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Original Research

Spatiotemporal Evolution of the Green Efficiency of Industrial Water Resources and Its Influencing Factors in the Middle Reaches of the Yangtze River of China

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Abstract

Exploring ways to improve the green efficiency of industry water resources (GEIWR) is an inevitable requirement for achieving harmonious and sustainable industrial development and water use. Taking the urban agglomerations in the middle reaches of the Yangtze River (UAMRYR) as an example, this paper constructed an industrial green water resource efficiency index system. Based on the slack based model (SBM), the spatiotemporal evolution characteristics of the GEIWR during 2006-2019 were analyzed, and its spatial differentiation characteristics were investigated by exploratory spatial data analysis (ESDA), Besides, a spatial Tobit model was constructed to reveal its influencing factors. The results are as follows: (1) Temporally, the GEIWR ranged between 0.525 and 0.745 from 2006 to 2019 with an overall flat change, showing two distinct phases of change. Spatially, the difference varied markedly, with the GEIWR showing a pattern of "high in the south and low in the north" from 2006-2010 and "high in the centre and low around" from 2014-2019. (2) GEIWR global Moran's I value between 0.003 and 0.462, showing positive correlation characteristics, but the coefficient gradually decreased and the spatial correlation decreased; The local autocorrelation aggregation region changed significantly, the spatial aggregation effect was apparent before 2014, the concentration area decreased in 2019, the spatial correlation decreased, the spatial disequilibrium appeared. (3) The economic and industrial structure and the level of science and education had a significant effect on GEIWR and the economic benefits of industrial water resources showed an inverse inhibitory effect, while the natural resource endowment and degree of industrialization had no significant impact on GEIWR. Thence,

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when formulating water resources protection policies, the spatial distribution and influencing factors should be taken into account and the specific situation should be analyzed, to provide scientific basis for improving the GEIWR.

Keywords: green efficiency of industrial water resources, spatiotemporal evolution, influencing factor, SBM model, the middle reaches of the Yangtze River

Introduction

Water plays an integral function in balancing the earth's ecology and stabilizing human development [1]. According to the report, the 17 Sustainable Development Goals (SDGs) were officially mentioned at the UN Sustainable Development Summit in 2015. Among them, SDG 6.4 and SDG 12.2 both emphasize the importance of water resources and their efficient use. However, according to the 2016-2018 report of China's Sustainable Development Goals Index, China's overall performance in SDG6 and SDG12 is yellow, indicating that it has a certain disparity in the 2030 goal [2]. China has only 7% of the world's water resources, but 20% of the world's population, and only 2300 m^3 of per capita water resources, which further illustrate its water scarcity [3-4]. Meanwhile, the industrial sector consumes a lot of water resources, the World Bank [5] estimates that before 2050, the agricultural water consumption rate will drop to roughly 50%, but the industrial water consumption rate will increase steadily. Thus improving the utilization of industrial water resources (UIWR) is the key to sustainability [6-7]. Therefore, how efficiently using water resources and scientifically and reasonably measuring the green efficiency of industry water resources (GEIWR) are the foundations for achieving green development in the region.

Existing research has focused on three main areas: efficiency measures, spatial variation and influencing factors. Efficiency measures mainly focus on agricultural water use, industrial water use, regional water use efficiency, and ecological efficiency. Some scholars study the water use efficiency of urban infrastructure in the hope of improving water use efficiency and saving urban water [8]. The diversity of research subjects shows the richness of water resources research and provides a scientific basis for further improving water efficiency. In addition, for efficiency measurement, some scholars usually use quantitative methods, analytical hierarchy process (AHP), ratio analysis and data envelopment analysis (DEA) [9-10]. Two-stage model evaluation with game cross-efficiency is also a valid model for the GEIWR evaluation [11]. Due to its DEA's comparative advantages, it is widely used by scholars. The DEA has comparative advantages. It does not require a priori determination of the functional relationships between variables in dealing with multiple inputs and multiple outputs, which is a clear difference from other evaluation methods, the use of this method is a key component of efficient research, ensuring maximum integrity of the original information widely used in efficiency studies, thus enabling further multi-input and multi-output water use efficiency measurements. And, in contrast to the AHP evaluation method, also uses an objective weighting approach designed to avoid the influence of the researcher's own subjective factors. So it has become a popular choice for scholars. Kamal et al. used the DEA to evaluate and compare the urban water supply and utilization efficiency in the Gaza Strip and Western developed countries from 1999 to 2002 [12]. Sun et al. used DEA to measure the GEIWR and investigated the spatially linked network characteristics of it in China based on the Social Network Analysis [13-14]. On the analysis of spatial variation, Zou et al. used Moran's I to verify the existence of spatial effects on industrial water use efficiency in China, hoping to achieve optimal allocation of water resources and alleviate the contradiction between water scarcity and the surge in industrial water demand [15]. Wei et al. also used spatial autocorrelation analysis to investigate spatial trends in agricultural water use in nine provinces in the Yellow River basin [16]. In terms of the selection of influencing factors, most choose factors with strong correlation according to regional characteristics. Many researchers have identified key factors affecting water resources efficiency based on regional development levels, the degree of rationalization of industrial structures and environmental pollution. Shi et al. established a GWR model and found that the effects of regional industrial structure and industrial water intensity significantly contributed to industrial water efficiency in central and western China, while environmental pollution had a dampening effect on southeast and central China [17]. Zou et al. used a spatial econometric model to find that GEIWR was promoted by natural resource endowment, economic development, industrialization and technological progress, but inhibited by industrial water intensity and environmental regulation [18].

In summary, the direction of water efficiency research is gradually moving from a single to a diversified approach. The research methods are continuously refined and expanded, and the study of the combination of other factors is strengthened. The research objects are also enriched, which gradually evolves into the study of the water efficiency of the whole factor, which provides a reference for the study of GEIWR in this paper. However, in terms of exploring GEIWR, there has been relatively little research involving industrial water efficiency and the drivers for larger urban agglomerations. Therefore, the innovations of this paper are as follows. Firstly, this paper chose the largest urban agglomeration in China with unique regional conditions, which is a crucial area for ecological protection in the Yangtze River Economic Belt, analyzed the industrial conditions and in this area, and had reference value for leading the development of the central region and rising to the "fifth pole" urban agglomeration of the Chinese economy. Secondly, in the traditional efficiency measurement aspect, green elements were introduced to analyze the GEIWR from a green development perspective. Thirdly, the economic benefits of industrial water resources were expressed by using the value-added water consumption index of 10^4 yuan to accurately reflect the water resources input in the industrial economic process.

As mentioned above, this paper is divided into the following steps. (1) We used DEA to measure the GEIWR of the urban agglomerations in the middle reaches of the Yangtze River (UAMRYR), the largest urban agglomeration in China, from 2006 to 2019. (2) We revealed spatial characteristics of the GEIWR through ESDA. (3) We analyzed the influencing factors of GEIWR using the Tobit regression model. (4) We finally discussed and made policy implications to alleviate industrial water stress and promote the GEIWR.

