Evaluation of China's water-resource utilization efficiency based on a DEA-Tobit two-stage model

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ABSTRACT

In this paper, a Data Envelopment Analysis-Tobit (DEA-Tobit) two-stage model was used to evaluate the efficiency of water-resource utilization, and the regional differences and influencing factors on water-resource utilization were analyzed. The results of the analysis of regional differences show that China's water-use efficiency is relatively low. Only Beijing, Shanghai, and Fujian have water-use efficiency higher than 0.8, whereas most other provinces and cities have an efficiency of 0.3–0.8. The eastern region demonstrates a higher water-resource utilization efficiency than the central and western regions. The analysis of the influencing factors of regional differences in water-use efficiency found that per capita water resources, per capita domestic water use, and the proportion of primary and secondary industries all have a negative impact on the efficiency of water use, and per capita GDP has a positive impact on the efficiency of water use. Agricultural water consumption, industrial water consumption, domestic water consumption, and total ecological water consumption all have a negative impact on water-resource utilization efficiency, of which domestic water consumption and industrial water consumption have a greater impact. Technological level and water-resource utilization efficiency show a significant positive correlation.

Key words | DEA-Tobit model, influence factors, regional differences, sustainable development, utilization efficiency, water resources

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HIGHLIGHTS

- Selects a DEA-Tobit two-stage model to evaluate water-resource utilization efficiency.
- Analyzed the differences in water use efficiency in various regions of China.
- Analyzed the influencing factors of water-resource utilization efficiency.
- Proposes countermeasures to improve water-resource utilization efficiency.

INTRODUCTION

Water resources, in a broad sense, refers to the total amount of water bodies in the hydrosphere, and more commonly refers to water resources that can be directly used by humans. Water resources endowed with economic significance can be regarded as an important guarantee for maintaining the healthy development of the social economy, protecting the environment, and maintaining the ecological balance. Water is an indispensable natural resource for human development and the material basis on which humans and all living things depend. Today, the water

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crisis caused by lack of water resources and water pollution seriously restricts the healthy development of the world economy. In the 21st century, countries around the world are generally facing severe water shortages. It is expected that by 2025, 3×10^9 (3 billion) people in the world will face water shortages, and 40 countries and regions will be seriously deficient in fresh water. With the development of social economy, population urbanization, and industrialization, water resources are no longer inexhaustible, but have become strategic economic resources and the main factors affecting the ecological environment. The current serious waste of water resources and unreasonable water-use make the problem of water shortage in China more serious. The issue of supply and demand due to inefficient use of water resources is also very prominent. The shortage of water resources and the contradiction between the supply and demand of water resources have had a large negative impact on China's economic growth, although rapid economic development will also increase pressure on water resources. People pay increasing attention to whether the current water resources can: support the food supply of China's huge population; solve the problems of water shortage, water resource pollution, and ecological degradation; properly deal with the impact of climate change; or support the steady and rapid development of the social economy. Therefore, the rational use of water resources in China is an important issue that needs to be resolved in China at this stage.

Since the beginning of the 21st century, the total amount of water consumption in China has increased. The proportions of industrial water, agricultural water, and domestic water have changed. In addition to the significant reduction in agricultural water, industrial water and domestic water have increased year by year. China has severe drought. The total freshwater resources are 280 billion m^3, accounting for 6% of the global total water resources, ranking fourth in the world, but only 2,200 m^3 per capita. In addition, the regional distribution of water resources in China is very uneven. The Yangtze River basin and its southern region have a land area which is 36.5% of the country and with 81% of the country's water resources. The region north of the Yangtze River basin has a land area of 63.5% of the country. Resources account for only 19% of the country. At the end of the 20th century, more than 400 cities out of more than 600 in China had insufficient water supply. Among them, there were 110 cities with serious water shortages, and the total amount of water shortages in the country was 6 billion m^3. Water resources are an important support and guarantee for national economic and social development. With the increasingly obvious impact of global climate change and the acceleration of China's industrialization and urbanization process, the contradiction between socio-economic development and the insufficient capacity of water resources and the water environment will become more prominent. There are many ways to solve the problem of water resources and most experts and scholars agree that an efficient and vital way of doing so is improving the efficiency of water-resource utilization. This could also include promoting the implementation and realization of work to build a water-saving society, implementing a scientific development approach, and coordinating regional development while maintaining the long-term and stable development of society. Increased use of water resources can not only maintain social and economic growth but also protect residents' daily water usage, while achieving cleaner production, protecting the environment, promoting the development of a water-saving society, and achieving sustainable socio-economic and ecological development. Thus, scientifically and objectively evaluating current water-resource utilization efficiency and its regional differences in China, and discussing the factors that affect water-resource utilization efficiency have become an urgent problem to be studied. This paper tries to answer the above questions to provide a solid reference for the formulation of China's policies on water resources.

The basic framework of the research is to first measure the utilization efficiency of China's water resources through the super-efficiency Data Envelopment Analysis (DEA) model, and evaluate the difference in water utilization efficiency in eastern, central and western China. The Tobit model is then used to empirically analyze the influencing factors of China's water use efficiency, and analyze the degree and magnitude of the explanatory variables' influence on China's water use efficiency. Finally, based on the results of the previous empirical analysis, the paper puts forward suggestions to improve the efficiency of water use in China, hoping to provide a theoretical reference for China's sustainable development.

