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A Spatial Equilibrium Evaluation Method of Water Resource Allocation: Case Study of the South-to-North Water Diversion Project in China

Yuan Liang [a,b,*], **Shaofeng Jia** [a,b], **Zikun Song** [a,b], **Lihua Lan** [a,b]

[a] *Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China*
[b] *College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100190, China*

KEYWORDS

Spatial Equilibrium Evaluation Method;
Water Resource Allocation;
Cost-Benefit Analysis;
Unit Cost of Water Diversion Projects;
South-To-North Water Diversion Project (SNWD)

ABSTRACT

Research on the spatial equilibrium of water resource allocation in China can inform the scientific planning of future water diversion projects, supporting water security and the sustainable development of socio-economic systems. Yet studies on spatial equilibrium remain limited. We developed an evaluation method for spatial equilibrium in water resource allocation and conducted regional validation using the South-to-North Water Diversion (SNWD) project. Based on general and spatial equilibrium theory, spatial equilibrium is defined as the equalisation of marginal benefits of water use when interregional water transfer costs are considered. Regions with higher marginal benefits are mainly located east of the “Hu Huanyong Line”, particularly Shandong, Henan, and Shaanxi. When project information is available, unit water diversion costs can be expressed as a function of delivery distance. Estimated unit costs range from 0.51–3.76 RMB/m³ along the East Route, 0.39–1.49 RMB/m³ along the Mid Route, and 1.80–4.45 RMB/m³ along the West Route. Linking Xuzhou (East Route), Zhengzhou (Mid Route), and Aba Prefecture (West Route) yields a projected spatial equilibrium boundary for eastern China. Further research on marginal benefits, water use costs, and dynamic updates is still needed.

INTRODUCTION

At a global scale, the intertwined impacts of climate change and anthropogenic activities are intensifying pressures on water resources, positioning water scarcity as one of the most critical challenges of the 21st century (Lyu et al., 2024; Rockström et al., 2014). At its core, this challenge stems from a profound mismatch between the inherent spatiotemporal heterogeneity of water resources and the geographical distribution of socio-economic activities (Hoekstra & Mekonnen, 2012). The water governance philosophy of "spatial equilibrium" has been instituted as China's guiding principle for a new era, seeking to foster a harmonious coexistence between water resources, population, economic development, and the environment (Y. Chen et al., 2025; Dong et al., 2025; Li et al., 2025; Lou et al., 2023). The South-to-North Water Diversion (SNWD) project, the world's largest water transfer project, was designed to alleviate severe water shortage and promote sustainable development in northern China (in-

* Corresponding author. E-mail address: liangy.15b@igsnrr.ac.cn

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cluding Beijing City). The impact of the SNWD has been one of the most hotly debated topics for a long time during the planning, design, construction, and operation phases of the project(Liu, 1998; Zhang et al., 2015). Numerous studies of the SNWD mainly focused on its impact on groundwater resources (Liang et al., 2019; Ye et al., 2014), and effect on phytoplankton (Z. Chen et al., 2018; Zeng et al., 2015), as well as the pricing system and water allocation schemes and policies (Du et al., 2019; Pohlner, 2016). However, few studies have discussed the implications of the SNWD for spatial equilibrium in water resource allocation.

The quantitative evaluation of the spatial equilibrium in water resources is still in an exploratory stage (Niu et al., 2022), and a complete and unified evaluation system and the standard have not yet been formed. Flinn and Guise (Flinn & Guise, 1970) developed an interregional equilibrium model to derive the optimal allocation and pricing of regulated supplies of water in a river basin, the quadratic programing model offers a potentially powerful technique for analyzing several problems of water allocation and valuation. As for the equity of water allocation among different regions, Gini coefficient (Dai et al., 2018) and the Moran'I (Tu & Xia, 2008) were also used to analyze the fairness of regional water use. Achieving spatial equilibrium of water resources can be explored from the perspective of limiting water resource development and utilization within the range of water resource carrying capacity(Xia et al., 2025). Bian et al. (2022) created a hybrid model with three stages, utilizing a framework incorporating the composite ecosystem of water-based economies, taking into account water resources and social, economic and natural factors, and conducted a comprehensive quantitative analysis of water resource spatial balance. Zheng et al. (2023) proposed that the water resources spatial equilibrium is a relatively stable equilibrium state for the composite system of water resources, social economy and ecological environment in a certain region, and also reaches equilibrium in the spatial distribution, and proposed a quantitative dynamic evaluation method for the spatial equilibrium degree in system-region two stages. Nevertheless, the spatial equilibrium should be employed to describe the state of water resource allocation, rather than the water resources themselves.

