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A study of industrial relative water use efficiency of Beijing: an application of data envelopment analysis

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Abstract

Evaluating and improving water use efficiency is considered one of the main ways of tackling water shortage challenges in water-scarce cities. A useful indicator for evaluating industrial water use efficiency is the relative water use efficiency (RWUE). In this paper, an industrial RWUE evaluation scheme is proposed based on data envelopment analysis (DEA) theory. In this scheme, the RWUE is divided into overall efficiency (OE), pure technical efficiency (PTE), and scale efficiency (SE). In order to help decision-makers specify the focal industry of efficiency improvement, direct water use is distinguished from indirect water use. By employing this industrial RWUE evaluation scheme, this research calculated the industrial RWUEs for 25 representative industries of Beijing (1990–2010). Results show that the OE, PTE, and SE of Beijing have improved significantly. In the primary industry, the scale adjustment fundamentally lifted OE. For the secondary industries, there still exists much room for water use efficiency improvement in technical innovation. Some emerging tertiary industries replaced traditional tertiary industries as the most efficient water users. This study serves as a valuable reference for the implementation of the Strictest Administration of Water Resources (SAWR) of China, and provides policymakers worldwide with a useful framework of understating industrial water use efficiency.

Keywords: Beijing; Data envelopment analysis (DEA); Industrial structure regulation; Relative water use efficiency (RWUE); Strictest Administration of Water Resources (SAWR)

1. Introduction

Water use efficiency was first proposed in the agriculture system. It is defined as the ratio of the amount of system output to the input or flux of water used in its production (Israelsen, 1932). In-depth research shows that the evaluation of the relative water use efficiency (RWUE) has been proven to

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be easier and practical in contrast with the absolute water use efficiency assessment (Zhou *et al.*, 2008). The Chinese Government pays much attention to water use efficiency improvement but still lacks experience in implementing water resources management. In order to support robust water resources management, the State Council of China issued the Strictest Administration of Water Resources (SAWR) (State Council, 2010), in which specific restrictions were set for the total water use, the water use efficiency, and the total pollution discharge in water resources function areas. As one of the three restrictions, water use efficiency is the key to tackling the water shortage problems in water-scarce cities (Zhao *et al.*, 2013). The restrictions are also called the three red lines that will be assessed once every five years based on specific indicators.

Beijing is a city suffering from extreme water shortage. For instance, Beijing's per capita water resources, 300 m^3/capita/year, is one-thirtieth of the world's average value, far below the internationally recognized water stress threshold (1,700 m^3/capita/year) (Falkenmark *et al.*, 1989; Wang & Wang, 2005; Zhang *et al.*, 2011). In spite of the extreme water pressure, Beijing's water use efficiency is unsatisfactory. In 2010, for example, the water use per million dollars GDP, the water use per agricultural value added, and the water use per industrial value added of Beijing were 175.05 m^3/millions of US$, 5,880.48 m^3/US$ and 150.51 m^3/US$, respectively (Beijing Statistical Information Net, 2010; Beijing Water Authority, 2010). Coupled with the trend that developed countries continuously transfer water-intensive products manufacturing to developing countries (such as China), it is a great challenge for Beijing to improve the water use efficiency and implement the SAWR. Since different water use industries have different production processes, improving water use efficiency essentially calls for cooperative efforts from different industries (Xu *et al.*, 2005).

In order to solve the different water use efficiency management problems of different industries, this paper proposes an industrial RWUE evaluation scheme based on the data envelopment analysis (DEA). Moreover, this paper provides a robust investigation on the RWUEs of 25 representative industries of Beijing in 1990–2010. It will provide policy-makers with a useful framework of understating industrial water use efficiency and design specified efficiency improvement strategy in both qualitative and quantitative perspectives. The remainder of the paper is organized in the following way. Section 2 describes the industrial structure and water use status of Beijing; Section 3 provides details on the RWUE evaluation methodology; Section 4 presents the scheme's application to the 25 representative industries of Beijing (1990–2010); Section 5 discusses the implications for water resources management by taking into account the industrial structure regulation; and Section 6 includes the conclusions and limitations of this work.

2. Methodology

2.1. Basic model

DEA is a nonparametric method of measuring the relative efficiency of a decision-making unit (DMU), which has the incomparable advantage of not needing to reassign weights for multiple input and outputs (Charnes *et al.*, 1978). Based on the DEA theory, RWUE is defined as the ratio of the minimum water input to the actual water input given a certain economic output.

Water input can be divided into direct water input and indirect water input. Direct water use is the volume of water directly used in production, such as the cooling water used in the steel industry, while indirect water is the embodied or virtual water use in the production of intermediate products (e.g., in the steel industry, the volume of freshwater that is used to produce the furnace equipment and transportation services). The sum of the direct and indirect water use equals the total water use (Chen, 2000). This division can help decision-makers to work out the efficiency difference between direct and indirect productions, which is important for water management decision-making. The minimum water input refers to the least water input that can be be used in producing the same economic output as the actual water input does.

RWUE includes three sub-concepts: overall efficiency (OE), pure technical efficiency (PTE), and scale efficiency (SE) (Lee, 2009). The OE is the ratio of the minimum water input on the efficient frontier to the actual water input under the same economic output. Therefore, the OE reflects the overall RWUE with constant returns to scale (CRS). Comparatively, when the returns to scale is variable, the measure of the OE becomes PTE. Thus, the PTE is a measure of how well water input is utilized compared to its maximum potential presented by the efficient frontier. An industry is considered as technically inefficient if it operates below the efficient frontier. The SE is related to the scale of the production. Scale inefficiency has two forms: decreasing returns to scale (DRS) and increasing returns to scale (IRS). DRS means that an industry is too large to take full advantage of its scale and has supra-optimum scale. In contrast, an industry experiencing IRS is too small for its scale to operations and, thus, operates at sub-optimum scale. An industry is scale efficient if it operates at CRS.

