large proportion of water, and its water utility coefficient is calculated in the residual value method as follows:

$$v_{1j} = \left[YP_a - \sum_{i} (P_iM_i) \right] \Big/ W_1 \ \ (i = 1, 2, 3\ldots) \quad (3)$$

Where Y represents the total output of planting industry, P_a represents the market price of output crops, M_i represents the input number of different factors of agricultural crops, P_i represents the market price of input factors, and W_1 represents the area irrigation water.

The water utility coefficient of the second and third industries is calculated by the benefit allocation coefficient method as follows:

$$v_{2j} = \sum_{i} (B_i\varepsilon_i + C_i) / W_2 \ \ (i = 1, 2, 3\ldots) \quad (4)$$

$$v_{3j} = \sum_{i} (B_i\varepsilon_i + C_i) / W_3 \ \ (i = 1, 2, 3\ldots) \quad (5)$$

Where v_{2j} and v_{3j} represent the water utility coefficients of the second and third industries in city j respectively, B_i represents the total profit and tax of various industries, ε_i represents the benefit allocation coefficient of water use in various industries, C_i represents the cost of water elements in various industries, W_2 and W_3 represent the total water use in the second and third industries respectively.

In addition, this paper construct lake ecoservice production function (LEPF) (Liu and Xu, 2023; Von Haefen R H et al., 2023) to analyze the contribution of different driving factors. The formula is:

$$LIRV = F(A_t, B_t, \Gamma_t, \Delta_t) = A_t^{\alpha} B_t^{\beta} \Gamma_t^{\gamma} \Delta_t^{\delta} e^{c} \quad (6)$$

Where, $LIRV$ is the water value of internal runoff in the lake, and A, B, Γ, Δ respectively represent the four influencing factors of lake water area, lake water level, evaporation and composite water quality index of the lake, and α, β, γ, δ respectively represent the relative yield elasticity coefficient of the four influencing factors, c represents the constant of ecological service level, and t represents years.

Table 1
Measurement system and measurement method of composite water value of transboundary lakes.

Composite water value	Key indicator	Evaluation formula	Measuring method
External runoff water value	Primary industry	V_1 = water utility coefficient of primary industry × external runoff consumption of primary industry	Residual value method (Matey H I and Garcia R L, 2023)
	Secondary industry	V_2 = water utility coefficient of secondary industry × external runoff consumption of secondary industry	Benefit allocation coefficient method (Li et al., 2020)
	Tertiary industry	V_3 = water utility coefficient of the tertiary industry × external runoff consumption of tertiary industry	Benefit allocation coefficient method
Internal runoff water value	Aquatic product	V_4 = aquatic product output x market price	Market value method (Li et al., 2023)
	Water quality regulation	V_5 = sewage intake × treatment cost	Shadow engineering method (Li et al., 2022a,b)
	Soil conservation	V_6 = wetland area × medium erosion depth of non-vegetated soil × soil capacity × average soil nutrient content × average fertilizer price	Alternative cost method (Li and Shi, 2024)
	Climate regulation	V_7 = carbon sequestration value + oxygen release value	Shadow engineering method
	Flood storage	V_8 = flood storage quantity × unit storage capacity cost	Shadow engineering method
	Water conservation	V_9 = water conservation quantity × unit storage cost	Shadow engineering method
	Habitat environment	V_{10} = wetland area × wetland function and natural capital value per unit area	Ecological value method (Zhang et al., 2023a)
	Shipping service	V_{11} = freight volume × market price	Shadow engineering method
	Leisure tourism	V_{12} = total number of natural landscape tourists × per capita consumption	Usage of tourism fee (He et al., 2023)
	Cultural research	V_{13} = wetland area × average research value of ecosystem	Shadow engineering method

4. Results

4.1. Changes of composite water value in Nansi Lake

The constructed transboundary lake composite water value measurement system is applied to the assessment of the composite water value of Nansi Lake. Fig. 3 presents the composite water value for Nansi Lake over 14 years from 2008 to 2021.