Accurately assessing the economic value of water resources is a prerequisite for conducting spatial equilibrium analysis. Methodologically, the production function approach, mathematical programming, and the benefit attribution method represent three mainstream techniques for estimating the economic value of water (Young et al., 1982). For instance, Peng et al.(2020) developed a computable general equilibrium model for water-receiving areas of water diversion projects, using Beijing as a case study to quantitatively evaluate the socio-economic impacts of such initiatives. In a broader assessment, Yu et al.(2018) adopted an integrated analytical approach to investigate the economic, environmental, and social implications of water transfer projects across China. Notably, the benefit attribution method—also referred to as the residual value method—has been widely applied in evaluating water use benefit at regional and sectoral scales, owing to its straightforward data requirements and computational procedure (Ju et al., 2024). In China, this method has been successfully implemented both at the provincial level (Yin et al., 2020) and within river basin contexts, confirming its validity and applicability. Despite considerable progress, significant knowledge gaps persist in enabling a spatially nuanced equilibrium analysis of water use in China (Ilyas et al., 2021; Ni & Chen, 2024).

Based on cost-benefit analysis, this study developed a spatial equilibrium evaluation method of water resource allocation and attempted regional validation by the SNWD in China. The objectives of this paper are as follows: **1)** to indicate the essence of spatial equilibrium in water resource allocation; **2)** to calculate the marginal benefit of water use across cities; **3)** to derive empirical equations for unit cost of water diversion projects; and **4)** to explore the spatial equilibrium pattern of water resource allocation by taking the SNWD as an example.

MATERIALS AND METHODOLOGY

Spatial Equilibrium Evaluation Method of Water Resource Allocation

According to the equilibrium conditions of the general equilibrium theory and the spatial equilibrium theory, the spatial equilibrium theory of water resources allocation is proposed as: the essence of the spatial equilibrium of water resources allocation is the marginal benefit equilibrium under the condition of considering the cost of water transfer between two places. The marginal benefit of water is determined by the inefficient water users, or in the case of administratively-dominant allocation, it is determined by the main purposes of water transfer. Spatial equilibrium is dynamic, and it is necessary to evaluate the current situation and analyze the future situation. For areas where the equilibrium is not achieved in the evaluation results, it is necessary to improve the efficiency of water resource allocation through water diversion projects.

$$\left(\frac{\partial b}{\partial w}\right) im = \left(\frac{\partial b}{\partial w}\right) ex + c \tag{1}$$

Formula (1) indicates that the marginal benefit of water use in the importing area equals the marginal benefit of water use in the exporting area plus the water transfer cost; b represents the economic benefit of local water use; w denotes water use volume; c signifies the water transfer cost between the receiving and source areas.

Under the condition of spatial equilibrium in water resource allocation, the assessment basis may primarily be expressed as water diversion costs and regional marginal benefits of water use. Should allocation be determined entirely by market forces, consideration should be given to the marginal benefits of all water usage types; where allocation is administratively directed, the marginal benefits of the primary water diversion purpose should be considered. Where measuring marginal benefits proves challenging, the water-use efficiency of the least efficient category or sector may serve as an approximate reference. When simplifying calculations, care must be taken to isolate water's contribution within sectoral water-use efficiency, expressed as a water-use efficiency allocation coefficient.

$$\frac{\partial b}{\partial w} = \min\left\{ \alpha_i \frac{b_i}{w_i} \right\} \tag{2}$$

Here b is the benefit, w is the water use volume, i is the type of water use, and α is the water-use efficiency allocation coefficient.

The cost of water diversion may be simplified as the ratio of total investment to water volume. However, it should be noted that total investment encompasses both initial capital expenditure and operational maintenance costs. Given uncertainties regarding the project's lifespan and the stability of actual water diversion volumes, expressing this as an average water diversion cost proves more intuitive and convenient for calculation.

$$\bar{c} = \frac{In}{w_{im-ex}} \tag{3}$$

Here is the average cost of water diversion project, In is total investment, and w_{im-ex} is annual design water diversion volume.

