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Assessment of interprovincial industrial water use efficiency in China from a sustainable development perspective

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Abstract. Against the backdrop of rapid industrialization and water scarcity, and in response to the United Nations' call for "sustainable development," this paper utilizes industrial sustainable water use indicator data from 30 provinces in China. Using a two-stage parallel two-stage SBM dynamic (PTSD) model, the paper calculates interprovincial industrial sustainable water use efficiency and employs a gravity shift model for evaluation, aiming to provide policy recommendations for achieving sustainable development in industrial water use. The analysis reveals (1) disparities in interprovincial sustainable water use efficiency in China, with higher efficiency observed in the eastern provinces and lower efficiency in the western provinces. (2) The environmental governance stage in the two-stage model exerts a greater influence on overall efficiency than the production stage. (3) The gravity shift shows an initial southward movement followed by a shift towards the northeast, with the overall efficiency being higher in the eastern regions compared to the central and western regions. This study not only fills the gap in the academic research on industrial water use efficiency from a sustainable development perspective but also aligns with the United Nations' call for sustainable development, reflecting the policy requirements of pursuing sustainable development in our country. It contributes to improving residents' living environment, promoting industrial upgrading, and facilitating balanced regional development.

Keywords: Sustainable development, Industrial water use efficiency, Parallel two-stage SBM dynamic model, Sustainable development goals, Environmental governance

1. Introduction

As the global energy crisis intensifies, water resources, as one of the primary sources of energy for human production and operation, have become a critical focus of societal concern. The concept of "sustainable development" was formally introduced by the United Nations World Commission on Environment and Development in 1987 [1], and in 2015, 17 Sustainable Development Goals (SDGs) were established. Accelerated urbanization and industrialization processes have led to a continuous growth in China's demand for water resources, with the proportion of industrial water use in the total water consumption rising. In response to these environmental challenges, the State Council of China successively issued the "Action Plan for China in the 21st Century: Sustainable Development" and the "2030 Agenda for Sustainable Development," integrating sustainable development goals into the "Thirteenth Five-Year Plan for National Economic and Social Development." Furthermore, based on

China's understanding of sustainable development, the status, trends, mechanisms, and capabilities of sustainable development are considered standards for evaluating the level of sustainability.

Zhao Qiting [2] first categorized China's research on sustainable water resource utilization into three stages and analyzed the prospects for research in this field under new circumstances. Zhang Xiangyong, Cao Yang, Wu Wenfei, and others [3] analyzed the spatiotemporal characteristics of water resource sustainability and ecosystem services value in China's provinces. In the international academic community, the concept of sustainable water management has gained increasing importance. R.R. Weerasooriya et al. [4] reviewed the integration of the concept of water footprint into sustainable development goals, aiming to chart the future path for industrial water conservation and sustainable water resource management. Additionally, BAUER S [5] evaluated the concept of water reuse by calculating the reuse factors of wastewater and all reclaimed water from central sewage treatment plants, focusing on an industrial wastewater management approach centered on reuse. In response to the urgent need for sustainable water resource development, scholars have established various evaluation systems for assessing water resource sustainability. Notable examples include Zhang Chenguang, Wen Zhang, Gong Jian, and others [6], who employed the Analytic Hierarchy Process (AHP), and Yang Zhuolin et al. [7], who assessed the United Nations' Sustainable Development Goals (SDGs) indicator system and evaluation methods. Wang Weilu, Liu Tie, Luo Gegping, and others [8] determined indicator weights using entropy and the Analytic Hierarchy Process (AHP), and employed principal component analysis to analyze the changing trends in Kyrgyzstan's water environment carrying capacity from 2006 to 2020. Sun Caizhi and Duan Xingjie [9] used energy analysis theory and methods, combined with entropy, to construct an ecological sustainable development evaluation indicator system for the water resources-energy-food system in the Yellow River Basin.

Subsequently, various methods of water management have been proposed. HU W Q et al. [10] introduced a comprehensive water management index (WSI) from the perspectives of water utilization, wastewater discharge, and reclaimed water reuse. They further built a decision-making model from a lifecycle perspective, encompassing stakeholder interests, water quantity-value-quality, and technology-economy-environment analysis, tailored to customized water management solutions for Chinese industrial parks [11]. Vörösmarty C J et al. [12] argued that traditional water management has not fully avoided environmental deterioration and controlling infrastructure costs. They explored the feasibility of integrating natural capital and engineering-based (green-gray) approaches globally to address 21st-century water security threats. Furthermore, LIU Y et al. [13] discussed approaches for comprehensive management of water use and pollution control in Shandong Province, SHAO Zhiping, XU Shengjun, and QIN Yu [14] proposed a development model based on the ecological resource economization and economic development ecologicalization in Zhejiang Province, and SEAH H [15] highlighted the use of recycled water using Singapore as an example.

Against the backdrop of sustainable water resource development, the topic of industrial water use efficiency remains prominent. In terms of researching industrial water use efficiency, one aspect involves employing different methods to determine efficiency, enhancing accuracy, scientific rigor, and comprehensiveness, as well as adding or reducing influencing factors and refining calculation methods. Among various research methods, Data Envelopment Analysis (DEA) has emerged as the mainstream approach in water resource efficiency research due to its unique advantages. Wang et al. [16] first defined the "total factor water use efficiency" using the DEA method. TMLA B et al. [17] utilized DEA to assess industrial water use efficiency and water-saving potential in industrial areas, revealing that reducing water use is not the sole potential measure to improve water use efficiency and move towards self-sufficiency in water metabolism. Ding et al. [18] measured industrial water use efficiency in the Yangtze Economic Belt using a DEA model with slack variables and super-efficiency improvement. He Jiayin and Wang Hongrui [19] utilized DEA-Data Envelopment Analysis, entropy weighting method, and grey relational analysis to construct a water resource utilization efficiency model for Hunan Province from 2004 to 2018, exploring the impact of different types of input proportions on industrial water use efficiency. Huang Zhen, Xu Ping [20] selected 14 highly competitive industrial countries and employed a three-stage DEA-Malmquist index to analyze industrial water use efficiency from 2011 to 2018.