The composite water value in Nansi Lake increases from 35.760 billion yuan in 2008 to 43.771 billion yuan in 2021, with an annual average of 39.628 billion yuan. The average annual internal runoff water value accounted for more than 75% of the composite water value. In the early stage from 2008 to 2013, the composite water value of Nansi Lake continued to increase. This is mainly because in 2003, Nansi Lake was planned as an important storage reservoir and water transmission channel for the eastern route of the national South-to-North Water Diversion project. After that, Jiangsu and Shandong provinces significantly reduced pollution. In 2011, with the implementation of the 12th Five-Year Plan, the economy recovered from the negative impact of the global financial crisis. The water value of external runoff of the Nansi Lake increased significantly. because of the government promoted the development mode of "low consumption", "low emission" and "high efficiency" (Liu et al., 2020). In 2013, before the east Route of the South-to-North Water Diversion Project went into operation, the ecological and environmental quality of the Nansi Lake had generally recovered to the level of the mid-1980s, indicating that the improvement of water quality had a positive effect on the composite water value of the lake. Over the period from 2013 to 2015, the composite water value of Nansi Lake decreased. In 2014, precipitation in the Nansi Lake fell dramatically, and the lake nearly dried up. The ecosystem services were affected, the climate regulation function was weakened, the survival and reproduction of aquatic and wetland organisms were threatened, biodiversity was damaged, and water withdrawal for regional industrial and agricultural production was limited. In the third stage, from 2015 to 2021, the water value of external runoff and internal runoff recovered and remained stable. With the implementation of the river chief system, the secondary industry, especially highly polluting companies, was closely monitored. Heavily polluting industrial enterprises were constrained or even shut down. In addition, the progress of water-saving technology improves the utilization efficiency of water resources. On the one hand, it reduces the use cost of water resources and improves the economic benefits of water resources. On the other hand, it reduces the water consumption, thereby indirectly reducing the discharge of wastewater generated by agricultural and industrial activities, reducing the pollution load of lake water bodies and improving the environmental value of water resources. And the government carried out large-scale water management measures to reduce the dependence of lake water on natural factors such as precipitation. The use of wetlands in Nansi Lake has changed from seasonal water to permanent water (Jean-François P et al., 2016). It also suggests that the water supply from the east route of the South-to-North Water diversion project is sufficient to maintain the stability of the water distribution of the lake.

In addition, the external and internal runoff water use results in various goals. This will create positive feedback (support and accommodation) and negative feedback (utilization and influence) between the two uses of lake water resources. The positive interaction between internal and external runoff is the key to promote the coordinated development of lakes. Therefore, the water value of external runoff and internal runoff is worth more attention.

4.2. Changes in external runoff water value in Nansi Lake

Lake water resources can promote regional economic development. Based on the data of main stakeholders in the upper and lower reaches of the Nansi Lake, combined with the water consumption data of each city and major industries, this paper uses the benefit allocation coefficient method and the residual value method to estimate the total water value of external runoff of the three major industries in Xuzhou City and Jining City according to the proportion of water consumption of each industry.

Fig. 4 shows that there are multiple uses of external runoff water in Nansi Lake, and its value differs significantly across regions. The water value in Xuzhou City is relatively low, increasing from 1.163 billion yuan in 2008 to 3.3 billion yuan in 2021, while the water value in Jining city is higher, with 2.666 billion yuan in 2008 and 7.277 billion yuan in 2021. The difference is related to the industrial structure, water withdrawal and water resources utilization mode in different regions.

Fig. 5 shows that the annual external runoff water value of Nansi Lake in the primary industry accounted for about 80% in Xuzhou and about 90% in Jining. This indicates that the water withdrawn from Nansi Lake played a more important role in the primary industry of the two cities, but the industrial added value accounted for less than 15%. This is related to the characteristics of crops. characteristics of crops and high-water consumption characteristics. In terms of the water utility coefficient, the average water utility coefficient of the primary industry in Xuzhou and Jining from 2008 to 2021 is 4.96 and 8.52 respectively. The agricultural production in Xuzhou is dominated by grain crops such as wheat and corn, and has a large demand for irrigation water. By contrast, the agricultural production in Jining is dominated by cash crops such as rice and cotton, and the output value of agricultural water is relatively high. However, the dependence on water resource demand is still large, and the increasing trend of water utility coefficient indicates that the agricultural water use efficiency in both cities is

Fig. 3. Composite water value in Nansi Lake during 2008–2021.