Study Area and Methods

Study Area

The UAMRYR (Fig. 1) is a mega-city agglomeration (with 31 cities including Ji'an and Fuzhou) mainly composed of the Wuhan urban circle, the Chang-Zhu-Tan urban agglomeration, and the urban agglomeration around the Poyang Lake. The climate is humid and mild, and the annual average precipitation is about 800-1943mm. There are many rivers and lakes in the area, such as Poyang Lake, Dongting Lake, Hanjiang River and Xiangjiang River, with abundant water resources. In September 2021, the Symposium on Coordinated Promotion of High-Quality Development among the Three Provinces reviewed and approved the "Deepening Coordinated Development and Accelerating Green Rise - Overall Concept of Strategic Cooperation among the three Provinces in the Middle Reaches of the Yangtze River" [19], emphasizing the coordinated promotion of the green transformation for traditional industries and the expansion and quality improvement of leading industries. The UAMRYR is a key area for the three provinces to jointly build a green growth pole. They empower each other, integrate and advance together, and the industry develops rapidly. By the end of 2019, the total industrial output value of the UAMRYR reached 13.83 trillion yuan. However, due to the excessive concentration of heavy and chemical industries, the extensive and inefficient way of using

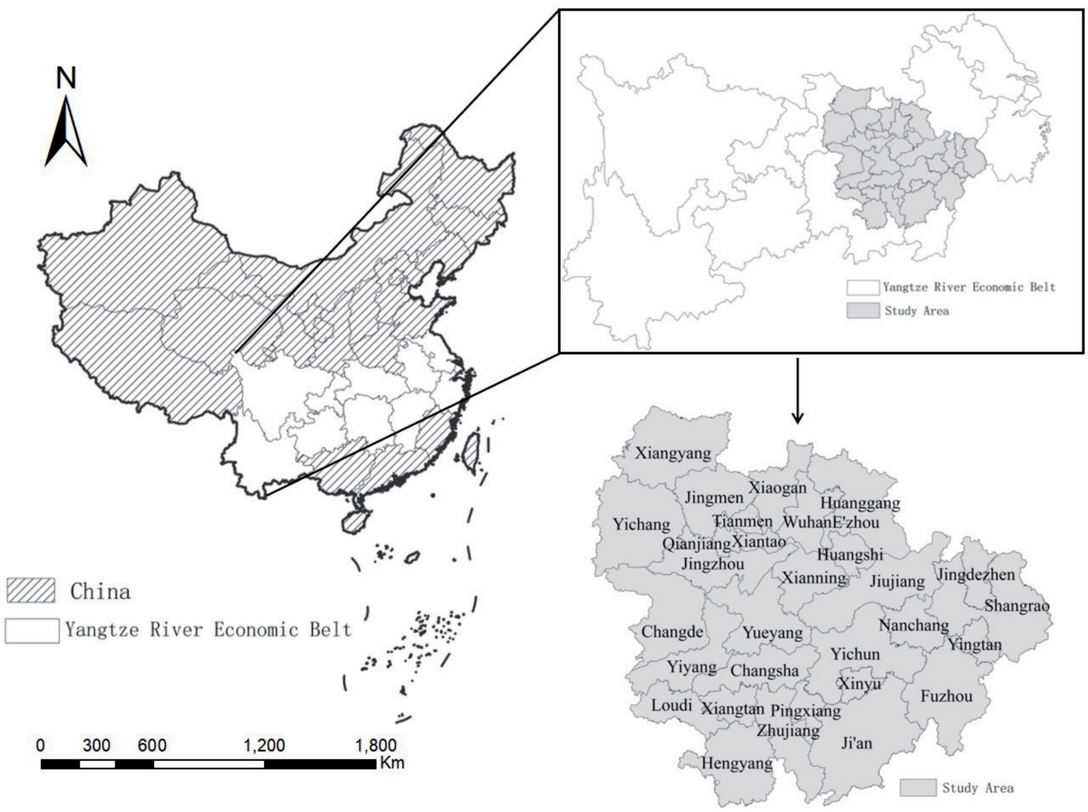

Fig. 1. The study area of the UAMRYR.

resources makes the distribution of water resources in the region uneven; the regional differences are obvious, and the water supply and consumption are huge and cause serious pollution [20]. By the end of 2019, the total water consumption in the Yangtze River basin was 206.45 billion m^3. Among them, the industrial water consumption was 70.40 billion m^3, accounting for 34.1% of the total water consumption [21-22]. And the industrial water con-sumption in the study area was 8.641 billion m^3, the industrial wastewater discharge was 859 million tons, accounting for 10% of the total industrial water consumption [23]. Therefore, discussing the GEIWR of the UAMRYR has become an important direction to promote the green development of industry in this region.

Methods

SBM-DEA Model

DEA calculates the distance between the actual production point and the production frontier of all decision-making units through input-output data [24]. It compares the relative efficiency between decision-making units, and evaluates decision-making units [25-26]. The SBM-DEA model improves on traditional DEA models that do not take enough ac-count of the slackness of data inputs and outputs in the calculation process [27]. Therefore, this paper adopts SBM model that can solve the problem of input slack to measure the GEIWR [28]. The formula is as follows:

$$p^* = min \frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{S_i^-}{x_{i0}}}{1+\frac{1}{S_1+S_2}\left[\sum_{r=1}^{S_1}\frac{S_r^g}{y_{r0}^g}+\sum_{r=1}^{S_2}\frac{S_r^b}{z_{r0}^b}\right]} \quad (1)$$

$$s.t\begin{Bmatrix} x_0 = X\lambda + S^-, y_0^g = Y^g\lambda - S^g, z_0^b = Z^b\lambda + S^b \\ S^- \quad 0, \quad S^b \quad 0, \quad \lambda \quad 0 \end{Bmatrix} \quad (2)$$

In the formula: P* represents the GEIWR value; S-, S^g, S^b are the slack of input, expected output and undesired output, respectively; x, y^g, z^b are respectively Input, expected output and undesired output value; λ is the weight vector. When $S^- = S^g = S^b = 0$, P* = 1 indicates that the decision-making unit is completely effective; otherwise, it indicates an efficiency loss, and the input and output need to be adjusted.

Exploratory Spatial Data Analysis

ESDA is a data analysis method to reveal the structure and regularity of data in different regions [29]. It is usually represented by global and local autocorrelation [30]. The global autocorrelation represents the total connection degree and spatial association pattern of the research objects in the area [31]. Local autocorrelation can express the spatial characteristics of a research unit and its adjacent spatial area units, and reflect the spatial aggregation characteristics of its local area [32]. The formula is:

$$\text{Moran's } I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}(x_i-\bar{x})(x_j-\bar{x})}{S^2\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}} \quad (3)$$

$$I_t = Z_i\sum_{j=1}^{n}W_{ij}Z_j \quad (4)$$

In the formula: $S^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})$; $\bar{x} = \frac{1}{n}\sum_{i=1}^{n}X_i$, x_j and X_i represent the GEIWR in area i and j, respectively; W_{ij} represents the adjacent space weight matrix. Z represents the normalized form between the attribute values of the sample space unit.

