Temporal-Spatial Evolution of Industrial Wastewater Discharge Efficiency in the Yangtze River Delta, China: A Nonparametric Analysis

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Abstract. Urban agglomeration has been the core of coordinated development of regional economy in China, since urban agglomeration is deemed as the main form of new urbanization by central government. The rapid industrialization in the Yangtze River Delta (YRD) brings about large consumption of water resources as well as massive industrial wastewater discharge. In this case, we incorporate industrial water consumption and wastewater discharges into the directional distance function to construct and analyze the industrial wastewater discharge efficiency (IWDE) of cities in the YRD. The results indicate that the overall IWDE in YRD proceeded in a fluctuation way during our study period. Also, IWDE varied among the cities in the YRD due to their spatial differences in economic development, water resource endowment and environmental regulation. In addition, there was an observed spatial cluster of IWDE among different clusters of cities in the YRD.

1. Introduction
As Chinese central government proposed urban agglomeration is the main form of new urbanization, urban agglomeration has been the core of coordinated development of regional economy in China. As such, it is necessary and significant to study the environmental problems regarding urban agglomeration. The past “12th Five Year Plan” period (2011-2015) is the five years for China’s economy to achieve great progress. However, with the rapid development of China’s economy, the country is faced with increasing environmental pressure. Now, China is in the “13th Five Year Plan” period (2016-2020) which is the crucial period for comprehensively deepening reform and promoting economic structure transformation and upgrading. It is a key period to build ecologically friendly environment and create a better life. On June 1, 2018, the Symposium of the main leaders in the Yangtze River Delta (YRD) was held in Shanghai. The theme of the symposium was “focusing on high quality and integrating forces” which aims to further plan and deepen the development of the higher quality integration of the YRD. After the first China International Import Expo on January 10, 2019, Shanghai, Jiangsu, Zhejiang and Anhui provinces and cities made the decision on supporting and ensuring the higher quality integrated development of the YRD and the “Yangtze River Delta integrated development demonstration zone” was thus proposed for the first time.

In China, the YRD has the densest population and industries, the most advanced science and technology and the most developed economic level. Based on the national statistics data, its total economic output is as high as US$2.67 trillion in 2016, which accounts for about 23% of the total
output of the country. Due to the location advantages of the YRD, polluting industries like chemistry, smelting, electricity concentrate in this region. Consequently, the rapid development of heavy industry leads to large consumption of water resources as well as mass discharge of industrial wastewater. Committedly, pollutant discharges from the industrial production should take the primary responsibility for the gradually deteriorating water environmental quality. In this case, the most direct and effective solution to mitigating passive impacts on the environment may be to regulate the wastewater discharges from industrial sectors. Therefore, in order to keep the stable economic growth, improving industrial wastewater discharge efficiency (IWDE) is crucial to strengthen water security, improve water environment and promote sustainable development in China.

Currently, studies relating to wastewater discharges mainly focused on the spatial-temporal distribution and evolution characteristics as well as its driving forces. For example, Cheng et al. [1] Combined the super-efficiency, slacks-based-measure, and global-frontier technology to estimate the total-factor eco-efficiency of cities in the YRD during the period 2003‒2016. Fujii and Shunsuke [2] employed the weighted Russell directional distance model to measure industrial wastewater management efficiency between 2004 and 2014. Chen et al. [3] focused on the wastewater discharges in Yangtze River Economic Zone and combined the Exploratory Spatial Data Analysis (ESDA) method and Logarithmic Mean Divisia Index (LMDI) to study its spatial-temporal distribution and evolution patterns. Yang and Li [4] applied Data Envelope Analysis (DEA) model to measure the total-factor efficiency of wastewater control in China’s industrial sectors during the period 2003–2014.

With regards to the YRD, Yang et al [5] used a stochastic frontier production function to estimate the total-factor water efficiency of 14 cities in YRD during the period of 2000 to 2009. Yue et al [6] analyzed water consumption and its spatial differences in the YRD by constructing a water resource consumption input-output model. However, relevant researches mainly focus on the water efficiency while few has studied the wastewater discharge efficiency of cities in the YRD. To this end, this study employs the directional distance function to define the industrial wastewater discharge efficiency (IWDE) index by constructing the environmental production technology. As such, the temporal-spatial distribution and evolution of IWDE from 2006 to 2015 in the YRD were analyzed and corresponding policy implications were provided to mitigate local industrial wastewater discharges.