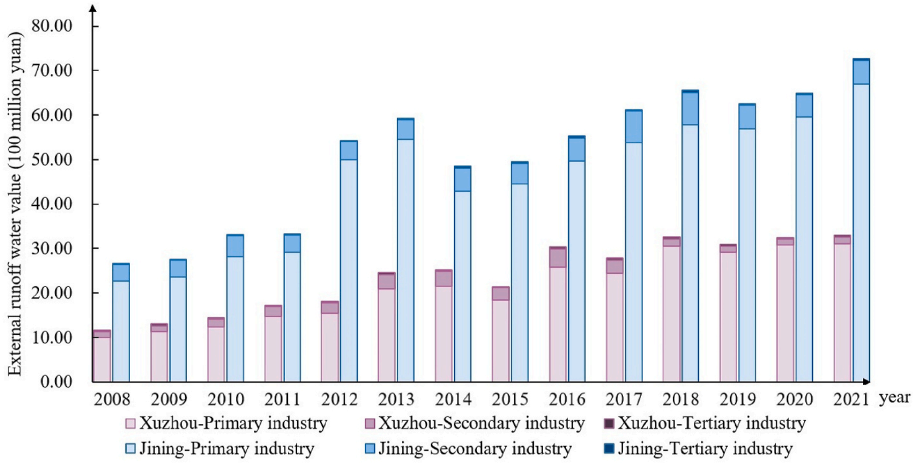

Fig. 4. Value of external runoff water of Nansi Lake in three industries of Xuzhou and Jining during 2008–2021.

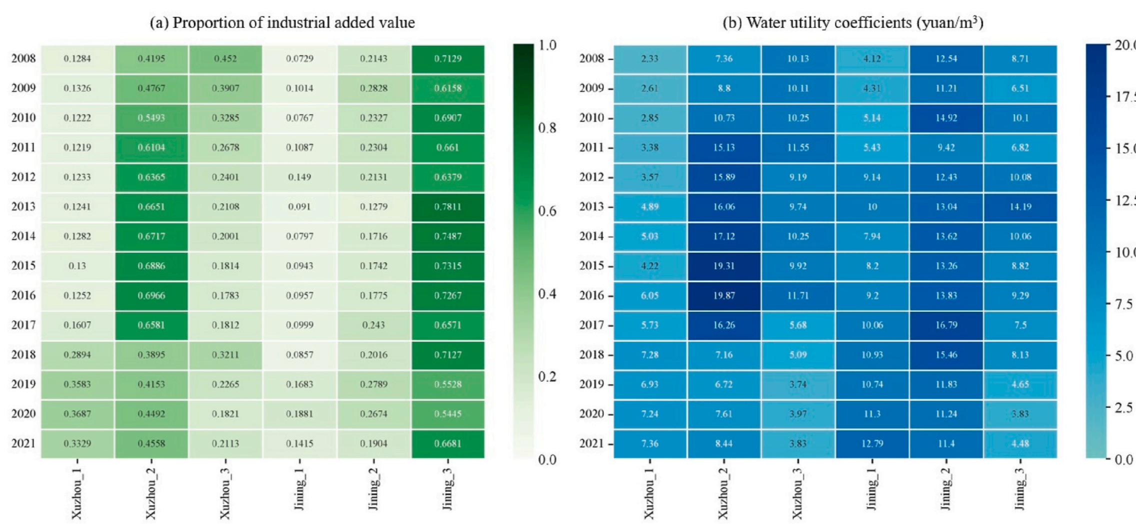

Fig. 5. Changes of influencing factors of external runoff water value in three industries in Xuzhou and Jining during 2008–2021.

increasing over time.

