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Decomposition of industrial water use from 2003 to 2012 in Tianjin, China

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ABSTRACT

This study analyzed the contributions of output, technological, and structural factors to industrial water use. Using Tianjin, a National Water-Saving City in China, as a case study, we adopted the refined Laspeyres and Logarithmic Mean Divisia Index models to decompose the driving forces of industrial water use changes. The decomposition results of both models show that output and technology have long-term, stable effects on industrial water use in Tianjin. Output stimulates water use, leading to an average annual growth of 7700×10^4 m^3, while technology inhibits water use, with an average annual reduction of 7900×10^4 m^3. However, the effects of structure on industrial water use are not stable. During the study period, the stimulation and inhibition of industrial water use alternated; however, stimulation was dominant after 2008, implying increased partiality of the industrial structure toward high water use. The results of the study contrasted the hypothesis that Tianjin's primary goal in restructuring local industries over the past decade has been the achievement of water use efficiency. Reduced water use may have resulted from Tianjin's development with targets other than water-savings.

1. Introduction

China has been known to have scarce water resources, and this is particularly true for Tianjin (He et al., 2014). In mainland China, Tianjin has the lowest per capita water resources at 182 m^3/a, only 1/15 of the national average and significantly lower than the internationally recognized poverty line of 500 m^3/a. Up to 76% of surface water has been utilized in the region, which is much greater than the 40% global threshold. Severe water scarcity and shortages in Tianjin have hindered socioeconomic development and further strained the ecological environment (Shang et al., 2015). To ease its increasingly prominent water crisis, Tianjin has pioneered "*the most stringent water management system*" (Shang et al., 2016b) in China, which sets out water use efficiency targets and has achieved remarkable results. In 2013, water use per 10,000 yuan of gross domestic product (GDP) was reduced to 17.52 m^3 (<1/6 of the national average), and water use per 10,000 yuan of industrial added value was reduced to 8.3 m^3, the greatest water use efficiency in the country. The Tianjin government believes that it has overcome the effects of water constraints on socioeconomic development by adjusting its industrial structure with water savings in mind. In light of this, we conducted an attribution analysis of industrial water use in Tianjin and believe that the findings will help alleviate water crises in northern regions and even achieve the synergetic and efficient use of water and energy resources.

Existing literature on industrial water use has mainly focused on industrial water availability or assessed the negative ecological impacts of industrial water use. For example, Flörke et al. (2013) simulated changes in global industrial water use from 1950 to 2010 using the Water Global Assessment and Prognosis model and predicted a continued increase in industrial water use. However, to provide an incremental water supply, water conservancy projects, entailing storage, diversion, pumping, and transfer, generally require huge investments (Wang et al., 2015), which can be challenging for developing countries characterized by poverty. Countries experiencing droughts face the most serious water resource shortages (Wang et al., 2012). To protect the water security of these countries, control over the scale of water-intensive industries should be combined with efforts for the effective improvement of water conservation and water use efficiency (Alnouri et al., 2014; Hidemichi et al., 2012). To this end, Pham et al. (2016) conducted a water mass balance analysis of an industrial park in Vietnam and concluded that the current water management system did not have a sufficient basis in industrial water conservation. Thus, they recommended "reducing sewage discharge" and "improving water reuse" to address the high industrial water use. Futher, Agana et al. (2013) held that the effective integrated management of water use processes in urban industrial sectors could reduce sewage and help meet water use efficiency targets. Boix et al. (2012) also established a water supply network

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optimization model for industrial parks using the mixed-integer linear programming approach. By enabling the unified distribution of freshwater and recycled water, the model considerably increased the reuse of water resources. Lévová and Hauschild (2011) evaluated the water use life cycle of the biotech industry. Taking the carrying capacity of water resources as a constraint, this study proposed a suitable development scale for the biotech industry. With increasing industrial water use, wastewater can substantially increase (Kirkpatrick et al., 2011), and its discharge to rivers without treatment can cause serious water pollution (Englert et al., 2013). Given that in-depth sewage treatment requires considerable amounts of money and energy (Kajenthira et al., 2012), industrial sewage in developing countries is often directly discharged into rivers without treatment (Yi et al., 2011), which further exacerbates water shortages. The aforementioned studies considered water as a factor in industrial production and conducted quantitative analyses of the industrial development scale and industrial wastewater discharge using input–output or similar models. Accordingly, they offer policy recommendations for water reuse and sewage reduction to achieve sustainable water use and healthy industrial development.