Dataset

To calculate economic benefit of water use, we establish 2017 as the baseline year and select 334 cities (the scope covers mainland China, excluding cities below the prefecture level and Hainan Province.) in China as our research samples. The study focuses on three key sectors: agriculture (crop cultivation), industry, and services. Sector-specific value added data were primarily compiled from provincial (municipal) statistical yearbooks, while the amount of sectoral water use data were obtained from provincial (municipal) water resources bulletins or related yearbooks. For partially missing data, government information is available upon request through channels such as telephone and email. If data remained incomplete, interpolation was performed using data from adjacent regions or years.

The information on water diversion projects is sourced from the Ministry of Water Resources of China (National Water Diversion Projects Database). A total of 22 projects were selected, each fully encompassing the design annual water diversion volume, delivery distance, investment, and type of water delivery (Here are two types of water delivery, G is gravitational water delivery and P is pumping water delivery in Table 1). Due to the data not being fully publicly available, the project names have been withheld here. The data for the 2017 Investment Conversion (**Table 1**) represents total investment discounted to 2017 by the discount rate.

Method for Calculating the Economic Benefit of Water Use

We employed the allocation coefficient method to quantify water use benefit across sectors. This approach allocates economic benefits proportionally according to the contribution of production factors, offering both conceptual clarity and practical data accessibility. To make the calculation simple, we assumed that the water benefit allocation coefficients do not differ across cities. This study employs the benefit allocation coefficient method. Specifically, the economic benefit of water use in a given sector is calculated as the ratio of its value-added to the amount of water use (i.e., benefit per unit of water) multiplied by a corresponding water benefit allocation coefficient.

$$WUEB = \alpha_i \times \frac{y_i}{w_i} \tag{4}$$

Here, $WUEB$ is the economic benefit of water use; y is the add value; w is the amount of water use; α is the water benefit allocation coefficient; and i is the water use sectors.

RESULTS AND ANALYSIS

Spatial Heterogeneity of Marginal Benefit of Water Use

As shown in **Figure 1**, regions exhibiting higher marginal benefit of water use were predominantly distributed east of the “Hu Huanyong Line”, with Liaoning, Hebei, Shandong, Henan, and Shaanxi Provinces being the most prominent. This also includes Ningxia, Gansu, Chongqing, Sichuan, and certain cities along the southeast coast. These areas are concentrated within a northeast-southwest strip extending from Liaoning, Hebei, Shandong, Henan, Shaanxi, Hubei, Sichuan, and Chongqing to northeastern Yunnan, as well as select cities along the southeast coast. Areas with lower marginal water benefits are primarily concentrated in the western inland regions, as well as cities situated on plateaus or in mountainous terrain within the northeast and southeast regions. Notably, Shandong Province accounts for nine of the top thirty cities by margin benefit of water use (**Figure 2**). Henan and Shaanxi Provinces both have five cities, which Yanan and Sanmenxia ranked second and fourth respectively and both marginal benefit of water use exceed 0.6 RMB/m^3. Marginal Benefit in the Yellow River basin are particularly significant nationwide, the primary considerations for agriculture are its low water use volume and the high added value of agricultural products. It should be noted that the marginal benefits in this study are approximate values, and results derived from different calculation methods will inevitably vary.

Empirical Equation for Unit Cost of Water Diversion Projects

Water turnover volume is a composite variable and one of the decisive factors in the unit cost measurement of water diversion projects., which calculated by segmented accumulation of the product of water diversion volume and water delivery distance. There are two types of water delivery, gravitational water delivery is set to 0 and pumping water delivery is set to 1. The type of water carrier is determined by a weighted average calculation based on the proportion of water transfer distance accounted for by each water carrier and their respective construction cost differences, as comprehensively characterized in the detailed project documentation. The basic values are: natural water bodies 0.1, open channels 0.4, pipelines 0.7, tunnels 1. Each