LITERATURE REVIEW

Connotation and measurement of water-resource utilization efficiency

Since the 20th century, the rapid development of industry and agriculture and the rapid increase in population have exacerbated the imbalance between water supply and demand. Many international scholars predict that the world will face serious water problems in the 21st century. Maintaining the sustainable and effective use of water resources requires a reasonable evaluation of water-resource utilization efficiency which is defined as the ratio of water-resource input to output. Therefore, many countries have based their efficiency on their own development needs and evaluated their water-resource status and utilization efficiency based on their actual water use. Foreign scholars' research on water-use efficiency mostly concentrates on micro-scale or small-scale fields. Ali & Klein (2014) used the DEA model and the Malmquist Index (MI) to estimate the agricultural water efficiency of agricultural irrigation areas in southern Alberta from 2008 to 2012. Watto & Mugera (2015) conducted research on water-use efficiency in agriculture in 2015. Egan (2014) studied cities in Japan, the United States, and other countries in 2001 to analyze water-resource utilization efficiency and concluded that improving water-resource management efficiency can better achieve sustainable use of water resources. Linderson *et al.* (2007) studied the efficiency of water-resource utilization and pointed out that improving it can effectively solve the problem of insufficient water resources.

Gai *et al.* (2016) used a stochastic frontier analysis (SFA) model and DEA-slacks based measure (DEA-SBM) method to measure the absolute efficiency and relative efficiency of water-resource utilization in 14 cities in Liaoning, and then used the Gini coefficient and coefficient of variation to study dynamic changes; Qu & Fang (2017) used 11 provinces in the western region as research locations, and used a DEA-Banker, Charnes & Cooper (DEA-BCC) model (Banker *et al.* 1984) and MI to explore the agricultural water-resource utilization efficiency and total factor productivity of various cities. Liu & Li (2008) analyzed the water-resource carrying capacity of 20 provincial administrative regions in China by using a DEA model. Peng (2019) used the Engel, Blackwell And Miniard (EBM) model to measure the utilization efficiency of industrial water resources in 11 provinces and cities in the Yangtze River Economic Belt from 2010 to 2016, and further studied its industrial water-saving potential, finding some difference in utilization efficiency. The utilization efficiency of industrial water resources in Shanghai remained stable and effective during the study period, and it was at an optimal level within the 11 provinces and cities in the Yangtze River Economic Belt. Yang & Xie (2019) established the super efficiency-SBM (SE-SBM) model to quantitatively analyze the spatial and temporal changes of green water resource utilization efficiency in the Yangtze River Economic Belt from 2002 to 2016, and discussed the influencing factors by using the MI method. Studies have shown that the utilization efficiency of green water resources in the Yangtze River Economic Zone has a slight downward trend with time, and the regional differences are obvious. The efficiency values of the upstream and downstream have declined to varying degrees, and the midstream is stable at a low level, forming the water-resource utilization efficiency as upstream > downstream > midstream.

Influencing factors of water-resource utilization efficiency

Wolfe (2009) believes that economic development, changes in resource endowments, and the degree of development and utilization of water resources are the fundamental reasons for the difference in the relative utilization efficiency of water resources. Of them, economic development is the main driving force for the change of water-resource utilization efficiency. Kuslu *et al.* (2014) analyzed the impact of water-resource reduction, economic development, and population increase on water-resource utilization efficiency from the perspective of supply and demand. Some scholars have done a lot of research on the methods of evaluating influencing factors, which provide a reference for the choice of empirical methods in this paper. For example, Simar & Wilson (2004) analyzed the existing problems of DEA-Tobit evaluation efficiency, proposed an iterated version of the bootstrap which may be used to improve bootstrap estimates of confidence intervals, and provided suggestions for the improvement of the research method in this paper. Some scholars also proposed double bootstrap and partial frontiers methods (De Witte & Marques 2010; Carvalho & Marques 2011; Marques *et al.* 2014; Pinto *et al.* 2017). Berg & Marques (2011) presented patterns regarding quantitative methods adopted over time, Pereira & Marques (2017) found more than thirty studies using deterministic and stochastic methods for measuring efficiency. These studies intended to measure efficiency and study its determinants and to compute efficiency as a tool for benchmarking or only estimating efficiency. Several methodologies were used, although the most popular technique adopted was the DEA method. The DEA method is frequently combined with a second-stage analysis to better understand the source of inefficiency. Ren *et al.* (2016) used the super-efficient DEA model and MI to estimate the water-use efficiency of 11 provincial capital cities in the Yangtze River Economic Belt from 2011 to 2013, and tested its influencing factors through the Tobit model. Lei *et al.* (2017) applied an SFA model to estimate the industrial water efficiency values of 31 provinces in China from 1999 to 2014, and constructed a Tobit regression model to study the impact of natural resources, economic level, industrial development, industrial structure, water-use structure, and government influence on industrial water-use efficiency. Wang *et al.* (2017) used the traditional DEA model and an improved model to estimate the relative utilization efficiency of water resources in Jiangsu, and used a typical correlation analysis model to analyze the relevant factors affecting the relative efficiency of water-resource utilization. Zhao *et al.* (2018) used an index decomposition model to quantitatively study the driving factors that affect changes in water consumption and water-use efficiency in China. The calculation results of the model show that during 2000–2015, economic development and population expansion promoted national water use. The main driving factor of the increase is the fact that the contribution rate of the former was much higher than the latter. Liang & Chen (2019) found that environmental factors such as economic development level, water-resource endowment, industrial structure, population quality, government support, and population density have varying degrees of impact on China's water-resource efficiency level.