In the secondary industry, the external runoff water value of Nansi Lake experienced fluctuations – first increasing and then decreasing. As ahistorical industrial base, the total profits and taxes of the secondary industry in Xuzhou account for a large proportion. In March 2008, the State Council of China identified the first batch of resource-exhausted cities, including Xuzhou. Jiangsu Government issued the " Accelerating the Revitalization of Xuzhou Old Industrial Base", Xuzhou's transformation kicked off. In recent years, Jining City has implemented the development strategy of manufacturing orientation, and aimed to foster advanced manufacturing industry clusters. In 2018, in order to accelerate the industrial transformation, the governments tightened the control of high-pollution, high-energy consumption and high-emission industries. Consequently, the water value and water utility coefficient of external runoff were significantly reduced. In addition, the average water utility coefficient of Jining's secondary industry is 12.93, slightly higher than that of Xuzhou's 12.61, thanks to abundant water resources in Jining. Due to its geographical advantage, Jining draws more water from Nansi Lake than Xuzhou, which is partly attributable to the higher water value of external runoff water in the primary and secondary industries.

For the tertiary industry, the proportion of the tertiary industry in both cities recently has declined due to the COVID impact. The total profit and tax of Xuzhou city is lower than that of Jining City, but the water value of the tertiary industry Nansi Lake external runoff is similar. The reason is that the proportion of high-tech industry in Xuzhou City is larger, and the average water utility coefficient of 8.23 is higher. Xuzhou focuses more on innovation, green development, high-end intelligence. In Jining City, the proportion of catering service industry is large, and the average water use efficiency of 8.08 is relatively low. The city focuses more on cultural tourism and modern services.

In summary, the total water value of external runoff in the composite water value of Nansi Lake differs between Xuzhou City and Jining city, which is attributed to the industrial structure, water withdrawal and water resource utilization mode. Therefore, those factors should be fully considered when allocating water resources in Nansi Lake. It is also important to strengthen the coordination between the two regions to promote the protection and utilization of water resources in the Nansi Lake.

4.3. *Changes in internal runoff water value of Nansi Lake*

Lake internal runoff water is an important factor to maintain lake ecosystem. Based on the GEP accounting system, this paper evaluates the quality of ecosystem services in Nansi Lake and measures the total value of internal runoff water. The total value of internal runoff water in Nansi Lake from 2008 to 2021 ranges from 30.915 to 32.823 billion yuan/year, with an average annual value of 31.847 billion yuan, and the average annual ecosystem service value coefficient is 2.52×10^7 yuan/hm^2. It was much higher than the average ecological service value per unit area of the world (6.914×10^3 yuan/hm^2) and China (5.831×10^3 yuan/hm^2) (State Environmental Protection Administration, 1997). The average value of various services in the lake ecosystem of Nansi Lake is shown in Fig. 6, in which flood storage and water conservation dominate others, accounting for 45.90% and 29.97% of the ecosystem service value, respectively. The average annual ecosystem service value coefficients are 1.15×10^7 and 7.54×10^6 yuan/hm^2, respectively. Therefore, ensuring adequate water supply is the key to maintaining the ecosystem service function of Nansi Lake. This result is consistent with the role of Nansi Lake as an important water storage of Shandong Province and the eastern route of China's South-to-North Water Diversion project, indicating that Nansi Lake plays an important role in climate regulation, soil conservation and aquatic product breeding.

This paper conducts a regression analysis. The water value of internal runoff and influencing factors in Nansi Lake were substituted into the LEPF. The ecological service production function of Nansi Lake from 2008 to 2021 was calculated as follows:

$$LIRV = F(\mathrm{A}_t, \mathrm{B}_t, \Gamma_t, \Delta_t) = \mathrm{A}_t^{0.02797}\mathrm{B}_t^{0.36496}\Gamma_t^{\gamma 0.25081}\Delta_t^{0.67272}e^{1.52518} \tag{7}$$

The composite water quality index of lakes and lake water level are closely related to the water value of internal runoff of Nansi Lake and are positively correlated. During the "12th Five-Year Plan" period (2011–2015), the composite lake water quality index of Nansi Lake gradually improved due to the upgrade of industrial structure. Since 2016, thanks to the implementation of the River Chief System, the water quality has gradually improved, which facilitated sustainable development of the water value of internal runoff in the lake.

