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Original Research

Analysis of Decoupling State between Water Use Efficiency and Economic Development under Rank-Sum Score Hierarchy –Anhui Province as an Example

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Abstract

Examining the interdependent relationship between water use and economic development can yield programs to foster sustainable economic growth in Anhui Province. The highly efficient SBM model was employed to assess the water use efficiency of 16 cities in Anhui from 2012 to 2022. The input-output of water resources was evaluated by the rank-sum grading method. The standard deviation ellipse and center of gravity migration were employed to analyze the spatial and temporal evolution of water use efficiency in Anhui cities. The Tapio decoupling model was employed to examine the relationship between water use efficiency and the level of economic development. The findings indicate that: (1) The water use efficiency in Anhui Province from 2012 to 2022 exhibits a "V"-shaped fluctuation with a rising trajectory. The average value ranges from 0.673 to 0.907. (2) The spatial distribution of water use in Anhui transitioned from "high in the north and south, low in the middle" in 2012 to "high in the east and low in the west" in 2022. The spatial center of gravity is shifting eastward in a "W" formation. (3) From 2012 to 2022, the decoupling of water use efficiency and economic development progressively showed a positive trend with periodic fluctuations.

Keywords: water use efficiency, economic development, rank-sum ratio approach, decoupling model, standard deviation ellipse

Introduction

Water is fundamental to survival and the foundation of civilization. The development and utilization of water resources, as a crucial natural resource for economic advancement, represents a significant bottleneck constraint on the degree of economic growth. As the economy rapidly develops, demand for water resources is escalating. Planning urban water resource infrastructure intricately links the water resources' overall quantity and allocation. It also influences the advancement of the local economy. In recent years, China has prioritized the escalating water resources crisis. The State Council's Opinions on the Implementation of the Strictest Water

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Resource Management System delineate the primary objectives of the three red lines: regulation of water resource development and utilization, enhancement of water-use efficiency, and restriction of pollution in water function zones. In 2021, China's Development and Reform Commission (NDRC) explicitly stated that advancing the establishment of a water-saving society necessitates a broad enhancement of the efficiency and efficacy of water resource utilization [1].

In the quantitative evaluation of water consumption efficiency, it is essential to identify the influencing variables and indicator factors [2]. Initially, researchers predominantly used measuring indicators for water use efficiency, utilizing capital, labor, and water resources as input variables, while gross regional product served as the output element [3]. An in-depth analysis of the study indicates that assessing water usage efficiency must encompass not only water resource input levels but also aspects of water pollution discharge within the output framework [4]. Xue Jianchun included the volume of sewage discharge in the undesirable output indicators while assessing the water usage efficiency of cities in the Yellow River Basin [5]. Yang Yi et al. employed the water footprint methodology to incorporate graywater footprint as an undesirable output while assessing the water usage efficiency of the Guanzhong Plain urban agglomeration, considering the detrimental effects of water pollution on ecological benefits [6]. Given the variability of water supplies and social, economic, and ecological variables between regions, indicators must be chosen based on the specific circumstances of the studied area. In Anhui Province, as a significant spatial unit for water ecological environmental management, regional disparities persist in the conditions of water pollution and management. The wastewater treatment rate serves as a measure of water resource recycling within a certain region. The outflow of wastewater serves as a significant metric for assessing regional water usage and contamination levels. Consequently, this article incorporates the sewage treatment rate and wastewater discharge as measures of water resources output in Anhui Province.

Water use efficiency is a critical element in advancing the sustainable development of water resources. The investigation into the effectiveness of water resource utilization primarily emphasizes the precise measurement of its extent [7]. Presently, the measuring techniques frequently employed by researchers encompass the trapezoidal fuzzy number approach [8], ecological footprint model [9], stochastic frontier method [10], and data envelopment analysis [11], among others. The parametric approach exemplified by stochastic frontier analysis (SFA) and the nonparametric approach exemplified by data envelopment analysis (DEA) are the most prevalent methodologies [12]. Both methods include the concept of total factor water use efficiency to develop the input-output system. Nonetheless, the parametric evaluation of water efficiency frequently presents difficulties owing to the intricate relationships between environmental variables and manufacturing processes in water utilization and treatment [13]. Conversely, the DEA technique evaluates the relative efficiency of decision-making units by developing a mathematical planning model that does not need the production function specification linking inputs and outputs, thus circumventing the influence of subjective elements [14]. Xie Yong Qin et al. employed a DEA model to assess the water use efficiency (WUE) of prefecture-level cities in China's Yangtze River Economic Zone (YREZ) from 2006 to 2017 [15]. Nonetheless, the DEA technique possesses certain drawbacks and does not adequately account for slack factors. The SBM model, including slack variables, addresses the issues of slackness and non-expected outputs inherent in standard DEA models, which result in biased efficiency ratings; hence, it is extensively employed to assess water usage efficiency [16]. The majority of scholars have primarily concentrated on the methodology of measuring water efficiency, while insufficient attention has been devoted to the scientific analysis of input and output indicators for assessing water usage efficiency. Therefore, this paper employs the weighted rank-sum ratio method that can directly rank the evaluation results of multiple indicators. Utilizing the Probit regression equation within the WRSR framework, it derives the graded critical values for input and output indicators related to water use efficiency measurements, evaluates the urban input and output classifications, and incorporates these graded results into the super-efficient SBM model to assess water use efficiency.

In recent years, in order to visualize regional differences in water use efficiency, more studies have introduced efficiency measurements to a regional perspective, focusing on characterizing regional spatial and temporal evolution [17]. The research regions for water usage efficiency have progressively expanded from national [18], basin [19], and provincial [20] levels to urban agglomerations [21] and municipalities [22]. The examination of water use efficiency is progressively evolving, transitioning from a singular measurement of efficiency to an analysis of its correlation with economic development, population distribution, natural geography, and other variables. Investigating the interdependent relationship between economic growth levels and water consumption efficiency is essential for regional sustainable development. To examine the interaction between the two, both domestically and internationally, researchers primarily consider resource and environmental constraints as the foundation [23]. They either apply the coupling concept from physics to assess the coupling and coordination relationship between the two or investigate the dynamic adaptation between them from the perspective of decoupling relationships [24]. Sun Jianfeng et al. employed the Tapio model to assess the decoupling status of water resource utilization and economic development across nine provinces of the Yellow River Basin from 2001 to 2020 [25]. Meng Qingjun et al. employed the coupled coordination degree model to conduct a retrospective analysis of the association between water resource usage efficiency and economic development across 29 provinces in China from 2010 to 2019 [26]. This study used the Tapio model to investigate the correlation between water use efficiency and economic development in the cities of Anhui Province, given the observed inconsistency between these two factors.