According to Lee (2009), the relationship of the three efficiencies is expressed as:

$$\textit{Overall efficiency} = \textit{Pure technical efficiency} \times \textit{Scale efficiency} \tag{1}$$

For simplification, it is presented as:

$$OE = PTE \times SE \tag{2}$$

In terms of modeling object, DEA models can be classified into the input-oriented model and output-oriented model (Lee, 2009). This study selected the input-oriented model since we focused on the input water use efficiency during production. Various forms of DEA models have been reported in the literature, such as the CCR (Charnes, Cooper, and Rhodes) model, the BCC (Banker, Charnes, and Cooper) model, the PK (Pareto–Koopmans) model, the FDH (free disposal Hull) model, and the cross efficiency model (Charnes *et al.*, 1985; Sexton *et al.*, 1986; Thrall, 1999). In this paper, we chose the CCR model to measure the OE and BCC model to recognize inefficient elements from technical and scale aspects (PTE, SE).

2.2. Evaluation index

The input and output indices (X, Y) of different industries (i.e., the primary, secondary, and tertiary industries) are determined based on the assessment indicators of the SAWR and data availability (Table 1) (Lai *et al.*, 2006; Sun & Liu, 2009).

In the SAWR, there are three water use efficiency assessment indicators for Beijing: the water use per 10,000 CNY gross domestic products (GDP), the water use per 10,000 CNY industrial values added, and the descent proportion of the fresh water use in agriculture (Beijing Government, 2012). Our indices cover the latter two indicators. It should be noted that the direct water coefficient refers to the volume of fresh water use for per product or service in direct RWUE evaluation, while the total water coefficient is the total volume of fresh water use for per product or service in total RWUE evaluation. The total

Table 1. The RWUE evaluation indices.

Industry	Input indices	Output indices
Primary industry	Proportion of fresh water use (%)	Agricultural output value per cubic meter of fresh water (CNY[a])
	Irrigation water per hectare (1,000 m^3/ha)	Primary industry output value per cubic meter of fresh water (CNY)
	Effective irrigation area ratio (%)	
Secondary industry and tertiary industry	Percentage of industry water use (%)	Direct income (CNY)
	Direct fresh water coefficient (m^3/10,000 CNY)	Total income (CNY)
	Total fresh water coefficient (m^3/10,000 CNY)	

[a] CNY is the standard currency symbol of the Chinese Yuan.

water coefficient equals to direct coefficient plus indirect coefficient. The direct wastewater discharge coefficient and total wastewater discharge are similar to them.

2.3. The CCR model

The CCR model is used to calculate the OE. It assumes that there are n DMUs to be evaluated, each DMU_j, ($j = 1, 2, \cdots, n$;) uses m inputs and generates s outputs, and the returns to scale is constant. When the object DMU_0 is under evaluation, the OE (θ_0) of the evaluated DMU_0 equals to (Charnes & Cooper 1963):

$$\begin{aligned} &\min\left\{\theta_0 - \varepsilon\left(\sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+\right)\right\} \\ &s.t. \sum_j \lambda_j x_{ij} + s_i^- - \theta_0 x_{i0} = 0,\ i = 1,\ \cdots, m \\ &\qquad \sum_j \lambda_j y_{rj} - s_r^+ - y_{r0} = 0,\ r = 1,\ \cdots, s \\ &\qquad \lambda_j,\ s_i^-,\ s_r^+ \geq 0,\ \forall r, i, j \end{aligned} \tag{3}$$

where (x_0,y_0) is the actual input and output of the evaluated DMU_0; (x_{ij}, y_{ij}) is the actual input and output of one DMU_j of all DMUs ($i = 1, \ldots, m$; $r = 1, .., s$; $j = 1, \ldots, n$); s_i^- and s_r^+ are slack variables of DMU_0 in which s_i^- is the i^{th} input redundancy and s_r^+ is the r^{th} output deficiency; λ_j is the scale return combination coefficient of water inputs of DMU_j. x, y, ε are known, θ, λ, S^+, S^- are unknown.

The first two constraints of Equation (3) are set to ensure that the inputs and outputs of each DMU are enveloped in the possible production set T which is defined as:

$$T = \{(X, Y)|X \geq \sum_j \lambda_j x_i,\ Y \leq \sum_j \lambda_j y_j,\ \lambda_j \geq 0\} \tag{4}$$

where the envelope surface of T is the efficient production frontier.

The optimal solution of Equation (3) is θ_0, λ_0, S_0^+ and S_0^-:

- when $\theta_0 = 1$ and $S_0^+ = S_0^- = 0$, DMU_0 is strongly efficient because both PTE and SE of DMU_0 are efficient and achieve the best production states;
- when $\theta_0 = 1$ and at least one of S_0^+ and S_0^- is greater than zero, DMU_0 is weakly efficient since PTE and SE of DMU_0 cannot be efficient at the same time;
- when $\theta_0 < 1$, DMU_0 is inefficient, and neither PTE nor SE is efficient.