Studies on improving water-resource utilization efficiency

In terms of improving research on water-resource utilization efficiency, scholars mainly focus on how to use the market to improve this efficiency. Vickers (1999) established an analysis system of water resource demand-side management. He believes that the way to strengthen demand-side management is to enhance the key to water-use efficiency. Tuppad *et al.* (2010) proposed a water-resource improvement path that considers the changes in water-resource use efficiency due to the reduction of water resources, economic development, and population increase from the perspective of supply and demand. Lambert *et al.* (2010) believe that regulating water-consumption behavior and using water-saving equipment are effective channels for improving water resources. Chen & Bai (2013) proposed establishing an entry-and-exit mechanism for industrial projects linked to water resources, to encourage enterprises to save water with a price-differentiated market allocation mechanism, and to increase investment in water-saving technologies and equipment research and development. Ren *et al.* (2020) pointed out that strengthening interregional technical cooperation, implementing measures such as adjusting industrial structure, introducing advanced production equipment, promoting the use of water-saving equipment, and other measures to improve the efficiency of water resources in accordance with local conditions are important ways to achieve sustainable urban development in China. Wu (2019) used a DEA model obtained from water-resource utilization efficiency data from 2008 to 2017 to study water-resource utilization efficiency evaluation indicators. The results show that to effectively improve the efficiency of water-resource utilization, it is necessary to: protect surface water well and distribute the use of water resources in a balanced manner; increase residents' awareness of saving water and effectively recycle domestic water; moderately develop water resources and establish scientific research funds.

Existing research provides a good reference for us to understand the problem of water-resource utilization efficiency in China, and also provides an initial perspective for us to further explore regional differences. The current research deficiencies mainly manifest in the following: first, most scholars equate the amount of water resources input with the amount of resource consumption, excluding the consumption of other resources, so as to conduct an isolated study of water-resource utilization efficiency. Water is a natural resource; its input does not directly bring economic benefits and product output, and must be combined with other production factors to bring real economic output. Therefore, it is too simplistic to directly link water resources input with economic output. Second, domestic and foreign scholars rarely consider environmental factors such as pollution in the evaluation of water-resource utilization efficiency, which cannot reflect the true level of water-resource utilization efficiency, and may even mislead the government when making policy decisions, resulting in sustainable water resources development being negatively affected. Based on the above understanding, this paper evaluates the efficiency of regional water-resource utilization in China from the perspective of total factor productivity, and on this basis characterizes the regional differences in water-resource utilization efficiency, and further explores the possible causes of the existing differences with the help of quantitative-analysis methods.

METHODS

DEA method

Data envelopment analysis (DEA) was created and developed in 1978 by the famous American operations researchers Charness, Cooper, and Rhodes. This method is based on the premise that the input or output of decision-making units (DMUs) are unchanged, a mathematical planning model and statistical data are used to obtain a relatively effective production frontier, and each DMU is projected onto the production frontier. The relative effectiveness of DMUs is evaluated by deviating from the frontier of the DEA. The DEA method can be defined as a non-parametric statistical evaluation model. This method does not need to consider the functional relationship between the various inputs and outputs, estimate parameters in advance, avoid subjective factors, simplify the calculation method, or reduce errors. In addition, this method can analyze multiple input and output indicators at the same time. The analysis results obtained are optimized for each DMU, and specific optimization suggestions are proposed for the analysis results. Since its inception, the DEA method has attracted attention for its unique advantages. It has become a commonly used analytical tool and method in the fields of management science, engineering efficiency evaluation, resource management, system engineering, decision analysis, and evaluation technology. The model of this paper was constructed as follows.

Suppose there is one production unit in the water resource production system, each unit has the same input and output indicators, including m input indicators and n output indicators, and the output indicators include n_1 expected output indicators and n_2 types of unexpected output indicator. Then, for the i-th decision unit T_i, and where R represents the expected output set, the input index value x_i, expected output index value y_i, and undesired output index value zi are, respectively:

$$\begin{cases} x_i = (x_{1i}, x_{2i}, \cdots, x_{mi}) \in R^{m\times n} \\ y_i = (y_{1i}, y_{2i}, \cdots, y_{mi}) \in R^{n_1\times n} \\ z_i = (z_{1i}, z_{2i}, \cdots, z_{mi}) \in R^{n_2\times n} \end{cases} \tag{1}$$

Since the constructed SBM model contains undesired output, the sample unit set T, referring to a collection of all technically feasible input and output models, can be determined as:

$$\mathrm{T} = \{(x, y, z)|x_k \geq X\lambda, y_k \geq Y\lambda, z_k \geq Z\lambda, \lambda \geq 0\} \tag{2}$$

Combined with the research of the data-envelopment analysis literature, the traditional DEA model measures the difference in the efficiency value of the invalid unit $(\rho < 1)$ under the condition of variable scale returns $\left(\sum_{k=1}^{n} \lambda_k = 1\right)$. The degree is magnified, which is not conducive to the decomposition of scale efficiency. Therefore, the SBM model including undesired output is constructed as follows:

$$\rho_0 = \min_{\lambda, s^+, s^-, s^{b^-}} \frac{1 - \frac{1}{m}\sum_{i=1}^{m} \frac{s_i^-}{x_{ik}}}{1 + \frac{1}{n_1 + n_2}\left(\sum_{j=1}^{n_1} \frac{s_j^+}{y_{ik}} + \sum_{j=1}^{n_2} \frac{s_j^{z^-}}{z_{ik}}\right)} \quad (3)$$

$$\text{s.t.} \begin{cases} \sum_{j=1}^{n} x_j \lambda_j + s^- = x_k \\ \sum_{j=1}^{n} y_j \lambda_j - s^+ = y_k \\ \sum_{j=1}^{n} y_j^{z^-} \lambda_j + s^{z^-} = y^{z^-} \\ \lambda_j \geq 0, s^- \geq 0, s^+ \geq 0, s^{z^-} \geq 0 \end{cases} \quad (4)$$