The existing achievements are constantly enriched in research methods, objects, and contents, but there is still room for expansion. The marginal contributions of this paper are as follows: (1) Prior to calculating water use efficiency, the weighted rank-sum ratio approach is employed to categorize the input and output indicators. On the one hand, it can objectively illustrate the magnitude of regional disparities in input and output phases while elucidating the intrinsic factors influencing variations in regional water use efficiency. On the other hand, it offers insights for examining the spatio-temporal evolution of water use efficiency in cities within Anhui Province and for formulating targeted strategies. (2) In light of the prevailing circumstances regarding water pollution discharge and treatment in Anhui Province, the sewage treatment rate is incorporated as an output of water resources, while wastewater discharge is regarded as an unintended output, thereby illustrating the regional disparities in urban water use efficiency within Anhui Province. Develop a super efficiency SBM model and a Tapio decoupling model to investigate the degree of coordination between water usage efficiency and economic development across various geographies and phases. It offers theoretical backing for effectively enhancing urban water use efficiency. (3) This study examines urban water resource utilization efficiency from a novel approach, focusing on 16 cities in Anhui Province. As a crucial spatial unit in ecological governance, Anhui Province examines the spatial and temporal variations in water use efficiency following regional input-output classification from an urban perspective, which holds significant practical implications for the region's green and high-quality development.

Materials and Methods

Overview of the Study Area and Data Sources

Anhui Province is situated in eastern China. The landscape includes plains, hills, and mountains. It comprises three principal river basins: the Yangtze River, the Huai River, and the Xin'an River. The aggregate area is 140,100 km^2. Anhui Province, one of China's more water-scarce regions, is being impacted by urbanization and industrialization, highlighting the disparity between water resource utilization and economic development. In 2022, Anhui Province's GDP reached 4504.5 billion yuan, reflecting a 3.5% rise from 2021 and constituting around 3.7% of the national total. The province's per capita GDP is 73,603 yuan, ranking second in the central area; however, it is 13.72% lower than the national average. The disposable income per capita of the province's people is 32,745 yuan, above the central region's average by 3.67%; however, it falls short of the national average by 11.22%. Anhui Province exhibits a marginal edge in economic development within the central region; nonetheless, significant potential for enhancement remains. The per capita GDP of northern Anhui is 502.86 billion yuan, central Anhui is 8192.8 billion yuan, and southern Anhui is 9400.5 billion yuan. The economic development of Anhui Province has a declining pattern from south to north, with the northern region still lacking in coordinated development within the Anhui area. In 2022, the province's total water resources will amount to 54.519 billion m^3, representing approximately 2% of the nation's total water resources for that year. The province's per capita water resources amount to 890.8 m^3, representing a reduction of around 53.56% compared to the national average. The water consumption of Anhui province for every 10,000 yuan of GDP is 55.2 m^3, representing a reduction of 11.29% compared to the national average. The province's water use per 10,000 yuan of industrial added value is 22.3 m^3, representing a 2.45% reduction compared to the central area. The effective utilization coefficient of irrigation water for farmland is 0.5642, which is below the national average for farmland irrigation coefficients. The total water resources are 106.28 m^3 in northern Anhui, 176.93 m^3 in central Anhui, and 261.98 m^3 in southern Anhui. Water resources in Anhui Province exhibit a growing tendency from north to south, paralleling economic development, but the shortage of water resources in northern Anhui hinders the province's coordinated development. In summary, the water scarcity issue in Anhui Province is severe and characterized by low water usage efficiency. There are major disparities in the utilization of water resources and economic development, with pronounced problems of unbalanced and uncoordinated spatial distribution.

The data sources are the Anhui Statistical Yearbook, the Anhui Water Resources Bulletin, and the statistical yearbooks and water resources bulletins of Anhui cities from 2012 to 2022. The values of some indicators are calculated according to the formula. Missing data are interpolated.

Research Methodology and Model Building

Selection of Water Use Efficiency and Economic Development Indicators

The assessment of water use efficiency must take into account both input and output variables. Based on prior study findings [27], an input and output index system for water use efficiency in Anhui Province was developed, taking into account its specific circumstances and data availability (Table 1). Four indicators for assessing water use were identified: agricultural water consumption,

Table 1. Composition of indicators of water use efficiency and economic development.

Target level	Classification of indicators	Composition of indicators
Water use efficiency	Input	Agricultural water consumption/10^4 m^3
		Industrial water consumption/10^4 m^3
		Domestic water consumption/10^4 m^3
		Total investment in social fixed assets/10^8 yuan
		Number of employees/10^4 people
	Output	GDP/10^8 yuan
		Sewage treatment rate/%
		Wastewater discharge/10^4 m^3
Level of economic development	Structure of economic development	Percentage of secondary and tertiary industries/%
		Urbanization rate/%
		Percentage of expenditure on science and technology/%
		Percentage of expenditure on education/%
	Scale of economic development	per capita GDP/yuan
		Per capita disposable income/yuan
		Total retail sales of consumer goods/10^8 yuan
		Total investment in social fixed assets/10^8 yuan

industrial water consumption, and domestic water consumption as material inputs; total investment in social fixed assets as capital inputs; and the number of employees as labor inputs. Three output metrics were identified: GDP representing economic production, sewage treatment rate indicating water resources output, and wastewater discharge signifying undesirable water resources output. Eight variables were chosen based on prior work to assess the level of economic development [28], encompassing two dimensions: the extent of economic development and the structure of economic development, as seen in Table 1.

Measurement and Grading of Water Input and Output Indices

The weighted rank-sum ratio, known as the WRSR approach, was introduced by Chinese academic Prof. Fengtiao Tian, previously associated with the Chinese Academy of Preventive Medicine, in 1988 [29]. Before measuring water use efficiency, the weight-weighting approach was employed to assess the input and output indices of water use efficiency based on the CRITIC [30] assignment. The computation of the WRSR rank is divided into integer and non-integer methodologies (higher superiority indicators are deemed "better" as the value increases, whereas lower superiority indicators are considered "better" as the value decreases).