When DMU_0 is inefficient, the projection approach could help to decrease inputs without outputs reduction in the input-oriented model, or increase outputs without inputs addition in the output-oriented model by the following equation:

$$\begin{aligned} \hat{X}_0 &= \theta_0 X_0 - S_0^- \\ \hat{Y}_0 &= Y_0 + S_0^+ \end{aligned} \tag{5}$$

where $(\hat{X}_0, \hat{Y}_0)$ is the efficient input and output in terms of the actual input and output (X_0, Y_0) projected to the efficient production frontier. Therefore, input savings (ΔX_0) and output additions (ΔY_0) of (X_0, Y_0) can be estimated as:

$$\begin{aligned} \Delta X_0 &= X_0 - \hat{X}_0 = (1 - \theta_0)X_0 + S_0^- \geq 0 \\ \Delta Y_0 &= \hat{Y}_0 - Y_0 = S_0^+ \geq 0 \end{aligned} \tag{6}$$

2.4. The BCC model

The PTE is estimated based on the BCC model which provides the variable returns to scale by adding the convexity constraint to λ_j, $\sum_{\mathrm{j}} \lambda_j = 1$ (Banker, 1984):

$$\begin{aligned} &\min \{\sigma - \varepsilon(\hat{e}^T S_{\mathrm{i}}^- + e^T S_r^+)\} \\ &s.t. \sum_{j=1}^{n} \lambda_j x_{ij} + s_i^- - \sigma x_{i_0} = 0 \\ &\sum_{j=1}^{n} \lambda_j y_{rj} + s_r^+ - y_{r_0} = 0 \\ &\sum_{j=1}^{n} \lambda_j = 1 \\ &\lambda_j, s_i^-, s_r^+ \geq 0, \forall r, i, j \end{aligned} \tag{7}$$

where σ is PTE of DMU_0; $\hat{e}^T = (1, 1, \cdots, 1) \in E_m$, and $e^T = (1, 1 \cdots, 1) \in E_s$. The optimal solution of this model is σ_0, λ_0, S_0^+, S_0^-, whose implications can be deduced from the CCR model by analogy in Section 2.1.

The SE (s_0) can be obtained from Equations (1) or (2):

$$s_0 = \frac{\theta_0}{\sigma_0} \tag{8}$$

- when $s_0 = 1$, DMU_0 is in the best scale condition which means the ratio of water input to output value is appropriate;
- when $s_0 \neq 1$, the water input or output of DMU_0 requires adjustments with reference to $\sum \lambda_j$ of the CCR model.

$$\begin{cases} \sum_{j=1}^{n} \lambda_j = 1 \Leftrightarrow \text{ Constant returns to scale} \\ \sum_{j=1}^{n} \lambda_j < 1 \Leftrightarrow \text{ Increasing returns to scale} \\ \sum_{j=1}^{n} \lambda_j > 1 \Leftrightarrow \text{ Decreasing returns to scale} \end{cases} \tag{9}$$

Whether the returns to scale is constant, increasing, or decreasing depends on whether $\sum_{j=1}^{n} \lambda_j^0$ is equal, less than, or greater than 1. The constant returns to scale means input and output change in the same proportion; the increasing returns to scale means the output changes faster than the input; and decreasing returns to scale means the output changes more slowly than the input.

3. Result analysis

This paper applied the industry RWUE evolution scheme to the RWUE evaluation of 25 representative industries of Beijing from 1990 to 2010. In this section, data description and industry background of Beijing are first introduced, and the detailed result analyses of the primary, secondary, and tertiary industries are expanded, individually.

3.1. Data description

Since 1949, two major economic regulations have been implemented in China. The first is the socialist transformation that occurred in the 1950s, and the second is the market-oriented reform between the 1980s and the 1990s (Liu & Li, 2002). In order to investigate the 'natural' correspondence between economic development and water use efficiency change, such human intervention periods were avoided so that the evaluation period of this research was chosen as 1990–2010. Moreover, all economy and water use data are cited from the Beijing Statistical Yearbook (Beijing Statistical Information Net, 2010) and Beijing Water Resources Bulletin (Beijing Water Authority, 2010). The 25 representative industries were extracted from the 44 major industries of China based

Table 2. The number and industry names of 25 representative industries of Beijing.

Industry classification	No.	Industry name
Primary industry	1	Agriculture/forestry/animal husbandry/side-line production/fishing
	2	Coal mining and dressing industry
	3	Metal mining and dressing industry
	4	Food manufacturing
	5	Textile industry
	6	Leather, fur, feathers and their products and footwear industry
	7	Wood processing and wood, bamboo, rattan, brown, grass products industry
	8	Paper and paper products industry
	9	Chemical materials and chemical products manufacturing industry
	10	Non-metallic mineral products industry
	11	Metal smelting and rolling processing industry
	12	Fabricated metal products
	13	General equipment manufacturing
Secondary industry	14	Transportation equipment Manufacturing
	15	Electrical machinery and equipment manufacturing
	16	Electronic equipment manufacturing
	17	Instrument manufacturing
	18	Electricity, heat production and supply industry
Tertiary industry	19	Transportation, warehousing and postal services industry
	20	Information transmission, software and IT services industry
	21	Wholesale and retail industry
	22	Accommodation and catering industry
	23	Financial industry
	24	Real estate industry
	25	Leasing and business services

on the latest National Industry Classification standards as well as the data availability after the years' industrial classification changes (National Bureau of Statistics of China, 2011) (Table 2). The price impact can be neglected in the RWUE evaluation scheme because it compares the relative efficiencies of different industries at the same time.

3.2. Industry background of Beijing

3.2.1. Industrial structure. Figure 1 describes the industrial structure changes of Beijing in 1990–2010. Generally, the added values' proportions of the primary and secondary industries decline, while the proportion of the tertiary industry keeps rising. This tendency is consistent with the theory of industrial structure upgrading, which refers to that when the economy development reaches a certain level, the secondary industry would be replaced by the tertiary industry as the dominant industry. It also shows that the industrial structure of Beijing had been progressing in a positive tendency (Liu & Li, 2002).