In Equation (3), the objective function ρ_0 is the production unit efficiency value; x_k is the input indicator, y_k is the expected output indicator, and z_k is the undesired output indicator; s^- is the input indicator relaxation variable, and s^+ is the expected output relaxation variable, s^{z-} is the undesired output relaxation amount; λ is the weight of input factors. The model incorporates slack variables into the objective function, taking into account the impact of negative external efficiency factors, optimizes the slack problem of input and output factors, and solves the problem of efficiency measurement when there is undesired output. However, when $\rho_0 < 1$, the model uses the furthest point on the envelope surface of the production unit as the standard, which results in a small efficiency measurement result. Therefore, it is necessary to further improve the model and adjust the vertex of the production frontier from the farthest distance to the most effective distance:

$$\rho_0^* = \min_{\lambda, s^+, s^-, s^{b^-}} \frac{1 - \frac{1}{m}\sum_{i=1}^{m} \frac{s_i^-}{x_{ik}}}{1 + \frac{1}{n_1 + n_2}\left(\sum_{j=1}^{n_1} \frac{s_j^+}{y_{ik}} + \sum_{j=1}^{n_2} \frac{s_j^{b^-}}{b_{ik}}\right)} \quad (5)$$

$$\text{s.t.} \begin{cases} \sum_{j \in R}^{n} x_j \lambda_j + s^- = x_k \\ \sum_{j \in R}^{n} y_j \lambda_j - s^+ = y_k \\ \sum_{j \in R}^{n} y_j^{b^-} \lambda_j + s^{b^-} = y^{b^-} \\ \lambda_j \geq 0, s^- \geq 0, s^+ \geq 0, s^{b^-} \geq 0 \end{cases} \quad (6)$$

The improved undesired SBM model can optimize the objective function, which is more in line with the actual situation of social production activities, and the envelope of the effective production unit is still the same as the original model. Therefore:

$$\rho_0^* \begin{cases} > \rho_0 & \rho_0 < 1 \\ = \rho_0 & \rho_0 = 1 \end{cases} \quad (7)$$

The Tobit model is also called the sample selection model and the restricted dependent variable model. It is often used to study regression where the dependent variable meets certain constraints. This model can solve the model construction problem of restricted dependent variables or truncated dependent variables. It is characterized by two parts: one is a selection equation model that represents the constraints, and the other is a continuous variable equation model that meets certain constraints. The classic Tobit model is a promotion of the probit regression by James Tobin in 1958 when analyzing household durable goods expenditure, and has since been used in a variety of situations. The standard Tobit regression model is as follows:

$$y^* = \beta x_i + \mu_i \qquad \mu_i{:}N(0, \sigma^2), \quad (8)$$

$$y_i = y^* \qquad if \quad y_i > 0 \quad (9)$$

$$y_i = 0 \qquad if \quad y_i \leq 0 \quad (10)$$

In the formulas, y_i is the dependent variable. When the dependent variable is greater than 0, the value is y*. When the dependent variable is less than or equal to 0, it is truncated at 0; x_i is the independent variable and obeys the normal distribution. When $y_i = 0$, its probability distribution function is:

$$P(y_i = 0) = P(y_i^* \leq 0) = \Phi\left(-\frac{\beta X_i}{\sigma}\right) = 1 - \Phi\left(-\frac{\beta X_i}{\sigma}\right) \quad (11)$$

where $\Phi\left(-\frac{\beta X_i}{\sigma}\right)$ is a standard normal distribution function. If $y_i = y_i^*$, the probability distribution of y_i is equal to the probability distribution of y_i^*; thus, the likelihood function class is expressed as:

$$l(\beta) = \sum_{y_i > 0} ln\left[\Phi\left(\frac{y_i - \beta X_i}{\sigma}\right)\right] + \sum_{y_i = 0} ln\left[1 - \Phi\left(\frac{\beta X_i}{\sigma}\right)\right] \quad (12)$$

This paper uses the maximum likelihood method to estimate the Tobit model.

RESULTS AND DISCUSSION

Calculation results of water-resource utilization efficiency in China

Variable selection

In the economic model for water-resource use efficiency, the input variables are labour force, fixed asset investment and total water resources, the expected output variable is the regional GDP, and the undesired output variable is the sewage discharge. The selection and calculation methods of these variables are as follows:

(1) Labour force (S). China has not yet conducted systematic statistics on labour time, the most direct indicator of labour force. This paper selected the total population of provinces and cities to represent labour input factors.
(2) Capital stock (K). This paper selects fixed capital investment to represent capital stock. The indicator data needed to be deflated, and the base period was set to 2008.
(3) The amount of water resources (E). In this paper, the total water supply of each province and city was selected to represent its water resources, which mainly included surface water (local surface water and cross-basin water transfer), groundwater, reclaimed water reuse, and seawater desalination. The data for this indicator could be obtained directly from the water resources bulletin.
(4) Expected output (Y). Selecting the total production value (GDP) of each province and city to represent the expected output, the indicator data also needed to be deflated. The base period was 2008.
(5) Unexpected output (B). The waste-water discharge is the undesired output index in the water-resource utilization efficiency model (3) and model (4), and is mainly composed of industrial wastewater and domestic wastewater.