The integer rank-ordering method:

$$R = (R_{ij})_{n\times m} \tag{1}$$

For high-optimality data:

$$R_{ij} = 1 + (n+1)\frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \tag{2}$$

For low-optimality data:

$$R_{ij} = 1 + (n+1)\frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \tag{3}$$

The formula for calculating the rank-sum ratio is:

$$WRSR_i = \frac{1}{n}\sum_{j=1}^{m} w_j R_{ij},\ \ i = 1,2,\cdots,n \tag{4}$$

Where i=1,2,...,n; j=1,2,....,m; R_{ij} denotes the rank of the indicator in the j-th column of the i-th row, n is the number of samples, and m is the number of indicators of water resources inputs and outputs. X_{ij} is the value of the original indicators of water resources inputs and outputs.

Utilizing the Probit regression equation in WRSR, the thresholds and bins for water use efficiency inputs and outputs in WRSR were derived, as presented in Table 2. Municipal water use can be classified into "low input, medium input, high input" and "low output, medium output, high output". In accordance with the classification presented in Table 2, we designated "low, medium, and high inputs" as "LI, MI, and HI" and "low, medium, and high outputs" as "LO, MO, and HO".

Table 2. RSR thresholds in grades.

Grade	Input RSR thresholds	Output RSR thresholds
1st gear (low)	0-0.290	0-0.409
2nd gear (medium)	0.290-0.708	0.409-0.593
3rd gear (high)	0.708-1	0.593-1

Evaluation of Water Use Efficiency

In the empirical analysis of efficiency assessment, the DEA model and its derivative models were predominantly utilized. Andersen et al. introduced the super-efficient SBM model to address the issues of slackness and non-expected outputs inherent in classic DEA models, which result in biased efficiency values [31]. Based on the calculation results of the water resources input and output index, the super efficiency SBM model is used to evaluate the water use efficiency of Anhui Province. Their framework is as follows:

$$\min \ \rho = \frac{\frac{1}{m}\sum_{i=1}^{m}\left(\bar{x}/x_{ik}\right)}{\frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\frac{\bar{y}^g}{y_{sk}^g}+\sum_{q=1}^{s_2}\frac{\bar{y}^b}{y_{qk}^b}\right)} \tag{5}$$

$$s.t.\begin{cases} \bar{x} \ge \sum_{j=1,\ne k}^{n} x_{ij}\lambda_j; \bar{y}^g \le \sum_{j=1,\ne k}^{n} y_{sj}^g\lambda_j; \bar{y}^g \ge \sum_{j=1,\ne k}^{n} y_{qj}^g\lambda_j; \\ \bar{x} \ge x_k; \bar{y} \le y_k^g; \bar{y}^b \ge y_k^b; \\ \lambda_j \ge 0, i = 1,2,\cdots,m; j = 1,2,\cdots,n; \\ j \ne 0, s = 1,2,\cdots,s_1; q = 1,2,\cdots,s_2; \end{cases} \tag{6}$$

In Eqs. (5) and (6), ρ is the value of efficiency. $\rho \ge 1$ indicates that the water use efficiency is relatively effective, with the larger symbol representing a more efficient DUM. $\rho < 1$ indicates that there is still room for progress and improvement in water use efficiency. X represents input factors; y^g and y^b represent desired as well as undesired output factors of water resource use, respectively; and m, s_1, and s_2 correspond to the number of indicators for the first three, respectively, as a vector of weights.

Description of Spatial Distribution Characteristics

The standard deviation ellipse (SDE) approach was initially introduced by Lefever in 1926. It quantitatively delineates the spatial distribution of water use efficiency in Anhui using fundamental parameters, including the spatial distribution range of the ellipse, the major and minor axes, and the azimuthal angle. The pertinent principles and formulas are available in the literature [32].

Evaluation of the Decoupling Relationship between Water Use Efficiency and Economic Development

This article employed the Tapio decoupling elasticity model from the field of physics [33] to investigate the relationship between water use efficiency and economic growth levels in the cities of Anhui. The model is structured as follows:

$$T = \frac{\Delta W}{\Delta E} = \frac{(W_t - W_{t-1})/W_{t-1}}{(E_t - E_{t-1})/E_{t-1}} \tag{7}$$

Where T is the decoupling elasticity coefficient, ΔW and ΔE are the rate of change in water use efficiency and economic development level. The eight decoupling criteria are shown in Fig. 1.

Results

Trend of Time Series Evolution of Water Use Efficiency in Anhui Province

The super-efficient SBM model was employed to assess the water use efficiency of each prefecture-level city in Anhui Province, with the findings illustrated in Fig. 2. From a comprehensive perspective (as illustrated in the left fig.), the annual mean values of water use efficiency in Anhui Province were consistently below 1, indicating spatial disparities in efficiency. The water use efficiency in Anhui Province showed an upward trend from 2012 to 2022, with an average value ranging from 0.673 to 0.907. The peak and valley values appeared in 2022 and 2016, respectively. This indicates that the water use efficiency in Anhui Province approached the production frontier in 2022, but it significantly diverged from it in 2016. In 2016, only Huaibei City and Xuancheng City attained the production frontier among prefecture-level cities; however, by 2022, the count of such cities increased to 11. It implies that Anhui Province has progressively achieved more favorable economic results through efficient investment in resource environments and human capital from 2016 to 2022. The water use efficiency in Anhui Province exhibited a "W"-shaped fluctuation with an upward trend from 2012 to