2. Methods and Materials

2.1. Environmental Production Technology

Assume a joint production activity where three production factors of water (W), labor force (L) and capital stock (K) are combined to generate the desirable output of industrial output (Y) and the undesirable output of industrial wastewater discharges (B). The production process is called as environmental production technology as both economic and environmental factors are included and it can be mathematically described in Eq. (1).

\[ T = \{(K, L, W, Y, B): (K, L, W) \text{ can produce } (Y, B)\} \]  

Here we assume the inputs and the desirable output to have strong disposability, while the undesirable output has weak disposability.

2.2. Directional Distance Function and Industrial Wastewater Discharge Efficiency

To construct the Industrial Wastewater Discharge Efficiency index in the framework of production theory, we define a directional distance function that can not only increase industrial output but also reduce wastewater discharges, as shown in Eq. (2).

\[ \tilde{D}(K, L, E, Y, B; g) = \sup\{\beta: \{Y + \beta g, B - \beta g\} \in T\} \]  


Where \( \left( g_v, g_b \right) \) denotes the direction vector which indicates the scale directions of desirable and undesirable outputs, and is usually specified as \( \left( Y, -B \right) \). \( \beta \) is the outcome of the directional distance function that measures the greatest degree to which \( Y \) and \( B \) can be respectively expanded and shrunk given production inputs.

According to the definition of the directional distance function above, the minimum wastewater discharges in the evaluated region is \( \left[ 1 - \bar{D}(K, L, E, Y, B; g) \right] \times B \). As such, the Industrial Wastewater Discharge Efficiency (IWDE) can be defined as below:

\[
\text{IWDE} = 1 - \bar{D}(K, L, E, Y, B; g)
\]

(3)

The directional distance function in Eq. (2) can be computed by solving a DEA model in the following:

\[
\bar{D}(K, L, E, Y, B; g) = \max \beta \\
\text{s.t.} \quad \sum_{j=1}^{n} \lambda_j K_j \leq K_0; \quad \sum_{j=1}^{n} \lambda_j L_j \leq L_0; \quad \sum_{j=1}^{n} \lambda_j W_j \leq W_0; \\
\sum_{j=1}^{n} \lambda_j Y_j = Y_0 \times (1 + \beta); \quad \sum_{j=1}^{n} \lambda_j B_j = B_0 \times (1 - \beta); \\
\lambda_j \geq 0, j = 1, 2, \ldots, n
\]

(4)

2.3. Regions and Data

The YRD locates in the eastern coastal area of China, consisting of 26 cities located in one municipality of Shanghai and three provinces of Anhui, Zhejiang and Jiangsu, as shown in Figure 1. The 26 cities are specifically 9 cities in Jiangsu like Changzhou (CAZ), Suzhou (SZ), Nantong (NT), Zhenjiang (ZJ), Nanjing (NJ), Yangzhou (YZ), Wuxi (WX), Taizhou (TZ) and Yancheng (YC); 8 cities in Zhejiang Province containing Ningbo (NB), Shaoxing (SX), Jiaxing (JX), Jinhua (JH), Hangzhou (HZ), Zhoushan (ZS), Huzhou (HUZ), Tai’zhou (TAZ); 8 cities in Anhui Province including Wuhu (WH), Anqing (AQ), Maanshan (MAS), Chuzhou (CUZ), Hefei (HF), Tongling (TL), Xuancheng (XC), Chizhou (CIZ).

![Figure 1. The location and components of the YRD.](image-url)
The data of 26 cities in terms of industrial water consumption (W), employment (L), capital (K), gross industrial output (Y) and industrial wastewater discharges (B) are gathered and calculated from Shanghai Statistical Yearbook, Jiangsu Statistical Yearbook, Zhejiang Statistical Yearbook, Anhui Statistical Yearbook and China’s City Statistical Yearbooks.