At the same time, different industries went through different internal structure changes. For the primary industry, the proportion of farming reduced with the fishing and animal husbandry expansion, and grain crops declined while economic crops emerged. For the secondary industry, its internal structure change is elaborated in Figure 2. In the 1990s, the major secondary industries were light industry and low-tech heavy industry such as the 4th food manufacturing, the 6th paper industry, and the 9th chemical industry. Then with the industrial structure upgrading after 2000, infrastructure industry and high-tech industry grew

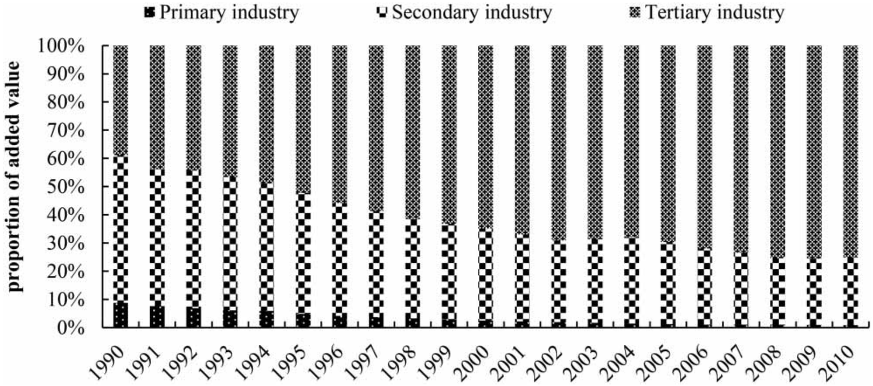

Fig. 1. The industrial structure of Beijing in 1990–2010.

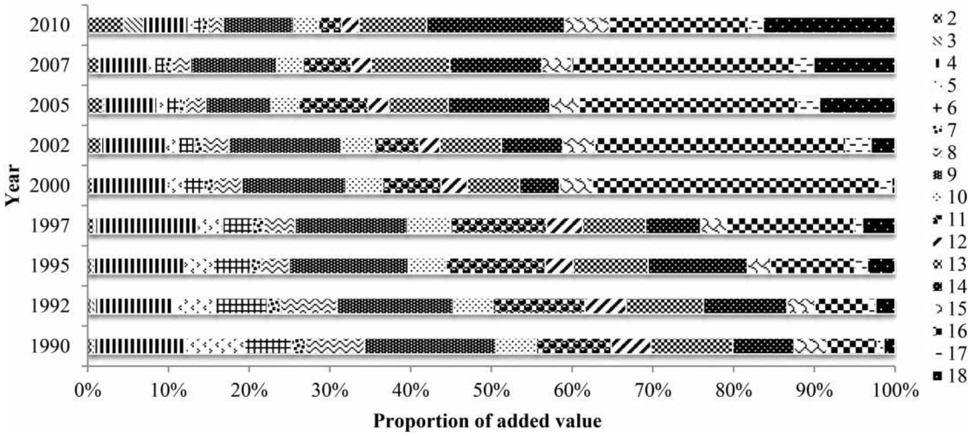

Fig. 2. The representative secondary industrial structure of Beijing in 1990–2010.

quickly. For instance, the output proportions of the 14th transportation industry and the 18th electricity and heat production and supply industry increased, and the 16th electronic equipment manufacturing became the dominant industry with the maximum added value proportion.

Limited to data continuity, the internal structure change of the tertiary industry was only analyzed for the period of 2000–2010. In Figure 3, the added value proportions of traditional service industries, including the 19th transportation, warehousing and postal services, the 21st wholesale and retail industry, and the 22nd accommodation and catering industry, first decreased and then remained at 30% in total. In contrast, the emerging service industries, such as the 20th information and IT services, the 23rd financial industry, the 24th real estate industry, and the 25th business service, extended to an enormous scale in total, accounting for 70% by 2010. In the future, the industrial structure of Beijing is expected to be: to cultivate modern service industry and high-tech industry which will become dominant industries; modern manufacturing industry and infrastructure service industry will be highlighted; and urban industry and modern agriculture will be regarded as supplements (Beijing Municipal Commission of Development and Reform, 2007).

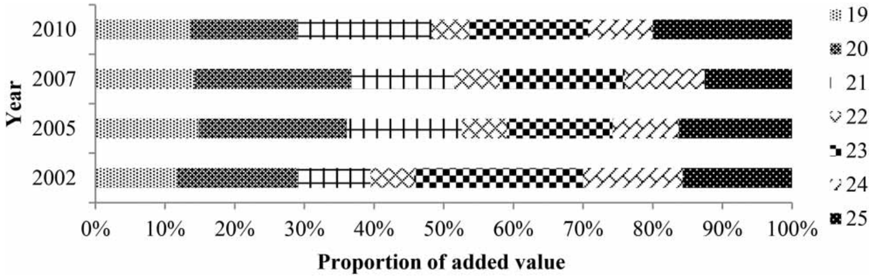

Fig. 3. The representative tertiary industrial structure of Beijing in 2002–2010.

3.2.2. Water use. Figure 4 shows that Beijing's water use experienced an increasing-decreasing-stabilized change tendency. The total water use fell below 40 million m^3 after 1996 and remained stable at 35 million m^3 after 2002. Specifically, the agricultural and industrial water use decreased significantly, while the domestic and environmental water use rose. This reveals that the water use structure modification benefited from the industrial structure modification (Jia *et al*., 2004).

3.3. RWUE in primary industry

As illustrated in Table 2, the primary industry is represented by one comprehensive industry, agriculture/forestry/animal husbandry/side-line production/fishing. Figure 5 shows that this representative industry's OE kept increasing and reached a strongly efficient position in 2010 (OE = PTE = SE = 1.0). Meanwhile, the PTE and the SE also reached the optimum by 2010. It is notable that Beijing's primary industry PTE always stayed at a very high level with a mean value of 0.85. Such good performances actually benefited from the clear agricultural zoning of the modern agriculture strategy and the 'high-end' industry development policy (Wang & Wang, 2009). Moreover, the rapid growth of the SE should not be overlooked. The reason behind it is that, in 1990–2009, the returns to scale of Beijing's primary industry kept decreasing ($\sum \lambda_j < 1$) due to agricultural scale reduction.