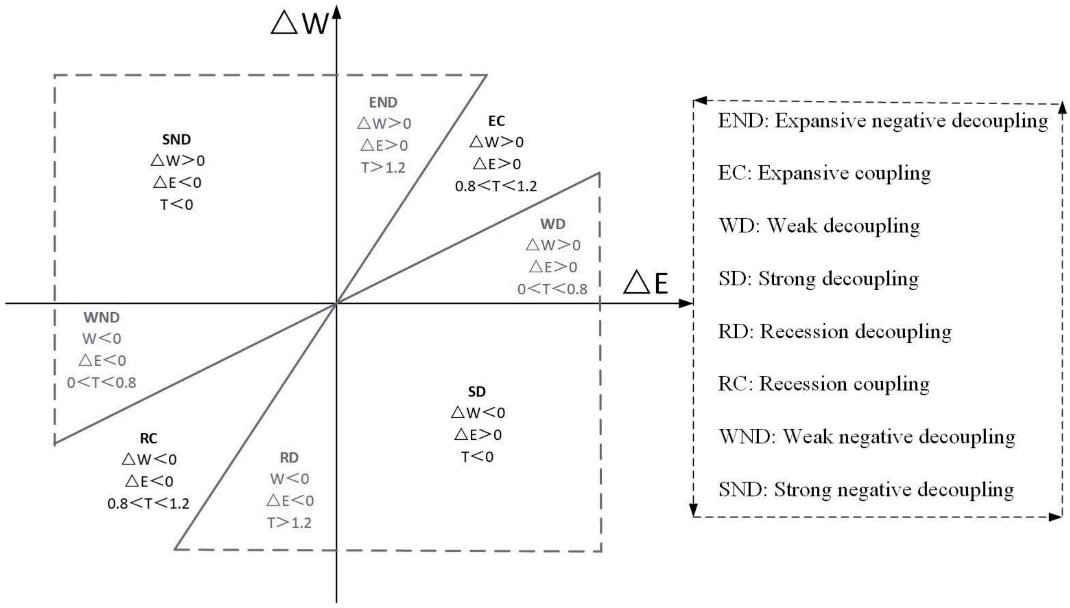

Fig. 1. Classification criteria for decoupling state.

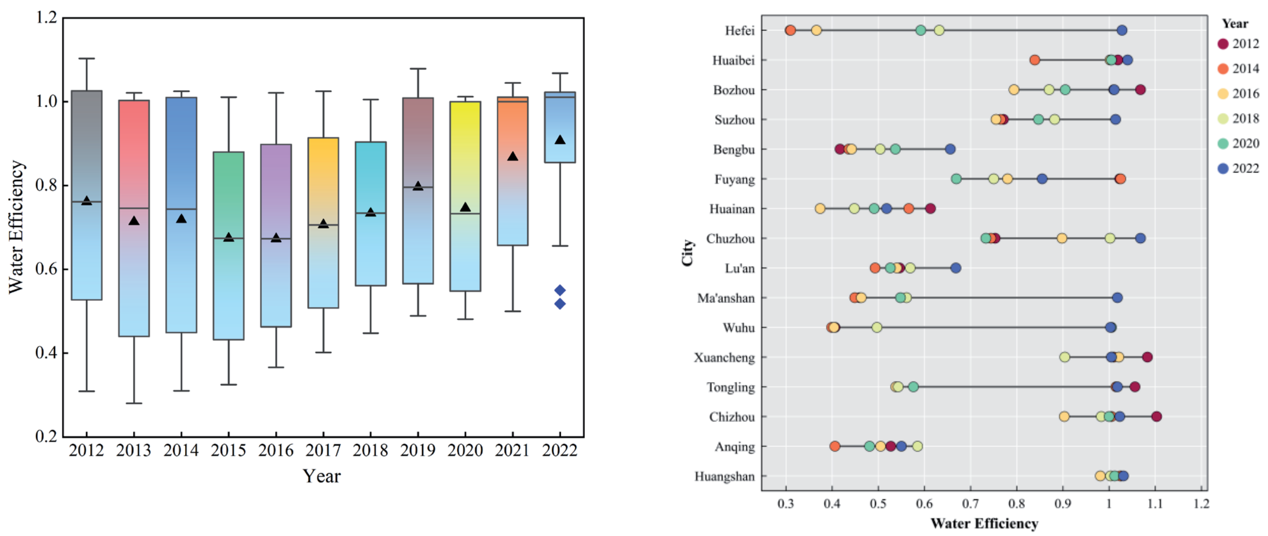

Fig. 2. Water use efficiency in Anhui Province, 2012-2022.

2022. From 2012 to 2016, there was a variable drop, followed by a 34.77% increase from 2016 to 2022. In 2022, water use efficiency attained 0.907, progressively nearing an optimal condition, with annual improvements in water use. In 2022, the gap between the upper and lower borders diminished, with unusual values of 0.51 and 0.54. The primary reason is that, although general regional variability diminished, the water use efficiency of Huainan City and Anqing City remained inferior to that of other municipalities that year.

Among the 16 prefecture-level cities in Anhui Province, 10 exhibited a water use efficiency trend that aligns with the provincial pattern, demonstrating a fluctuating upward trajectory. Hefei City, Ma'anshan City, and Wuhu City had a pronounced upward trend, with water use efficiency in 2022 surpassing 2012 by over 0.5. Hefei City increased from 0.309 in 2012 to 1.028 in 2022. The primary reason for this was the introduction of the "three red lines" for water resource management in Hefei City in 2016, which rigorously regulated overall water use and consequently enhanced water use efficiency. Six prefecture-level cities exhibited variable declines in water use efficiency. Fuyang City exhibited a notable declining tendency, with a reduction of 16.42% in 2022 compared to 2012. The efficiency of water resource consumption in Bozhou City, Huainan City, Xuancheng City, and Tongling City exhibited a declining trend of less than 0.1.

