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Water resource utilization efficiency and driving factors in northern Anhui (China) based on the DEA-Malmquist model

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ABSTRACT

Based on the DEA-Malmquist method, this study analyzes water resource utilization efficiency in six cities of the northern Anhui region. The input indicators covered per capita water resources, industrial water consumption, agricultural water consumption, domestic water consumption, fixed assets investment, and number of employees. The output indicator was per capita GDP of each city. The findings of the study revealed that only Huaibei achieved efficiency according to the DEA model, while the other cities in the northern Anhui region did not exhibit the same level of efficiency. The overall water resource utilization efficiency in the region was low, with significant variations among the cities ($p \leq 0.05$; ANOVA test). The order of water resource utilization efficiency from high to low was Huaibei, Huainan, Bengbu, Bozhou, Suzhou, and Fuyang. An analysis of investment redundancy revealed that a large number of employees and an unreasonable water use structure were key factors that restricted the efficiency of water resource utilization in the region. The overall TFP index of water resource utilization efficiency in the region showed an upward trend, with a value of 1.02. By addressing them, decision-makers can work toward promoting sustainable economic development and effective water resource management in the region.

Key words: Anhui province, Malmquist index, utilization efficiency, water resources

HIGHLIGHTS

- When establishing evaluation indicators, water resource conditions, socio-economic conditions, and water use structure factors can reflect the actual situation.
- There are significant regional differences in the utilization of water resources in the northern Anhui region.
- Technological progress is driving factor for water resource utilization efficiency in the northern Anhui region as references for decision-makers.

1. INTRODUCTION

China possesses a vast territory and relatively abundant total water resources. However, the country's per capita water resources are limited, while the distribution of water resources across the country is uneven. Consequently, China has been designated as a 'water-scarce' country by the United Nations (UN) (Fu *et al.* 2017).

In recent years, water resources have emerged as a constraining factor for China's sustainable socio-economic development (Li *et al.* 2021a). Considering the comprehensive impact of global climate change, economic and population growth, conflict between water demand and water resources will increasingly become acute, especially in economically underdeveloped agricultural areas. For this reason, accurate evaluation and gradual improvement of water resource utilization efficiency are crucial to promote sustainable development of water resources and identify the driving factors for an efficient utilization of water resources in different regions. It is an ideal approach to solve the current water resource problem in northern Anhui (He *et al.* 2021; Yang 2021; Zhang *et al.* 2022).

'Northern Anhui (China)' generally refers to the areas north of the Huaihe River and across the River in Anhui province, including six prefecture level cities: Huainan, Bengbu, Suzhou, Fuyang, Huaibei, and Bozhou. In 2020, the total population of the six cities in the northern Anhui accounted for 44% of the total population of the Anhui province. However, their GDP only represented 29% of the province, while the average annual water resources availability only accounted for 13% of the province's allocation. Hence, there are substantial disparities between the northern Anhui and the southern Anhui in terms of socio-economic conditions and water resources (Kurniawan *et al.* 2011).

In general, there are significant differences in water resource utilization efficiency between the two different regions due to various factors. As an important base for coal, energy, and agriculture in the Anhui province, northern Anhui is a typical representative area with relatively backward economy, low water resources, large population, and high water pressure (Liang & Huang 2014). Based on the analysis of water resource carrying capacity in the Anhui province, the northern region of Anhui has experienced periodical water resource shortages. Compared to the southern Anhui, the development of mining and chemical industries, as well as non-point source pollution and groundwater overexploitation, have seriously damaged water ecology. As a result, the water resource carrying capacity in northern Anhui is insufficient (Chen *et al.* 2022; Jiang & He 2023). Therefore, the water resource utilization efficiency of northern Anhui needs to be evaluated, as it is an important part of the sustainable development of water resources and social economy in Anhui province, and has practical significance to achieve a healthy socio-economic development in the northern region of the province.

Researchers from around the world and China have systematically evaluated water resource utilization efficiency. Currently, the most popular methods are analytic hierarchy process (AHP) (Shabbir & Ahmad 2016), water footprint method (WFM) (Chen *et al.* 2021), data envelopment analysis (DEA), and stochastic frontier approach (SFA) (Liu *et al.* 2019). Among these methods, the combined model based on the DEA-Malmquist is widely used for evaluating water resource utilization efficiency (Zheng *et al.* 2020; Xie *et al.* 2021). In the context of climate change, Zhang *et al.* (2023) analyzed the main influencing factors of water use in various sectors using the DEA-AHP combination model. Ying *et al.* (2021) analyzed and evaluated the efficiency and influencing factors of water resource utilization in Henan province using the DEA-Tobit combination model. Although the DEA model can comprehensively evaluate water resource utilization efficiency, it can only achieve a static evaluation of water resource utilization efficiency. In order to further conduct dynamic evaluation and analyze the driving factor of water resource utilization efficiency, the Malmquist productivity index model was introduced in this study.

Previous studies have utilized the Malmquist index model to dynamically analyze regional water resource utilization efficiency (Ali & Klein 2014; Sun *et al.* 2019; Cheng *et al.* 2022). However, they did not consider the influencing factors of water use efficiency when using the DEA-Malmquist model for evaluation, nor evaluated the trend of water resource utilization efficiency based on the TFP index value. Without decomposing the TFP value, it is difficult to further analyze the root causes of efficiency changes. In order to demonstrate its novelty, this article investigates various factors such as water resource conditions, socio-economic conditions, and water use structure as input indicators when establishing the model, and conduct statistical analysis based on a long series of 10-year data (2011–2020). For this purpose, the DEA-BCC is used to calculate its water use efficiency level, while the Malmquist index is introduced to analyze dynamic change. Decomposing the Malmquist index is used to identify the driving factors for an efficient water use in the study area (Qiu & Sheng 2020).

