Measuring Industrial Water Efficiency under Environmental Constraints in the Yangtze River Delta, China: A Nonparametric Frontier Approach

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Keywords: Nonparametric, Yangtze River Delta, Environmental Constraints

Abstract: The Yangtze River Delta (YRD), one of the most developed regions in China, is experiencing rapid industrialization and urbanization accompanied by huge water consumption. Also, Chinese government has recently redefined the scope of YRD to include 8 cities in Anhui Province. In this case, it is crucial to evaluate new-YRD's water sustainability by studying industrial water efficiency (IWE) under environmental constraints at city level. To this end, IWE of 26 cities in YRD and its space-time distribution during 2006-2015 are evaluated based on Shephard water distance function and GIS visualization method, respectively. The findings reveal that IWE in YRD shows an ascending trend during the study period. Moreover, the saptial distribution of the IWE presents the characteristics of low in north and high in south, indicating the existence of a spatial cluster. Finally, a couple of suggestions are concluded.

1. Introduction

As the largest water consumer and CO_2 emitter in the world, China is faced by great challenges of resource and environment from home and abroad. It is accepted that improving water efficiency is one of the most cost-effective ways to increase water security and promote water sustainability. Due to the fact that industrial sector is the largest water end-user of China, improving industrial water efficiency plays a significant role for China to enhance water security and promote sustainable development. In this context, the analysis of industrial water efficiency performance in China may provide empirical and condensed information for policy makers to assess the effectiveness of water efficiency policies and measures.

The Yangtze River Delta region is known for its two major water systems, the Yangtze River and Taihu. South of Jiangsu and Northern Zhejiang were once known as "land of fish and rice". But at present, many cities in the Yangtze River Delta are facing the pressure of water shortage, and some cities even enter the list of serious water shortage cities in the whole country. With the development of urbanization in the region to a higher level, the water shortage constraints in the Yangtze River Delta will be further strengthened. Therefore, it is an urgent research topic to analyze the current situation of water resources consumption in the Yangtze River Delta and formulate relevant policies to alleviate the pressure of water resources.

As one of the six largest urban agglomerations in the world, Yangtze River Delta (YRD) urban agglomeration accounted for 19.78% of China's GDP in 2016. In 2014, the State Department has incorporated Anhui Province as a part of YRD, and the scope of YRD has been expanded accordingly. According to the "Development Plan of Urban Agglomeration in the Yangtze River Delta" approved by the State Council in May 2016, YRD urban agglomeration was extended to include 26 cities. In this sense, it is of great theoretical and practical value to study the (IWE) of the 26 cities in new-YRD. The literature of studies on YRD is abundant. Yue et al. measured water consumption of three industries and double-digit industries in the Yangtze River Delta. Sun and Li measured the total-factor water efficiency of the YRD region during 1992-2010 based on the DEA-Malmquist model. Yang et al. estimated the total-factor water efficiency 14 representative cities in YRD from 2000 to 2009 by using a stochastic frontier production function. Nevertheless, IWE

  DOI: 10.25236/iwass.2018.057

under environmental constraints in the new-YRD urban agglomeration has not been investigated, and this paper is conducted to fill the gap in this field. The reminder of this paper proceeds as follows. Section 2 introduces methods and materials. Section 3 presents the results and discussions. Section 4 draws conclusions and provides policy implications.

2. Methods and Materials

2.1. Environmental Production Technology

Consider a productive process in which capital stock (K), labor force (L) and water (W) are utilized to jointly produce gross industrial output (Y) and waste water (B) as the single desirable output and undesirable output, respectively. Mathematically, the joint production can be presented as Eq. (1), which is so-called environmental production technology.

$$T = \{(K, L, W, Y, B) : (K, L, W) \text{ can produce } (Y, B)\} \quad (1)$$

Notably, in the joint-production process, inputs and the desirable output are usually assumed to be strongly disposable, while the undesirable output is weakly disposable.

2.2. Industrial Water Efficiency Index

To measure the industrial water efficiency performance, we first define a Shephard sub-vector input distance function for water use (hereafter referred to as the Shephard water distance function) as follows:

$$D_w(K, L, W, Y, B) = \sup\{\beta : (K, L, W/\beta, Y, B) \in T\} \quad (2)$$

Eq. (2) seeks to measure the maximal possible reduction in water use, while keeping the resulting input-output combination within the production technology set as defined by Eq. (1).