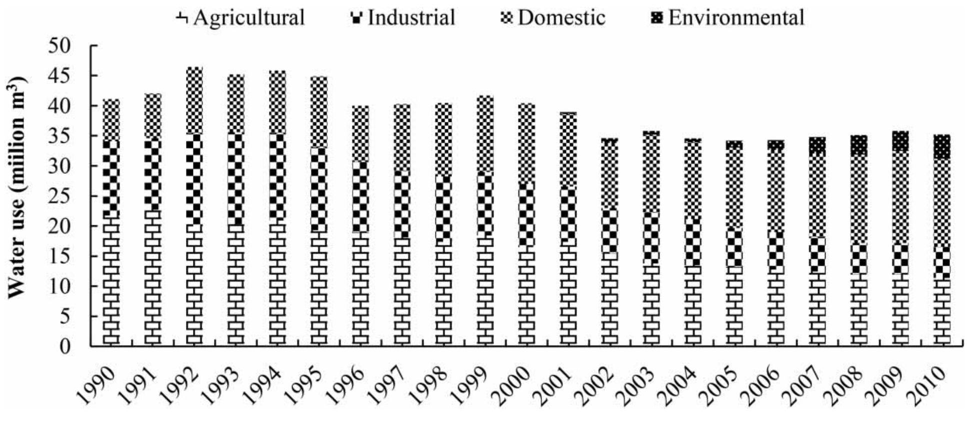

Fig. 4. The water use structure of Beijing in 1990–2010.

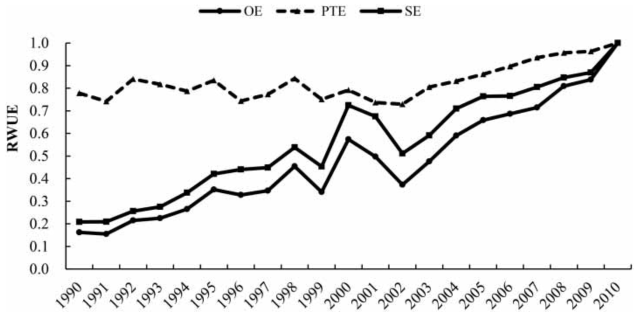

Fig. 5. The RWUE of the primary industry in 1990–2010.

3.4. RWUE in secondary industry

3.4.1. OE analysis. Figures 6 and 7 respectively summarize the direct and total OE of the secondary industry in 1990, 1992, 2000, 2005, and 2010. Generally speaking, except the 13th industry, all representative industries receive significant OE increases (direct and total). However, by 2010, only two industries reached direct OE efficiency (direct OE = 1), and six industries reached total OE efficiency (total OE = 1).

Furthermore, a detailed comparison between direct OE and total OE was conducted for the year 2010 (Table 3). It can help decision-makers to work out which water using section (i.e., direct or indirect) should be paid more attention in efficiency improvement. The comparison results were classified into three types as follows:

- Type I: the direct OE is better than the total OE. There are 11 industries in Type I, accounting for 64.71% of the secondary industries, characterized by low efficiencies. The 4th, 5th, 6th, and 8th industries are priority industries of the light industry; the 9th, 10th, 11th, 12th, 13th, 14th and 18th industries belong to traditional heavy industry. Their direct production utilized water more efficiently

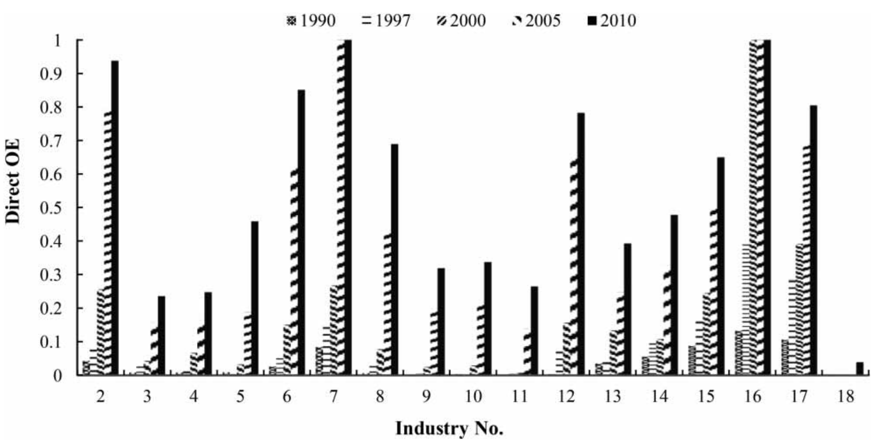

Fig. 6. Direct OE of the secondary industry in 1990, 1997, 2000, 2005, and 2010.

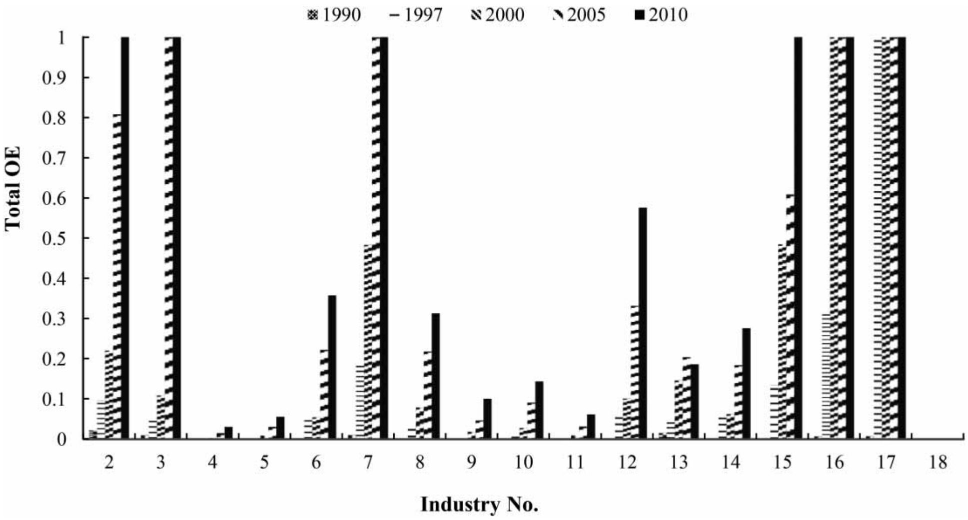

Fig. 7. Total OE of the secondary industry in 1990, 1997, 2000, 2005, and 2010.