Measurement results

According to the statistics of relevant indicators of water-resource utilization efficiency analysis for various provinces and cities, combined with the improved SBM model (4) and using MaxDEA5.2 and MATLAB software, the 2007–2019 water-resource utilization efficiency measurement results of 30 regions in China are shown in Table 1.

As can be seen from the table, the overall situation in the country was that the efficiency of water-resource utilization was between 0.518 and 0.502. During 2007–2019, the overall level of the country was relatively stable, and the efficiency value of each year was mostly above 0.5; during 2007–2011, the overall level declined and reached the lowest point of 0.473 in 2011; in particular, in 2011 the annual efficiency value dropped significantly. From 2012 to 2019, the efficiency of water-resource utilization was basically stable, with a slight increase, and a slight decrease in 2019. Overall, during the past 13 years, the nationwide water-resource utilization efficiency showed a trend of decreasing first and then increasing.

The value of water-resource utilization efficiency in the eastern region did not fluctuate significantly during these 13 years, and it showed a downward trend from 0.728 in 2007 to 0.677 in 2011; the water-use efficiency in 2012–2019 increased. It rose from 0.69 in 2003 to 0.715; after 2013 it was relatively stable, with efficiency values above 0.7.

In general, the value of water-resource utilization efficiency in the central region fluctuated relatively. Although its water-resource utilization efficiency value was relatively stable during 2007–2019, with a slight increase, in 2011 there was a large decline, from 0.422 to 0.368, a decrease of 0.66 (12.8%). Overall, during 2019, there was a rising pattern, but the scale was not large. Although the water-resource utilization efficiency value in the western region fluctuated relatively between 2007 and 2019, the overall efficiency value was relatively low. The water-resource utilization efficiency values were all between 0.384 and

Table 1 | Calculation results of water-resource utilization efficiency in China

	Region	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Mean
Eastern	Beijing	0.952	0.917	0.885	0.821	0.834	0.858	0.887	0.899	0.932	0.936	0.942	0.949	0.953	0.905
	Tianjin	0.597	0.589	0.561	0.542	0.543	0.562	0.573	0.594	0.613	0.613	0.621	0.619	0.625	0.589
	Hebei	0.388	0.373	0.359	0.334	0.337	0.349	0.362	0.371	0.381	0.384	0.382	0.388	0.393	0.369
	Liaoning	0.445	0.432	0.421	0.409	0.418	0.428	0.439	0.451	0.468	0.469	0.473	0.476	0.478	0.447
	Shanghai	0.965	0.943	0.923	0.901	0.915	0.924	0.935	0.957	0.977	0.984	0.988	0.983	0.989	0.953
	Jiangsu	0.754	0.732	0.711	0.696	0.701	0.713	0.726	0.736	0.758	0.759	0.763	0.767	0.778	0.738
	Zhejiang	0.778	0.764	0.745	0.731	0.736	0.746	0.756	0.769	0.777	0.779	0.784	0.785	0.796	0.765
	Fujian	0.823	0.803	0.785	0.761	0.762	0.777	0.784	0.795	0.816	0.824	0.821	0.833	0.835	0.801
	Shandong	0.788	0.766	0.745	0.732	0.739	0.751	0.766	0.786	0.799	0.804	0.802	0.813	0.815	0.777
	Guangdong	0.764	0.756	0.741	0.732	0.739	0.745	0.754	0.769	0.779	0.783	0.788	0.791	0.794	0.764
	Hainan	0.753	0.743	0.725	0.715	0.724	0.739	0.754	0.768	0.784	0.787	0.793	0.793	0.798	0.760
Eastern mean		0.728	0.711	0.691	0.670	0.677	0.690	0.703	0.718	0.735	0.738	0.742	0.745	0.750	0.715
Central	Shanxi	0.361	0.351	0.339	0.321	0.304	0.305	0.315	0.326	0.339	0.343	0.358	0.361	0.373	0.338
	Jilin	0.381	0.378	0.373	0.369	0.324	0.321	0.332	0.333	0.321	0.316	0.313	0.311	0.306	0.337
	Heilongjiang	0.555	0.554	0.546	0.542	0.507	0.506	0.503	0.518	0.528	0.548	0.558	0.567	0.573	0.539
	Anhui	0.367	0.365	0.361	0.358	0.316	0.317	0.322	0.324	0.332	0.338	0.343	0.359	0.369	0.344
	Jiangxi	0.356	0.348	0.345	0.341	0.312	0.314	0.327	0.337	0.349	0.353	0.364	0.369	0.372	0.345
	Henan	0.377	0.368	0.363	0.359	0.319	0.322	0.344	0.344	0.358	0.369	0.378	0.382	0.389	0.359
	Hubei	0.489	0.481	0.475	0.466	0.441	0.445	0.448	0.458	0.463	0.477	0.483	0.488	0.494	0.470
	Hunan	0.486	0.481	0.472	0.463	0.421	0.422	0.428	0.432	0.438	0.442	0.459	0.469	0.474	0.453
Central mean		0.422	0.416	0.409	0.402	0.368	0.369	0.377	0.384	0.391	0.398	0.407	0.413	0.419	0.398
Western	Inner Mongolia	0.268	0.254	0.243	0.242	0.238	0.231	0.234	0.249	0.254	0.264	0.278	0.284	0.288	0.256
	Guangxi	0.355	0.347	0.343	0.332	0.321	0.323	0.326	0.331	0.338	0.344	0.346	0.349	0.351	0.339
	Chongqing	0.544	0.541	0.533	0.532	0.519	0.517	0.519	0.527	0.531	0.543	0.549	0.548	0.551	0.535
	Sichuan	0.299	0.291	0.289	0.276	0.269	0.249	0.247	0.255	0.265	0.274	0.288	0.292	0.298	0.276
	Guizhou	0.264	0.261	0.255	0.249	0.247	0.239	0.241	0.246	0.253	0.256	0.257	0.258	0.263	0.253
	Yunnan	0.355	0.349	0.346	0.343	0.327	0.333	0.336	0.338	0.341	0.343	0.346	0.354	0.356	0.344
	Shaanxi	0.377	0.374	0.367	0.361	0.348	0.351	0.354	0.356	0.362	0.365	0.369	0.372	0.381	0.364
	Gansu	0.263	0.259	0.249	0.241	0.232	0.234	0.238	0.239	0.243	0.253	0.264	0.274	0.279	0.251
	Qinghai	0.477	0.471	0.464	0.452	0.443	0.435	0.446	0.448	0.451	0.459	0.464	0.479	0.486	0.460
	Ningxia	0.576	0.574	0.565	0.551	0.529	0.532	0.533	0.538	0.548	0.551	0.564	0.575	0.585	0.555
	Xinjiang	0.374	0.369	0.365	0.358	0.336	0.342	0.349	0.352	0.359	0.368	0.376	0.381	0.386	0.363
Western mean		0.377	0.372	0.365	0.358	0.346	0.344	0.348	0.353	0.359	0.365	0.373	0.379	0.384	0.363
National mean		0.518	0.508	0.496	0.484	0.473	0.478	0.486	0.495	0.505	0.511	0.517	0.522	0.528	0.502