Fig. 7 shows that from 2008 to 2013, the water level of Nansi Lake remained at a high level, and the water value of internal runoff in the lake was relatively stable. From 2013 to 2015, In Shandong Province, the drought persisted, and the South-to-North Water Diversion project diverted water from the Yangtze River to the Nansi Lake. The water value of internal runoff in the lakes fluctuated at a low level, and its change was lagging behind the water level. From 2015 to 2021, as the amount of water used by the cities along the Nansi Lake increases, the amount of retained water in the lake decreases, so the water value of internal runoff in the Nansi Lake decreases. Thanks to the east Route of the South-to-North Water Diversion project, the water level of the Nansi Lake gradually rises, and the water value of internal runoff in the lake also returns to a high level. In addition, when the water quality of the runoff in the lake is improved and the amount of water is abundant, it will have a chain reaction on the water withdrawal and economic development of wetlands, rivers and other ecosystems connected to the lake as well as surrounding cities, such as changing the water quality and hydrodynamic characteristics of the lake, positively affecting the biodiversity and ecological balance in the lake, and increasing the area of wetlands around the lake, and providing more living, breeding environment and food resources makes the wetland ecosystem more abundant, and may also change the interaction between the lake and the surrounding land, thus affecting vegetation growth and soil quality, and increasing its water value. On the contrary, if there are problems in the internal runoff, such as the deterioration of water quality and the reduction of water volume, it will also have a negative impact on the external runoff. In short, a higher water level is not necessarily better. The optimal water level of the Nansi Lake still needs to be identified through longer time of monitoring and observation.

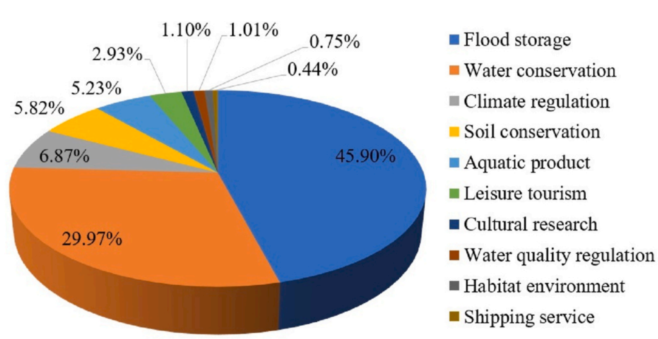

Fig. 6. The average value of each service function in the lake ecosystem of Nansi Lake during 2008–2021.

To sum up, Nansi Lake provides important ecosystem services function, and the water value of internal runoff in the lake can be quantified by assessing the ecosystem service value. the lake water quality index and lake water level have a close and positive correlation with the water value of internal runoff in Nansi Lake. Therefore, it is important to fully consider the composite value and multiple functions of Nansi Lake, formulate scientific and reasonable management policies and measures, and balance the allocation of external runoff water and internal runoff water consumption.

5. Discussion

5.1. Theoretical contribution

Among the United Nations Sustainable Development Goals (UN SDGs), SDG 6 and SDG 15 are respectively "Clean water and sanitation" and "Life on land", which provide important guidance for the development and protection of transboundary lakes (Ghulam M et al., 2024; Huan and Zhu, 2022). With economic development, water resources have become increasingly important (Le P V, 2023; Das S et al., 2023). As an important freshwater resource connecting multiple regions and an important part of the ecosystem, cross-border lakes directly contribute to the quality of life and the regional economic development. Also, the ecosystems of transboundary lakes directly affect the terrestrial ecosystem. Thus, how to evaluate the water value scientifically, and to achieve the sustainable development of the ecology, economy and society is an urgent problem.

The current assessment on the value of lake water resources does not fully consider the social and economic benefits generated by the external runoff water and the ecosystem service benefits generated by the internal runoff. The comprehensive and quantitative measurement of the composite water value of transboundary lakes will help to better manage and utilize water resources and achieve sustainable development. Therefore, this study proposes a theoretical framework of the composite water value of transboundary lakes. From the ES perspective, the study constructed the composite water value measurement system by considering the external runoff water value and internal runoff water value of lakes, in the residual value method, benefit allocation coefficient method and GEP accounting system and integrating multiple attribute indicators. The study further applied the composite water value measurement to the case of Nansi Lake.