Table 1 | Basic information of selected 22 water diversion projects

Serial number	Type of water delivery	Design annual water diversion volume (10^8 m^3)	Water delivery distance (km)	2017 Investment conversion (10^8 RMB)
1	P	87.66	1466.50	574.54
2	G	10.00	234.00	34.96
3	P	1.43	482.00	9.96
4	G	95.00	1432.00	1989.36
5	G	6.20	482.00	42.41
6	P	2.79	265.90	12.99
7	P	43.00	1048.68	896.59
8	P	6.02	384.50	73.26
9	G	4.43	191.03	45.83
10	G	39.80	27.05	48.78
11	P	34.03	664.24	825.76
12	P	6.40	285.26	134.89
13	P	2.43	252.00	156.27
14	P	5.72	115.85	87.45
15	G	15.00	98.30	197.92
16	P	5.60	43.67	51.89
17	P	8.90	241.00	127.90
18	G	4.54	390.26	252.16
19	P	17.08	113.10	301.81
20	P	7.20	106.00	23.90
21	G	18.00	85.32	60.65
22	G	7.70	269.67	189.90

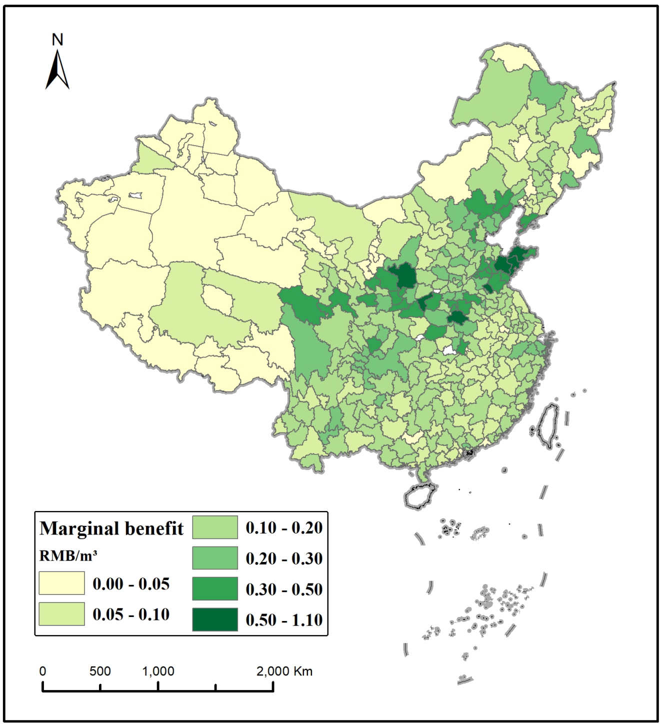

Figure 1 | Spatial distribution of margin benefit of water use across major cities in China.

water carrier is converted according to its distance proportion and then summed. The final value of the water carrier variable shall not exceed 1. Terrain-related factors influencing construction difficulty encompass ecological conservation costs. Typical terrain types are assigned values as follows: plains 0.1, hills 0.4, mountains 0.8, plateaus 1. The difficulty factor represents a composite expression of water delivery, water carrier, and terrain factors, calculated as the average of these three components. Values range between 0 and 1 inclusive (**Table 2**).

Experimental equation fitting for investment per unit of water turnover volume in water diversion projects, where independent variables X_1 to X_7 are respectively: design annual water diversion volume, water delivery distance, type of water delivery, type of water carrier, terrain factor, water turnover volume, and composite difficulty factor. Multiple regression models incorporating unit investment and various combinations of variables were tested. Based on the fitting results of different models, a slightly improved composite variable linear regression model is presented:

$$\bar{In} = -5.38 \times 10^{-9} X_6 + 0.011 X_7, \ (R^2 = 0.59) \quad (5)$$

Here $\bar{In}$ is investment per unit of water turnover volume, X_6 is water turnover volume, and X_7 is composite difficulty factor.

In accordance with relevant regulations governing water conservancy projects, the maintenance costs and operational management fees for water diversion