The Shephard water distance function $D_w(K, L, W, Y, B)$ measures the degree to which water use can be reduced. As such, its reciprocal may be taken as a water efficiency index that can be used to compare the industrial water efficiency performance. Here we refer to the reciprocal of the Shephard water distance function as the industrial water efficiency (IWE):

$$\text{IWE} = \frac{1}{D_w(K, L, W, Y, B)} \quad (3)$$

The Shephard water distance function can be measured by solving the following DEA model exhibiting constant returns to scale:

$$\begin{aligned} & \left[D_w(K_j, L_j, W_j, Y_j, B_j)\right]^{-1} = \min \theta \\ s.t. \quad & \sum_{j=1}^{n} \lambda_j K_j \le K_j; \sum_{j=1}^{n} \lambda_j L_j \le L_j; \sum_{j=1}^{n} \lambda_j W_j \le \theta W_j; \\ & \sum_{j=1}^{n} \lambda_j Y_j \ge Y_j; \sum_{j=1}^{n} \lambda_j B_j = B_j; \lambda_j \ge 0, j = 1, 2, ..., n \end{aligned} \quad (4)$$

2.3. Regions and Data

The research object in this paper is urban agglomeration in YRD which contains 26 cities located in three provinces of Jiangsu, Zhejiang, Anhui and one municipality of Shanghai. Specifically, cities in Jiangsu Province contain Nanjing (NJ), Suzhou (SZ), Wuxi (WX), Changzhou (CAZ), Zhenjiang (ZJ), Yangzhou (YZ), Taizhou (TZ), Nantong (NT) and Yancheng (YC); cities in Zhejiang Province contain Hangzhou (HZ), Ningbo (NB), Jiaxing (JX), Huzhou (HUZ), Shaoxing (SX), Jinhua (JH), Zhoushan (ZS), Tai'zhou (TAZ); cities in Anhui Province contain Hefei (HF), Wuhu (WH), Maanshan (MAS), Tongling (TL), Anqing (AQ), Chuzhou (CUZ), Chizhou (CIZ), Xuancheng (XC).

The data of capital stock (K), average number of employees (L), water consumption (W), gross industrial output value (G) and wastewater discharge (B) are gathered and calculated from the relevant City Statistical Yearbooks.

3. Results and Discussion

3.1. Industrial Water Efficiency Estimates

We computed the IWE scores for 26 cities by solving Eq. (4) with MaxDEA Ultra. The results were listed in Table 1. At city level, average efficiency of Hangzhou, Shaoxing, Taizhou and Hefei is at high levels with scores of more than 0.9. In contrast, the average IWE of Maanshan (0.565) is the lowest, followed by Xuancheng with the value of 0.580. At province level, Shanghai is found with the highest average IWE of 0.875, followed by Zhejiang (0.841). Moreover, the average IWE of Anhui (0.686) is much lower than the average level of YRD (0.778).

Table 1. IWE of 26 cities in YRD.