Tobit Regression Model

As the efficiency values measured by the SBM model are constrained to be between 0 and 1, the data have truncated characteristics and direct least squares estimation may be biased. Besides, the Tobit model differs most from other discrete choice models and continuous variable choice models in general in that the dependent variable is restricted [33]. It is typically used to analyze the factors influencing the dependent variable in the presence of truncated data [34]. Therefore, in order to more accurately estimate the relationship between the variables, the Tobit model was chosen for the influence factor analysis. After calculating the GEIWR of each city in the study area, a regression model was built to analyze the data with the GEIWR as the dependent variable and each influence factor as the independent variable. The formula is as follows:

$$Y = \beta X_i + u_i, \quad u_i : N\ (0,\ \sigma^2) \quad (5)$$

$$y_i = y, \quad if\, y_i > 0 \quad (6)$$

$$y_i = 0, \quad if\, y_i \leq 0 \quad (7)$$

In the formula: *Y* is the dependent variable, β is the coefficient, X_i is the independent variable, and u_i is independent and obeys Normal distribution.

Variable Selection and Data Sources

Explanation of Input and Output Indicators

Based on the input-output perspective, environmental pollution factors are introduced into the traditional definition of water resources efficiency, referring to previous studies [35], and defined as "GEIWR" (Table 1). Regarding its evaluation index, it should reflect whether the UIWR is reasonable, whether the configuration elements can obtain the maximum

Table 1. Input-output indicators of GEIWR .

Indicators	Specific indicators	Description	Unit
Input	Industrial water consumption	Water input	10,000 tons
	Employment in the secondary industry	Labor input	person
	Fixed asset investment	Capital investment	10^6 yuan
Expected output	The total industrial output value	Economic benefit	10^6 yuan
	The added value of the secondary industry	Social benefit	10^6 yuan
Unexpected output	Industrial wastewater discharge	Environmental pollution	10^4 tons

output, and comprehensively consider the environmental pollution caused by the discharge of wastewater in the industrialization process.

(1) The efficiency evaluation of industrial green water resources should fully consider both input and output, and the input indicators should reflect the input of water, capital, and labor. Water input reflects the input and consumption of water resources in industrial production in the region. Drawing on relevant scholarly research, industrial water consumption is used to measure [36]. The labor input is measured through employment in the secondary industry which reflects the labor consumption in the UIWR [37]. The capital input is measured by the fixed asset investment, which reflects capital investment in the process of water use [3], expressing the scale, speed, and quality of fixed asset investment in the region.

(2) Expected output mainly refers to economic and social benefits. Using the methodology described by Shi et al. [38], economic benefit are expressed in terms of total industrial output value to reflect the total scale and level of industrial production over a period of time. Drawing on the method of existing research [39], social benefits are expressed in terms of the added value of the secondary industry in that this indicator reflects the extent to which the growth of industry contributes to the economy in a certain period. The unexpected output refers mainly to the environmental output, drawing on the method of Fujii et al. [40], using industrial wastewater discharge. Excessive industrial wastewater discharge will not only bring pollution to the ecological environment, but also affect the green use of water resources.

Selection of Influence Factor Indicators

The efficiency value measured by the DEA method is also affected by other factors. Therefore, it is necessary to adopt a new index of influencing factors to judge the influence of each factor on the UIWR in the study area by analyzing the regression results of the explanatory variables [41].

In light of the actual situation in the UAMRYR and the fact that data are available, indicators are selected from five aspects: natural resource endowment, economic and industrial structure, economic benefits of industrial water resources, degree of industrialization, and level of science and education. The specific selection of indicators can be found in Table 2.

(1) Natural resource endowment (NRE). The NRE affects the efficiency of water use. Abundant water resources can promote the agglomeration of factors, promote economies of scale, and thus improve the GEIWR, which is the "resource blessing" hypothesis; on the other hand, where water resources are abundant, water prices inexpensive, leading to people's lack of water-saving awareness, that is, the "resource curse" hypothesis [42]. So, drawing on the example of Lv et al. [4], the per capita water resources is used as a representative indicator of NRE to explore whether the impact is positive or negative.

(2) Economic and industrial structure (EIS). The regional water use efficiency is generally affected by the industrial structure. The secondary industry has the characteristics of large water consumption. The increase or decrease of the added value of the secondary industry will promote the consumption of industrial water resources. Thus, with reference to the research by Xu et al. [43], which used the indicator of the added value of the secondary industry as a percentage of GDP to represent the EIS.

(3) Economic benefits of industrial water resources (EBIWR). The economic benefits produced by industrial water resources aim to quantify the economic value of water use. It represents the water consumption required for every 10^4 yuan of industrial added value produced in industrial production, which more accurately reflects the level of industrial water consumption in the production process. Therefore, by drawing on the research results of Zhang et al, the EBIWR is expressed in terms of water consumption per 10^4 Yuan of industrial value added by drawing on the research results of Zhang et al. [44].

(4) Degree of industrialization (DI). The degree of industrialization development is a comprehensive reflection of industrial agglomeration and optimization strength. With the continuous development of industry, industrial agglomeration will affect industrial water consumption, and the improvement of its efficiency may break through the space limitation. Drawing on the research of Wang et al. [31], the DI is expressed by the industrial added value as a percentage of GDP.

Table 2. Index system of influencing factors.

Indicator classification	Variable description	Unit	Prediction direction
Natural resource endowment	The per capita water resources	m^3/person	unknown
Economic and industrial structure	The added value of the secondary industry as a percentage of GDP	%	+
Economic benefits of industrial water resources	Water consumption per 10^4 Yuan of industrial value added	$m^3/10^4$ yuan	unknown
Degree of industrialization	Industrial added value as a percentage of GDP	%	unknown
Level of science and education	Science and technology expenditures	10^4yuan	+

(5) The level of science and education (LSE). The progress of the LSE can upgrade water-saving technologies and equipment for the GEIWR, as well as improve the efficiency and management of water resources. Taking reference from the findings of Zhou et al. [45], science and technology expenditures are used to represent the LSE.

Data Sources

It takes 2006-2019 as the research period, and according to the research objectives, selects the water, capital, labor input, and related output indicators to measure GEIWR and further analyze influencing factors. The data used to calculate the efficiency index and the influencing factors index in this paper mainly come from China Urban Statistical Yearbook, Hubei, Hunan and Jiangxi Statistical Yearbook (2006-2019), and the Water Resources Bulletin of the three provinces (2006-2019). For individual missing data, interpolation was used to supplement. To better understand the interrelationships between variables, the DEA variables and impact factor panel data are described and counted. Variable statistics include mean, standard deviation, maximum, and minimum values. The specific characteristics are shown in Table 3. In addition, the stationarity of the panel data is identified by the unit root test to ensure the effectiveness of the results.