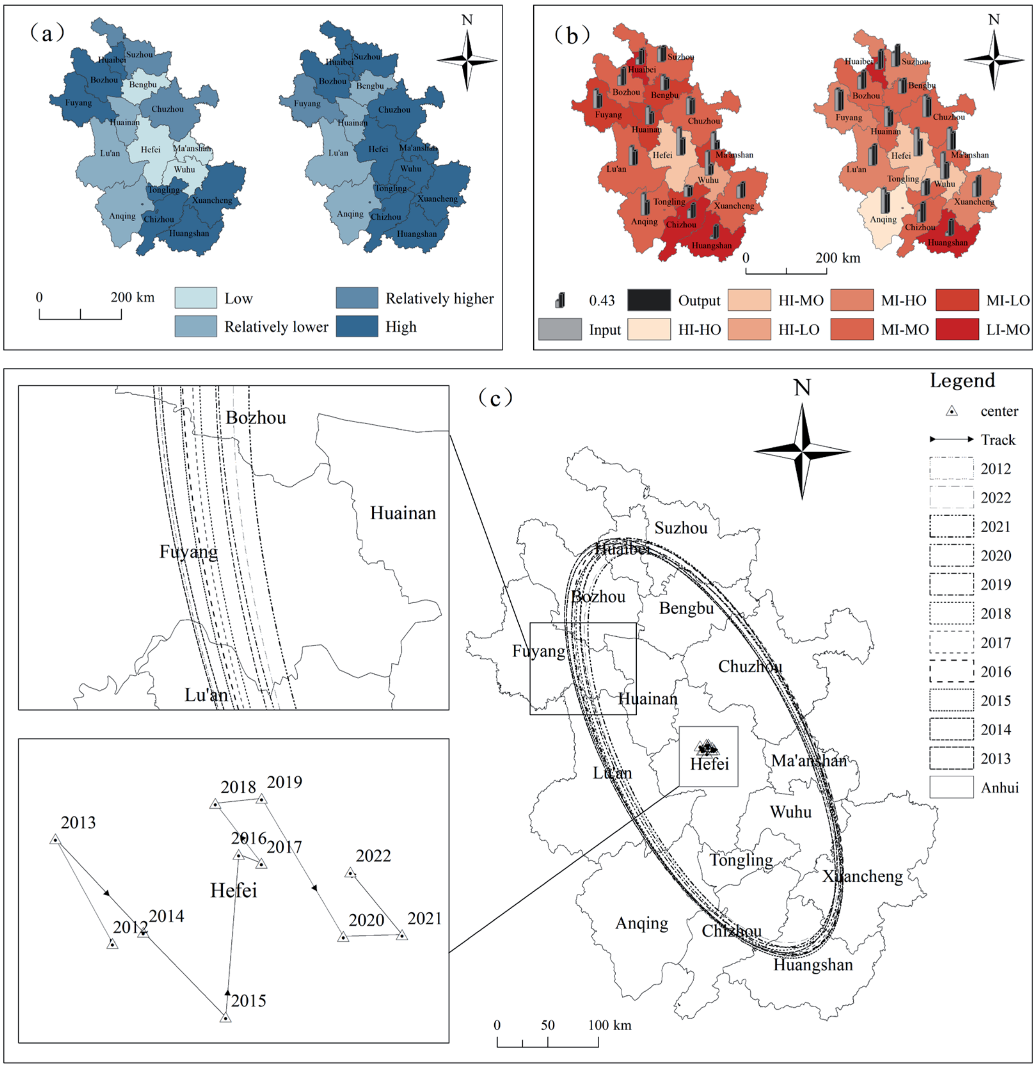

Fig. 3. Spatial distribution of water use efficiency in 16 cities of Anhui Province.

Spatial Evolution Pattern of Water Use Efficiency in Anhui Province

According to the natural breakpoint method, the water use efficiency in Anhui Province is divided into 4 categories: 0,0.4925 is low efficiency, 0.4925,0.6851 is relatively lower efficiency, 0.6851,0.9144 is higher efficiency, and 0.9144,1.103 is high efficiency. Then, the water use efficiency of 16 cities in Anhui Province for the years 2012 and 2022 is illustrated in Fig. 3a). Subsequently, based on RSR thresholds in grades, we obtained the water use efficiency input and output values for 16 cities in Anhui Province for the years 2012 and 2022, together with the regional division results depicted in Fig. 3b).

As shown in Fig. 3a), from the perspective of overall distribution, the water use efficiency of each city in Anhui Province exhibited significant regional diversity in 2012 and 2022. The spatial distribution of efficiency levels gradually transitioned from "high in the north and south and low in the center" in 2012 to "high in the east and low in the west" in 2022. In 2012, the seven high-efficiency cities were Huaibei City, Bozhou City, Fuyang City, Tongling City, Chizhou City, Huangshan City, and Xuancheng City. Among them, Chizhou City, Huaibei City, and Huangshan City ranked in the top three for water use efficiency. According to Fig. 3b), these three cities were classified as the LI-MO type. It can be seen that these three cities were characterized by a "low input – medium output" phase, marked by reduced water use and a greater focus on sustainable development. Municipalities with water use efficiency at relatively lower levels included Suzhou and Chuzhou. Both were classified as MI-MO type cities. Industrial water consumption only accounted for 53.77% and 56.74% of the provincial average, and sewage discharge accounted for 48.83% and 56.96% of the provincial average. This results in a high level of water use efficiency. Three prefectural-level cities had water use efficiency at a relatively lower level, while four others had water use efficiency at a low level. Among them, Huainan City, Bengbu City, and Ma'anshan City were all MI-LO type

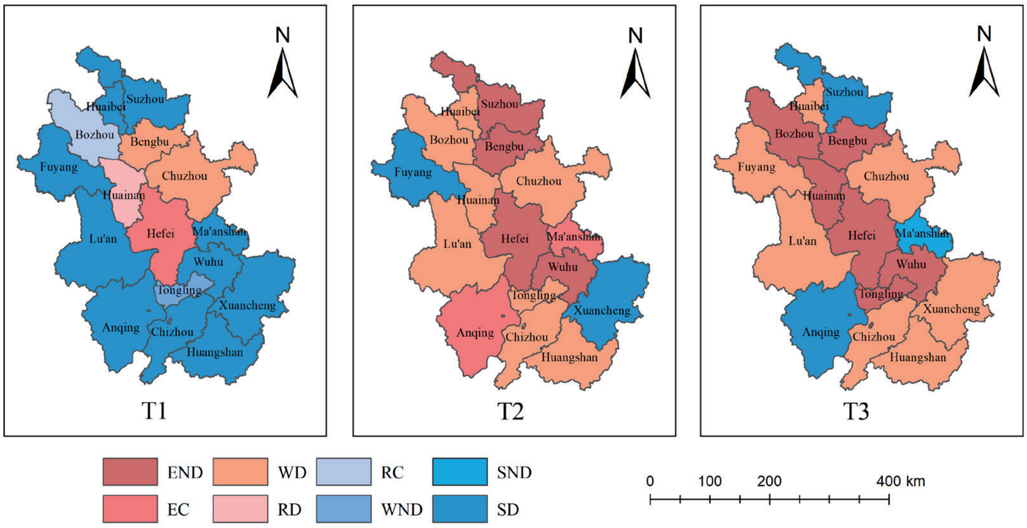

Fig. 4. Decoupling of water use efficiency and economic development in municipalities in Anhui.

cities characterized by poor water resource output. This is mainly attributable to the expansion of industrial enterprises, resulting in sewage discharge levels above the provincial averages by 1.95%, 50.76%, and 60.89%, respectively. As regions with advanced economic development, Hefei City and Wuhu City were classified as HI-MO and HI-LO types, respectively. Their substantial resource input led to high sewage output, rendering the water use efficiency comparatively low. This indicates a non-essential link between economic development and water use efficiency.