The framework goes beyond the traditional literature focusing only on the economic value of water resources and divides the value of water resources into different components. This division helps us further understand the value of water resources and consider the balance of multiple values in water resources management and policy design. The study emphasizes the value of ecosystem services, aiming to raise public awareness of the value of water resources, reduce the waste of water resources, and better protect the ecosystems of transboundary lakes (Nakiyende H et al., 2023). Moreover, since transboundary lakes involve multiple regions or countries, their management and protection require cooperation among all parties. The theoretical framework of composite water value for transboundary lakes can help promote cooperation among all parties, and provides theoretical support for policy formulation to achieve sustainable development of lakes.

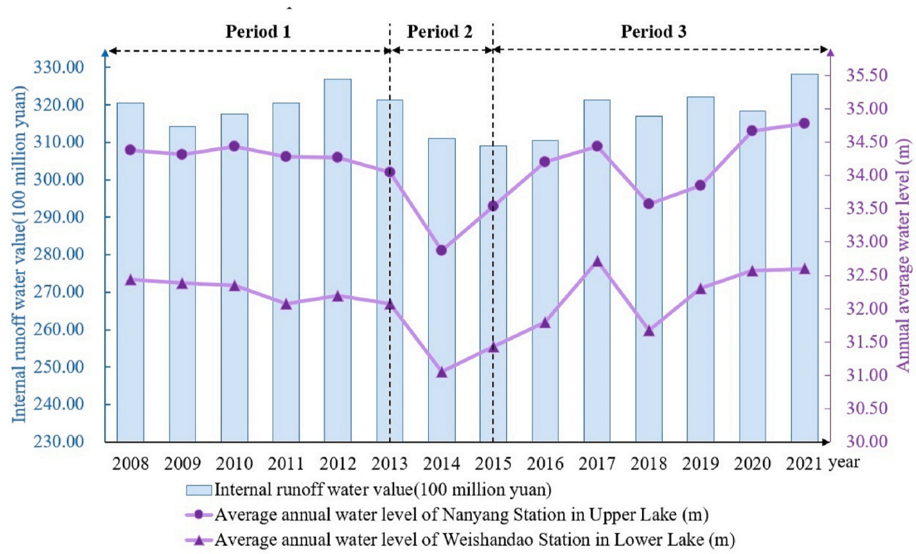

Fig. 7. Variation trend of total water value of internal runoff and water level in Nansi Lake.

5.2. Policy suggestions

This paper makes the following suggestions for improving the composite water value of lakes and optimizing the allocation of water resources:

First, the benefits of external runoff water and internal runoff water depend on the sustainable economic development and the improvement of water environment quality, so it is important to consider the relationship between urban water use and lake composite water value, and establish a demand-side model. and adopt a scientific and reasonable management system to develop and utilize water resources and reform planning for flood prevention and control under the premise of ensuring the basic ecological water demand of the lake, so as to guide the effective operation of the reservoir more scientifically. Reasonable allocation should be made according to the water balance of the lake, seasonal changes and other factors, so as to ensure the effective utilization of the water resources of the upstream and downstream stakeholders of the transboundary lake, meet the needs of economic development, and take into account the factors affecting the water value of internal runoff in the lake, so as to realize the balanced allocation and coordination of the external runoff water and the internal runoff water.

Second, it is also important to upgrade the industrial structure and promote water-saving to improve the water value of external runoff. According to the characteristics of the economic development of cities that draw water from lakes, the internal causes of changes in the water utility coefficient of different industries are analyzed. The government can realize the green development model by formulating industrial policies conducive to economic transformation and upgrading, increasing investment in research and development, and vigorously developing industrial enterprises with low pollution, low energy consumption and high efficiency. At the same time, formulate water-saving development plans, implement classified pricing policies according to the use, quality and regional differences of water resources, ensure that water prices can reflect the scarcity and value of water resources, promote water-saving technologies such as reclaimed water reuse and rainwater collection, put forward water-saving goals, tasks and measures, and promote enterprises to strengthen water-saving work. In addition, supervision and law enforcement should be strengthened, enterprises that violate industrial policies and water-saving regulations should be punished according to law, an effective restriction mechanism should be formed, and publicity and education on the composite value of water resources should be strengthened to improve the public's understanding of the composite value of water resources.