Temporal and Spatial Differentiation of GEIWR in UAMRYR

Dynamic Analysis of Spatiotemporal Evolution of the UAMRYR

Time Series Variation Characteristics

The GEIWR of the UAMRYR was calculated by using the Max-DEA software to calculate the comprehensive technical efficiency (TE) value, pure technical efficiency (PTE), and scale efficiency (SE) of UIWR in 31 cities in the UAMRYR from 2006-2019 as specified in Table 4. The efficiency values were then aggregated and

Table 3 Descriptive statistics of variables.

Variables	Meaning	Number of samples	Mean value	Standard deviation	Minimum	Maximum
Input-outputs	Water input	434	6895	41487.809	980	20020
	Labor input	434	237772.069	204216.595	3900	1943330
	Capital investment	434	134677.800	150551.194	5422	949312.602
	Economic benefit output	434	248981.900	313830.513	8740	4166540
	Social benefit output	434	81510.400	93519.354	4520	637775
	Unexpected output	434	6034.647	4749.127	205	8619
Influencing factors	Natural resource endowment	434	2928.167	3623.738	28	29225
	Economic and industrial structure	434	0.495	0.081	0.119	0.6691
	Economic benefits of industrial water resources	434	165.287	267.993	28	4335
	Degree of industrialization	434	0.438	0.084	0.153	0.622
	Level of science and education	434	62827.702	141959.207	30.5	1764277

averaged over 14 years to analyze the specific changes in TE, PTE and SE over 14 years for the 31 cities.

From the overall trend, the GEIWR showed a fluctuating trend, with two main stages (Fig. 2). The first stage was from 2006 to 2014. Despite the temporary increase, the overall trend was declining, and reached a low of 0.525 in 2010. The main reason was that affected by the financial crisis in 2008, and China launched a series of measures to stimulate domestic demand in 2009. With the rise of the central area planning, the UAMRYR has increased the consumption of water resources to vigorously develop its economy, therefore giving priority to the development of the equipment manufacturing industry, which has a dominant position.

The second stage was from 2014 to 2019, showing little change and a slow upward trend. Mainly because the state proposed to implement the strictest resource protection system during the "Twelfth Five-Year Plan." period. In 2015, the "Water Pollution Prevention and Control Action Plan" was released, which made specific provisions on how China will implement water conservation measures. Prominent problems such as ecological degradation of water are beginning to improve. The citizens' awareness of water conservation has been enhanced, and the retrofit of water-saving devices has gradually increased the GEIWR from a trough.

These efficiency values for TE, PTE and SE were aggregated and averaged over 14 years to analyze the specific changes in TE, PTE and SE over 14 years for these 31 cities (Table 5).

(1) From the perspective of TE, from 2006 to 2019, the GEIWR reached the maximum in Changsha, Yueyang, and Yingtan, and the efficiency reached above 0.98, indicating that the UIWR has reached the optimal level. The minimum comprehensive technical efficiency is Xiaogan City and Huanggang City, both below 0.4, indicating that the two cities have extremely low water resource utilization efficiency, poor factor allocation, and extensive utilization of industrial resources and water resources. The 8 cities including Xiangtan, Yiyang, and Loudi, have industrial water resource utilization efficiency below 0.6 all year round, indicating that there remains a wide disparity between maximum output and the output obtained from each factor input of industry, the efficiency of green water resources needs to be improved. The construction of centralized sewage discharge treatment facilities in industrial parks needs to be advanced in an orderly manner.

(2) From the perspective of PTE, from 2006 to 2019, the region with the best pure technical scale increased compared with the overall efficiency. The cities with an efficiency value of 1 include Changsha, Yueyang, Xinyu and other six cities, indicating that these region adopts relatively advanced production technology and equipment and facilities, carries out scientific and effective management, and various production factors play their due production potential to achieve the optimal level of UIWR. The six PTE values of Changde City, Pingxiang City, and Yichang City are all above 0.8, indicating that these regions attach great importance to investment in science and technology, continuously optimize production processes, realize the full potential of investment in industrial resources pay attention to water conservation, and pursue the goal of optimal

Table 4. Changes of GEIWR in the UAMRYR from 2006 to 2019.

Year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
TE	0.708	0.745	0.734	0.704	0.525	0.666	0.654	0.644	0.599	0.648	0.642	0.675	0.673	0.624
PTE	0.819	0.798	0.795	0.785	0.709	0.760	0.740	0.735	0.720	0.769	0.755	0.753	0.739	0.689
SE	0.877	0.934	0.934	0.910	0.758	0.875	0.904	0.899	0.837	0.858	0.861	0.901	0.915	0.933

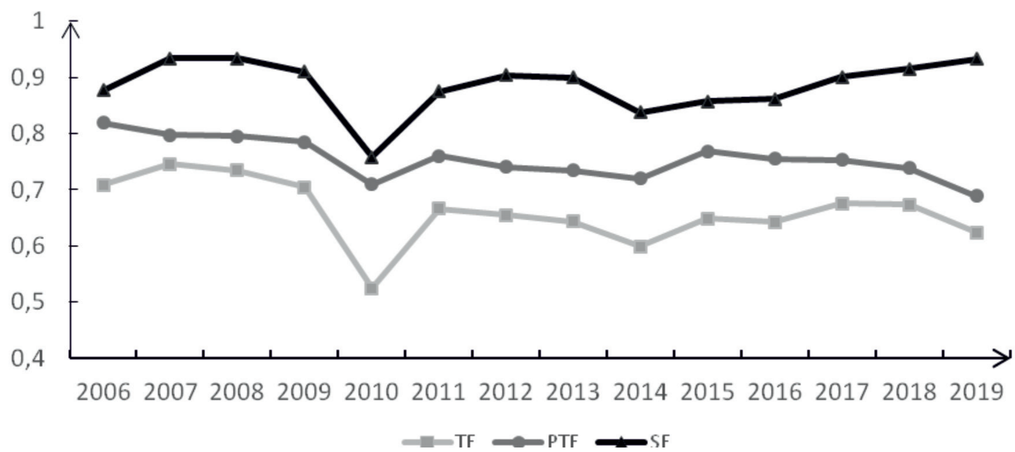

Fig. 2. Trends of GEIWR in the UAMRYR from 2006 to 2019.

output. Huangshi City and Xiaogan City have the lowest PTE values, both below 0.45, indicating that the two cities have less investment in science and technology and little deployment of new technology. There is a need to strengthen technological innovation, tackle key technologies, and promote the green transformation of the industry.

(3) From the perspective of SE, the SE value is relatively high across the regions from 2006 to 2019, the SE value reached 1 in Changsha City and Yingtan City, indicating that the industrial water resources in the two places have achieved optimal utilization, and various elements have been invested in reaching the optimal output scale. The SE value of Yueyang City, Nanchang City, Shangrao City and Xiaogan City has always been above 0.96, indicating that their industrial production has reached a certain scale. However, the SE value of E'zhou is the lowest, only 0.635, indicating that its industrial development has not formed agglomeration benefits with surrounding cities, the scale benefits have not been well reflected. From now on, industrial production should increase input of water resources on a larger scale and adopt scientific management models to improve the UIWR.