Table 2 | Components of water diversion project unit investment

No.	investment per unit of water turnover volume 10^8RMB/(10^8m^3·km)	water turnover volume 10^8m^3·km	type of water delivery	type of water carrier	terrain factor	composite difficulty factor
1	0.0002	128553.39	1	0.4	0.4	0.60
2	0.0007	2340.00	0	0.4	0.1	0.17
3	0.0007	689.26	1	0.4	0.4	0.60
4	0.0007	136040.00	0	0.4	0.1	0.17
5	0.0007	2988.40	0	0.4	0.1	0.17
6	0.0009	741.86	1	0.2	0.1	0.43
7	0.0010	45093.24	1	0.3	0.1	0.47
8	0.0016	2314.69	1	1	0.8	0.93
9	0.0027	846.26	0	1	0.8	0.60
10	0.0023	1076.59	0	0.4	0.1	0.17
11	0.0018	22603.95	1	1	0.8	0.93
12	0.0037	1825.66	1	0.8	0.8	0.87
13	0.0128	612.36	1	0.4	0.1	0.50
14	0.0066	662.66	1	1	0.8	0.93
15	0.0067	1474.50	0	0.8	0.8	0.53
16	0.0106	244.55	1	0.8	0.8	0.87
17	0.0030	2144.90	1	0.4	0.4	0.60
18	0.0071	1771.79	0	0.8	0.8	0.53
19	0.0078	1931.75	1	0.7	0.1	0.60
20	0.0016	763.20	1	0.7	0.1	0.60
21	0.0020	1535.76	0	1	0.4	0.47
22	0.0046	2076.46	0	0.6	0.4	0.33

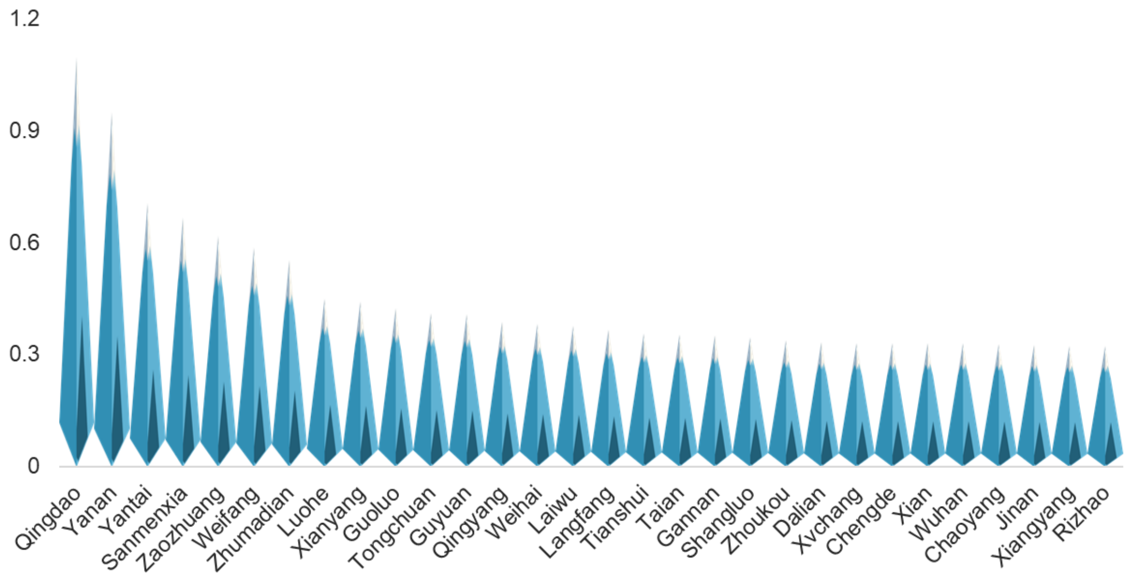

Figure 2 | The top 30 cities by value of margin benefit of water use across major cities in China (Unit: RMB/m³)

projects shall be calculated at 1.5% and 2% of the total investment respectively. With the project's operation period set at 20 years, the unit cost of the water diversion project may be expressed as:

$$\bar{c} = (3.5\% \cdot t + 1)\,\bar{In} \cdot X_2 = 1.7X_2\left(-5.38 \times 10^{-9} X_6 + 0.011 X_7\right) \quad (6)$$

Here $\bar{c}$ is the unit cost of the water diversion project, $\bar{In}$ is investment per unit of water turnover volume, t is the project's operation period, and X_2 is water delivery distance, X_6 is water turnover volume, and X_7 is composite difficulty factor.