Region	*2006*	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*Mean*
Shanghai	1.000	1.000	0.729	0.976	1.000	0.885	0.753	0.812	0.825	0.769	0.875
Nanjing	0.701	0.681	0.681	0.981	0.802	0.749	0.700	0.925	0.951	0.837	0.801
Suzhou	0.674	0.658	0.662	0.825	0.800	0.782	0.712	0.658	0.615	0.606	0.699
Wuxi	0.684	0.670	0.656	0.805	0.728	0.774	0.726	0.669	0.637	0.630	0.698
Changzhou	0.700	0.670	0.722	0.912	0.906	0.940	0.917	0.923	0.859	0.860	0.841
Zhenjiang	0.425	0.468	0.457	0.757	0.738	0.641	0.713	0.782	0.797	0.779	0.656
Yangzhou	0.582	0.522	0.584	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.869
Nantong	0.704	0.744	0.743	0.985	0.857	0.813	0.810	0.809	0.819	0.827	0.811
Taizhou	0.711	0.740	0.674	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.912
Yancheng	0.626	0.696	0.767	1.000	1.000	1.000	1.000	0.831	0.781	0.798	0.850
Hangzhou	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.983	0.945	0.951	0.988
Ningbo	0.948	0.917	0.806	0.775	0.908	0.881	0.835	0.742	0.748	0.802	0.836
Jiaxing	0.636	0.661	0.665	0.677	0.786	0.757	0.666	0.700	0.707	0.726	0.698
Huzhou	0.692	0.716	0.783	0.870	0.851	0.817	0.857	0.867	0.847	0.892	0.819
Shaoxing	0.837	0.846	0.865	0.882	0.853	1.000	1.000	1.000	1.000	1.000	0.928
Jinhua	0.754	0.695	0.735	0.749	0.713	0.897	0.916	0.933	0.982	1.000	0.837
Zhoushan	0.571	0.629	0.536	0.978	0.816	0.720	0.820	0.959	1.000	0.955	0.798
Tai'zhou	1.000	1.000	0.818	0.819	0.791	0.784	0.817	0.736	0.754	0.738	0.826
Hefei	0.545	0.647	1.000	1.000	1.000	0.941	1.000	1.000	0.894	1.000	0.903
Wuhu	0.499	0.450	0.470	0.795	0.834	1.000	1.000	1.000	0.540	0.800	0.739
Maanshan	0.401	0.416	0.476	0.856	0.728	0.591	0.530	0.721	0.267	0.668	0.565
Tongling	0.383	0.352	0.276	0.885	0.951	1.000	0.611	1.000	0.324	1.000	0.678
Anqing	0.351	0.338	0.290	0.865	0.877	0.902	0.856	0.781	0.183	0.716	0.616
Chuzhou	0.738	0.679	0.588	0.782	1.000	1.000	0.843	0.746	0.142	0.896	0.741
Chizhou	1.000	1.000	1.000	0.577	0.590	0.599	0.577	0.588	0.095	0.661	0.669
Xuancheng	0.500	0.486	0.417	0.710	0.802	0.821	0.670	0.674	0.091	0.626	0.580
Shanghai	1.000	1.000	0.729	0.976	1.000	0.885	0.753	0.812	0.825	0.769	0.875
Jiangsu	0.645	0.650	0.661	0.918	0.870	0.856	0.842	0.844	0.829	0.815	0.793
Zhejiang	0.805	0.808	0.776	0.844	0.840	0.857	0.864	0.865	0.873	0.883	0.841
Anhui	0.552	0.546	0.565	0.809	0.848	0.857	0.761	0.814	0.317	0.796	0.686
YRD	0.679	0.680	0.669	0.864	0.859	0.857	0.820	0.840	0.685	0.828	0.778

3.2. Spatial-temporal Distribution of IWE

Figure 1 illustrates the distribution patterns of IWE in 2006, 2009, 2012 and 2015, which can help us to analyze the space-time distribution of IWE more intuitively. From this figure, we can observe that the IWE scores in YRD generally show an upward trend. From the distribution of 2006, IWE is generally found with a descend tendency from west to east. As for 2009, the distribution of IWE presents the characteristics of low in south, high in north. On the contrary, the distribution of IWE presents the characteristics of low in north, high in south in 2012 and 2015. Obviously, the higher efficiencies are mostly concentrated in Taizhou, Nantong, Changzhou, Huzhou, Hangzhou, Shaoxing, Ningbo, Tai'zhou, while the lower ones are primarily concentrated in Anqing, Chizhou, Xuancheng, Maanshan, Zhenjiang, indicating the existence of a spatial cluster. More specifically, Shaoxing and Hangzhou are the two cities with IWE above 0.8 throughout the period of 2006 to 2015. On the one hand, Yangzhou, Taizhou, Hefei, Changzhou, Jinhua, Zhoushan, Tongling and Wuhu are found with considerable growth during the study period. On the other hand, Tai'zhou and Chizhou both have decreased significantly in the same period, which may be the causes of the low efficiency in Zhejiang and Anhui.