In 2022, Anhui Province showed higher water use efficiency in the eastern region and lower efficiency in the western region, contrasting with the situation in 2012. The overall level of water use efficiency in Anhui Province was enhanced by 2022. The number of municipalities attaining high and relatively higher levels increased from 9 in 2012 to 12 in 2022. Seventy-five percent of the overall research region was comprised of communities that have attained a reasonably higher level or above. The number of low-efficiency municipalities decreased from 4 in 2012 to 0 in 2022. Specifically, of the seven cities that achieved a high-efficiency level in 2012, six cities – Bengbu City, Huaibei City, Tongling City, Chuzhou City, Huangshan City, and Xuancheng City – sustained their high-efficiency status in 2022. Meanwhile, 6 out of 16 cities showed increasing levels of water use efficiency, and 3 prefecture-level cities transitioned from low efficiency to high efficiency. Among them, both Hefei City and Wuhu City were classified as HI-MO type in 2022. It indicated that improving the economic development level can elevate the water use efficiency to reach a higher level. Nonetheless, the high investment in the economy and resources remains an inadequate long-term solution, and the sustainable development of resources should be prioritized. Bengbu shifted from low efficiency to relatively lower efficiency, moving from MI-LO type in 2012 to MI-MO type in 2022, with wastewater discharges increasing by just 36.48% of the total increase. Two municipalities transitioned from relatively higher efficiency to high efficiency, including Chuzhou City and Suzhou City. Chuzhou City remained in the MI-MO type, accompanied by a 17.01% enhancement in output efficiency. Suzhou City transitioned from the MI-MO type to the MI-HO type, advancing from medium to high output while maintaining the same input level.

In order to more intuitively analyze the spatial pattern of the overall water use efficiency in Anhui Province, the standard deviation ellipse and spatial movement trajectory for the years 2012-2022 are illustrated in Fig. 3c). Throughout the study period, the center of gravity of water use efficiency in Anhui Province has been in Hefei City, situated in the central region of the study area. The center of gravity of water use efficiency in the area from 2012 to 2022 showed a "W"-shaped migration towards the east. It indicates that although the water use efficiency in Anhui Province is reasonably consistent, the eastern region has broken the previous trend of "high in the west and low in the east" by virtue of its leading advantage in economic development. The maximum distance of 6.63 km was shifted towards the southeast in 2019-2020, indicating that the development of water use efficiency in 2020 was better in the southeast than in the northwest. The alteration in the standard deviation ellipse indicated a slight reduction in the long axis length. The length decreased from 225.67 km in 2012 to 211.10 km in 2022, while the short axis did not change significantly for the time being, but the ellipse flattening gradually narrowed. It can be seen that the water use efficiency in Anhui Province gradually presented a "southwest-northeast" contraction distribution. Water use efficiency improvement in the northeast should focus on addressing water quality issues, particularly groundwater contamination with heavy metals that exceed permissible limits. While the southwest has abundant rainfall, enhancing water use efficiency should prioritize addressing the issue of the temporal and spatial unevenness of water resource distribution.

The Decoupling of Water Use Efficiency and Economic Development in Anhui

Table 3 shows the decoupling status of water use efficiency and economic development in Anhui Province and in subregions from 2012 to 2022. From an overall perspective, there were three expansive connections, three weak decouplings, and four strong decouplings in Anhui Province as a whole during the study period, with the decoupling status exhibiting a tendency of stage fluctuation. Expansionary negative decoupling transpired over the three backward time periods of 2018-2019, 2020-2021, and 2021-2022. Water use efficiency has increased by 8.54%, 16.28%, and 4.55%, respectively, while economic development has progressed by 4.43%, 7.23%, and 1.18%, respectively. Weak decoupling occurred in 2013-2014, 2016-2017, and 2017-2018. Water use efficiency has increased by 0.71%, 4.94%, and 3.92%, and economic development level has increased by 1.80%, 7.96%, and 10.32%, respectively. It can be seen that the overall water use efficiency and economic development in Anhui Province have progressively achieved benign coordination. Strong decoupling occurred in 2012-2013, 2014-2015, 2015-2016, and 2019-2020. The data indicates that despite economic development growth, the level of water use efficiency declined by 6.29%, 6.20%, 0.16%, and 6.36%, respectively. Over these years, evident discrepancies were seen between water use efficiency and economic development. The primary cause of this phenomenon is that before 2016, Anhui Province was undergoing a shift from resource-consuming rough development to environment-friendly intensive development. The green development concept of water-efficient use needs to be perpetually popularized.

From a zoning perspective, there were significant differences in the decoupling status between regions. Northern Anhui Province had the most volatile decoupling status, experiencing six distinct states during the 11-year duration. However, water use efficiency showed an increasing trend from 2016 to 2022, culminating in a maximum increase of 8.54%. This indicated that water use efficiency in the northern Anhui region showed a positive developmental trend. Southern Anhui Province experienced a period of weak decoupling from 2016 to 2018, which was followed by a stabilization of an expansive negative decoupling from 2018 to 2021. The water use efficiency exhibited an increasing trend from 2016 to 2022, with a maximum increase of 16.73%. Middle Anhui Province recorded the highest frequency of expansive negative decoupling and expansive coupling from 2012 to 2022, with six instances over the 11-year span and the greatest increase in the efficiency value of 13.92%. It indicates that its water use efficiency and economic development are in the stage of simultaneous improvement.

In order to visualize the decoupling status of the municipalities, the entire study period was segmented into three phases: 2012-2015 (phase T1), 2016-2018 (phase T2), and 2019-2022 (phase T3), as depicted in Fig. 4. During the T1 stage, ten prefectural-level cities in Anhui Province exhibited a strong decoupling status between water use efficiency and economic development level. This indicates that, although the economic development of these 10 cities was advancing, the water use efficiency was declining.