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Stochastic Frontier Analysis (SFA) is another method used. Lei Yutao and Huang Liping [21] used the SFA method to calculate the industrial water use efficiency of 13 major industrial provinces and regions in China, dividing them into three types based on water-saving potential, and revealing differences in industrial water use efficiency and water-saving potential among different provinces and regions. Some improved methods based on DEA or SFA are also utilized. For instance, Yang Mingming [22] explored the impact of low scale efficiency on water use efficiency in Shanxi Province. Sun Fuhua et al. [23] evaluated the industrial water use efficiency of 30 Chinese provinces using an improved three-stage SBM-DEA model, and employed the Theil index to investigate regional differences in industrial water use efficiency across the country. Lastly, there are measurement methods based on SBM models. Luo Jingyi and Dong Mei [24] calculated the green water use efficiency of grain production in 18 counties and districts of Ningxia from 2006 to 2020, employing the three-stage super-efficiency SBM-Malmquist model with grain water footprint as an input indicator and grain grey water footprint as an undesired output indicator. Yao Lingling [25] used Shaanxi Province as an example to study the optimization of local industrial water use efficiency improvement through water resource taxation and provided relevant suggestions. Moreover, SHI C F et al. [26] researched the efficient utilization of water resources using a dynamic SBM model and density curve, offering a new perspective for assessing industrial water use efficiency.

On the other hand, research on factors influencing industrial water use efficiency is also explored. Yue Li and Cao Yuxuan [27] studied the positive and negative correlations between urbanization level, industrial development level, water resource abundance, government research and development support, environmental regulations, economic development level, population scale, and industrial water use efficiency for various provinces (regions) in the Yellow River Basin from 2007 to 2017. Li Jing and Ren Jida [28] analyzed the differences in industrial water use efficiency across China’s eastern, central, and western regions from 2005 to 2015 using input and output indicators related to industrial employees, net industrial assets, industrial water use, and expected output indicators like industrial added value, undesired outputs like COD emissions, and ammonia nitrogen emissions. Yu-fang Zhang et al. [29] decomposed the factors influencing the changes in total water consumption and water use efficiency in Urumqi from 1995 to 2012 using a comprehensive decomposition model and logarithmic mean deviation index (LMDI) decomposition method. Building upon this, Yizi Shang et al. [30] developed a decomposition method to quantify the influence of each factor. Additionally, LIU X Y et al. [31] used the EBM model and Tobit model to find that environmental regulations and technological progress have a certain impact on industrial water resource green efficiency.

In summary, current academic research on this topic still faces challenges such as limited exploration of industrial water use structure, insufficient exploration of the correlation between sustainable development and industrial water use, and lack of comprehensive research on national and global sustainable industrial water use indicator systems. Research areas have been confined to specific regions or industries. This paper adopts a sustainable development perspective, focusing on the 30 provinces in China, conducting comprehensive calculations and research on interprovincial sustainable industrial water use total efficiency and stage efficiency. It explores a more comprehensive and general evaluation system for various indicators of industrial water use at the national level, providing recommendations for industrial upgrading, transformation, and sustainable development for enterprises and provinces.

2. Research Model and Data Sources

2.1. Research Model

2.1.1. Parallel Two-Stage SBM Dynamic (PTSD) Model. Assuming there are n Decision Making Units (DMUs) (j = 1,…,n), each DMU has k partitions (k = 1,…,K), and T time periods (t = 1,…,T). Each DMU has inputs and outputs in time period t, along with a carry-over to the next time period t+1 (link).

Let mk and rk in each partition k represent inputs and outputs, (k,h)i denotes the link from partition k to h, and Lhk represents links between partition K and h. The following paragraphs outline input, output, link, and carry-over definitions.

This paper's model consists of two stages: industrial production stage and environmental governance stage. The following paragraphs outline input, output, link, and carry-over definitions.

Industrial Production Stage: X_{1ij}: Industrial employment, industrial water consumption, industrial energy consumption, and industrial fixed assets; Y_{1good}: Industrial GDP; Y_{1bad}: Carbon dioxide emissions; $Z_{(12)in}$ (linking industrial production stage and environmental governance stage): Industrial wastewater emissions, industrial solid waste emissions, and industrial gas emissions. Environmental Governance Stage: X_{2ij}: Industrial pollution control investment; Y_{2good}: Industrial wastewater recycling and industrial solid waste utilization; $Z_{(21)in}$: (linking environmental governance stage and industrial production stage): Industrial wastewater recycling and industrial solid waste utilization; $Z^{(t,(t+1))}_{ok_l input}$ (Carry-over): Industrial fixed assets.