Table 3. Comparison between direct OE and total OE in 2010.

Type	Percentage	No.	Industry name	Direct OE	Total OE
I. Direct OE is higher than total OE	64.71	4	Food manufacturing	0.25	0.03
		5	Textile industry	0.46	0.06
		6	Leather, fur, feathers and their products and footwear industry	0.85	0.36
		8	Paper and paper products industry	0.69	0.31
		9	Chemical materials and chemical products manufacturing industry	0.32	0.10
		10	Non-metallic mineral products industry	0.34	0.14
		11	Metal smelting and rolling processing industry	0.26	0.06
		12	Fabricated metal products	0.78	0.58
		13	General equipment manufacturing	0.39	0.19
		14	Transportation equipment manufacturing	0.48	0.28
		18	Electricity, heat production and supply industry	0.04	0.00
II. Direct OE is lower than total OE	23.53	2	Coal mining and dressing industry	0.94	1.00
		3	Ferrous metal mining and dressing industry	0.24	1.00
		15	Electrical machinery and equipment manufacturing	0.65	1.00
		17	Instrument manufacturing	0.80	1.00
III. Direct OE is identical with total OE	11.76	7	Wood processing and wood, bamboo, rattan, brown, grass products industry	1.00	1.00
		16	Electronic equipment manufacturing	1.00	1.00

than the indirect processes so that the priority attention should be paid to the indirect production in the future (Wang, 2006). However, the direct efficiency improvement cannot be ignored since their direct OEs were relatively low compared with other industries of Type II and III.

- Type II: the direct OE is worse than the total OE. There are four industries in Type II accounting for 23.53% of the secondary industries utilizing input water more efficiently than those of Type I. Although they are water-intensive industries, they occupied the least GDP market share of Beijing. Moreover, Beijing only participated in the technology-intensive links rather than labor-intensive links such as transportation and technical deep processing so that they achieved relatively high efficiency (Xu *et al*., 2005). Further, future efforts should be paid to the direct water use production section, if it exists, to improve the OE.
- Type III: the direct OE and the total OE are ideal. The direct OE and the total OE of the 7th and 16th industries reached efficiency. The 7th wood industry accounted for no more than 1% of GDP of Beijing in 2010, while the 16th electronic industry developed rapidly with GDP proportion increase from 5% in 1994 to 15% in 2010. Moreover, the electronic industry usually uses a small amount of water in a super-efficient and high-tech way, so its OE had been efficient since 2000 compared with other secondary industries.

3.4.2. PTE and SE analysis. Figures 8 and 9 summarize the direct and total PTE and SE of the representative secondary industries in 1990, 2000, and 2010. From both direct and total perspectives, all

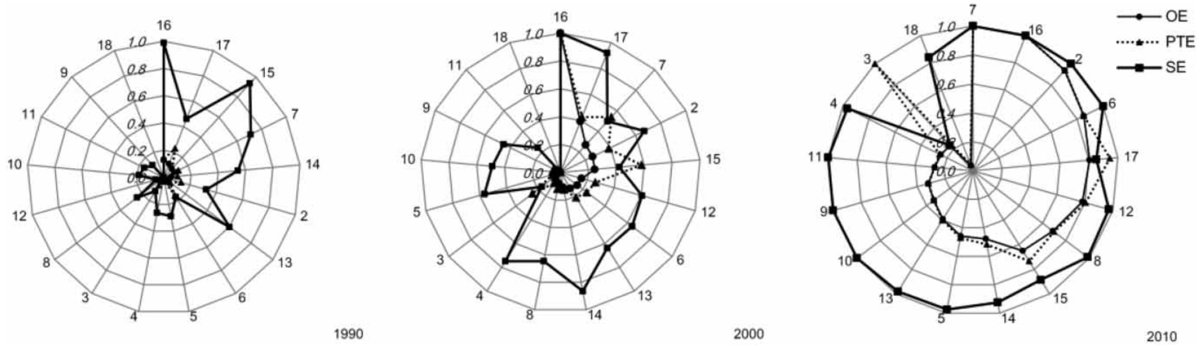

Fig. 8. Direct PTE and SE in 1990, 2000, and 2010. *Note:* The peripheral number is industry number. 0–1 is the relative efficiency value ranges in bold. OE is drawn in an ascendant order.