3. Results and Discussions

3.1. Estimates of Industrial Water Discharge Efficiency

Table 1 indicates the IWDE estimates of 26 cities from 2006 to 2015 which were computed by solving Eq. (4) with MaxDEA Ultra. First, at province level, Anhui was observed with the highest score of 0.827, followed by Zhejiang (0.823) and Jiangsu (0.818), while Shanghai had the lowest average IWDE (0.715). On the other hand, with regards to the city level, the average IWDE of Hangzhou, Yancheng, Shaoxing, Tongling, Chizhou and Xuancheng were at high levels with scores higher than 0.9. On the contrary, the mean value of Wuhu (0.626) was at the bottom, followed by Zhenjiang (0.659), and both of them were below 0.7.

| Region | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | Mean |
|--------|------|------|------|------|------|------|------|------|------|------|------|
| Shanghai | 1.000 | 0.661 | 0.535 | 0.969 | 0.842 | 0.676 | 0.573 | 0.795 | 0.353 | 0.752 | 0.715 |
| Nanjing | 0.701 | 1.000 | 1.000 | 1.000 | 1.000 | 0.921 | 0.814 | 0.991 | 0.626 | 0.901 | 0.895 |
| Suzhou | 0.726 | 0.725 | 0.711 | 0.840 | 0.790 | 0.762 | 0.709 | 0.759 | 0.682 | 0.781 | 0.749 |
| Wuxi | 0.684 | 0.796 | 0.773 | 0.865 | 0.781 | 0.725 | 0.639 | 0.726 | 0.449 | 0.706 | 0.714 |
| Changzhou | 0.700 | 0.978 | 1.000 | 1.000 | 1.000 | 0.878 | 0.846 | 0.896 | 0.501 | 0.864 | 0.866 |
| Zhenjiang | 0.698 | 0.499 | 0.521 | 0.865 | 0.781 | 0.725 | 0.639 | 0.726 | 0.449 | 0.706 | 0.714 |
| Yangzhou | 0.724 | 0.633 | 0.651 | 1.000 | 1.000 | 1.000 | 1.000 | 0.549 | 1.000 | 0.817 | 0.659 |
| Nantong | 0.745 | 0.816 | 0.802 | 0.989 | 0.887 | 0.826 | 0.809 | 0.836 | 0.535 | 0.879 | 0.812 |
| Taizhou | 0.838 | 0.687 | 0.701 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 0.918 |
| Yancheng | 0.693 | 0.866 | 0.874 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 0.942 |
| Hangzhou | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 0.985 | 0.919 | 0.997 | 0.936 | 0.984 |
| Ningbo | 0.969 | 0.783 | 0.770 | 0.723 | 0.891 | 0.730 | 0.672 | 0.649 | 0.365 | 0.682 | 0.723 |
| Jiaxing | 0.705 | 0.744 | 0.746 | 0.739 | 0.853 | 0.740 | 0.764 | 0.798 | 0.874 | 0.839 | 0.780 |
| Huzhou | 0.697 | 0.885 | 0.982 | 0.935 | 0.911 | 0.854 | 0.880 | 0.938 | 0.844 | 0.846 | 0.877 |
| Shaoyang | 0.837 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| Jinhua | 0.754 | 0.802 | 0.814 | 0.811 | 0.791 | 0.793 | 0.732 | 0.748 | 0.558 | 0.826 | 0.759 |
| Zoushan | 0.771 | 0.613 | 0.539 | 0.981 | 0.724 | 0.764 | 0.704 | 1.000 | 0.587 | 0.951 | 0.763 |
| Tai’zoux | 1.000 | 0.900 | 0.733 | 0.719 | 0.727 | 0.647 | 0.637 | 0.648 | 0.460 | 0.654 | 0.713 |
| Hefei | 0.722 | 0.656 | 0.686 | 0.968 | 0.804 | 0.728 | 0.825 | 0.884 | 0.373 | 0.933 | 0.758 |
| Wuhu | 0.701 | 0.568 | 0.557 | 0.800 | 0.616 | 0.652 | 0.559 | 0.768 | 0.270 | 0.775 | 0.626 |
| Maanshan | 0.690 | 0.581 | 0.477 | 0.869 | 1.000 | 0.948 | 0.848 | 0.839 | 0.763 | 0.881 | 0.789 |
| Tongling | 0.655 | 0.923 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 0.958 |
| Anqing | 0.660 | 0.733 | 0.775 | 1.000 | 1.000 | 0.986 | 0.938 | 0.903 | 0.750 | 0.849 | 0.859 |
| Chuzhou | 0.853 | 0.519 | 0.490 | 0.610 | 0.791 | 0.908 | 0.726 | 0.740 | 0.856 | 0.874 | 0.737 |
| Chizhou | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 0.989 | 0.863 | 1.000 | 1.000 | 1.000 | 0.985 |