When the fundamental information for a specific water diversion project is complete, the unit cost for water diversion project can be expressed as a function of the water delivery distance X_2. The unit cost of water volume in one receiving area can be estimated using the following equation based on the transfer distance.

$$\bar{c} = (-9.146 \times 10^{-9} X_1)\, X_2^2 + 0.006233(X_3 + X_4 + X_5)\, X_2 \quad (7)$$

Table 3 | The unit cost of cities along the routes of SNWD (RMB/m3)

East route			Mid route			West route	
cities	Estima-ted cost	water price	cities	Estima-ted cost	water price	cities	Estima-ted cost
Beijing	3.76		Beijing	1.49	2.33	Lanzhou	4.45
Tianjin	3.37		Baoding	1.43	Hebei Province 0.97	Linxia	3.96
Cangzhou	3.14		Shijiazhuang	1.36		Gannan	3.07
Dezhou	2.93		Xingtai	1.28		Aba	1.80
Hengshui	2.73		Handan	1.20		Ganzi	0.00
Liaocheng	2.29		Anyang	1.12	North of the Yellow River in Henan Province 0.58		
Jinan	1.98		Hebi	1.10			
Jining	1.77	0.36	Xinxiang	1.03			
Zaozhuang	1.52		Jiaozuo	0.91			
Xvzhou	1.37	0.41	Zhengzhou	0.82	South of the Yellow River in Henan Province 0.34		
Suqian	1.01		Xvchang	0.72			
Huai'an	0.80		Pingdingshan	0.59			
Yangzhou	0.51		Nanyang	0.39	0.18		

Estimated Cost for Cities Along the Routes of SNWD

The cities traversed by the East and Mid Routes of the SNWD are the cities along the route. For the West Route, analysis was conducted based on estimated cities along the planned route (where the junction of Gansu, Qinghai, and Tibet are considered to exhibit little difference in water diversion distance and water use benefits). Lanzhou City was solely to show the estimated cost. Employing empirical unit cost equations for water diversion projects, distance from cities along the route to the source area was calculated, then the unit cost was estimated. **Table 3** Showed that unit costs for cities along the East Route ranged from 0.51 to 3.76 RMB/m³ from starting point to terminus, the estimated unit costs of the Mid Route ranged from 0.39 to 1.49 RMB/m³, and for the West Route ranged from 1.80 to 4.45 RMB/m³. Comparing water supply tariffs for the SNWD in certain regions, the unit cost estimates derived from empirical equations exceed tariffs in the initial phase but fall below them in the latter phase. The estimated costs of cities along the East Route were two to five times higher than the water price. For Mid Route, water price of Beijing was 2.33 RMB/m³, which Manifested as approximately 0.5 times higher than the estimated value. In fact, relative supporting infrastructure has been constructed by the water importing cities, yet this part did not belong to the investment for the water diversion project. The estimated cost of cities along West Route demonstrates a possible situation, should the West Route Project be realized, the price of imported water is highly likely to exceed the estimated figure. This discrepancy arises partly because current tariffs remain suboptimal, failing to cover full costs or accurately reflect project expenditures. Additionally, the empirical equation possessed inherent limitations, primarily relying on investment projections that inadequately account for operational factors such as pumping requirements. Theoretically, such estimates typically yield conservative results.

Spatial Equilibrium Line Assessment of Water Resource Allocation in SNWD Area

According to the theory of spatial equilibrium in water resource allocation, without considering variations in local water supply costs, taking the three routes of the SNWD as examples, the condition for spatial equilibrium in cities along the routes is as follows: the difference between the marginal benefit of water use at the equilibrium point and that at the starting point should equal the unit cost of water diversion from the starting point to the equilibrium point. Using the three routes of the SNWD as primary directional benchmarks, we compare the marginal benefit of water use between cities along the routes and their respective starting points. By analyzing variations in the difference between marginal water benefit and unit water diversion cost, we identify potential spatial equilibrium cities and connect them to form a rough equilibrium boundary. As illustrated in **Figure 3**, when comparing the marginal benefit differential between regions with the water diversion cost, the latter must scarcely exceed 0.5 RMB/m³. This macro-level analysis indicates the equilibrium point lies very close to the Yangtze River basin. Under an administratively-driven scenario, however, comparing the benefit differentials of primary water usage types within the diversion project could shift the equilibrium point northwards. Using the marginal benefits from this study as an example, connecting the three points of Xuzhou City on the East Route, Zhengzhou City on the Mid Route, and Aba Prefecture on the West Route forms a line representing the projected spatial equilibrium boundary for China's eastern region.