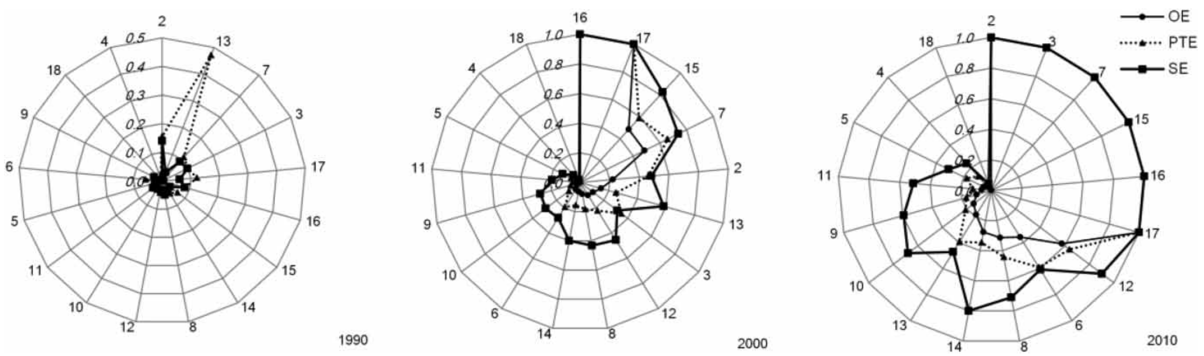

Fig. 9. Total PTE and SE in 1990, 2000, and 2010.

industries' PTE and SE received increases with time. In particular, most industries got higher SE than PTE. Therefore, the overall inefficiency in these industries is primarily attributed to the technical inefficiency rather the scale inefficiency. This confirms the problem that the secondary industry of Beijing is 'big' but not 'strong', which was concluded by Zou & Ouyang (2008) as well.

From the output scale perspective, incoming was already satisfactory for most industries in 2010, especially in direct production. It means that the economic scale of these industries had been maximized through the vigorous economic development in the last two decades. However, managers have to divert attention to the technical development in order to improve water productivity. This is also forced by the water supply capacity and industrial scale limit of Beijing. Although it was previously proved that Beijing has achieved encouraging progress in water-saving through technical innovation (Yang *et al.*, 2015), there is still much room for improvement in efficiency for more than half of the secondary industries under the existing production scale (Figures 8 and 9).

In order to find out the specialized water input adjustment strategies for different industries, the total OE of inefficient DMUs of the secondary industries in 2010 was projected (as shown in Table 4). For inefficient industries, the water use percentage and total fresh water coefficient were excessive and could be reduced with the proportion of θ^0. The decreasing return to scale means that, with water input decrease and water use coefficient decrease, the economic output decrease proportion was less than the input decrease so that reducing water input and water use coefficient will lead to economic output efficiency reduction, but the water-saving cost is considerable and worthwhile.

3.5. RWUE in tertiary industry

For the tertiary industries, it is difficult to conduct a continuous efficiency analysis during a long time period. This is because of the significant changes in the industry classification according to the National Industry Classification. Therefore, we herein computed the direct OEs and indirect OEs in two years, 1990 and 2010 (Figures 10 and 11).

According to Figures 10 and 11, from 1990 to 2010, the OE efficient industry (i.e., finance and insurance industry) was replaced by the 20th information and IT industry and the 21st wholesale and retailing

Table 4. The input redundancy and scale returns of the secondary industry of 2010.

No.	Industry name	s_1^-	s_2^-	Scale returns
4	Food manufacturing	6.15	239.73	Decreasing
5	Textile industry	2.52	187.27	Decreasing
6	Leather, fur, feathers and their products and footwear industry	0.54	75.27	Decreasing
8	Paper and paper products industry	1.71	51.52	Decreasing
9	Chemical materials and chemical products manufacturing industry	10.63	78.86	Decreasing
10	Non-metallic mineral products industry	4.44	78.25	Decreasing
11	Metal smelting and rolling processing industry	8.23	137.74	Decreasing
12	Fabricated metal products	0.60	48.48	Decreasing
13	General equipment manufacturing	3.04	45.54	Decreasing
14	Transportation equipment manufacturing	2.97	53.76	Decreasing
18	Electricity, heat production and supply industry	10.88	2.56	Decreasing

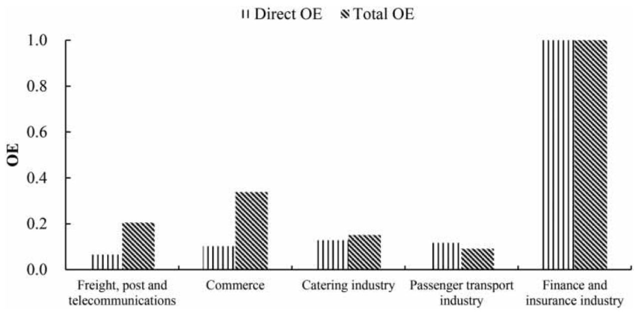

Fig. 10. The tertiary industry's OEs of 1990.

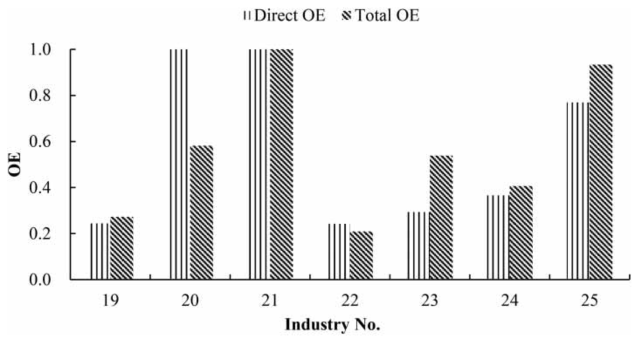

Fig. 11. The tertiary industry's OEs of 2010.

industry. It means that, with market requirement changes, emerging high-tech information services and modern commerce services gradually surpassed traditional industry to be the most efficient water users. However, huge efficiency gaps existed among different industries in the same year. Specifically, in 2010, the water use efficiency of traditional tertiary industry (transportation and catering) and some emerging industry (real estate) had the lowest efficiencies among representative tertiary industries, and the previously leading efficient industry (financial industry) fell behind the 20th and 21st industries in 2010. There are three main reasons for that. The first reason is that some basic service sectors are monopolized by the country-owned enterprises of China, such as transportation and financial industry. This places these sectors under the uncompetitive operation mechanism, causing water use inefficiency. Second, for small-scale industry (e.g., accommodation and catering industry), the industry admittance standard is low and operation supervision is not easily carried out, so water use efficiency cannot be guaranteed. The third reason is related to the incomplete industry admittance and supervision regulations.