Spatial Variation Characteristics

To more visually demonstrate the spatiotemporal dynamic evolution of the GEIWR, this paper selects the GEIWR data in four years in 2006, 2010, 2014, and 2019, and uses ArcGIS software for visualization (Fig. 3).

It can be seen from Fig. 3 that from 2006 to 2019, the GEIWR generally showed a dynamic trend of low all around, and the high-efficiency value areas tended to move from the south to the center. During 2006-2010, most of the high-efficiency values of UIWR were located in Jiangxi Province, indicating that Jiangxi Province has reached a high level in terms of input and GEIWR 2006-2010, not only attaching importance to industrial development but also water resource consumption problems.

In 2014, there were only six high-efficiency areas of industrial water resources, accounting for 19% of the total study areas, and most of them were located in the middle of urban agglomerations. This means that under the guidance of the "Twelfth Five-Year Plan", relevant enterprises have started to attach importance to the total control of industrial water use and water pollution discharge. UIWR is moving towards intensive use. However, in 2006 and 2010, Jiangxi Province had always been located in areas with high-efficiency values, but the stamina was insufficient. After a period of sustainable UIWR, the protection of water resources was slack, leading to a decline in sustainable UIWR.

In 2019, the high-efficiency value area in the central part of the city cluster increased, from six in 2014 to nine, accounting for 29%. With the introduction of "the Yangtze River Economic Belt Ecological and Environmental Protection Plan" in 2017, China strongly supports the development of high-tech industries and promotes technological innovation. The concentration of industrial industries on a large scale and technical

Table 5. Average value of GEIWR in the UAMRYR from 2006 to 2019.

Areas	TE	PTE	SE	Areas	TE	PTE	SE
Changsha	1.000	1.000	1.000	Fuzhou	0.631	0.760	0.831
Zhuzhou	0.700	0.736	0.947	Shangrao	0.733	0.750	0.973
Xiangtan	0.522	0.557	0.933	Wuhan	0.790	1.000	0.790
Hengyang	0.647	0.677	0.947	Huangshi	0.447	0.482	0.921
Yueyang	0.981	1.000	0.981	Yichang	0.857	0.897	0.957
Changde	0.796	0.848	0.937	Xiangyang	0.598	0.679	0.902
Yiyang	0.459	0.526	0.883	E'zhou	0.429	0.758	0.635
Loudi	0.562	0.612	0.919	Jingmen	0.623	0.643	0.956
Nanchang	0.710	0.719	0.983	Xiaogan	0.343	0.354	0.962
Jingdezhen	0.558	0.759	0.768	Jingzhou	0.426	0.457	0.925
Pingxiang	0.808	0.979	0.825	Huanggang	0.345	0.406	0.850
Jiujiang	0.622	0.680	0.913	Xianning	0.591	0.823	0.751
Xinyu	0.760	1.000	0.790	Xiantao	0.666	0.925	0.730
Yingtan	1.000	1.000	1.000	Qianjiang	0.781	0.973	0.805
Ji'an	0.663	0.739	0.904	Tianmen	0.796	1.000	0.796
Yichun	0.618	0.656	0.936	mean	0.660	0.755	0.885

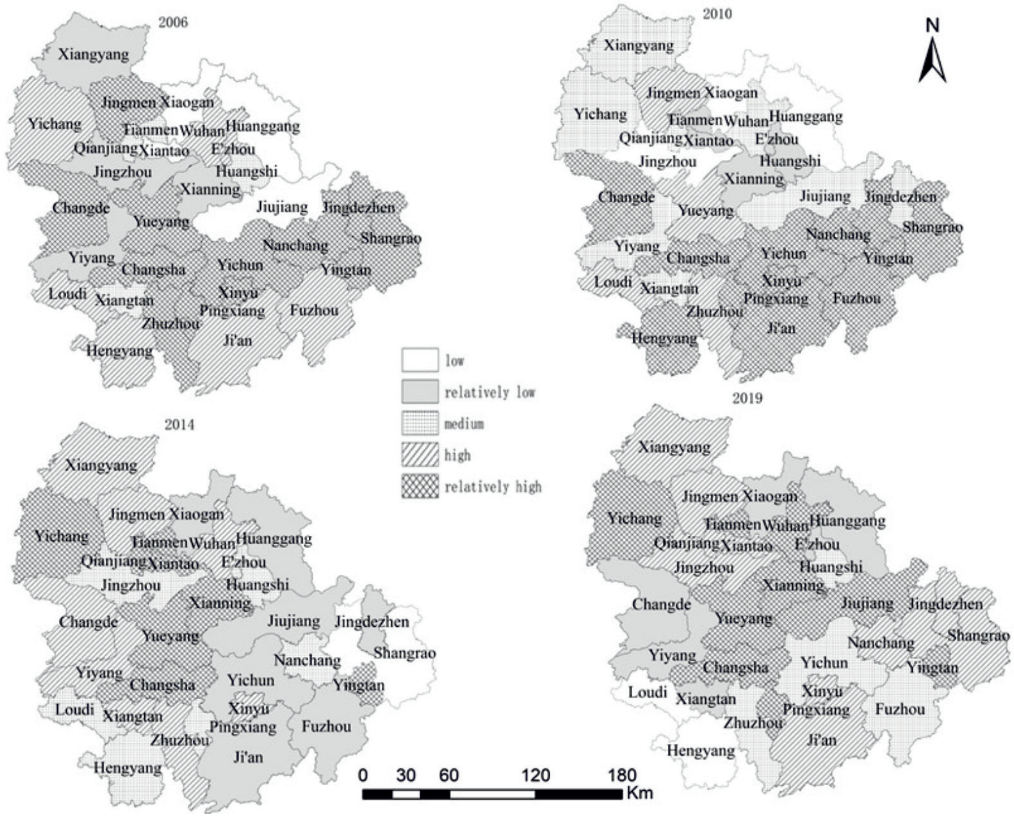

Fig. 3. The spatial distribution of GEIWR in the UAMRYR.

innovation has increased, and as a result water pollution has been treated accordingly.

As can be seen from the Fig. 3, Changsha has always been in the high-efficiency area of UIWR, indicating that its industrial resources and water resources allocation capacity. It gives full play to the economies of scale in water use. However, the regions with low-efficiency values are not fixed and are mostly scattered around the urban agglomeration, which shows that with the increasing advocacy of sustainable development goals, they more or less started to focus on the optimal allocation of water resources to improve equipment technology in industry.

Spatial Correlation Analysis of GEIWR in the UAMRAR

To further reveal the spatial correlation of GEIWR, a global autocorrelation analysis and a local autocorrelation for GEIWR were carried out by means of Geoda software.