With respect to water resource utilization efficiency, different scholars have evaluated it based on time and spatial scales. For instance, Qin *et al.* (2023) calculated the spatial distribution differences of water resource utilization efficiency in Central Asia from 2001 to 2021 based on a long series of data analysis. Hatamkhani & Moridi (2021) considered the interaction of water supply and demand according to economic and social factors. They employed a multi-objective optimization model to optimize the utilization efficiency of agricultural water resources. Pang & Zhou (2020) conducted a comprehensive evaluation and analysis of the seven major watersheds in China. Their study revealed variations in water resource utilization efficiency among the watersheds, with scale efficiency being identified as the primary driving factor. Wang *et al.* (2022a) analyzed and calculated the dynamic evolution trend and driving factors of water resource utilization efficiency in nine provinces within the Yellow River Basin (China). Their research has shown regional differences in the level of water resource utilization efficiency (Zhu & Liang 2015; Hai *et al.* 2018), natural factors (water resource endowment conditions), economic development level, sustainable utilization level, technological progress, humanistic literacy, and water resource management measures (Avarideh *et al.* 2017; Moridi *et al.* 2018).

While all have a significant impact on water resource utilization efficiency, the impact of water resource endowment conditions on areas with low water use efficiency is significant. However, the impact on areas with medium and high water use efficiency is not significant (Qian & He 2011). Based on the analysis of water use structure, an increase in the proportion of primary industry improves the efficiency of water resource utilization, while an increase in the proportion of agricultural water will reduce the efficiency of water resource utilization (Ying *et al.* 2021). Wang *et al.* (2022b) found that there is no mutually beneficial relationship between urbanization and water resource utilization in most regions of China. Chen *et al.* (2019) studied the spatial spillover effect of marketization on the water resource utilization efficiency in China. The regression results show that the marketization has a positive spatial spillover effect on the water resource utilization efficiency in China.

As reflected by the literature survey, input indicators are not comprehensive when establishing the DEA-Malmquist models. Therefore, when establishing evaluation indicators in this study, full consideration was given to factors that may affect the efficiency of water resource utilization such as water resource conditions, socio-economic factors, labor force, and water use structure to reflect a comprehensive utilization efficiency of regional water resources (Kurniawan *et al.* 2010).

To the best of our knowledge, so far none has studied the comprehensive utilization efficiency of water resources in northern Anhui based on the long series of Panel data using statistical methods, nor identified the driving factors of efficient water use. Therefore, with respect to regional differences in water pressure and water resource utilization efficiency in the northern Anhui region, to investigate the current status of water resource utilization and the driving factors in the 'North Anhui' region, the DEA-Malmquist model is employed for the analysis and evaluation of water resources.

In order to demonstrate its novelty, this article investigates various factors such as water resource conditions, socio-economic conditions, and water use structure as input indicators when establishing the model, and conduct statistical analysis based on a long series of 10-year data 2011–2020. The DEA-BCC model is used to calculate water resource utilization efficiency based on a long series of data, while the Malmquist index is utilized to analyze the dynamic changes in water resource utilization efficiency. Simultaneously, this study decomposes the TFP value, which can be used to further analyze the driving factors of efficient water resource utilization.

To bridge the knowledge gaps in the body of literature, this work has specific objectives as follows: (1) To analyze and calculate the level of comprehensive utilization efficiency of water resources under its water resource conditions, socio-economic structure, and water use structure. (2) To study the spatial distribution characteristics of water resource efficiency in the northern Anhui region, and identify the main factors that constrain the low comprehensive efficiency of water resource utilization in different cities through investment redundancy analysis. For this purpose, a dynamic analysis of water resource utilization efficiency was conducted using the Malmquist productivity index, and the driving factors for improving water resource utilization efficiency in northern Anhui were identified through index decomposition. Based on the findings, various suggestions are recommended to protect water resources and improve water resource utilization efficiency.

It is expected that this research result can provide useful inputs for formulating effective policies, strategies, and actions to optimize water resource management in the region to improve water resource utilization efficiency and sustainable development in the northern Anhui region in the future. It is anticipated that this would provide references for alleviating the contradiction between supply and demand of regional water resources, while promoting the construction of a water-saving society, and contributing to the development and well-being of the northern Anhui region (Fu *et al.* 2018).

2. OVERVIEW OF RESEARCH AREA

The northern part of Anhui province, referred to as 'northern Anhui', is the Yangtze River Delta region of China and the only area where the 'the Belt and Road' passes through the province. The regional terrain is mainly plain, with a land area of approximately 39,000 km^2 and a population of approximately 26.8 million in 2020. The northern Anhui region belongs to a warm temperate with semi-humid monsoon climate zone, with a mild climate and distinct four seasons. The average annual rainfall is about 950 mm. All rivers within the territory belong to the Huaihe River system, with a total annual water resource of about 9.652 billion m^3. Although groundwater resources are relatively abundant, there is a problem of local groundwater overexploitation. Presently, the water resource situation in the northern Anhui region is in an overloaded state, due to the small support and regulation capacity of water resources in the region, as well as the high pressure, resulting in an unfavorable final water resource situation (Jin *et al.* 2019). With the changing global climate, average drought duration ranged between 3.29 and 3.69 months in the study area. The highest values of moderate, severe, and extreme droughts occurred in the northern part of Anhui province (Wang *et al.* 2019).

3. DATA SOURCES AND METHODS

3.1. Data collection

All data in the article were obtained from the 'Anhui Statistical Yearbook' and 'Anhui Province Water Resources Bulletin' that covered the period between 2011 and 2020. These bulletins are directly available on the website, including http://slt.ah.gov.cn/ and http://tjj.ah.gov.cn/.

3.2. Research methods

3.2.1. DEA model

This work utilized the DEA model, which enabled an effective analysis and evaluation of decision-making units (DMUs) based on multiple inputs and outputs using mathematical planning and statistical data (Ma 2007). DEA did not assume the weight values of inputs and outputs, but optimized weights from actual data, thereby avoiding subjective biases. It has been widely employed in the evaluation and analysis of water resource efficiency.