The industrial structure of a city is by no means static; rather, it constantly changes (Bao and Fang, 2012). The industrial structure can include new industries, some that are new, traditional but renovated industries, and those targeted for elimination. Industrial development and structural adjustment are subject to multiple factors and drivers, and those processes can affect industrial water use (Geng et al., 2012). Researchers have gradually realized that identifying the key factors influencing industrial development and catering national macro-control policy to local conditions and circumstances are fundamental to healthy industrial development and water security (Yoo et al., 2007). In the late 20th century, the Kuznets curve was introduced for describing the relationship between economic growth and income inequity. According to this theory, in the early stages of economic development, income inequality increases with economic growth but is then expected to decrease towards equity once a certain level of average income is reached (Tate, 1986). The Kuznets curve has been widely used in many fields, including environmental protection and resource development (Foster, 2015; Muhammad et al., 2012; Saboori et al., 2012). In 1997, Merrett (1997) extended the theory to the field of water resources and found that, with continuous socioeconomic development, the demand for water grows, then exhibits zero growth and finally, declines. These three phases are also seen with industrial water demand in most developed countries. Many factors contribute to this decline, such as, optimized industrial structure, high water use efficiency, and a sound water system and economic instruments et al. Reynaud (2003) explored the impacts of different factors on incremental industrial water use by empirically analyzing factories. The results revealed that the water price, as well as government policies, significantly affected factories' water use. Renzetti (2005) studied the relationship between industrial water use and economic development and suggested the use of economic instruments within a legal framework to promote industrial water conservation. However, these studies were limited to the qualitative description of laws governing water use and a rough exploration of influencing factors. Quantitative analyses of the contribution of different factors to incremental water use are sparse.

With decomposition methods widely used in the energy field, in this study, we aimed to analyze quantitatively the factors affecting and contributing to industrial water use. Specifically, we adopt the Laspeyres and Logarithmic Mean Divisia Index (LMDI) models (Ang et al., 2015). Designed by German scientist E. Laspeyres in 1864, the Laspeyres model is easy to understand and has been widely used in various economics and societal fields (Armknecht and Mick, 2014; Blundell, 2012; Whyte et al., 2013; Zhang and Da, 2015). However, the model cannot fully decompose all factors, and the residual of the decomposition results increases with the number of factors. When a factor significantly changes in the short term, the residual error can be significantly large, and if ignored, can undermine the model's accuracy (Ang, 2004). In 1998, Sun (1998) optimized the Laspeyres model according to the “jointly produced and averagely shared” principle. In the refined Laspeyres model, the produced residual errors are equally assigned to the derivatives of their sources items. In 2004, Ang (Ang and Zhang, 2000) summarized the advantages and disadvantages of existing decomposition models and concluded that the LMDI model is superior to traditional models owing to its complete decomposition of factors through the construction of a log-mean formula. Thus, this study applies the refined Laspeyres and LMDI models to the quantitative assessment of factors influencing industrial water use through a case study of Tianjin, a National Water-Saving City in China. The results are expected to provide a theoretical basis and data supporting the creation of more National Water-Saving Cities.

2. Industrial development and restructuring in Tianjin

Tianjin is one of the birthplaces of modern Chinese industry and had become the country's second largest industrial city by the 1930s or 40s. After the founding of the modern People's Republic of China (1949), industry developed rapidly in Tianjin owing to a solid industrial base and strong state support. With the emergence of the metallurgical, chemical, machinery, and electronics industries, the pace of traditional textile industry growth slowed down, while heavy industries rapidly became more prominent. Tianjin has gradually become an important integrated industrial base in China, and its location is shown in Fig. 1.

Since the reform and opening up (1978), Tianjin, together with other cities, has experienced the rapid growth of an industrial economy. From 1994 to 2002, Tianjin's industrial output substantially increased through the introduction of foreign investment in the merging, renovation, and adjustment of 748 state-owned enterprises. An industrial pattern has been established, underpinned by the information technology, automobile, metallurgy, chemical, medicine, and new energy industries. This has been exemplified by the creation and rapid development of the sub-provincial district of the Binhai New Area (TBNA) in Tianjin. Industrial clusters and chains have scaled up, and a new comprehensive industrial base has taken shape. In 2003, Tianjin launched a new round of industrial reforms to improve the capacity and competitiveness of enterprises. Those reforms focused on fostering numerous profitable tech-rich projects that reflect global advancement levels and present-day industrial development trends to deepen industrial restructuring. Unlike the previously mechanized enterprise-situ adjustments, this round of reforms involved the adjustment of industries as a whole or business groups within certain sectors; however, in line with Haihe development strategy, a strategic eastward transfer is still needed to further accelerate the pace of TBNA development and boost industrial clusters.