Table 3. Subregional decoupling of water use efficiency and economic development.

	Northern Anhui	Southern Anhui	Middle Anhui	Anhui Province
2012-2013	Recessive decoupling	Strong decoupling	Strong decoupling	Strong decoupling
2013-2014	Weak negative decoupling	Expansive negative decoupling	Strong decoupling	Weak decoupling
2014-2015	Strong decoupling	Strong decoupling	Expansive coupling	Strong decoupling
2015-2016	Weak decoupling	Strong decoupling	Expansive negative decoupling	Strong decoupling
2016-2017	Weak decoupling	Weak decoupling	Expansive negative decoupling	Weak decoupling
2017-2018	Weak decoupling	Weak decoupling	Weak decoupling	Weak decoupling
2018-2019	Expansive coupling	Expansive negative decoupling	Expansive negative decoupling	Expansive negative decoupling
2019-2020	Strong decoupling	Expansive negative decoupling	Strong decoupling	Strong decoupling
2020-2021	Expansive coupling	Expansive negative decoupling	Expansive negative decoupling	Expansive negative decoupling
2021-2022	Expansive negative decoupling	Strong negative decoupling	Expansive negative decoupling	Expansive negative decoupling

Huainan City experienced the most rapid reduction in efficiency, with a drop of 30.84%, and its value added output merely accounted for 60.57% of the input value added. The decoupling types of Tongling City, Bozhou City, and Huainan City were characterized as weak negative decoupling, recessive coupling, and recessive decoupling, indicating that the water use efficiency and economic development level were declining at the same time. Bozhou City experienced the most noticeable decline in economic development, with a recorded rate of 21.40%. The primary cause of this decline was Bozhou City's experience with structural adjustment challenges and a shift in the economic growth rate during the 12th Five-Year Plan period. The decoupling types of Hefei City, Bengbu City, and Chuzhou City were expansive coupling, weak decoupling, and weak decoupling, indicating simultaneous growth in the water use efficiency and economic development level across the three cities. The growth rates of water use efficiency and the economic development level in Hefei City were 5.14% and 5.32%, respectively. The development of the two was more balanced.

During the T2 stage, the majority of cities have experienced an enhancement in the decoupling of water use efficiency and economic development. The number of cities exhibiting expansive negative decoupling, expansive coupling, and weak decoupling has increased significantly. The number of expansive negative decoupling cities increased from 0 to 4; expansive coupling cities went from 1 to 2, and weak decoupling cities rose from 2 to 8. This indicates that several municipalities in Anhui Province experienced a concurrent enhancement in their economic development and water use efficiency from 2016 to 2018. However, there remains potential for enhancement in water use efficiency in Anhui Province. In particular, Fuyang City and Xuancheng City remained in a strong decoupling state, with water use efficiency decreasing by 3.78% and 11.47%, respectively. The sewage discharge in Xuancheng City has even increased by 59.79%. The main reason for this decrease is that, at this stage, the two cities showed a significant disparity between water resource supply and demand, excessive water consumption, and substantial sewage output.

During the T3 stage, most cities in Anhui Province have reached a well-coordinated relationship between water use efficiency and economic development level. The number of expansive negative decoupling cities increased from 4 in the T2 stage to 6 in the T3 stage, indicating that the rate of improvement in water use efficiency surpassed that of economic development. Nonetheless, Suzhou City and Anqing City showed a strong decoupling rebound phenomenon, mostly affected by the increase in agricultural and domestic water consumption. It is worth noting that Ma'anshan City experienced strong negative decoupling during this period, and its reliance on a single industrial structure had reduced its economic development level. To summarize, the development trend of the decoupling status between water use efficiency and economic development is getting better and better in the T1~T3 stages in Anhui Province, with an increasing number of municipalities exhibiting expansive negative decoupling types in segments.

Discussion

Coordinating the relationship between water resource utilization and economic development is crucial for fostering the construction of resource-saving and environment-friendly cities. In measuring water use efficiency in Anhui Province, most studies only analyze the variations in efficiency and the spatial and temporal distribution across each prefecture-level city [34] or simply analyze its superficial influence. For instance, Jiao Shixing et al. asserted that advancements in social civilization could influence the enhancement of water use efficiency [35], but they failed to take into account the direct influence of sub-regional input-output grading on water efficiency. The efficiency of each region is affected not only by the external environment but also by the variability in the hierarchy of input and output norms in different municipalities. Unlike the last study, which only graded the efficiency results, this study uses the rank-sum ratio to sort the water input and output elements into groups for city classification after screening indicator elements. It also looks into how changes in water use efficiency affect the changes in the city's input-output hierarchy. For example, Bengbu City has improved its water use efficiency. The regional grading type reveals that Bengbu City has transitioned from an MI-LO type to an MI-MO type, signifying an improvement in its output impact. The main explanation is that the increasing rate of wastewater discharge has slowed since 2012, and a decline commenced in 2016, with a 5.54% decrease in emissions by 2022.

The overall water use efficiency in Anhui Province showed a "W" type fluctuation and an upward trajectory. In terms of time distribution, water use progressively achieved an effective level throughout the period from 2018 to 2019. This aligns with the findings of Ma Huijun et al. [36], which state that water use efficiency in Anhui province exhibited significant fluctuations and reached an effective level in 2018. Further analyzing the reasons for the fluctuating state of its water use efficiency, Anhui Province, situated in the lower reaches of the Yangtze River Basin, possesses abundant water resources; however, it trails other provinces in economic development, leading to suboptimal allocation and utilization of these resources [37]. However, the development trend of water use efficiency in Anhui Province was good. The main reason is that Anhui province spans three major river basins, the Yangtze River, the Huaihe River, and the Xin'an River, and policies such as ecological compensation and water ecological environment monitoring and assessment in each basin play an important role in improving water use efficiency [38]. The spatial distribution of water use efficiency in Anhui Province has shifted from “high in the north and south, low in the middle” to “high in the east and low in the west". The eastern region has disrupted the initial "high in the west and low in the east" pattern by leveraging its dominant position in economic development. It can be seen that the water use efficiency in Anhui Province exhibited significant spatial diversity. Hefei City and Wuhu City, classified as HI-MO types in 2022, prioritized economic development to enhance water use efficiency. Pan Qiangwei et al. [39] also considered that the water use efficiency of Hefei City in Chaohu Lake Basin was at a high-grade level, but the difference was that he considered that the water use efficiency of Hefei City showed a decreasing trend. This paper argued that the efficiency of the two cities over the study period increased more rapidly, with Hefei City exhibiting a consistent year-on-year upward trend. This indicates that the improvement of economic growth, to a certain extent, promotes the enhancement of the rational allocation capacity of water resources. This aligns with the research findings of Zhao Yexin et al. [40], which show a correlation between the level of water use and economic development. Consequently, the water resource management system should be executed in accordance with local conditions. Classification and zoning policies should be implemented to maintain the matching degree between water consumption and economic output, according to the actual situation of input-output and each city’s level of economic development. These approaches can jointly promote the coordinated and sustainable development of water resources, the economy, and ecology.