The two commonly used DEA models are the constant return scale (CRS) model and the variable return scale (VRS) model. The CRS model assumes a CRS, surmising that all evaluated DMUs are operating at the optimal production scale, which does not reflect changes in regional comprehensive water use efficiency. On the other hand, the VRS model assumes the VRS, adding constraints to the Banker–Charnes–Cooper (BCC) model, as compared to the Charnes–Cooper–Rhodes (CCR) model. By solving the BCC model, one can obtain comprehensive technical efficiency, and scale efficiency, facilitating further analysis of water resource utilization efficiency and its influencing factors (Li *et al.* 2021b).

For this study, the BCC model was adopted, considering DMUs, each with m inputs and t outputs. The weight vector of inputs and outputs is denoted as λ_j. The model expression is presented in Equation (1):

$$\begin{cases} \min\left[\theta - \varepsilon\left(\sum_{i=1}^{t} s_r^+ + \sum_{r=1}^{m} s_i^-\right)\right] \\ \sum_{j=1}^{n} x_j\lambda_j + s_i^+ = \theta x_0 \\ \sum_{j=1}^{n} y_j\lambda_j - s_r^+ = y_0 \\ \sum_{j}^{n} \lambda_j = 1 \\ \lambda_j \geq 0,\ \ (j = 1, 2, \ \ldots, n) \end{cases} \tag{1}$$

In Equation (1), ε represents the non-Archimedean infinitesimal, often assigned a value of 10^6. This infinitesimal value was used to handle numerical approximations and ensure mathematical precision in the DEA model, while s_r^+ represents the output relaxation variable, which is a non-negative value ($s_r^+ \geq 0$). It was used in the DEA model to relax the constraints on output variables, allowing for flexibility in evaluating the efficiency of water resource utilization. s_i^- represents the input relaxation variable, which is also a non-negative value ($s_i^- \geq 0$). It served a similar purpose to s_r^+, but applied to input variables, providing flexibility in assessing the efficiency of water resource utilization (Li & Ren 2018).

θ is the comprehensive efficiency evaluation index for water resources. Its value was determined through the DEA model and represented the efficiency level of the DMU in utilizing water resources. When θ is equal to 1, it indicates the DMU is DEA efficient. This indicates that it has achieved optimum water resource utilization with both pure technical efficiency and scale efficiency being effective. When θ is less than 1, it suggests the DMU is DEA inefficient, indicating that either the pure technical efficiency or scale efficiency is ineffective. A higher value of θ (closer to 1) signifies a higher level of efficiency in water resource utilization.

When the value of θ is equal to 1 in the DEA model, it indicates that the DMU is deemed DEA efficient. This means that the water resource input and output levels have reached an optimal state, and both the pure technical efficiency and scale efficiency are effective. On the other hand, when the value of θ is less than 1, it signifies that the DMU is considered DEA inefficient. This implies that either the pure technical efficiency or the scale efficiency of the DMU is ineffective. Moreover, the closer the value of θ is to 1, the higher the efficiency of the DMU. In other words, as θ approaches 1, it indicates that the DMU is operating closer to its optimal level, demonstrating an improved efficiency in water resource utilization.

3.2.2. Malmquist productivity index model

The DEA model's research on water resource utilization efficiency is basically static comparison, and the introduction of the Malmquist index model can further study the dynamic changes in regional water resource utilization efficiency. The Malmquist productivity index was first proposed by Malmquist, a Swedish economist and statistician, in 1953. In 1995, Rolf *et al.* combined a non-parametric linear programming method of this theory with DEA, and the combination of the two was widely used to measure dynamic efficiency across time periods.

This analysis method can measure the dynamic changes in total factor productivity (TFP_{ch}) period by period, and decompose water use efficiency into technical changes (TE_{ch}) and efficiency changes (EFF_{ch}). By assuming variable economies of scale (VRS), efficiency changes are further decomposed into pure technical efficiency changes (PE_{ch}) and scale efficiency changes (SE_{ch}). The expression is presented in Equation (2) (Sun *et al.* 2018; Zheng 2021):

$$\begin{aligned}
&M(x^{t+1}, y^{t+1}, x^t, y^t) = \frac{D^{t+1}(x^{t+1}, y^{t+1})}{D^t(x^t, y^t)} \times \sqrt{\frac{D^t(x^t, y^t)}{D^{t+1}(x^{t+1}, y^{t+1})}} \times \sqrt{\frac{D^{t+1}(x^{t+1}, y^{t+1})}{D^t(x^t, y^t)}} \\
&\mathrm{EFF_{ch}} = \frac{D^{t+1}(x^{t+1}, y^{t+1})}{D^t(x^t, y^t)} = \mathrm{PE_{ch}} \times \mathrm{SE_{ch}} \\
&\mathrm{TE_{ch}} = \sqrt{\frac{D^t(x^t, y^t)}{D^{t+1}(x^{t+1}, y^{t+1})}} \times \sqrt{\frac{D^{t+1}(x^{t+1}, y^{t+1})}{D^t(x^t, y^t)}} \\
&\mathrm{TFP_{ch}} = \mathrm{TE_{ch}} \times \mathrm{EFF_{ch}} = \mathrm{TE_{ch}} \times \mathrm{PE_{ch}} \times \mathrm{SE_{ch}}
\end{aligned} \tag{2}$$

In the formula, where D^t (x^t, y^t) and $D^{t+1}(x^{t+1}, y^{t+1})$ are distance functions, and M $(x^{t+1}, y^{t+1}, x^t, y^t)$ represents the TFP index based on t and $t+1$ periods. Several indicators provide valuable insights into the changes in water resource utilization efficiency:

- When TFP_{ch} is greater than 1, it signifies an increase in overall productivity from period t to $t+1$. Conversely, if TFP_{ch} is less than 1, it indicates a decrease in productivity over time.
- TE_{ch} (Technical changes) represents the impact of progress in production technology on the DMU. When TE_{ch} is greater than 1, it suggests technological progress or innovation. On the other hand, if TE_{ch} is less than 1, it implies technological regression.
- EFF_{ch} (Efficiency changes) refers to the utilization of existing technology by the DMU. When EFF_{ch} is greater than 1, it signifies that the DMU is moving closer to the production frontier and improving technical efficiency. Conversely, if EFF_{ch} is less than 1, it indicates that the DMU's efficiency is not ideal.
- PE_{ch} (Pure technical efficiency changes) indicates the role of technology in promoting efficiency improvement. When PE_{ch} is greater than 1, it suggests that pure technology has facilitated efficiency improvement. Conversely, if PE_{ch} is less than 1, it implies that pure technology hinders efficiency improvement.
- SE_{ch} (Scale efficiency changes) reflects the DMU's movement toward or away from the optimal scale in the long run. When SE_{ch} is greater than 1, it indicates that the DMU is gradually approaching the optimal scale. Conversely, if SE_{ch} is less than 1, this implies that the DMU is moving away from the optimal scale.