0.344, and the lowest value was 0.344 in 2012. Overall, the western region is the lowest among the three major regions in the country, and lower than the national average.

On the whole, there are great differences in the utilization efficiency of water resources between various regions of China. From 2007 to 2019, the average water-resource utilization efficiency value of the provinces in the eastern region fluctuated around 0.715, for the provinces in the central region it fluctuated around 0.398, and for the provinces in the western region it fluctuated around 0.363. From 2007 to 2019, the trends of water-resource utilization efficiency in the three major regions are basically the same, roughly consistent with the overall change trend of the whole country. By analyzing the change trend of each region, it can be seen that the difference in regional water-resources usage efficiency was also substantially the same as the difference in the economic development level of each region. The water resource utilization efficiency in the eastern region was relatively high, which corresponds to its high level of development. The market mechanism in the eastern region was relatively complete, and its economy was relatively developed. However, the economic development level in the western region was relatively low, and there was no perfect market management and operation mechanism, which leads to a large amount of redundant input and waste in the production process, which leads to inefficient use of water resources. By comprehensively ranking the water-resource utilization efficiency of various provinces, it can be found that the water-resource utilization efficiency of each province in the eastern region was generally higher, followed by the central region and the western region, which was lowest. There was a general decline in water-resource utilization efficiency from the eastern coastal region to the inland areas.

Tobit regression results of influencing factors of water-use efficiency

Variable selection

(1) Data source

For water-resource utilization efficiency, the data come from the calculation results in this paper.

(2) Explanation of variables

Economic development level (ED). The indicators used to measure the ED of various provinces were regional GDP and regional GDP per capita. However, considering the objectivity and rationality of the selection of indicators, regional GDP per capita could measure living standards of people in the region more truly than regional GDP. Therefore, in this regression analysis, the per capita GDP was used as a variable to measure the economic development level of each region.

Regional water-resource richness (WE). Existing research suggests that in regions with abundant water resources, because water resources are relatively easy to obtain, people's awareness of saving water is relatively poor, and there is more waste in the use of water resources, which makes the water-resource utilization efficiency of the region comparably low. By contrast, in areas where water resources are scarce, due to that scarcity, people will consciously reduce the waste of water resources, thereby making water-resource usage relatively efficient. Therefore, differences in regional water resources and natural conditions will affect the efficiency of water-resource usage. This paper uses per capita water resources as an indicator to measure water resources in different regions.

Industrial structure (IS). The formation of a water resource consumption structure is largely affected by IS, and the rational adjustment of the proportion of each industry has a great impact on the improvement of water-resource utilization efficiency. The indicators used in this paper to study the impact of IS are the proportion of primary industry (ISF) and the proportion of secondary industry (ISS).

Industrial water structure (IW). The Environmental Kuznets Curve (EKC) shows that environmental quality is also related to industrial structure, and Chinese researchers have also analyzed the relationship between industrial water use structure and water-resource use efficiency. Yang & Liu (2015) proposed that 'farm water conservancy construction and environmental regulation have a significant role in promoting the efficiency of China's agricultural water-resource utilization'. Mai *et al.* (2014) discussed the use of industrial water resources for water-resource utilization and the effect of efficiency. This paper suggests that the structure of industrial water use will affect the efficiency of water-resource utilization to a certain extent, and on this basis, it chooses total agricultural water use (IWA), total industrial water use (IWI), total domestic water use (IWL), and total ecological water use (IWE), as characteristic values of industrial water use structure, and examines the impact of differences in industrial water use structure among provinces on water resource utilization efficiency.

Technological level (TECH). The level of science and technology is one of the important factors influencing environmental performance. Production technology has a positive effect on the efficiency of agricultural water-resource utilization, and technological progress is conducive to improving the efficiency of water-resource utilization. This paper determines that the level of science and technology is one of the influencing factors of water-resource utilization efficiency, and on this basis, determines the local financial science and technology expenditure as the characteristic value of the level of science and technology, to analyze the difference between the provincial scientific and technological levels and the difference in water-resource utilization efficiency correlation.