The projection results for the inefficient DMUs in 2010 are shown in Tables 5 and 6. For direct production, the water use of the financial industry and business services should be reduced (Table 5). For indirect production, in spite of the wholesale industry, all tertiary industries have room for great efficiency improvement (Table 6).

Table 5. The input redundancy and scale returns of the tertiary industry of 2010 (direct OE).

No.	Industry name	θ^0	Rank	s_1^-	s_2^-	Scale returns
19	Transportation, warehousing and postal services industry	0.06	6	0	0	Decreasing
20	Information transmission, software and IT services industry	1.00	1	0	0	Constant
21	Wholesale and retail industries	1.00	1	0	0	Constant
22	Accommodation and catering industry	0.06	7	0	0	Decreasing
23	Financial industry	0.09	5	0.76	0	Decreasing
24	Real estate industry	0.13	4	0	0	Decreasing
25	Leasing and business services	0.59	3	2.53	0	Decreasing

Table 6. The input redundancy and scale returns of the tertiary industry of 2010 (total OE).

No.	Industry name	θ^0	Rank	s_1^-	s_2^-	Scale returns
19	Transportation, warehousing and postal services industry	0.07	6	0.86	0	Decreasing
20	Information transmission, software and IT services industry	0.34	3	1.70	0	Constant
21	Wholesale and retail industries	1.00	1	0	0	Constant
22	Accommodation and catering industry	0.04	7	0.60	0	Decreasing
23	Financial industry	0.29	4	8.52	0	Decreasing
24	Real estate industry	0.17	5	2.17	0	Decreasing
25	Leasing and business services	0.87	2	10.28	0	Decreasing

4. Implications for water resources management

The above RWUE analysis proves that all the industries of Beijing achieved significant water use efficiency improvements from 1990 to 2010, but there are some deep-seated efficiency problems within inefficient industries. In order to effectively implement the SAWR as well as continuously support economic development, we proposed explicit efficiency improvement directions for different water-using industries, separately, as follows.

For the primary industry, highlighting virtual water importing and upgrading agricultural production can help to increase water conductivity. By 2007, the volume of the imported virtual water of Beijing was 237 million m^3, accounting for 5.93% of the total fresh water use of Beijing. In consideration of this situation, virtual water trade serves as a key factor to improve efficiency by importing low-efficiency crops and developing high-efficiency agriculture (Wang *et al.*, 2007). Moreover, promoting ecologic and tourism agriculture and broadening the foreign market with featured agricultural products can accelerate agricultural economic growth as well as increase the water use efficiency.

For the secondary industry, PTE should be given the priority in improving efficiency, and SE can be modified by taking into account the industrial structure regulations. Driven by the GDP-oriented development mode, some managers did not pay enough attention to technical innovation. However, based on our findings, more effort should be spent on technical aspects in both direct and indirect productions, for example, upgrading existing water-saving equipment and making use of unconventional water resources (i.e., recycled water, desalinated seawater, and rainwater). As for the scale modification, it is beneficial to encourage electronics, biomedicine, new energy, environmental protection industry and high-tech industry, and to eliminate the water-intense and low value-added industry, fostering certain famous brands instead of enlarging industry scales.

For the tertiary industry, the efficiency gaps among different industries can be made up by strengthening efficiency regulations and taking advantage of the market competition mechanism. Although the modern service industry has gradually become the dominant industry of Beijing, the water use efficiencies of some modern service industries were still inefficient, e.g., real estate industry and financial industry. It is necessary to tighten the industrial admittance criteria and strengthen operation supervision on water use efficiency for the traditionally scattered industry and some rapid-developing industries. Additionally, it is also important to employ the market competition mechanism to attract external high-efficiency projects, processes, and products, breaking the existing industrial monopoly.

5. Conclusions and limits

In order to solve the differentiated water use efficiency management problems among economic industries, this paper proposed an industry RWUE evaluation scheme based on the DEA theory. This industrial RWUE evaluation scheme has two advantages for decision-making in water resources management, especially in implementing the SAWR. First, it can qualitatively specify an efficiency improvement emphasis among direct and indirect production processes from the technical and scale perspectives. Second, for each inefficient water-using industry, the industrial RWUE evaluation scheme can provide a quantitative input and output slack to enforce target assessment and fulfillment. As to the SAWR, two of its three water use efficiency assessment indicators were included in the input indices of the scheme. This can greatly facilitate policy implementation based on the industrial water efficiency assessment using the RWUE evaluation scheme.

Applying the RWUE evaluation scheme, this research evaluated the RWUEs of 25 representative industries of Beijing during 1990–2010. The main conclusions that can be drawn are as follows. (1) The RWUEs of all industries were markedly increased. (2) For primary industry, the future efficiency improvement can rely on importing virtual water and developing modern agriculture. (3) For secondary industry, the industrial production process (direct or indirect) plays an important role in water use efficiency. The future efficiency improvement emphases of secondary industry are technology innovation and scale modification under industrial structure regulations. (4) As for tertiary industry, some emerging industries replaced the traditional industries as the most efficient water users, but efficiency gaps existed among the industries. Attention should be paid by managers to legislation and supervision implementation, and market competition utilization in the future.

Regretfully, there are two limitations existing in this study. The first one is that it lacks the ability to add the absolute water use efficiency into the evaluation scheme. This is due to the restriction of the DEA method, in which the DEA can only calculate the relative efficiency. Moreover, the RWUE evaluation scheme is not robust enough to support the implementation of China's SAWR. This is because the scheme does not consider one indicator in the SAWR (i.e., the water use per 10,000 CNY GDP). In the future, further attempts should be made to deal with these limitations.

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