By comparing and analyzing the magnitudes of TE_{ch} and EFF_{ch}, one can explore whether the changes in TFP_{ch} were driven by technological progress or changes in technological efficiency. Comparing and analyzing the sizes of PE_{ch} and SE_{ch} allows for an in-depth analysis of the constraints on water resource utilization efficiency (Lu & Xu 2019).

3.3. Indicator selection

Considering the interdependence between water resources and various factors such as human activities, the environment, and the economy, the comprehensive utilization efficiency of regional water resources is influenced by multiple factors. The factors include natural climate conditions, the level of social development, industrial structure, production technology level, urbanization, industrial water use, and economic openness.

In this work, evaluation indicators were chosen based on the principle of representativeness, comprehensiveness, and measurability, while ensuring the effectiveness of the DEA evaluation model and avoiding excessive correlation between indicators to reduce differentiation ability (Chen *et al.* 2022; Cui *et al.* 2022). It needs to be noticed that the water use efficiency is a dependent variable, while the independent variables include the factors affecting water use efficiency, namely per capita water resources, industrial water consumption, agricultural water consumption, domestic water consumption, fixed assets investment, number of employees, and per capita GDP.

Water use efficiency calculated by the DEA model is a relative efficiency, as compared to the frontier. However, since DEA does not assume the weight value of input and output, the input indicators are directly chosen, namely: per capita water resources, industrial water consumption, agricultural water consumption, domestic water consumption, fixed assets investment, and number of employees. Additionally, per capita GDP of each city was chosen as a single output indicator. They are all the independent variables that influence water use efficiency. The independent variables covered natural factors, social factors, and the structure of water use. The statistical analysis of indicator data was based on the 'Anhui Statistical Yearbook' and the 'Anhui Province Water Resources Bulletin'. Only two indicators, per capita water resources and per capita GDP, have been quantified per capita. The characterization and statistical analysis for each indicator are listed in Table 1.

Other factors affect the efficiency of water resource utilization, such as water environment quality and water conservation project construction. However, based on the statistical and panel nature of the data, they are the focus of the authors' next work.

Based on the above DEA-Malmquist method and indicator selection, the DEAP 2.1 calculation software can be used to solve. The flowchart of this work is presented in Figure 1.

4. RESULTS AND DISCUSSION

4.1. Water resource development and utilization structure

Between 2011 and 2020, a time series analysis revealed that the total water consumption in the northern Anhui region transitioned from a stable growth trend to a stage of slow change, in line with the implementation of the 'red line of total water use' policy (Shang 2017). The water resource development and utilization structure in six cities of northern Anhui are illustrated in Figure 2.

From the perspective of water use structure, the order of water usage proportions was listed as follows: farmland irrigation water > industrial water > domestic water > water for forestry, animal husbandry, fishing, and livestock > ecological environment water. Regional agricultural water usage held an absolute dominant position, accounting for 50–61% of the total water consumption.

By analyzing the time series data, some observations can be made here:

1. Industrial water consumption exhibited a continuous downward trend, indicating an improvement in industrial water use efficiency, in spite of a consistent increase in industrial added value over the years.
2. Daily water consumption by residents remained stable, suggesting an increasing awareness of water-saving practices among the population, even with their growth.

Table 1 | Evaluation of the index system based on the DEA-Malmquist model

Category	Indicator name	Indicator representative	Method of calculation
Input	Per capita water resources	Water resource endowment level	Total water resources/total population
	Fixed assets investment	Characterizing capital investment and indirectly reflecting the distribution of social capital	Cite Statistical Yearbook Data
	Number of people engaged	Characterizing the input of labor force	Cite Statistical Yearbook Data
	Industrial water consumption	Reflect the distribution status of industrial water use	Cite data from the Water Resources Bulletin
	Agricultural water consumption	Reflect the distribution status of agricultural water use	Cite data from the Water Resources Bulletin
	Residential water consumption	Reflect the distribution status of domestic water	Cite data from the Water Resources Bulletin
Output	Per capita GDP	Economic benefits generated by effective utilization of water resources	GDP/total population

Note: The total population refers to the permanent population of each city.

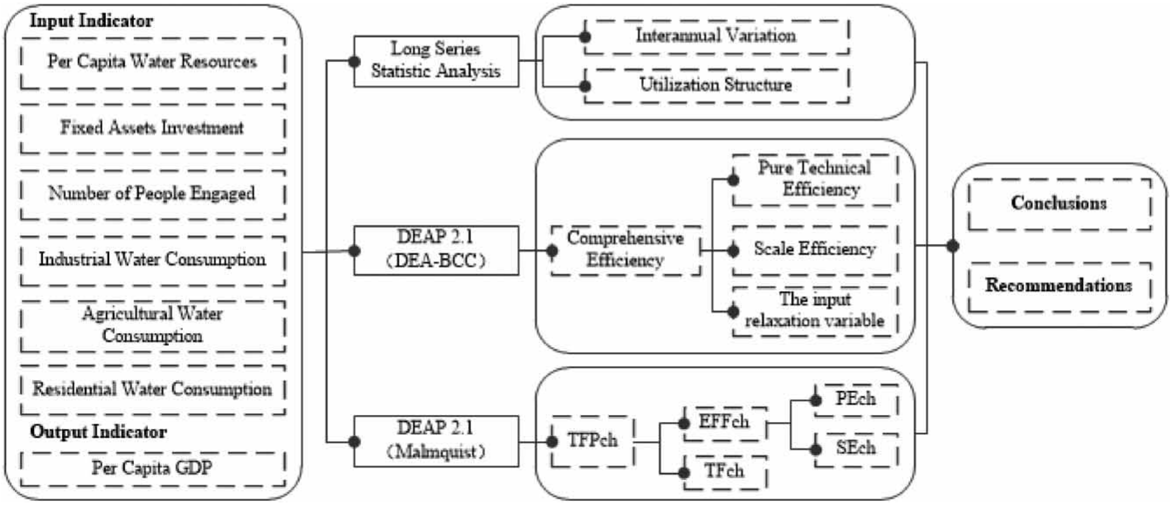

Figure 1 | Flowchart of this study.