(a) Objective Function

$$\theta_0^* = \min \frac{\sum_{t=1}^{T} W^t \left[\sum_{k=1}^{K} W^k \left[1 - \frac{1}{(m_k + linkin_k + ninput_k)} \left(\sum_{i=1}^{m_k} \frac{S_{iok}^{t-}}{x_{iok}^t} + \sum_{(kh)_l=1}^{linkin_k} \frac{s_{o(kh)_l in}^t}{z_{o(kh)_l in}^t} + \sum_{k_l}^{ninput_k} \frac{s_{ok_l input}^{(t,t+1)}}{z_{ok_l input}^{(t,t+1)}}\right)\right]\right]}{\sum_{t=1}^{T} W^t \left[\sum_{k=1}^{K} W^k \left[1 + \frac{1}{(r_{1k} + r_{2k})}\left(\sum_{r=1}^{r_{1k}} \frac{S_{rokgood}^{t+}}{y_{rokgood}^t} + \sum_{r=1}^{r_{2k}} \frac{S_{rokbad}^{t-}}{y_{rokbad}^t}\right)\right]\right]} \quad (1)$$

Overall Efficiency:

Subordinate to:

$$\begin{gathered} x_{o1}^t = X_1^t \lambda_1^t + s_{1o}^{t-} \ (\forall t) \\ y_{o1good}^t = Y_{1good}^t \lambda_1^t - s_{1ogood}^{t+} \ (\forall t) \\ y_{o1bad}^t = Y_{1bad}^t \lambda_1^t + s_{1obad}^{t-} \ (\forall t) \\ \lambda_1^t \geq 0, s_{1o}^{t-} \geq 0, s_{1ogood}^{t+} \geq 0, s_{1obad}^{t-} \geq 0 \ (\forall t) \\ Z_{o(12)in}^t = Z_{(12)in}^t \lambda_1^t + S_{o(12)in}^t \end{gathered} \quad (2)$$

Industrial Production Stage

$$\begin{gathered} x_{o2}^t = X_2^t \lambda_2^t + s_{2o}^{t-} \ (\forall t) \\ y_{o2good}^t = Y_{2good}^t \lambda_2^t - s_{2ogood}^{t+} \ (\forall t) \\ \lambda_2^t \geq 0, s_{2o}^{t-} \geq 0, s_{2ogood}^{t+} \geq 0 \ (\forall t) \\ Z_{o(21)in}^t = Z_{(21)in}^t \lambda_2^t + S_{o(21)in}^t \\ e\lambda_k^t = 1 (\forall k, \forall t) \\ Z_{o(kh)in}^t = Z_{(kh)in}^t \lambda_k^t + S_{o(kh)in}^t ((kh)in = 1, \ldots, linkin_k) \\ \sum_{j=1}^{n} Z_{jk_l\alpha}^{(t,(t+1))} \lambda_{jk}^t = \sum_{j=1}^{n} z_{jk_l\alpha}^{(t,(t+1))} \lambda_{jk}^{t+1} \ (\forall k; \forall k_l; t = 1, \ldots, T-1) \\ Z_{ok_l input}^{(t,(t+1))} = \sum_{j=1}^{n} z_{jk_l input}^{(t,(t+1))} \lambda_{jk}^t + s_{ok_l input}^{(t,(t+1))} \ k_l = 1, \ldots, ngood_k; \forall k; \forall t) \end{gathered} \quad (3)$$

Environmental Governance Stage

(b) Staged and Partitioned Efficiency

Staged and partitioned efficiency is as follows:

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$$\partial_0^* = \min \frac{\sum_{k=1}^{K} W^k \left[1 - \frac{1}{(m_k + linkin_k + ngood_k)} \left(\sum_{i=1}^{m_k} \frac{S_{iok}^{t-}}{x_{iok}^{t}} + \sum_{(kh)_l=1}^{linkin_k} \frac{S_{o(kh)_l in}^{t}}{z_{o(kh)_l in}^{t}} + \sum_{k_l}^{ngood_k} \frac{S_{ok_l good}^{(t,t+1)}}{z_{ok_l good}^{(t,t+1)}}\right)\right]}{\sum_{k=1}^{K} W^k \left[1 + \frac{1}{(r_{1k} + r_{2k})\left(\sum_{r=1}^{r_{1k}} \frac{S_{rokgood}^{t+}}{y_{rokgood}^{t}} + \sum_{r=1}^{r_{2k}} \frac{S_{rokbad}^{t-}}{y_{rokbad}^{t}}\right)}\right]} \quad (4)$$

(b1) Staged Efficiency:

$$\varphi_0^* = \min \frac{\sum_{t=1}^{T} W^t \left[1 - \frac{1}{m_k + linkin_k + ninput_k} \left(\sum_{i=1}^{m_k} \frac{S_{iok}^{t-}}{x_{iok}^{t}} + \sum_{(kh)_l=1}^{linkin_k} \frac{S_{o(kh)_l in}^{t}}{z_{o(kh)_l in}^{t}} + \sum_{k_l}^{ninput_k} \frac{S_{ok_l input}^{(t,t+1)}}{z_{ok_l input}^{(t,t+1)}}\right)\right]}{\sum_{t=1}^{T} W^t \left[1 + \frac{1}{(r_{1k} + r_{2k})\left(\sum_{r=1}^{r_{1k}} \frac{S_{rokgood}^{t+}}{y_{rokgood}^{t}} + \sum_{r=1}^{r_{2k}} \frac{S_{rokbad}^{t-}}{y_{rokbad}^{t}}\right)}\right]} \quad (5)$$

(b2) Partitioned Efficiency:

$$\rho_0^* = min \frac{1 - \frac{1}{m_k + linkin_k + ninput_k} \left(\sum_{i=1}^{m_k} \frac{S_{iok}^{t-}}{x_{iok}^{t}} + \sum_{(kh)_l=1}^{linkin_k} \frac{S_{o(kh)_l in}^{t}}{z_{o(kh)_l in}^{t}} \sum_{k_l}^{ninput_k} \frac{S_{ok_{linput} input}^{(t,t+1)}}{z_{ok_l input}^{(t,t+1)}}\right)}{1 + \frac{1}{r_{1k} + r_{2k}} \left(\sum_{r=1}^{r_{1k}} \frac{S_{rokgood}^{t+}}{y_{rokgood}^{t}} + \sum_{r=1}^{r_{2k}} \frac{S_{rokbad}^{t-}}{y_{rokbad}^{t}}\right)} \quad (6)$$