DISCUSSION

Spatial equilibrium in water resource allocation cannot be simplistically defined as the balanced distribution of water resources, nor does it refer to the equitable distribution of water consumption volumes, nor to the equilibrium of development utilization rates or supply-demand imbalances. Spatial equilibrium fundamentally represents the balanced allocation of water resources across geographical areas, requiring coordination with

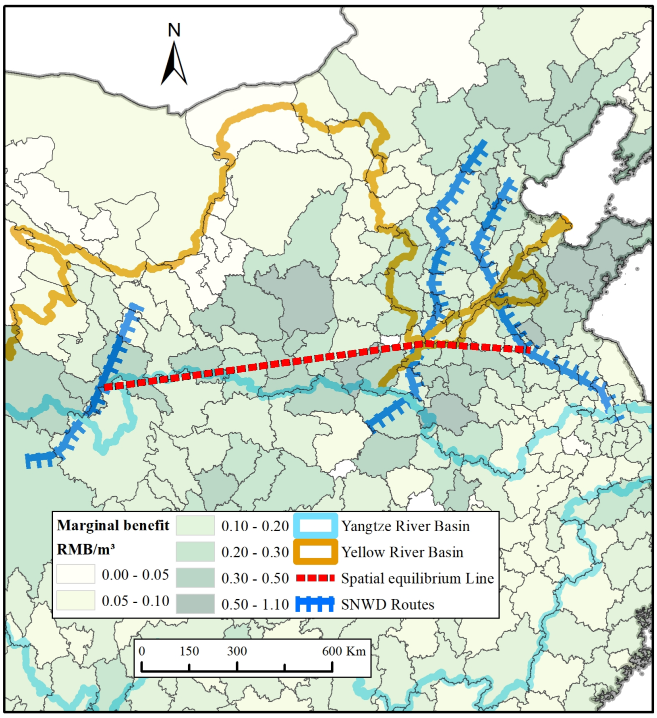

Figure 3 | Spatial equilibrium line of water resource allocation in SNWD area

regional socio-economic development and ecological conservation. At the unit scale, its core essence lies in balancing socio-economic progress with water resource carrying capacity. Regarding this capacity, the capital, technology and other inputs determining it are outcomes of balanced resource allocation principles. Water resource allocation seeks to maximize overall benefits, prioritizing distribution to water users with high marginal benefits and allocating to those with low marginal benefits last. The spatial distribution of marginal water benefits determines the sequence of interregional water resource allocation. It should be clarified that the selection of marginal water benefits was not weighed against domestic or ecological water benefits. This approach recognizes that ecological water use is paramount in safeguarding public wellbeing and quality of life, warranting priority akin to domestic water supply. Under ideal conditions, the marginal benefit of water allocated for ecological purposes should be equivalent to that of other water uses. Similarly, the marginal benefit of reserving water bodies and aquatic spaces for ecological purposes should be equal to that derived from human development and utilization. Under ideal conditions, the greater the marginally higher benefit of water use in the receiving area compared to the source area, the more it can offset the project investment and ecological compensation costs, thereby enhancing water resource allocation efficiency. Although SNWD is significantly influenced by political, strategic and ecological factors, these non-economic objectives and constraints can still be reflected within the economic dimension of cost-benefit analysis. Therefore, the urgent challenge is to calculate the marginal benefits of water use with greater precision. Therefore, in advancing the high-quality development of the follow-up projects for the SNWD and continuing the scientific implementation of water diversion projects, emphasis should be placed on conducting reliable analyses of the marginal benefits of water use and the costs of water diversion across regions. This will enable the scientific determination of project scale and overall layout, ensuring a balanced approach to socio-economic development, sustainable water resource utilization, and ecological and environmental protection.

The allocation coefficient method employed in this study offers a feasible framework for the unified quantification of water use benefits across multiple sectors. The value assigned to the allocation coefficient is central to this method and constitutes the primary source of uncertainty. Actually, the allocation coefficients of numerous studies are constant (Berrittella et al., 2007; Grafton et al., 2018; Yin et al., 2020), despite large observed regional differences in industrial composition, technological efficiency, water tariffs, and regulatory regimes. The availability of data at the city and sector level is limited, considering that refining regional allocation coefficients would introduce more errors, fixed allocation coefficients were therefore used. Future research should focus on developing dynamic allocation coefficient systems that adapt to technological progress, climatic variations and shifts in industrial structure (Okamoto et al., 1990; E. R. Yu et al., 2024).