Global Autocorrelation Analysis

Global autocorrelation analysis was performed based on Geoda software to get global correlation coefficient (Table 6). The results indicated that Moran's I value vary between 0.003 and 0.462. The Moran's I value in 2010 was 0.462, and it passed the 5% significance test, showing significant correlations in spatial patterns. The Moran's I value gradually decreased between 2014 and 2019, while Moran's I decreased to its lowest point in 2019. Its spatial correlation is not obvious. It shows that the scale effect of industrial park in UAMRYR is not strong, and the supporting industries do not produce cluster effect. Influenced by policy documents, industry in the same region or transfer or rectification, may also have to undertake the transfer of foreign industrial plants and the development of each industrial park is temporarily unstable, so the agglomeration effect is weakening after 2014.

Local Autocorrelation Analysis

As the global autocorrelation cannot reveal the spatial agglomeration characteristics of a specific region, it remains unclear whether there is the local agglomeration of GEIWR. Therefore, a local autocorrelation analysis was conducted for the four periods of 2006, 2010, 2014, and 2019 to draw a LISA agglomeration map of GEIWR (Fig. 4).

Before 2014, industrial water resources showed an agglomeration effect in space, and the agglomeration area was the largest in 2010. Driven by radiation, the types of high-high (H-H) aggregation and low-low (L-L) aggregation areas both increased from 2006. However, in 2019, there was no significant spatial correlation, which was mutually confirmed with the global autocorrelation results.

Table 6. Global Moran's I index of GEIWR in the UAMRYR.

Year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Moran's *I*	0.244	0.085	0.031	0.182	0.462	0.163	0.062	0.086	0.134	0.046	0.022	0.029	-0.006	0.003
P-value	0.015	0.151	0.254	0.042	0.001	0.165	0.204	0.131	0.071	0.217	0.269	0.248	0.363	0.273

In 2006, Xiaogan, Wuhan, Huanggang, Xiantao, E'zhou, and Huangshi cities in Hubei Province were characterized by L-L agglomeration, which is in the northeast of the urban agglomeration and is less affected by the radiation of the central industrial park, and the technology of water resources utilization is not yet mature. While in Jiangxi Province, Yichun City, Pingxiang City, and Ji'an City are in H-H type area, with the rapid development of heavy industry and aircraft manufacturing, the formation of scale effects, optimal allocation of water resources factors and strong agglomeration effects. Jingmen City is in the high-low (H-L) aggregation type, its connection with the surrounding areas, and the driving effect is weak, and Fuzhou is a low-high (L-H) aggregation area, industrial water resources efficiency and the surrounding links are less common.

In 2010, there were 11 municipalities in L-L aggregation, occupying 35.5% of the total study area, an increase of 16.2% over 2006, with most areas within Hubei Province being industrially water efficient. The H-H aggregation type areas also radiated outwards from 2006, with the number of areas increasing to five. Fuzhou was transformed into H-H aggregation by the influence of neighboring cities. At the same time, Jingdezhen and Zhuzhou changed from insignificant areas to L-H type areas, driven by industry within Jiangxi province. Although the value of GEIWR is low, its development is also related to the surrounding cities.

In 2014, the L-L agglomeration area changed from Hubei Province to Jiangxi Province. The L-L agglomeration varies from north to south within the study area, a phenomenon that may be explained by the fact that Jiangxi Province, located in the southern part of the urban agglomeration, is influenced by traditional transport and has a poorer geographical radiation effect, leading to a weaker agglomeration.The agglomeration effect of Jingdezhen City, Nanchang City, Fuzhou City, and Ji'an City declined after saturation, and GEIWR slowed down. At the same time, two H-L types of areas in Yingtan City and Xinyu City were newly added, and the agglomeration was weakened. Jingzhou has changed from an L-L agglomeration in 2010 to an L-H agglomeration area, indicating that its GEIWR has started to correlate with the surrounding cities and radiate the surrounding area, but the efficiency values are still in a weak state.

In 2019, there were basically no significant spatial characteristics in the study area, the H-H aggregation type area decreased sharply. The reason for this may be the national demand for "high quality economic development", the transformation and upgrading of industries and the consolidation and growth of similar types of enterprises, which has led to the unstable development of industrial parks and the lack of spatial clusters. Xianning City, located in the center of the urban agglomeration, was H-H aggregation, which developed more closely with the surrounding cities. Hengyang City in the southwest corner was reflected in L-L aggregation

Influencing Factors of GEIWR in the UAMRYR

From the local autocorrelation analysis, we can also see the complexity of the changing trend of GEIWR in the study area. That there is no uniform methodology or criteria regarding the choice of factors affecting GEIWR. This paper refers to relevant literature (Zhou et al., 2019; Zhang et al., 2020; Zuo et al., 2020; Liang et al., 2021), selected from 5 aspects: natural resources endowment, economic and industrial structure, economic benefits of industrial water resources, degree of industrialization, and level of science and education. The regression results for the factors influencing the GEIWR were derived by constructing the Tobit model (Table 7).

(1) The regression coefficient of the EIS is 0.8732. It demonstrates that the UIWR is influenced by the industrial structure. For every 1% increase in the EIS, the GEIWR increases by 0.8732%, reflecting the fact that the increase in economic value of the secondary industry has an obvious positive driving impact on GEIWR. Accordingly, to meet the target of improving the GEIWR, the industrial structure can be adjusted reasonably. For example, the Chang-Zhu-Tan urban agglomeration promotes comprehensive supporting reforms at a higher level; the urban agglomeration around Poyang Lake upgrades old and heavy industries, cultivates emerging industries, and reduces water consumption in high water-consuming industries; the Wuhan city circle develops toward high-quality economic benefits and sustainable development, and promotes the intensive use of industrial green water resources.

(2) The regression coefficient of EBIWR is -0.001, indicating that for every 1% increase in EBIWR, the GEIWR will decrease by 0.001%. Water consumption per 10^4 Yuan of industrial value added is an indicator of energy management, reflecting the EBIWR. With the intensification of industrial production and increased