Third, water environment protection needs to be strengthened. The change of water quality of transboundary lakes is heavily driven by sewage discharge from surrounding cities and economic benefits of aquaculture. The River Chief System can be further implemented in the Nansi Lake to control water pollution, and improve pollution treatment efficiency. Establish a monitoring system for lake water level and water quality to monitor lake conditions in real time. Through data analysis, the fluctuation of water level is controlled within a reasonable range to avoid the negative impact of too high or too low water level on the lake ecosystem and water resources utilization. In dry season and wet season, according to the water demand in the lake internal runoff, relying on the South-to-North Water diversion project to adjust the water quantity, not only meet the production and life needs, but also maintain the stability of the lake ecosystem and biodiversity, and maintain the self-purification capacity of the lake.

5.3. Limitations and future research directions

The accuracy and reliability of the assessment depends on data availability and quality. Transboundary lakes differ in sizes, types and regions, so it is costly in terms of both money and time to collect the data. For example, the data on fish catch and reed production are missing, and their ecosystem service value is not included. Therefore, this paper cannot cover all factors but focus on key factors. In addition, there are not many quantitative studies on the composite water value of transboundary lakes, so this study is an attempt of quantitative contributions. The assessment system for the composite water value of transboundary lakes can be improved in the future.

The future research will focus on two aspects. First, more lakes will be selected for case studies, such as Poyang Lake and Taihu Lake, so we can further verify the assessment method in the presence of different types of lakes. Second, the results of the composite water value of transboundary lakes will be used to guide the allocation of water resources in transboundary lakes, including water allocation, water quality protection, and ecological flows.

6. Conclusions

This paper proposed a theoretical framework to measure the composite water value of transboundary lakes, including both the external and internal runoff water value of lake water resources. The study constructed the measurement system of composite water value of transboundary lakes based on multiple uses of lake water resources and ecosystem services, and applied the system to on the case of Nansi Lake – a representative transboundary lake in eastern China.

There are several main results. First, the composite water value of transboundary lakes depends on multiple internal and external factors. The composite water value in Nansi Lake increased from 36.178 billion yuan to 40.83 billion yuan, and decreased afterward until 38.222 billion yuan, and then increased again after 43.771 billion yuan, with an annual average value of 39.628 billion yuan over the period of 2008–2021. The water value of external runoff differs across cities, which is related to different industrial structure, water withdrawal and water resources use. Among the10 types of ecosystem services of internal runoff water value in Nansi Lake, flood storage and water conservation are two dominant services; Second, the internal runoff value is much higher than the external runoff value. Over the period of 2008–2021, the internal runoff water value in Nansi Lake accounts for more than 75% of the composite water value. So, it is important to consider the ecological benefits of transboundary lakes when making development and protection policies of transboundary lakes. Third, there is a linkage between the external and internal runoff value. The two are linked to each other through material, energy and information flows. Also, the fluctuation of lake composite water quality and water level is closely related to the change of runoff water value in Nansi Lake. To maximize the composite water value, it is important to fully consider the supply and demand of water resources, water quality, and the balance between ecological environment protection and economic development. This linkage can be optimized by strengthening water resources management, promoting water-saving technology and strengthening water quality protection.

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CRediT authorship contribution statement

Gaofeng Liu: Project administration, Methodology, Formal analysis, Conceptualization. **Feifei Li:** Writing – original draft, Data curation. **Lei Qiu:** Investigation. **Huimin Wang:** Supervision, Resources. **Zhou Fang:** Writing – review & editing. **Zhili Xu:** Validation. **Shengqi Yao:** Visualization.

Declaration of competing interest

All authors have no conflicts of interest. On behalf of all authors, the corresponding author declares that there is no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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