Assessing the spatial equilibrium of water resource allocation aims to enhance the conditions for human survival and development. For areas with water use imbalances, assessments should identify the root causes of industrial water consumption issues and propose improvement strategies tailored to regional characteristics. For instance, the agricultural sector, the 'irrigation economic benefit paradox highlighted by Grafton et al. (2018) serves as a critical warning. Singularly pursuing higher efficiency or economic benefit—for instance, through technological advances that reduce irrigation withdrawals—does not guarantee increased water availability at the basin scale and may instead intensify regional water stress by incentivizing the expansion of irrigated area(Cai et al., 2023; Lankford, 2023). Consequently, water allocation policies for strategic granaries like Xinjiang and Northeast China must look beyond mere 'efficiency'. The imperative of 'equity'—in this context, their vital role in safeguarding national food security—must be integral to the calculus (Zhu et al., 2024). Furthermore, the water reallocation strategy must be coupled with carefully designed compensation mechanisms to mitigate inter-regional 'equity' conflicts that may arise from the redistribution of water rights (Shi et al., 2023; Zou & Cong, 2021).

This study employs simplified calculations for both marginal benefits and water diversion costs. Water resource allocation involves all natural and socio-economic processes, and the dynamic nature of spatial equilibrium states further increases the system's complexity. Attempting to comprehensively generalize such complex systems poses significant challenges for model design. This study designed a spatial equilibrium evaluation method of water resource allocation and attempted regional validation in China. Large-scale water diversion projects also exert multifaceted impacts across economic, social and ecological dimensions, which, together with investment costs, contribute to the actual cost of water usage. Constrained by data, parameters and modelling assumptions, calculations of marginal benefit and estimates of water diversion costs remain scope for further enhancement. Future research may explore incorporating multi-year data, regionally differentiated parameters and city-level input-output tables to refine marginal benefit assessments., which is one of the considerations for adopting 2017 as the base year in this study.

CONCLUSIONS

Based on cost-benefit analysis, this study developed a spatial equilibrium evaluation method of water resource allocation and attempted regional validation by the SNWD in China. We analyzed spatial heterogeneity of marginal benefit of water use, derived empirical equations for unit investment and unit cost in water diversion projects Empirical equation for unit cost of water diversion projects, and estimated cost for cities along the routes of SNWD and assessed spatial equilibrium line to explore the spatial equilibrium pattern of water resource allocation in China under constraints of marginal benefits and water diversion costs.

According to the equilibrium condition of general equilibrium theory and spatial equilibrium theory, the essence of spatial equilibrium in water resource allocation lies in achieving marginal benefit equilibrium under the consideration of water transfer costs between regions. The marginal benefit of water is determined by those who use it inefficiently, or, in the context of administratively-led allocation, is defined by the primary purpose of the water transfer. Spatial equilibrium is dynamic, necessitating both an assessment of the current situation and an analysis of future prospects. For regions identified as imbalanced in the evaluation results, water transfer projects are required to enhance the efficiency of water resource allocation.

Regions exhibiting higher marginal benefit of water use were predominantly distributed east of the “Hu Huanyong Line”, with Shandong Province accounting for nine of the top thirty cities by margin benefit of water use. Henan and Shaanxi Provinces both have five cities, which Yanan and Sanmenxia ranked second and fourth respectively and both marginal benefit of water use exceed 0.6 RMB/m^3.

When the fundamental information for a specific water diversion project is complete, the unit cost for water diversion project can be expressed as a function of the water delivery distance. The overall estimation results of the empirical equations exhibit a systematic underestimation. Basis on empirical unit cost equations and the distance from cities along the route to the source area, the unit cost was estimated: The unit costs for cities along the East Route ranged from 0.51 to 3.76 RMB/m^3, unit costs of the Mid Route ranged from 0.39 to 1.49 RMB/m^3, and for the West Route ranged from 1.80 to 4.45 RMB/m^3. Theoretically, such estimates typically yield conservative results.

When comparing the marginal benefit differential between regions with the water diversion cost, the latter must scarcely exceed 0.5 RMB/m^3. Connecting the three points of Xuzhou City on the East Route, Zhengzhou City on the Mid Route, and Aba Prefecture on the West Route forms a line representing the projected spatial equilibrium boundary for China's eastern region.

Under an administratively-driven scenario, however, comparing the benefit differentials of primary water use types within the diversion project could shift the equilibrium point northwards. Further research about marginal benefits and water use costs, along with dynamic updates, is required for water diversion projects and the spatial equilibrium of water resource allocation.

Declaration of competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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