This paper combines the existing literature and considers the availability of data. It combines ED, WE, ISF, ISS, IWA, IWI, IWL, IWE, and TECH as explanatory variables. The sample interval is from 2007 to 2019. The regression equation is as follows:

$$\ln WRE = \alpha + \beta_1 \ln ED_i + \beta_2 \ln WE_i + \beta_3 \ln ISF_i + \beta_4 \ln ISS_i + \beta_5 \ln IWA_i + \beta_6 \ln IWI_i + \beta_7 \ln IWL_i + \beta_8 \ln IWE_i + \beta_9 \ln TECH_i + \mu \quad (13)$$

Regression results

The estimation results of the Tobit model estimation method in this paper are shown in Table 2.

Table 2 | Regression results

Explanatory variables	Parameter estimates	T-Statistics	*P*-value
LnED	0.00024***	−4.554	0.0001
LnWE	−0.1042***	4.213	0.0000
LnISF	−0.3311***	−0.501	0.0032
LnISS	−0.0951***	−6.124	0.0002
LnIWA	−0.2433***	−5.554	0.0311
LnIWI	−0.2124***	−3.325	0.0041
LnIWL	−0.0233***	−6.123	0.0133
LnIWE	−0.0329***	−3.113	0.0020
LnTECH	0.3422***	8.324	0.0021

Note: *** significant at the 1% level.

(1) There was a positive correlation between the level of economic development and the efficiency of water-resource utilization. The coefficient of influence of GDP per capita on the efficiency of water-resource utilization was 0.00024, that is, for every 1 percentage point increase in GDP per capita, the efficiency of water-resource utilization increased by 0.00024%, which means that the efficiency of water-resource utilization improved. With the continuous development of the social economy, social production is accelerating, and the demand for water resources will also increase day by day. However, in the case of limited total water resources, people need to find ways to efficiently recycle water resources to meet the needs of social production. In this case, people will reduce the consumption of water resources through technological innovation, elimination of more expensive equipment, and use of water-saving equipment, which will increase the utilization rate of water resources somewhat. Therefore, the impact of the regional economic development level on the efficiency of water-resource utilization cannot be ignored.

(2) The abundance of regional water resources had a significant negative impact on the utilization efficiency of water resources. Through regression, the coefficient of water resources per capita was negative, which indicates that the water-resource utilization efficiency per capita in a region is diametrically opposed to the trend of water-resource utilization efficiency in that region. When people are not plagued by a shortage of water resources, they often fail to realize the importance of water conservation, which leads to many problems such as serious waste and inefficient use of water resources. This requires the relevant departments to promote water saving and the recycling of water resources, so that everyone has a sense of water saving and recognizes the seriousness of the water-resources problem.

(3) The industrial structure (the proportion of primary and secondary industries) had a negative correlation with the utilization efficiency of water resources. The regression coefficient of the primary industry was −0.3311, which means that as the proportion of agriculture decreases by 1%, the water-resource utilization efficiency would increase by 0.3311%. The regression coefficient corresponding to the proportion of the secondary industry was −0.0951, which means that for every 1% decrease in the proportion of the industry, the water resource utilization efficiency would increase by 0.0951%. In China, agriculture and industry are large water users, and the current utilization rate of industrial water resources and agricultural irrigation water in China is relatively low. The traditional agricultural irrigation model consumes a lot of water resources, and it also causes a lot of waste, making for a sub-optimal utilization rate. It can be seen that scientific and reasonable adjustment of the industrial structure can not only improve the efficiency of water-resource utilization but also is highly significant for the construction of a water-saving society.
(4) There is a negative correlation between industrial water use structure and water-resource use efficiency, of which domestic water use and industrial water use have a relatively large degree of influence. That is, whether it is agricultural, industrial, ecological, or everyday water use, it has a negative impact on the environment. The impact of ecological water use is relatively low, which is consistent with the purpose of improving water-use efficiency and improving water-use structure. It may be considered necessary to further analyze the influencing factors of regional differences in water-resource utilization efficiency based on the industrial-water consumption structure and the water consumption of specific industries.
(5) The level of science and technology had a significant positive correlation with water-resource utilization efficiency, in which the impact of local fiscal science and technology expenditure on water-resource utilization efficiency was lower than the comprehensive production capacity of water supply. As the level of science and technology improves, water-purification capacity and water-supply capacity increase, efficiency increases, and the positive impact on the environment increases. Therefore, the higher the level of technology, the higher the efficiency of water-resource utilization. The higher water-use efficiency in eastern and northern China also confirms this analysis.

CONCLUSIONS AND RECOMMENDATIONS

Conclusion

This paper adopted a DEA method, based on panel data from 30 provinces in China from 2007 to 2019, and calculated water-resource utilization efficiency in the country and various regions. The MI method was used to analyze the total element of water resources. The dynamic changes of utilization efficiency over 13 years and the influencing factors of this efficiency were studied, and the main conclusions reached are as follows:

From 2007 to 2019, the average water-use efficiency in China was 0.502, indicating that China's overall water use efficiency level is still low. From the perspective of various regions, the difference in water-use efficiency between regions is obvious. At the same time, the water-use efficiency shows a spatially decreasing distribution pattern from the eastern coastal area to the western inland area. With regard to the changing trend of water-resource utilization efficiency over 13 years, it is basically the same across the three major regions, and is consistent with the changing trend of the whole country. Through research on the redundancy of water resources input in various regions, it was found that the amount of water-resource input redundancy in the country and the three major regions was relatively large, which shows that each region of China has great potential in saving water.