From 2012 to 2022, Anhui province exhibited a concurrent increase in water use efficiency and economic development, with the decoupling state demonstrating a pattern of phase variation. 2016 saw the transition of Anhui province from a state of strong decoupling to one of weak decoupling and expansive negative decoupling. This is different from the conclusion of Li Baochun et al. [41], which indicated that Anhui Province has remained in a prolonged weak decoupling state. The reason is that in 2016, Anhui Province was transitioning from a resource-consuming to an environmentally friendly municipality. The Outline of the Development Plan for the Yangtze River Economic Belt, approved by the Political Bureau of the CPC Central Committee in March of the same year, has a positive effect on promoting the improvement of water use efficiency [42]. The decoupling status of municipalities in Anhui Province in the T1-T3 stages gradually approached the optimal condition. The number of prefectural-level cities with expansive negative decoupling types has been progressively rising, with 13 cities achieving simultaneous growth in water use efficiency and economic development during the T3 stage. This indicates that the construction of environmentally friendly cities in Anhui Province has begun to yield results. It should actively promote the transformation and upgrading of green industries in Anhui and strengthen the influence of well-decoupled regions. Simultaneously, we should leverage regional advantages to propel overall development while imposing strict constraints on water resources to foster the development of distinctive low-water-consumption agricultural industries.

This paper possesses specific constraints. (1) This research analyzes the evolutionary trend of water usage efficiency in Anhui Province from temporal and spatial perspectives, although it inadequately illustrates the impact of water resource mobility on interregional relationships. Future consideration may be given to expanding the study area. (2) Due to the volatility of water supplies and the swift pace of economic development, the selection of indicators in this study must be more dynamic. Future research on the interrelated dynamics of water use efficiency and economic development should involve the optimization and correlation analysis of relevant indicators, alongside a comprehensive evaluation of various treatment models, to further investigate the driving factors behind the decoupling of water use from economic growth.

Conclusions

This paper took 16 prefectural-level cities in Anhui Province as the research object from 2012 to 2022 and explored the spatial and temporal evolution patterns of water use efficiency in each city via the lenses of inputs and outputs. It also applied the decoupling model to investigate the relationship between water use efficiency and economic development. The conclusions are as follows:

(1) From 2012 to 2022, the water use efficiency in Anhui Province fluctuated in a "V" type, with an increasing trend observed. The average value ranged from 0.673 to 0.907. 10 cities had a change in water use efficiency consistent with the overall trend. Among them, Hefei City, Maanshan City, and Wuhu City had a more obvious upward trend, while Fuyang City demonstrated the most significant downward trend.

(2) The spatial distribution of water use efficiency in Anhui Province has gradually changed from “high in the north and south, low in the middle” in 2012 to “high in the east and low in the west” in 2022. The spatial center of gravity shifted eastward in a “W” shape. There were obvious spatial differences in the water use efficiency of each city. The number of prefectural-level cities with high and relatively higher water use efficiency increased from 9 in 2012 to 12 in 2022, while the number of low-efficiency cities decreased from 4 in 2012 to 0 in 2022.

(3) Overall, water use efficiency and economic development in Anhui Province have progressively achieved benign coordination from 2012 to 2022. The decoupling status showed a fluctuating trend. The number of prefectural-level cities with expansive negative decoupling has risen annually. 13 cities have achieved synchronized growth in water use efficiency

and economic development at the T3 stage. Significant regional disparities were seen, with southern Anhui exhibiting the most instability and lagging, while middle and northern Anhui were in a more advantageous decoupling state.

Policy Implications

The findings of the aforementioned study indicate the direction of development of water resource usage across various regions of Anhui Province. To scientifically and rationally optimize water resource utilization across Anhui Province and enhance efficiency, the following recommendations are proposed based on input and output city classification.

(1) HI-LO, HI-MO, and HI-HO type cities will be designated locations with significant water use restriction zones. Regions such as Hefei and Anqing, characterized by a significant reliance on agricultural water, should regard water resources as a stringent limitation, optimize crop selection, advance water-efficient irrigation technologies, cultivate specialized low-water-consumption agricultural sectors, and enhance the efficiency of agricultural water utilization. Wuhu City and other regions with significant industrial water usage should proactively advance the transformation and enhancement of green industries, intensify the oversight and management of industrial water consumption reduction, and implement a target accountability system for industrial water conservation and emission reduction.

(2) MI-LO, MI-MO, and LI-LO type cities will be classified as high pollution control zones. Bengbu City, Huainan City, Maanshan City, and other regions with significant sewage discharge should enhance government regulation, fortify the water resources management system, rigorously regulate sewage discharge, and ameliorate the aquatic ecological environment. Chuzhou City, Chizhou City, and other areas with low sewage treatment rates should fully leverage market regulatory mechanisms, establish appropriate environmental tariffs, compel firms to pursue technological innovation, enhance water resource reuse rates, and promote a circular economy.

(3) LI-HO, MI-HO, and LI-MO type cities will be classified as high-efficiency demonstration zones. Despite being high-efficiency demonstration zones for water resources, Lu'an City, Huangshan City, and Xuancheng City have significant deficiencies in economic development. These cities ought to profit from the radiation-driven function of an effective decoupling area and, by virtue of their advantageous geographical position, persist in advancing the high-quality development of cultural and tourism integration through various avenues, augment the capacity for innovation and development, and achieve synergy between water resource utilization and economic growth.

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Conflict of Interest

The authors declare no conflict of interest.

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