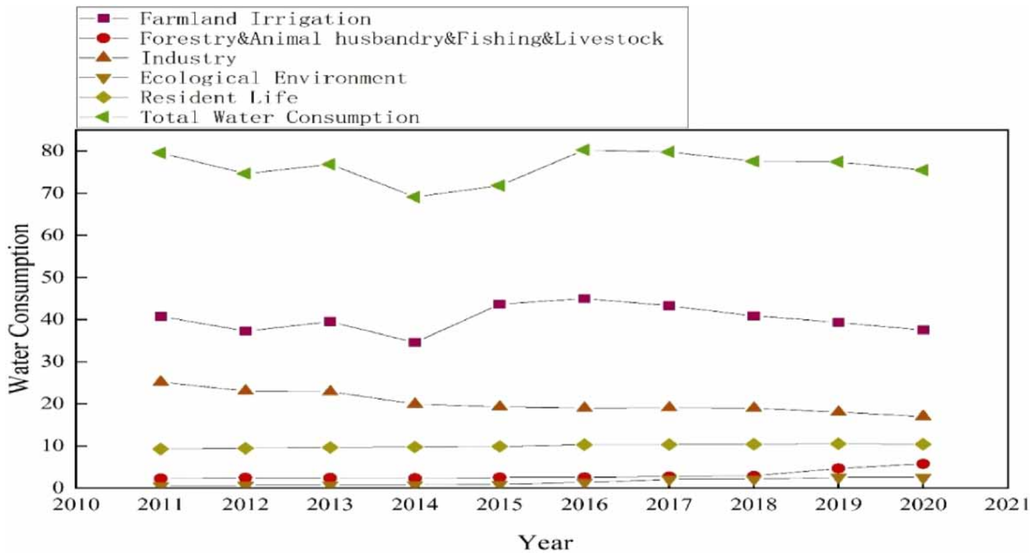

Figure 2 | Trend of water consumption in northern Anhui province (2011–2020).

3. Fluctuations in agricultural water consumption were influenced by climatic conditions, implying the sensitivity of agricultural water usage to climate variations.
4. During the 13th Five Year Plan period of China, there was a notable increase in ecological water use and water consumption for forestry, animal husbandry, fishing, and livestock. This indicates a growing emphasis on water ecology and the health of water environments, reflecting increased attention from the public.

The findings highlight the evolving dynamics of water resource utilization in the northern Anhui region, including improvements in industrial water efficiency, increasing awareness of water-saving among residents, and a heightened focus on ecological and environmental water use.

4.2. Evaluation of water resource utilization efficiency based on DEA-BBC

In this study, the DEAP 2.1 was utilized to perform the calculations using the BCC model, which assumed variable returns to scale (VRS). The software was applied to analyze the panel data that consisted of six input indicators and a single output indicator. The input-leading model was selected for its static efficiency analysis, which provided values for comprehensive efficiency, pure technical efficiency, and scale efficiency. The results are presented in Table 2.

The DEA model calculated the relative effectiveness of water use efficiency, with results equal to or close to 1 (higher efficiency) and less than 1 (lower efficiency). The calculated data gap is relatively large (1–0.296), indicating that the calculation results are reasonable.

According to the data presented in Table 2, it was observed that Huaibei achieved DEA effectiveness throughout the period from 2011 to 2020, with comprehensive efficiency, pure technical efficiency, and scale efficiency values of 1. This indicates the city's level of water resource utilization efficiency, considering that its water resource conditions and water use structure were effective and had reached the optimal scale efficiency.

Huainan experienced non-DEA effectiveness only from 2015 to 2016, while achieving DEA effectiveness in the remaining years. The comprehensive efficiency, pure technical efficiency, and scale efficiency values were all 1 in those years, indicating a high level of water resource utilization efficiency. On the other hand, Bengbu, Fuyang, Suzhou, and Bozhou exhibited DEA ineffectiveness throughout the period. This suggests that the water resource utilization efficiency in the cities needs to be improved. The results highlighted the varying levels of water resource utilization efficiency among the cities in the northern Anhui region and emphasized the importance of addressing inefficiencies to enhance water resource management and utilization.

The regional average of time distribution chart (Figure 3) revealed the fluctuating trend of water resource utilization efficiency in the northern Anhui region over the past decade. The efficiency values experienced a decrease, followed by an increase, and then a slight decrease in 2020. The lowest efficiency value of 0.661 was observed in 2016, while the highest value of 0.774 was recorded in 2019 with 16% as the coefficient of variation. This indicates that the comprehensive utilization efficiency of water resources in the study area did not change significantly in the past decade. Traditionally, a coefficient of variation exceeding 30% indicates a significant degree of variation. The lowest technical efficiency value of 0.880 was observed in 2017, while the highest value of 0.962 was recorded in 2010 with 94% as the coefficient of variation.