(b3) Staged and Partitioned Efficiency:

(c) Input, Desirable Output, and Undesirable Output Efficiency

Hu and Wang’s (2006) Total Factor Energy Efficiency Index is used to overcome any biases that may exist in traditional energy efficiency indicators. There are twelve key energy efficiency models: industrial employment, industrial water consumption, industrial energy consumption, industrial fixed assets, industrial GDP, carbon dioxide emissions, industrial wastewater emissions, industrial solid waste emissions, industrial gas emissions, industrial pollution control investment, industrial wastewater recycling, and industrial solid waste utilization. “I” denotes area, and “t” denotes time. The efficiency models are defined as follows:

$$\text{Input Efficiency} = \frac{Target\ Inputs}{Actual\ Inputs} \quad (7)$$

$$\text{Input Efficiency} = \frac{Target\ Inputs}{Actual\ Inputs} \quad (8)$$

$$\text{Desirable Output Efficiency} = \frac{\text{Actual Desirable Output}}{\text{Target Desirable Output}} \quad (9)$$

If target inputs are equal to actual inputs, the efficiency is 1, representing overall efficiency. However, if target inputs are less than actual inputs, efficiency is less than 1, indicating lower overall efficiency.

If target expected outputs are equal to actual expected outputs, the efficiency is 1, representing overall efficiency. However, if target expected outputs exceed actual expected outputs, efficiency is less than 1, indicating lower overall efficiency.

If target undesirable outputs are equal to actual undesirable outputs, the efficiency is 1, representing overall efficiency. However, if target undesirable outputs are less than actual undesirable outputs, efficiency is less than 1, indicating lower overall efficiency.

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2.1.2. Gravity Shift Model. Assuming the 30 provinces are situated on a unified and homogeneous plane, with the sustainable development efficiency of interprovincial areas located at the center, it becomes possible to further calculate their gravity center. In equation (4.10), $\mathrm{LONG_t}$ and $\mathrm{LAT_t}$ represent the longitude and latitude of the gravity center, where $\mathrm{t} = (2014{,}2015{,}2016{,}2017{,}2018)$; $\mathrm{E_t^i}$ represents the efficiency value of sustainable industrial water use for province i in year t.

$$LONG_t = \frac{\sum_{i=1}^{30} (E_t^i \times \mathrm{long}_i)}{\sum_{i=1}^{30} E_t^i}$$

$$LAT_t = \frac{\sum_{i=1}^{30} (E_t^i \times \mathrm{lat}_i)}{\sum_{i=1}^{30} E_t^i} \tag{10}$$

Assuming that the efficiency center of gravity coordinates for year t is $(\mathrm{LONG_t}°, \mathrm{LAT_t}°)$, and for year j is $(\mathrm{LONG_j}°, \mathrm{LAT_j}°)$, the distance of movement D and the direction θ of the center of gravity from year t to year j are given by:

$$D = R \times \sqrt{(LAT_t - LAT_j)^2 + (LONG_t - LONG_j)^2}$$

$$\theta_{t-j} = \frac{n\pi}{2} + \arctan\left(\frac{LAT_t - LAT_j}{LONG_t - LONG_j}\right) \quad (n = 0,1,2) \tag{11}$$

3. Data Sources and Analysis

3.1. Data Sources

This study focuses on all 30 provinces (municipalities, autonomous regions) in China, excluding the Hong Kong, Macau, and Taiwan regions. Due to data limitations for Tibet, this administrative unit is not included in this study.

Based on the “Seventh Five-Year Plan” passed at the Fourth Session of the Sixth National People’s Congress in 1986, and considering geographical location and economic development levels, China is divided into three regions: Eastern, Western, and Central. Furthermore, at the Fifth Session of the Eighth National People’s Congress in 1997, Chongqing was designated as a centrally administered municipality and included within the scope of the Western region. Refer to Table 1 for specific regional divisions.

Table 1. Regional Division of China

Region	Provinces (Municipalities, Autonomous Regions)
Eastern Region	Beijing, Tianjin, Shanghai, Liaoning, Hebei, Shandong, Jiangsu, Zhejiang, Fujian, Guangdong, Hainan
Central Region	Heilongjiang, Jilin, Henan, Shanxi, Anhui, Hubei, Hunan, Jiangxi
Western Region	Gansu, Guizhou, Ningxia, Qinghai, Shaanxi, Yunnan, Xinjiang, Sichuan, Chongqing, Guangxi, Inner Mongolia

Considering data timeliness and availability, this study analyzes efficiency variables for the 30 provinces and municipalities in China between 2014 and 2018. To account for the complexity and interrelatedness of industrial water circulation, this study divides the industrial sustainable development water system into production and environmental governance stages. The indicators used are sourced from national statistical data, “China Statistical Yearbook,” and “China Environmental Statistical Yearbook.”

3.2. Data Analysis

3.2.1. Dynamic Evolution Analysis of Regional Water Use Efficiency. In the Eastern region, the overall efficiency level is the highest among the three major regions, with most provinces exhibiting a total efficiency level of 1, indicating optimal values. Notable provinces with optimal efficiency include Shanghai, Shandong, Tianjin, Beijing, Jiangsu, Hainan, and Zhejiang. This optimization is attributed to advanced technology in the Eastern region, which stems from its economic development level. Hebei Province records the lowest efficiency level, with a total efficiency of 0.6958. Although there was a brief increase in 2016 and 2017, by 2018, it remained the lowest within the Eastern region.