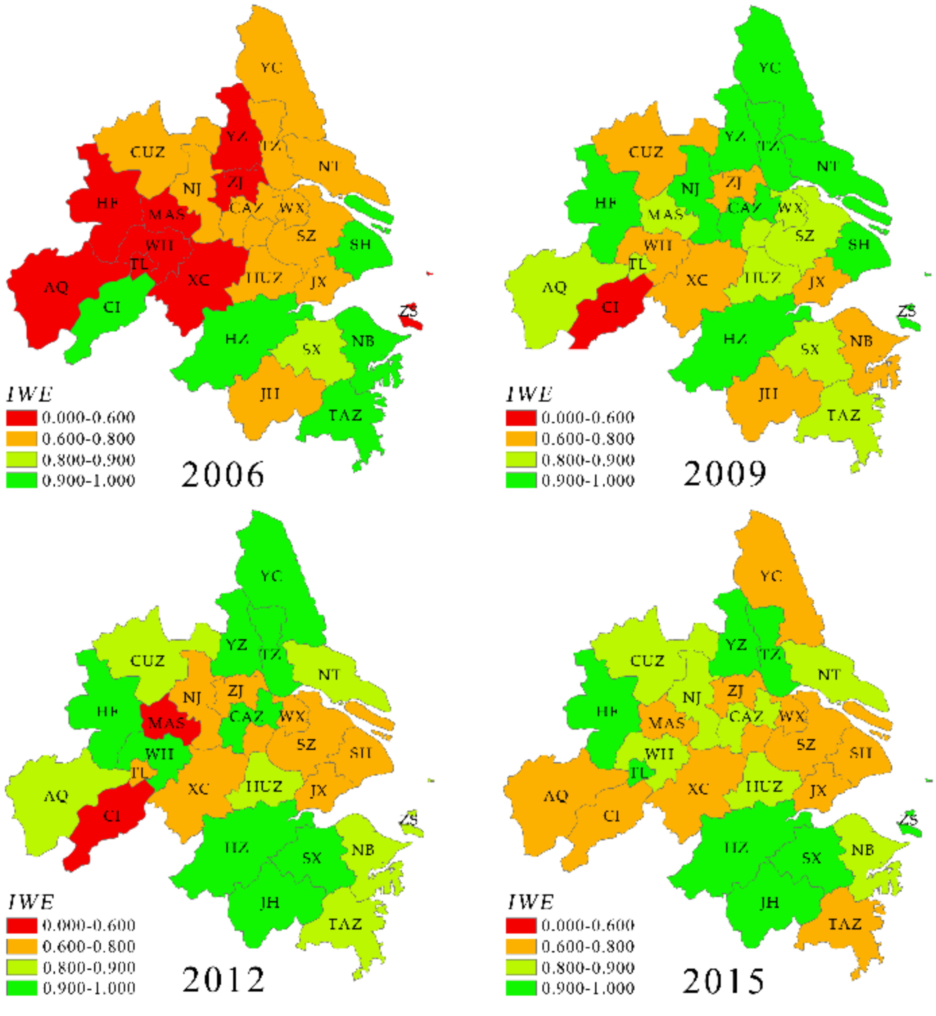

Figure 1. Spatial distribution of IWE in YRD.

4. Conclusions and Policy Implications

In this paper, we measure the IWE under environmental constraints of the 26 cities in YRD based on the Shephard water distance function and further study its space-time distribution with the GIS visualization method. The findings are as follows: First, efficiency varies greatly due to the differences of economic development, government policy, water consumption and other aspects in terms of the spatial distribution of the IWE. Additionally, from the distribution of regions with high

IWE and low IWE, a spatial cluster was observed. In terms of the change trend of IWE, efficiencies in YRD increase slowly in fluctuation during our study period.

Based on the above conclusions, the following suggestions are provided to improve IWE: Firstly, to guarantee a smooth and effective implementation of all measures taken to enhance IWE, it is necessary to develop relevant laws and regulations. While maintaining momentum in economy, YRD can improve its overall IWE, and achieve government’s commitment to saving water by taking appropriate measures. As mentioned above, there are disparities of IWE between various regions in YRD. The key to improve IWE is to balance economic growth and water consumption. In this case, it is necessary to develop differentiated water saving policies for different regions. Cities with higher levels of industrialization such as Zhenjiang and Jiaxing, should develop high-technology industries energetically to promote the transformation of economic growth modes. Whereas cities with lower levels, such as Maanshan and Xuancheng should enhance the level of industry concentration, which plays a positive role in forming scale effect and upgrading technological level. Additionally, cities with backward production technology should accelerate technology replacement to narrow disparities in industrial water-saving technology.

Acknowledgments

The authors would like to thank the financial support provided by the National Natural Science Foundation of China (Grant No. 41471457), and the Fundamental Research Funds for the Central Universities (Grant Nos. 2016B09414, 2018B41314).

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