Qiu & Sheng (2020) used the SE-DEA model to analyze the water resource utilization efficiency in Anhui province from 2011 to 2017 and the DEA-BCC calculation results were similar to theirs. These findings indicate that the pure technical

Table 2 | Calculation results of water resource utilization efficiency in northern Anhui province from 2011 to 2020

District	Efficiency	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Huainan	Comprehensive efficiency	1.000	1.000	1.000	1.000	0.758	0.772	1.000	1.000	1.000	1.000
	Pure technical efficiency	1.000	1.000	1.000	1.000	0.993	0.967	1.000	1.000	1.000	1.000
	Scale efficiency	1.000	1.000	1.000	1.000	0.763	0.798	1.000	1.000	1.000	1.000
Bengbu	Comprehensive efficiency	0.740	0.631	0.630	0.692	0.695	0.715	0.699	0.749	0.858	0.753
	Pure technical efficiency	0.776	0.647	0.654	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	Scale efficiency	0.954	0.976	0.964	0.692	0.695	0.715	0.699	0.749	0.858	0.753
Fuyang	Comprehensive efficiency	0.462	0.479	0.455	0.448	0.423	0.359	0.296	0.639	0.703	0.460
	Pure technical efficiency	1.000	1.000	1.000	0.923	0.867	0.736	0.623	1.000	1.000	0.758
	Scale efficiency	0.462	0.479	0.455	0.486	0.488	0.488	0.474	0.639	0.703	0.607
Suzhou	Comprehensive efficiency	0.638	0.544	0.515	0.524	0.522	0.503	0.461	0.455	0.496	0.477
	Pure technical efficiency	0.997	0.825	0.805	0.830	0.786	0.745	0.730	0.690	0.675	0.700
	Scale efficiency	0.640	0.660	0.640	0.631	0.664	0.675	0.631	0.660	0.735	0.681
Huaibei	Comprehensive efficiency	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	Pure technical efficiency	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	Scale efficiency	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Bozhou	Comprehensive efficiency	0.645	0.667	0.630	0.647	0.646	0.620	0.508	0.632	0.589	0.605
	Pure technical efficiency	1.000	1.000	1.000	1.000	1.000	1.000	0.927	1.000	0.827	0.928
	Scale efficiency	0.645	0.667	0.630	0.647	0.646	0.620	0.547	0.632	0.713	0.652
Average	Comprehensive efficiency	0.747	0.720	0.705	0.719	0.674	0.661	0.661	0.746	0.774	0.716
	Pure technical efficiency	0.962	0.912	0.910	0.959	0.941	0.908	0.880	0.948	0.917	0.898
	Scale efficiency	0.783	0.797	0.782	0.743	0.709	0.716	0.725	0.780	0.835	0.782

Note: Comprehensive efficiency = Pure technical efficiency × Scale efficiency.

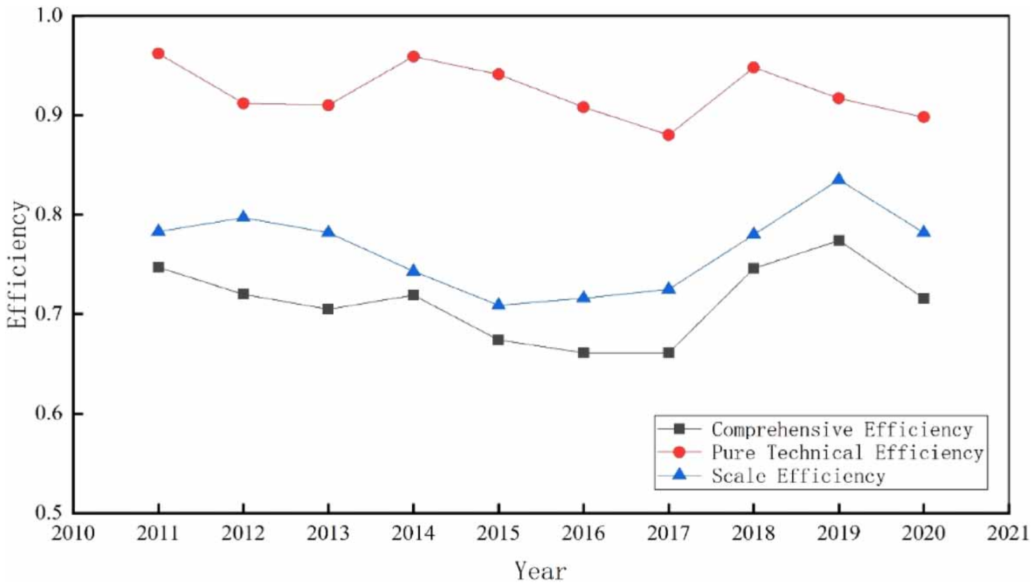

Figure 3 | Mean time distribution of water resource utilization efficiency in northern Anhui (2011–2020).

efficiency has a significant interannual variation. The lowest scale efficiency value of 0.709 was observed in 2015, while the highest value of 0.835 was recorded in 2019 with 29% as the coefficient of variation. This indicated that the scale efficiency of water resources in the study area did not change significantly in the past decade.

Analyzing the three types of efficiency, the time variation pattern of pure technical efficiency was consistent with that of comprehensive efficiency, indicating that changes in comprehensive efficiency depended on changes in technical efficiency. The input-oriented DEA model used in this study indicated that scale efficiency was the key factor that contributed to DEA inefficiency. This suggests an excess of investment, where increased investment did not proportionally increase the output. To improve water resource comprehensive efficiency, it became necessary to reduce investment scale and allocate resources effectively.

The findings highlight the importance of optimizing investment strategies and resource allocation to achieve enhanced water resource utilization efficiency in the northern Anhui region. By reducing excess investment and adopting a rational approach, a substantial improvement in comprehensive efficiency can be achieved.

From the spatial distribution perspective (Figure 3), the overall efficiency of water resource utilization in the northern Anhui region, ranked from high to low, was listed as follows: Huaibei (1.000) > Huainan (0.953) > Bengbu (0.716) > Bozhou (0.619) > Suzhou (0.514) > Fuyang (0.472). This distribution pattern indicates a decreasing trend from the southeast to the northwest of the region. Huainan and Huaibei exhibited higher efficiency, while Bengbu and Bozhou demonstrated medium efficiency, Suzhou and Fuyang had low efficiency.