In the Central region, Anhui Province shows the highest total efficiency of 1, maintaining the same level over five years. The provinces in the Central region exhibit distinct efficiency levels. Anhui Province, along with Hunan and Hubei Provinces, has levels above 0.85, while provinces such as Heilongjiang and Jilin have levels below 0.6. The varying efficiency levels in certain Central regions are due to these areas receiving a considerable share of the coarse industries gradually transferred from the Eastern region, leading to lower environmental quality and comparatively lower technological levels.

In the Western region, provinces exhibit diverse total efficiency levels, displaying a trend of being either optimal, limited, or moderately efficient. Qinghai Province and Chongqing maintain optimal efficiency levels of 1 over five years, possibly due to the substantial scale of water use in the Western region. However, Gansu Province, Inner Mongolia Autonomous Region, and Guangxi Zhuang Autonomous Region consistently maintain levels below 0.6, while most other areas are around 0.7. The primary reason for this variation is the upgrading and transformation of industries on a national level. Currently, the Western region predominantly features heavy industries centered on energy and raw materials, resulting in significant environmental pollution, substantial water use, and high governance challenges. Figure 1 illustrates the distribution of China's interprovincial sustainable industrial water use efficiency.

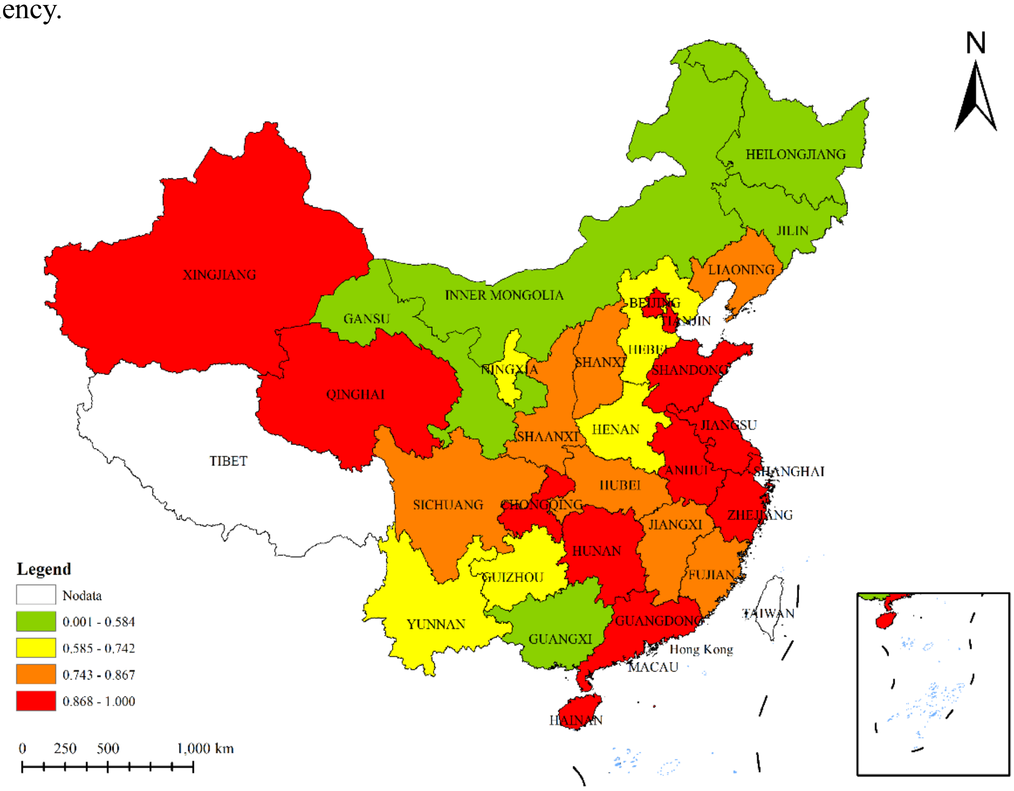

Figure 1. Interprovincial Distribution of China's Industrial Sustainable Development Water Use Efficiency

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3.2.2. Analysis of Water Use Efficiency in Production and Environmental Governance Stages. Regarding the production stage of the industrial sustainable development water system studied in this paper, the water use efficiency in various provinces and municipalities generally exhibits a higher level, all surpassing 0.7. Only the Guangxi Zhuang Autonomous Region records a lower efficiency level of around 0.71, while other provinces and municipalities reach 0.77 or higher. Nearly half of these regions achieve optimal water use efficiency of 1 in the production stage. The provinces and municipalities exhibiting this trend are concentrated in two geographic features: the first includes provinces like Shanxi, Shaanxi, Anhui, Hunan, and Guangdong, located in the eastern plains of China, where the Yellow River, Huai River, and Yangtze River flow, resulting in abundant water resources. They are mostly situated in the central and eastern economic belts. The second group includes Xinjiang Uyghur Autonomous Region and Qinghai Province in the western plateau region of China, which is embedded with plateau basins and valleys that have limited usable water resources. They are positioned within the western economic belt.