| Xuancheng | 0.561 | 1.000 | 1.000 | 1.000 | 1.000 | 0.811 | 0.840 | 1.000 | 0.815 | 0.903 |
| Shanghai | 1.000 | 0.661 | 0.535 | 0.969 | 0.842 | 0.676 | 0.573 | 0.795 | 0.353 | 0.752 | 0.715 |
| Jiangsu | 0.723 | 0.778 | 0.781 | 0.939 | 0.903 | 0.870 | 0.836 | 0.892 | 0.570 | 0.883 | 0.818 |
| Zhejiang | 0.842 | 0.841 | 0.823 | 0.864 | 0.862 | 0.811 | 0.797 | 0.838 | 0.711 | 0.842 | 0.823 |
| Anhui | 0.730 | 0.747 | 0.748 | 0.905 | 0.884 | 0.903 | 0.838 | 0.872 | 0.751 | 0.891 | 0.827 |
| YRD | 0.773 | 0.783 | 0.774 | 0.906 | 0.882 | 0.854 | 0.814 | 0.865 | 0.661 | 0.868 | 0.818 |
3.2. Spatial-temporal Distribution of IWDE
The Arcgis software was applied to plot the regional distribution and evolution patterns of IWDE as displayed in Figure 2. Obviously, it unveiled the temporal-spatial evolution of IWDE in the YRD in an intuitive way. By comparing the four figures in Figure 2, it was observed that the changes in IWDE scores of the YRD proceeded in a fluctuating way. More specifically, the IWDE distribution in 2006 is observed with a pattern of “high in the south and low in the north”. As for 2009, the distribution of IWDE switched into that of “high in the west and low in the east”. With regards to 2012 and 2015, the central cities in the YRD like Changzhou, Suzhou, Wuxi, Wuhu, Xuancheng, Huzhou and Shanghai witnessed a decline in the IWDE. As such, the patterns in the two years indicated spatial clustering characteristics as shown in Figure 1. More specifically, the cluster of Yancheng, Yangzhou, Taizhou and Nantong were found to have a higher IWDE score and a similar situation was also observed in the cluster of Anqing, Chizhou and Tongling. However, the cluster of Shanghai, Suzhou, Wuxi and Jiaxing was found to have a lower IWDE score.

![Figure 2. Spatial distribution of IWDE in YRD.](image)

4. Conclusions and Policy Implications
This study measured the IWDE of the 26 cities in YRD by defining the directional distance function and further investigating its temporal-spatial distribution and evolution by using the visibility analysis
method. The findings indicate that the overall IWDE in YRD proceeded in a fluctuation way during our study period. Also, IWDE varied among the cities in the YRD and it is mainly because their spatial differences in economic development, water resource endowment and environmental regulation. In addition, there was an observed spatial cluster of IWDE among different clusters of cities in the YRD. Based on the findings above, some suggestions can be proposed. First of all, because of the existence of regional disparities in IWDE in the YRD, differentiated industrial wastewater mitigation policies and measures should be formulated for different regions. More specifically, cities with higher IWDE levels should focus on the development of high-technology industries and give a full play of technology spillover effect to help the technological improvement of undeveloped regions. On the other hand, cities with lower levels should take the transformation of industrial structure as the focus of policy making and introduce advanced production technologies and management experience through commercial cooperation and trade.

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