When comparing the data across different years, Bengbu and Fuyang exhibited a fluctuating upward trend in comprehensive efficiency, whereas Bozhou and Suzhou demonstrated a fluctuating downward trend. To further analyze the non-DEA efficient cities, projections and adjustments were made using the DEAP 2.1 software on the effective plane. The input relaxation variable was obtained, indicating the need to reduce the input indicator, while keeping the output indicator (per capita GDP) unchanged. Due to space limitations, the evaluation focused on the 2015 and 2016 data of Huainan, Bengbu, Bozhou, Suzhou, and Fuyang, which were deemed DEA inefficient. The projection results are presented in Table 3.

Based on Table 3, the authors uncovered the following findings:

1. Bengbu and Bozhou did not exhibit investment redundancy across the evaluated indicators.
2. Huainan, Fuyang, and Suzhou showed investment redundancy in terms of employees, industrial water, agricultural water, and domestic water. However, their water resource conditions and fixed assets investment were reasonable.
3. To achieve DEA efficiency such as effective utilization of water resources, while maintaining constant output, the redundant input elements in each city need to be reduced.

Table 3 | Input index relaxation variables of non-DEA effective decision units

Administrative division	2015 S_1^-	S_2^-	S_3^-	S_4^-	S_5^-	S_6^-	2016 S_1^-	S_2^-	S_3^-	S_4^-	S_5^-	S_6^-
Huainan	0.00	0.00	0.00	5.77	9.95	0.27	0.00	0.00	0.00	5.49	8.17	0.29
Bengbu	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fuyang	0.00	0.00	348.19	0.75	5.10	1.33	0.00	0.00	346.57	0.57	5.57	1.15
Suzhou	0.00	0.00	126.71	0.33	0.58	0.68	0.00	0.00	126.95	0.21	0.93	0.63
Bozhou	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Remarks: S_1^-, S_2^-, S_3^-, S_4^-, S_5^-, and S_6^-, respectively, represent the per capita water resources (m^3), fixed assets investment (10,000 yuan), number of employees (10,000), industrial water consumption (100 million m^3), agricultural water consumption (100 million m^3), and domestic water consumption (100 million m^3) that could be reduced by DMU when reaching the same output.

4. Taking the case of Huainan in 2015 as an example, DEA efficiency was achieved by reducing 577 million m^3 of industrial water consumption, 995 million m^3 of agricultural water consumption, or 27 million m^3 of domestic water consumption. The reduction proportions in investment were 76, 81, and 23%, respectively.

Based on the above analysis, the main factors that restricted the low comprehensive efficiency of water resource utilization in Huainan were industrial water consumption and agricultural water use. Similarly, for Fuyang and Suzhou, the main factors involved were the large number of employees (labor input) and domestic water use.

4.3. Water resource utilization efficiency based on the Malmquist productivity index

The Malmquist productivity index was used to analyze changes in total factor productivity (TFP_{ch}) over time. It measured the efficiency change and technological change components that contributed to TFP_{ch} growth or decline. The index was calculated based on the relative positions of production frontiers in different time periods.

Table 4 shows the TFP index values for each year and city, indicating the overall productivity changes. An index value greater than 1 indicated an increase in productivity, while a value less than 1 suggested a decline. Based on the trends, an analysis of the dynamic changes in water resource utilization in the northern Anhui region is presented as follows:

1. Total factor productivity (TFP_{ch}): The average TFP_{ch} index of 1.020 indicates an overall increase in water use output rate over the study period. However, the TFP_{ch} index showed a declining trend from 2011 to 2016, suggesting a decrease in productivity during that period. From 2016 to 2019, there was a significant upward stage, with a notable increase in the TFP_{ch} index, especially in 2018–2019 where the increase rate was close to 100%. However, there was a significant decline in TFP_{ch} from 2019 to 2020. According to the latest research results, the TFP of water resources in 16 prefecture

Table 4 | TFP index and decomposition of water resource utilization efficiency (2011–2020)

Year	EFF_{ch}	TE_{ch}	PE_{ch}	SE_{ch}	Malmquist productivity index TFP_{ch}	Rate of change (%)
2011–2012	0.960	0.889	0.940	1.021	0.853	− 14.7
2012–2013	0.973	0.972	0.997	0.975	0.945	− 5.5
2013–2014	1.020	0.928	1.065	0.959	0.947	− 5.3
2014–2015	0.945	0.947	0.980	0.965	0.895	− 10.5
2015–2016	0.968	0.993	0.960	1.008	0.961	− 3.9
2016–2017	0.960	1.324	0.963	0.997	1.271	+ 27.1
2017–2018	1.191	0.854	1.085	1.097	1.017	+ 1.7
2018–2019	1.043	1.916	0.966	1.080	1.999	+ 99.9
2019–2020	0.909	0.776	0.979	0.929	0.705	− 29.5
Average	0.994	1.027	0.992	1.002	1.020	+ 2.0

level cities in Anhui province showed an overall upward trend from 2012 to 2021 with an average growth rate of 1.5% (Li & Chen 2023). Lu & Xu (2019) analyzed and calculated that the average annual growth rate of China's TFP of water resources was 7.9%. After comparison, the overall output rate of northern aquatic products in northern Anhui was slightly higher than the provincial average level in Anhui province, but less than the national level.
2. Technological change (TE_{ch}): The average TE_{ch} index of 1.027 indicates an overall technological progress in water resource utilization. However, the TE_{ch} index showed a continuous trend of technological decline before 2016, suggesting a regression in technology during that period. In the later years, technological progress occurred in 2016–2017 and 2018–2019.
3. Efficiency change (EFF_{ch}): The average EFF_{ch} index of 0.994 indicates that technical efficiency is not ideal in water resource utilization. However, the change in technical efficiency is relatively gentle compared to the evolution of TFP and technological changes. This suggests that the main driver of the TFP index is technological changes.

Overall, the analysis indicates that the increase in TFP in the northern Anhui region was primarily driven by technological changes. The trends in technological progress aligned with the changes in TFP, while technical efficiency showed less significant variation over the study period. It is important to note that these findings were based on the average values and trends observed in the data. Further analysis and examination of specific years or cities within the region might provide insights into the dynamics of water resource utilization efficiency.