Regarding the environmental governance stage, the water use efficiency among provinces and municipalities exhibits a clear tiered pattern. For instance, Inner Mongolia Autonomous Region, Heilongjiang Province, Gansu Province, and Jilin Province all exhibit efficiencies below 0.4, indicating a relatively low level. Notably, the efficiency in Inner Mongolia Autonomous Region is the lowest at 0.22. Moreover, provinces and municipalities with efficiency levels ranging from 0.4 to 0.6 fall into the moderate range. Examples include the Guangxi Zhuang Autonomous Region, Hebei Province, Ningxia Hui Autonomous Region, and Shaanxi Province. Additionally, provinces such as Guizhou, Hubei, Shanxi, and Sichuan exhibit good efficiency levels ranging from 0.6 to 0.8. Finally, in the environmental governance stage, 12 provinces and municipalities achieve a relatively high level of 0.8 to 1. These include Anhui Province, Beijing, Hainan Province, Jiangsu Province, Qinghai Province, Shandong Province, Shanghai, Tianjin, Zhejiang Province, and Chongqing, all attaining optimal efficiency of 1. The provinces and municipalities displaying lower efficiency levels are primarily located in the northern part of China's central economic belt, while those with higher efficiency levels are found in developed economic regions like the Yangtze River Delta and Pearl River Delta, as well as in the western economic belt. Figures 2 and 3 respectively illustrate the distribution of industrial sustainable development water use efficiency in the production and environmental governance stages.

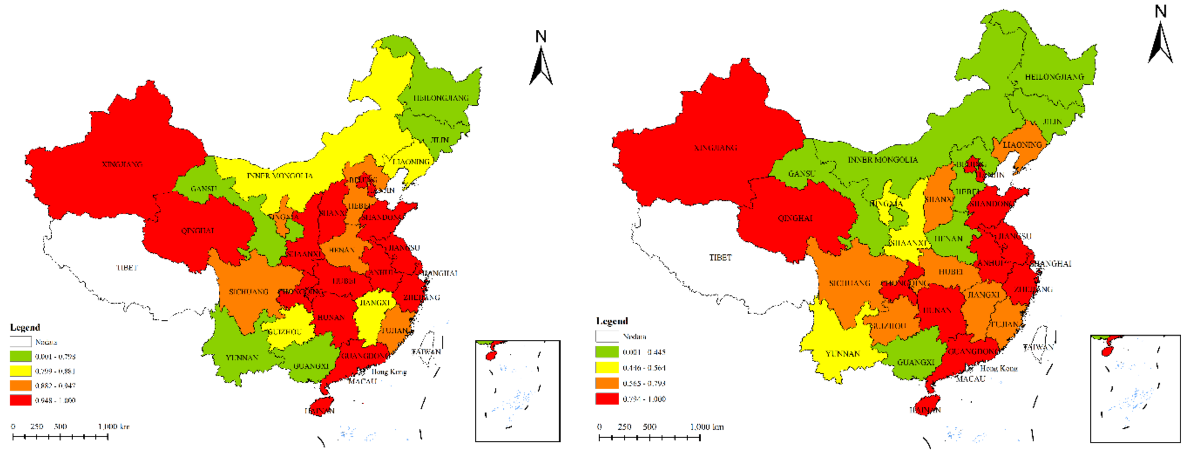

Figure 2. Interprovincial Efficiency of Industrial Sustainable Development Water Use in Two Stages (Left: Production Stage, Right: Governance Stage)

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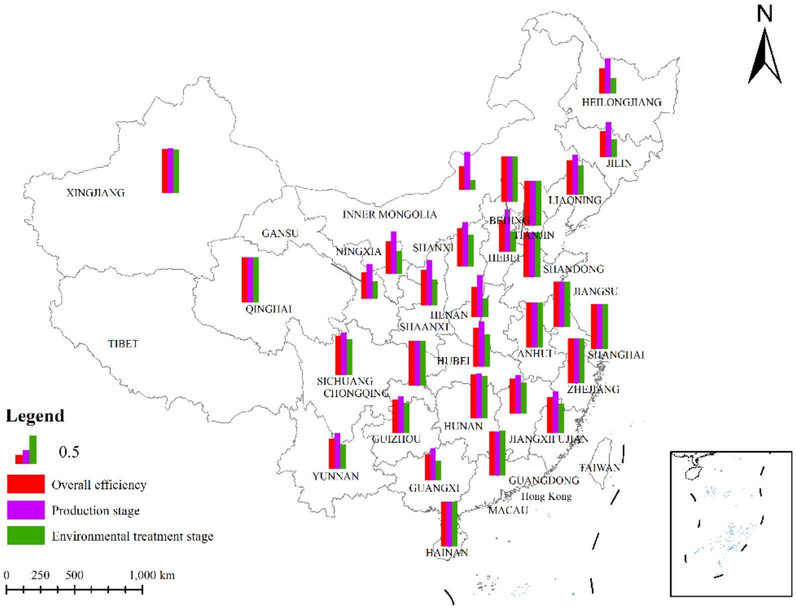

Figure 3. Efficiency of Industrial Sustainable Development Water Use in Different Stages

3.2.3. Analysis of Regional Water Use Efficiency Center of Gravity Migration. In the migration of total efficiency, the center of gravity is located in Henan Province. Between 2014 and 2015, the increase in the total efficiency values of Sichuan, Gansu, Guizhou, and Shaanxi pushed the center of gravity westward. From 2015 to 2017, the overall efficiency growth in regions like Fujian and Yunnan shifted the focus towards the southeast. Between 2017 and 2018, the center of gravity moved further northeast, influenced by efficiency improvements in cities such as Liaoning, Jilin, and Harbin, driving the shift of efficiency values to the northeastern regions. In the migration process of the production stage, the focus also landed on Henan Province. From 2014 to 2016, the focal point of sustainable industrial water use efficiency roughly shifted southward and later shifted to the northeast after 2016. Figures 4, 5, 6 respectively depict the migration direction changes of China's interprovincial sustainable industrial water use efficiency from 2014 to 2018 for total efficiency, production stage, and environmental governance stage.