Through the analysis of the influencing factors of water-resource utilization efficiency through the Tobit model, it was found that, among the variables corresponding to the influencing factors selected by the model, the amount of water resources per capita, domestic water consumption per capita, and the proportion of primary and secondary industries all had a negative impact on utilization efficiency, and per capita GDP had a positive impact on water-resource utilization efficiency. Agricultural water consumption, industrial water consumption, domestic water consumption, and total ecological water consumption had a negative impact on water-resource utilization efficiency, of which domestic water consumption was the worst. Industrial water consumption had a greater influence; the level of science and technology and water-resource utilization efficiency showed a significant positive correlation.

Recommendations

The government should increase its support for improving the efficiency of water-resource utilization

The government does a good job of supporting and guiding, increasing investment in science and technology, cultivating technical talent, improving the level of science and technology, and providing technical support for water-resource utilization efficiency, with a view to building the most stringent water resources management system, controlling and using water resources as early as possible, and collecting fees at an appropriate time. External environmental taxes reduce water-resource pollution, and gradually establish and improve water-resource property rights and use a control system. For the eastern zone, the government taps the water-saving potential, improves sewage-treatment capacity and reuses water capacity as much as possible, increases environmental protection publicity, and promotes the construction of a water-saving society. Based on improving the level of science and technology, the central and western regions have strengthened environmental monitoring and government supervision, and established an evaluation system and enforcement mechanism for water-resource utilization efficiency to better promote it.

Formulate reasonable water resource utilization efficiency targets based on regional realities

The improvement of water-resource utilization efficiency is based on economic development and requires investment. The purpose of improving water-resource utilization efficiency is to make socio-economic development better and faster. Then, when formulating the speed and range of regional water-resource utilization efficiency improvement, it must take the economic level of the region into consideration, and it is impossible to blindly formulate development goals for water-resource utilization efficiency without departing from the economic development stage. If the target value is too high, the investment will be greatly increased, which will inevitably slow down and hinder economic development. If the target value is too low, it cannot effectively limit the increase in water consumption and sewage discharge, and it cannot be reduced. A lot of pressure is put on the ecosystem by a low water supply and inadequate sewage purification, and modest or overambitious goals cannot achieve the ultimate aim of improving the efficiency of water-resource utilization, so it is particularly important to formulate reasonable water-resource utilization efficiency targets.

Vigorously raise awareness of water saving for everyone

Water-resource management policies and measures are external guarantees for water conservation, but profound water-resource crisis awareness is the most fundamental internal motivation for water conservation and the basis for sustainable use of water resources. Citizens' awareness of environmental protection is a concentrated expression of a country's civilization, and it is also the basis for the formulation of national environmental policies. Raising public awareness of saving water, appreciating water, and protecting the ecological environment of water resources will directly affect the sustainable use of water resources. To effectively raise citizens' awareness of water-resource protection, it is necessary to improve the traditional propagandist and educational methods and turn them into forms of participation and interaction. Make the public aware of the seriousness of water pollution by strengthening science education and other methods; by strengthening legal education, raise the level of public awareness of environmental protection laws and regulations; by giving the public the right to know about the environment, open up environmental information and encourage citizens to participate in environmental policy formulation, and strengthen supervision of environmental management; by supporting environmental protection activities initiated by private environmental protection organizations, abandon the misconception that wastewater is waste, encourage the public to start with small things around them to gradually improve the effectiveness of sewage resources. The utilization rate protects the limited water resources.

Cross-regional cooperation and exchange

With the development of regional economies, the establishment of regional innovation systems at various levels has produced a spillover effect of water-resource utilization efficiency. The key to this spillover effect is whether regions with lower water-use efficiency will absorb water-use technologies and management systems from regions with higher water-use efficiency. Therefore, cross-regional cooperation and exchanges need to gradually change the efficiency of water-resource utilization in the regions from low to high according to their own capabilities. Through convergence analysis of water-resource utilization efficiency of various provinces and cities in China, it was found that there is significant absolute convergence of water-resource utilization efficiency in China, but the convergence is slow, and the gap of water-resource utilization efficiency among provinces and cities still persists. At the same time, the empirical research in this paper also shows that geographical factors have a significant positive effect on China's water-resource utilization efficiency. The level of water-resource utilization efficiency of a region depends to a certain extent on the level of water-resource utilization efficiency of neighbouring regions with similar spatial characteristics. Therefore, for the long-term development of water-resource utilization efficiency in various provinces and cities, it is necessary to further strengthen measures to promote cross-regional economic and technological exchanges, accelerate the process of technology diffusion from advanced regions to developing regions, and improve the level of water-resource utilization efficiency in the latter.

Strengthen water resources protection and improve water resources management systems

Human beings are inseparable from water resources in the process of production and life. The protection of water resources is the most basic condition for human survival and development. Building a conservation-oriented society is an important national policy proposed based on the current state of water resources. The protection of water resources is not only about the country taking compulsory measures to control the development and utilization of water resources, but also about the mutual supervision and cooperation of all sectors of society. At present, many countries carry out environmental impact assessments on water conservancy projects. China also needs environmental assessments at the feasibility study stage for water resources projects. Large-scale and general projects need to prepare environmental impact reports, and small-scale projects should prepare environmental impact assessment forms. This is the specific manifestation of the government's macro-control of water resources. The essence of improving the water resources management system is to strengthen the government's supervision of the use of water resources, and to improve the efficiency of water use and the optimal allocation of water resources.

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DATA AVAILABILITY STATEMENT

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

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