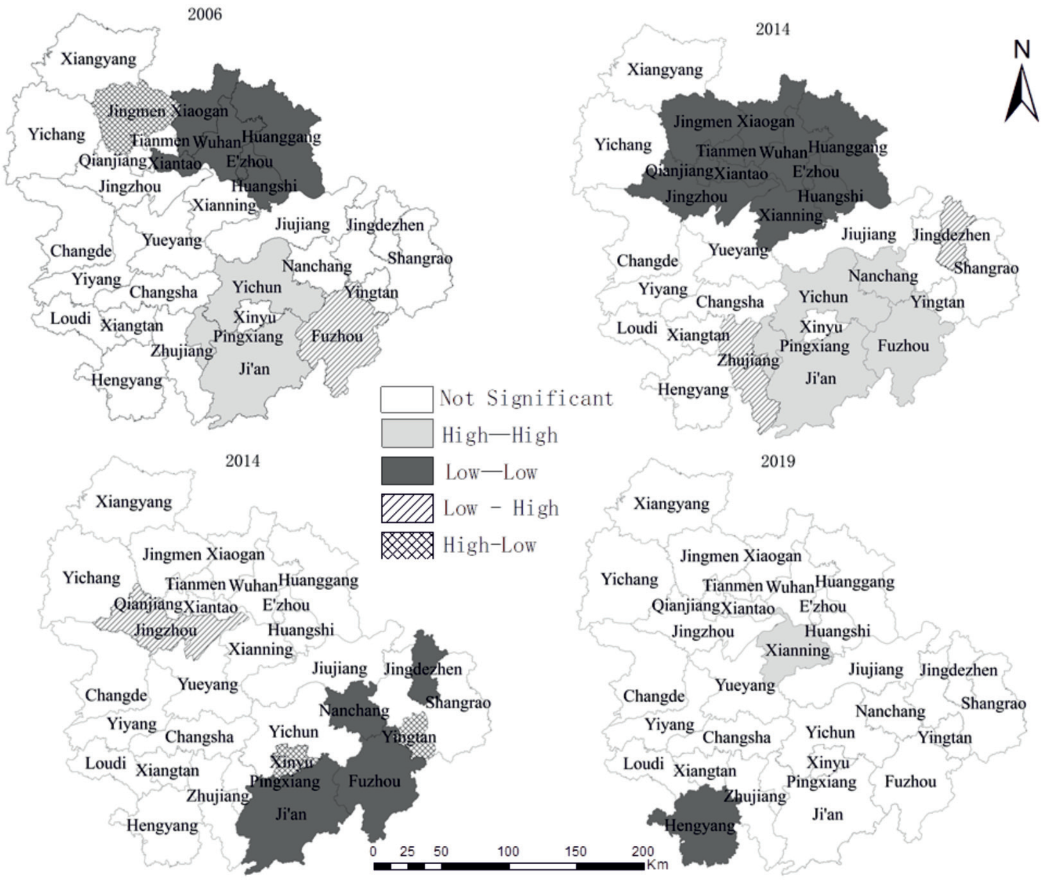

Fig. 4. LISA map of the GEIWR in the UAMRYR.

awareness of water conservation, the share of water use in industrial value added will gradually decrease, and water resource efficiency will gradually increase. Improving the recycling rate of water can contribute significantly to improving GEIWR.

(3) The regression coefficient of LSE is 0.0356. It means that for every 1% increase in LSE, the GEIWR will increase by 0.0356%. This reflects the obvious positive effect of technological innovation on GEIWR. With the innovation of regional green technology and wastewater technology, industrial wastewater emissions are effectively reduced. The industrial agglomeration of the three major city clusters can strengthen cooperation and innovation, Changsha, Nanchang, and Wuhan provincial capitals to jointly develop advantageous resources and introduce industrial water-saving technologies, thus reducing industrial effluent discharge, improving the quality of the water environment and alleviating the current stage of severe water pollution.

(4) The regression coefficients for NRE and DI are 4.43E-06 and 0.0071 respectively; however, both p-values are greater than 0.1, indicating that these two explanatory variables have little effect on the GEIWR because they did not pass the significance test. The NRE is related to the environment, topography, and actual precipitation, and is affected by a variety of factors, so it has little impact on the GEIWR. The DI has no significant effect on the GEIWR. This result seems to be contrary to the theory. However, after analysis, it is found that industry in Jiangxi Province within the urban agglomeration around Poyang Lake focuses on the development of aviation manufacturing, while in the Chang-Zhu-Tan urban agglomeration, the thermal power generation and iron and steel industry in Hunan Province is the vital industrial industries. And Hubei Province is dominated by the Wuhan city circle, and industries such as integrated circuits and intelligent manufacturing are relatively developed. In 2015, China launched specific policies on the standardized development of the UAMRYR, industries around the region deepened their synergistic development, relevant industrial enterprises were reorganized, and development resources were shared, so the degree of industrialization was at a high and low level, so there was not much impact on the GEIWR.

Discussion

Hidden Causes of Heterogeneity of the Spatiotemporal Evolution of GEIWR

By measuring and analyzing the Spatiotemporal divergence characteristics of the GEIWR in the

Table 7. Tobit regression of factors affecting GEIWR in the UAMRYR.

Independent variable	Regression coefficients	Standard deviation	Test	P value
C	0.1990	0.0809	2.4601	0.0139
NRE	4.43E-06	3.30E-06	1.3420	0.1796
EIS	0.8732	0.1593	5.4815	0.0000***
EBIWR	-0.0010	4.40E-05	-2.3148	0.0206**
DI	0.0071	0.0006	1.1825	0.2370
LSE	0.0356	0.0008	4.2174	0.0000***

Significance test: *** $p<0.01$, ** $p<0.05$

UAMRYR, GEIWR reached its lowest point of 0.525 in 2010 and generally showed a downward trend during the period 2006-2014, mainly due to the global financial crisis in 2008 and China put forward many measures to stimulate domestic demand and encourage industrial development. The adoption of the "To promote the rise of the central area planning" is intended to promote development in the central region and strengthen the capacity to support the country's development as a whole, building on the comparative advantage of the central region. The UAMRYR has responded positively to the call to vigorously develop the dominant manufacturing and chemical industries, thus increasing wastewater discharge and water consumption. The 2010 is the year when the "Eleventh Five-Year Plan" comes to an end, the economic structure of the urban agglomerations was dominated by industry, with a large number of resources being used inefficiently, and the scale of heavy industry and crude water use causing a significant decline in the GEIWR.

The spatial properties of GEIWR were revealed by the ESDA method, with Moran's I showing a maximum value of 0.462 in 2010 and a decrease to a minimum value of 0.003 in 2019. In contrast, the spatial agglomeration effect of GEIWR was attenuated. In 2014 and 2019, the region has no significant spatial correlation. The hidden reason lies in the development of the industrial park in the UAMRYR is unstable, the related industries to transfer or transformation and upgrade. The industrial park industry can not realize effective links, comprehensive service guarantee is not in place. In the future, it is necessary to steadily promote the development of industrial parks, attract talented people from enterprises, optimize the relevant industrial layout and form an integrated treatment, recycling and recycling system.

Research Comparison

As the largest urban agglomeration region in China, the UAMRYR contains most of the cities in Hubei, Jiangxi and Hunan. The current system for the efficient use of water resources in the region needs to be strengthened, and overall industrial water use efficiency is not very high, falling short of the water use efficiency target control requirements set out in the "National Water Conservation Action Plan". Water-saving technology transformation in high water-consuming industries and key water-using units still needs to be strengthened. The distribution of industrial clusters in the region is multi-layered, and the analysis of industrial water use plays an important role in promoting the integrated development of urban agglomeration and the rise of the central region. It is found that both the EIS and science and LSE have a positive effect, and that adjusting rationally the industrial structure and improving technology will both reduce water consumption and improve GEIWR. The EBIWR has a negative impact, with the higher the water use per 10,000 Yuan of industrial value added, the lower the efficiency.