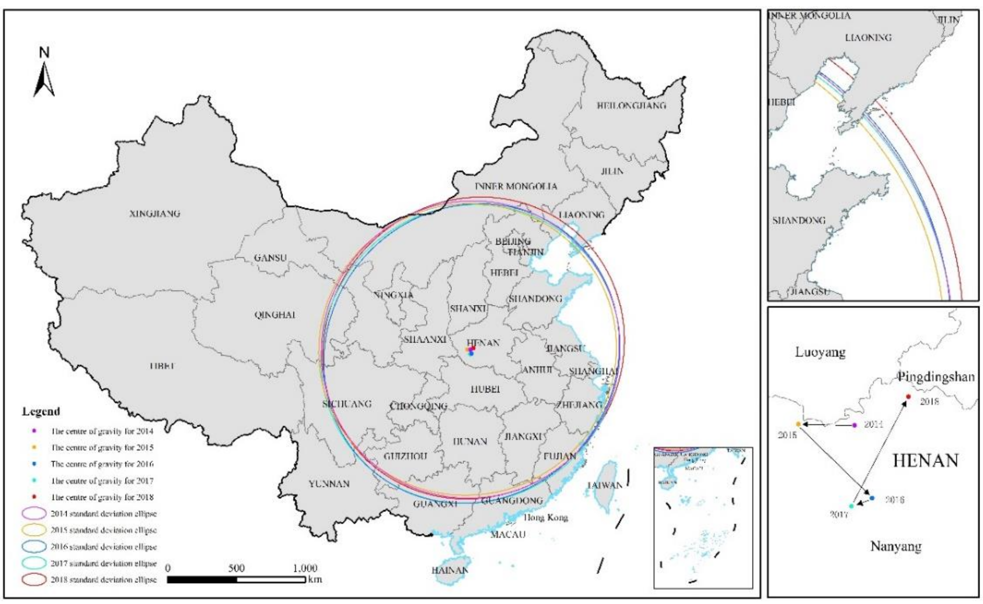

Figure 4. Changes in Migration Direction of Total Efficiency from 2014 to 2018

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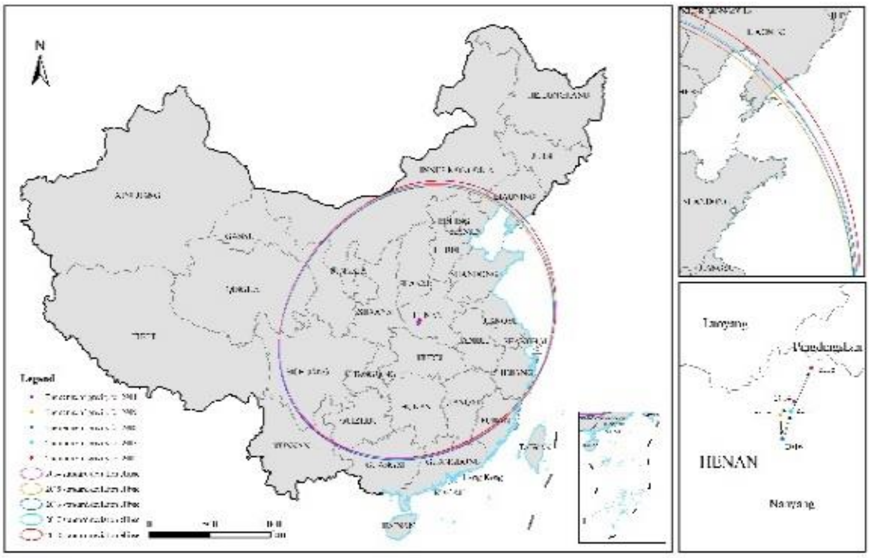

Figure 5. Changes in Migration of Production Stage Efficiency from 2014 to 2018

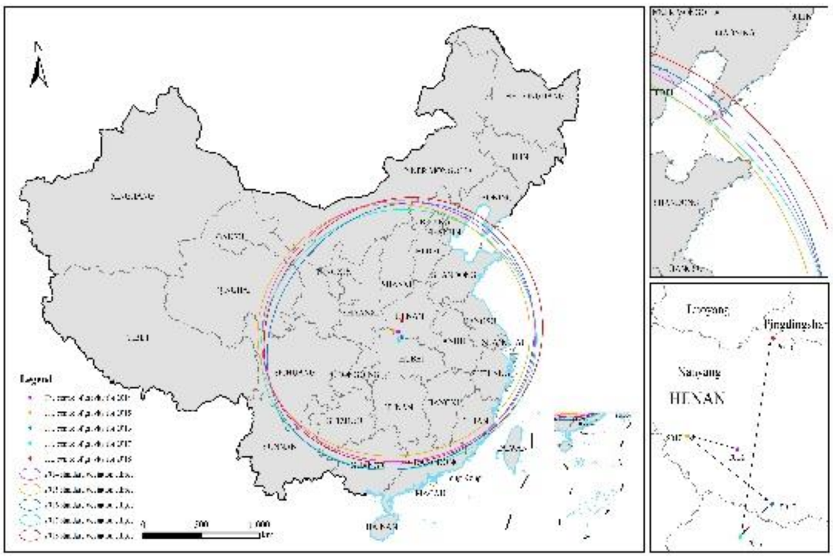

Figure 6. Changes in Migration of Environmental Governance Stage Efficiency from 2014 to 2018

4. Conclusion and Recommendations

In response to the United Nations Sustainable Development Goal 6, "Clean Water and Sanitation," this paper employs the PTSD model to assess China's interprovincial industrial sustainable development water use efficiency. By integrating the Center of Gravity Migration model for evaluation, the following main conclusions are drawn:

(1) Disparities exist in the industrial sustainable development water use efficiency among China's Eastern, Central, and Western regions. These disparities manifest in two aspects. Firstly, there are differences in the overall efficiency levels of industrial water use cycles among the three regions. The total efficiency level is optimal in the East, with the Central region slightly better than the West. Over time, excluding a slight Western lead over the Central region in 2016 and 2017, the trends in total

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efficiency levels remain consistent. Most Eastern provinces exhibit a total efficiency of 1, including Shanghai, Tianjin, Jiangsu, and others. This can be attributed to the concentration of industries in the Eastern region, particularly in high-tech and low-energy consumption sectors, which provide economies of scale. Moreover, due to the concentration of labor force in the East, it holds a significant advantage in terms of employment input. The Central region's total efficiency lags behind due to its role in accommodating the transfer of coarse, low-tech industries from the East. The Western region, characterized by energy-intensive heavy industries, faces greater challenges in governance and larger water consumption, resulting in lower efficiency compared to the Central and Eastern regions.