Table 5 presents the decomposition results of the Malmquist productivity index, breaking down the productivity changes into technological change (TE_{ch}) and efficiency change (EFF_{ch}). TE_{ch} represented improvements or regressions in production technology, while EFF_{ch} reflected the utilization of existing technology. By examining the tables, one could identify the trends in TFP and understand the contributions of technological change and efficiency change to productivity growth or decline in each city over the years (Zhang & Fang 2017).

Based on Table 5, an analysis of the TFP_{ch} index and its decomposition for the northern Anhui region is presented as follows:

1. Huainan, Bengbu, and Huaibei

The TFP_{ch} index for these cities exceeded 1, indicating positive growth in TFP of water resources. Huainan showed the highest growth rate at 12.7%. The decomposition of the index suggests that technological progress was the main driving force behind the TFP_{ch} growth in these cities.

2. Fuyang, Suzhou, and Bozhou

The cities showed a declining trend in TFP_{ch} over the 10-year period. Among them, Suzhou had the largest decline at 5.6%. The decomposition of the index revealed that the main reason for the decline in TFP_{ch} was a technological decline in Fuyang. In Suzhou and Bozhou, both technological decline and efficiency reduction contributed to the decrease in water resource utilization efficiency. The main factor for the efficiency decrease was technological efficiency.

Table 5 | TFP index and decomposition of water resource utilization efficiency by cities (2011–2020)

					Malmquist productivity index	
District	**EFF_{ch}**	**TE_{ch}**	**PE_{ch}**	**SE_{ch}**	**TFP_{ch}**	**Rate of change (%)**
Huainan	1.000	1.127	1.000	1.000	1.127	+ 12.7
Bengbu	1.002	1.052	1.029	0.974	1.054	+ 5.4
Fuyang	1.000	0.974	0.970	1.031	0.974	− 2.6
Suzhou	0.968	0.975	0.961	1.007	0.944	− 5.6
Huaibei	1.000	1.047	1.000	1.000	1.047	+ 4.7
Bozhou	0.993	0.993	0.992	1.001	0.986	− 1.4
Average	0.994	1.027	0.992	1.002	1.020	+ 2.0

Based on this analysis, it can be concluded that in Huainan, Bengbu, and Huaibei, the growth in TFP of water resources was driven by technological progress. However, Fuyang, Suzhou, and Bozhou experienced a decline in TFP_{ch} with varying reasons such as technological decline and efficiency reduction. This indicates the need for measures to address the factors and improve water resource utilization efficiency in those cities. It is important to note that the findings were based on the provided data and the decomposition analysis. Further research and analysis are needed to gain a comprehensive understanding of the factors that influenced water resource utilization efficiency in each city and to identify specific strategies for improvement.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

Overall, there has been a shift in water usage patterns in northern Anhui over the past decade, with agricultural water consumption dominating, while industrial water use declining. Ecological water use has shown a significant increase, while the total regional water usage has reached a stage of slow change. The comprehensive utilization efficiency of water resources was at a moderate level with the DEA index ranging from 0.661 to 0.774. The main factor contributing to ineffective DEA was scale efficiency, indicating investment redundancy. To improve efficiency, it was necessary to reduce the investment scale and allocate resources more effectively.

There were significant regional differences in the utilization efficiency of water resources among the administrative regions. Only Huaibei achieved DEA effectiveness consistently throughout the study period. The overall efficiency ranking, from high to low, is Huaibei > Huainan > Bengbu > Bozhou > Suzhou > Fuyang, showing a decreasing trend from southeast to northwest. Analysis of investment redundancy reveals that insufficient economic output was the main factor limiting efficiency in Bengbu and Bozhou, while industrial water and agricultural water usage were the main factors in Huainan. Large numbers of employees and domestic water usage were the key factors in Fuyang and Suzhou cities, respectively.

The Malmquist productivity index indicates that the TFP of water resource utilization in the northern Anhui province exceeded 1 between 2016 and 2019, with an average annual value of 1.02. This indicates a slight upward trend in water output under existing resource conditions. Huainan exhibits the fastest growth rate, followed by Bengbu and Huaibei. Conversely, Fuyang, Suzhou, and Bozhou show a declining trend with Suzhou experiencing the largest decline. Technological progress and improvements in technological efficiency are the main driving factors for water resource utilization efficiency in the region. Therefore, focusing on enhancing technical efficiency was crucial for improving water resource utilization in the northern Anhui region.

5.2. Recommendations

The findings provided valuable insights into the water resource utilization efficiency and productivity trends in the northern Anhui region. Specifically, this work includes the following recommendations:

(1) Promote regional internal cooperation and optimize resource allocation

Based on the common characteristics of social and economic relations and water resource endowments within the region, utilizing one's own advantages to drive vulnerable areas, Suzhou and Fuyang with low water resource utilization efficiency can refer to the experience of Huaibei and Huainan. Through regional cooperation, integrated management of water resource utilization can be strengthened.

(2) Transform traditional agricultural water use models and adhere to technological innovation

The northern Anhui region is an important agricultural production area in China, and the progress of agricultural technology is a breakthrough point in solving the problem of water scarcity. Adjusting the agricultural industrial structure, eliminating high water consumption and low-income agricultural byproducts, implementing agricultural water quota management, or utilizing the leverage of agricultural water prices are crucial to improve agricultural water consumption efficiency.

(3) Develop regional economy

The development of the economy can attract the inflow of funds and talents, which will drive the optimization of regional industrial structure and technological progress, promote the improvement of water efficiency and sustainable utilization of water resources.

In this work, the DEA-BCC-Malmquist model was used to evaluate the comprehensive utilization efficiency of water resources by taking into account the input indicators of water resources, fixed asset investment, labor force, and water use structure. However, it did not reflect the impact of changes in the water ecological environment on water resource utilization efficiency. Efficient and sustainable water resource utilization efficiency should be based on the sustainable water ecological environment. For this reason, the future direction of this work is to study the quantification of water ecological security indicators based on river discharge the amount of pollutants discharged into rivers with the aim of establishing a comprehensive evaluation index system.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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