The factors influencing UIWR in other urban agglomerations vary from region to region (Table 8). Zhao et al. [46] also analyzed efficiency of UIWR in the middle and lower reaches of the Yellow River Basin in China, showing that increased urbanization is beneficial to industrial water use efficiency. Combining the analysis of agriculture and industry and distinguishing between sectoral water use efficiency through comparison provides a scientific basis for detailed policy development in the future. This is part of the paper that needs to be further deepened later on, and the relationship between the level of urbanization and the GEIWR needs to be explored Bubuna et al. [47] and Xu et al. [48] argue that urban water use encompasses industrial, agricultural, and ecological aspects and considers it more comprehensively and abundantly. The water use efficiency of 35 cities in the Yangtze River Economic Belt was assessed through Gini coefficient. The study found that inequality in water use efficiency is decreasing in this area. In addition, in industry, excessive industrial demand is a major cause of urban water efficiency, which is one of the main objectives of this paper, which is to provide a basis for the establishment of scientific water demand plans.

It is equally relevant to explore the impact of industrial pollutants on industrial water efficiency.

Table 8. A comparison study of UIWR influencing factors

Researchers	Area	Methods	Influencing factors	Main conclusion
Zhao et al.	Middle and lower reaches of the Yellow River Basin, China	SBM Model	Urbanization level	Higher levels of urbanization are conducive to more efficient industrial water use.
Bubuna et al.	the Yangtze River Economic Delta of China	Gini Coefficient	Poor irrigation technology and high industrial demand	Inequalities in water efficiency are decreasing. In addition, on the industrial side, excessive industrial demand is an important cause of water efficiency in cities.
Wang et al.	30 regional in China	DEA Model	Pollutant abatement potential and costs	Optimizing water management and reducing pollutant emissions have new implications for improving water use efficiency in China.
Weerasooriya et al.	Global Industrial Sector	Literature Review	Changes in population, land, and climate	Integrating the water footprint with SDG to achieve industrial water conservation sustainable development goals.
García-Valinas et al.	The urban area of Zaragoza, Spain	a DEA framework based on directional distance functions	Public policies Different production sectors of manufacturing	Water pollution and water management technologies are essential to improve water use efficiency.

External environmental factors have a negligible effect on GEIWR. Wang et al. [49] used a DEA model to analyze the industrial water use efficiency of 31 regions in China, focusing on the impact of industrial system-related pollutants COD and NH_4-N on water use efficiency, mainly focusing on industrial environmental pollution, broken down into pollutant reduction potential and cost, providing a scientific basis for improving industrial water purification. Weerasooriya et al. [50] explored new ways to conserve water in industry by combining water footprint and SDG in a literature review. García-Valinas et al. [51] further refined the water efficiency of manufacturing by dividing Zaragoza manufacturing in Spain into three production sectors, comparing the water efficiency of these three sectors and finding that water pollution and consumption were higher in the food processing and chemical industries.

Overall, the GEIWR varies from region to region depending on the actual situation, with the general conclusion being that improving science and technology is conducive to promoting water use efficiency, which is exactly the same as the conclusion obtained in this paper. The industrial restructuring promotes the development and upgrading of industrial parks as a means of improving water use efficiency. The UAMRYR gathers the major industrial bases of three provinces, and the industrialization process is in a different way from that of the Yellow River Basin in China, where ecology is under key protection, or the economically developed Yangtze River Delta urban agglomeration. Studying industrial water consumption in the UAMRYR can contribute to the achievement of green transformation of industry and the conservation of available water reserves.

Although this paper adopts the SBM model to avoid bias between the measured values and the actual water use efficiency results, due to data availability and data quality limitations, this study does not consider the industrial wastewater COD and N_2O as undesired outputs. Due to data availability, the time frame of the study is relatively limited. In addition, the UAMRYR is making concerted efforts to promote the ecological environment and reduce pollution and carbon emissions. In terms of research dimensions, how to improve the GEIWR under environmental constraints is also one of the directions for future research.

Conclusions and Policy Implications

Conclusions

This paper uses the SBM model to measure the GEIWR values of the UAMRYR from 2006 to 2019, and analyses the spatial and temporal evolution characteristics, uses the ESDA method to explore in depth the spatial agglomeration effect of GEIWR, and constructs the Tobit model to reveal the various factors, and lead to the following conclusions:

During 2006-2019, the GEIWR was 0.525-0.745 and the overall change was moderate. It generally exhibited a volatile trend: from 2006 to 2014, although there was a brief increase, it generally showed a downward trend, and from 2014 to 2019, it showed a slow upward trend. Spatially, there is a general dynamic trend of low efficiency of UIWR around the region, and there is a tendency for areas of high-efficiency values to move towards the center of the region. From 2006 to 2010, the high-efficiency value of industrial water resource utilization was generally distributed in Jiangxi Province, the southern part of the urban agglomeration. From 2014-2019, the industrial high-efficiency values were mostly distributed in the middle of the urban agglomeration.

The global Moran's I coefficient of GEIWR ranged from 0.003-0.462, showing a positive spatial correlation, and the value gradually decreased after 2014; in terms of local autocorrelation, the study area showed a significant clustering effect in 2006, 2010 and 2014. In terms of local autocorrelation, the study area showed a significant clustering effect in 2006, 2010 and 2014, and the largest number of clustering areas in 2010, but no significant spatial correlation in 2019, and the clustering phenomenon weakened.

The NRE and DI have no significant impact on GEIWR. The EIS and the LSE have a favorable driving effect, and EBIWR has a negative impact on it.

Policy Implications

Water efficiency varies from region to region, indicating that it is important to formulate actual optimization or continuous maintenance measures according to the industrial water resources utilization conditions of different provinces and cities. To be effective in improving the GEIWR, the main policies are as follows:

From the spatial and temporal distribution of GEIWR efficiency, Changsha City has always been an area with a high-efficiency value of the GEIWR, and the factor input is at an optimal level. Thereafter Changsha should continue to promote the construction of a water-saving city, a scientific plan for water use and saving, and efficient use of water resources. In 2019, the cities of Hengyang and Loudi were in the low-efficiency zone. These two cities, whose economies are supported by energy-intensive enterprises and heavy chemical industries, should promote the upgrading of traditional industrial industries and adopt efficient and safe water treatment technology equipment to improve enterprises' water-saving management ability and wastewater resource utilization rate.

From the results of the influencing factors, the EIS and LSE have a positive impact on the GEIWR. In the future, the UAMRYR should reasonably adjust its industrial structure and promote the transformation of high water-consuming and heavily polluting enterprises. For cities with high industrial water intensity such as Huanggang and Xiangtan should strengthen water conservation management, invest in the construction of recycled water utilization facilities and improve the efficiency of wastewater recycling.

From the perspective of national development, the UAMRYR needs to encourage industrial clustering and emphasize the role of coordinated regional development as a guide to improve GEIWR and solve the constraining dilemma of water stress. The GEIWR of the UAMRYR is affected by the interaction and influence of multiple factors. Therefore, the road to improvig the GEIWR of the UAMRYR needs to be further advanced in multiple dimensions.

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Conflict of Interest

The authors declare no conflict of interest.

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