Secondly, disparities exist in the industrial sustainable water use efficiency within each of the three major regions. Individual provinces in all three regions demonstrate higher levels of sustainable industrial water use efficiency. These include Shanghai, Shandong, Tianjin, Beijing, Jiangsu in the East; Anhui in the Central region; and Qinghai and Chongqing in the West. Regarding geographical distribution, provinces in the northern part tend to exhibit lower efficiency levels due to their outdated industrial structure and disadvantageous labor input, with a focus on extensive industries.

(2) In China's two-stage industrial sustainable development water use efficiency, the efficiency level in the environmental governance stage has a more significant impact on the overall industrial water use efficiency than the production stage. The efficiency levels in the production stage show a relatively consistent high level across provinces and municipalities, while those in the environmental governance stage display a more dispersed and lower level. This discrepancy arises from the economic development level of regions, influencing the investment and personnel allocation in environmental governance. The Eastern region, possessing strong economic capabilities, allocates far more resources in both investment and personnel than the Central and Western regions, resulting in higher efficiency in the environmental governance stage. Notable regions include Hebei, Henan, Ningxia Hui Autonomous Region, Heilongjiang, and Inner Mongolia. Thus, areas aiming to enhance industrial sustainable water use efficiency should focus on the environmental governance stage.

(3) The migration of the efficiency center of gravity approximately follows a trajectory of moving southward in the early stages and then shifting northeastward, with an overall better performance in the East compared to the Central and Western regions. The migration of the total efficiency center of gravity experiences three stages: westward migration from 2014 to 2015, southeastward migration from 2015 to 2017, and northeastward migration from 2017 to 2018. Similarly, the migration direction of the efficiency center of gravity in the environmental governance stage aligns closely with that of the overall efficiency center of gravity. This correlation indicates that the migration of the total efficiency direction is significantly influenced by the migration in the environmental governance stage.

Based on these conclusions, to promote sustainable industrial water use development in different regions across the country, the following recommendations are proposed:

(1) Conduct in-depth social research and implement differentiated water-saving policies in the Eastern, Central, and Western regions. Due to differences in economic development levels, resource endowments, and industrial characteristics, regions across the country to varying extents impact the overall industrial sustainable development water use efficiency. To ensure the effective implementation of national water-saving and environmental protection policies, governments at all levels need to conduct thorough research on the industrial water use structure, characteristics, resource endowments, and economic development status of provinces in the three major regions. Based on this information, tailored industrial water-saving policies should be formulated, along with corresponding financial support. For example, higher standards and requirements can be set for regions in the East with higher industrial water use efficiency, while regions with poor resource endowments such as Inner Mongolia, Heilongjiang, and Yunnan can receive financial or infrastructure support to gradually improve industrial water use efficiency.

(2) Promote industrial structural upgrading from extensive to innovative industries. In developed Eastern regions like Jiangsu, Shanghai, Beijing, and Tianjin, leveraging economic advantages, enhancing innovation capabilities, and promoting the transformation of scientific achievements into practical applications to develop high-tech enterprises is essential for advancing the path of innovation-

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driven development. For the Central and Western regions, where industrial water use is concentrated in environmentally polluting sectors such as textiles, petrochemicals, papermaking, and metallurgy, further upgrading the industrial structure through the absorption of excess capacity from the Eastern region is advisable. Additionally, the Central and Western regions can harness their major cities, such as Chongqing and Wuhan, to drive the development of high-tech industries using local resources, stimulating high-end innovative industries from extensive industries. Furthermore, the Western regions like Urumqi and Kunming can capitalize on their geographical advantages, engaging in sub-regional cooperation with neighboring countries to promote large-scale development.

(3) Drive technological upgrades for industrial water conservation in two stages to enhance water use efficiency. First, in the production stage, eliminate low-end, high-water consumption industries and equipment, expedite the adoption of advanced water-saving processes, technologies, and equipment. Simultaneously, widely promote water-saving technology and clean production in production processes. In the environmental governance stage, allocate financial and research subsidies based on regional economic development status, increase investment in environmental governance, and enhance research and development funding for technological innovation. Incentivize water-saving technology innovation, intensify efforts to combat industrial water pollution, and elevate the utilization of recycled and reclaimed water.

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Symbol List

Symbol	Description
X_{1ij}	Industrial employment, total industrial water consumption, industrial energy consumption, and industrial fixed assets
Y_{1good}	Industrial GDP
Y_{1bad}	CO_2 emissions
$Z_{(12)in}$	(Connects industrial production stage and environmental governance stage): Industrial wastewater discharge, industrial solid waste emission, and industrial gas emission
X_{2ij}	Industrial pollution control investment
Y_{2good}	Industrial wastewater recycling and industrial solid waste utilization
$\mathrm{Z}_{(21)in}$	(Connects environmental governance stage and industrial production stage): Industrial wastewater recycling and industrial solid waste utilization
$Z_{ok_l input}^{(t,(t+1))}$ (Carry-over)	Industrial fixed assets