The reforms have led to a dramatic increase in Tianjin's industrial output since 1994. More specifically, the industrial output nearly doubled from 175.4 billion yuan in 1994 to 371.8 billion yuan in 2002, and reached 2.4194 trillion yuan in 2012 through the second round of reforms, quadrupling its 2002 level. The registered annual growth rates of industrial output were 9.9% and 21.4% during the two sequential rounds of reforms. Clearly, industrial development has picked up since 2003. The share of Tianjin's industrial output in its GDP also rapidly increased from 45% to 51% from 2002 to 2008, but slightly declined in 2008 owing to the global economic crisis. The change in the share of Tianjin's industrial output in GDP from 1994 to 2012 is shown in Fig. 2.

Tianjin's industrial structure has changed tremendously through the two rounds of reform, which resulted from the declining output proportion of the traditionally advantageous light industries and the increasing proportion of output of heavy industries. In particular, the output proportion of heavy industries grew from 56.7% in 1994 to 81.3% in 2006 and remained high thereafter. Industrial capital was also transferred with the relocation of industrial enterprises from central areas to the outlying Dongli District and TBNA, giving rise to a TBNA-based industrial layout complemented by the Dongli District (and similar areas). Fig. 3 shows the transfer of industrial output in Tianjin over the past decade.

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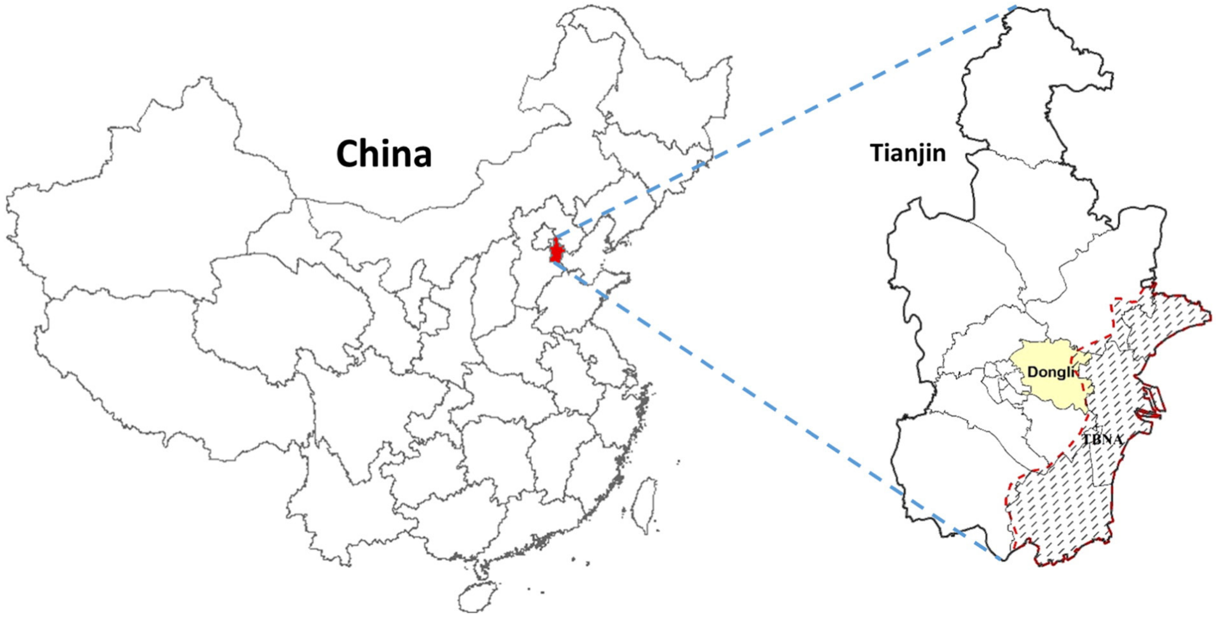

Fig. 1. The location of Tianjin in China.

Along with these changes in the output proportions of light and heavy industries, the industrial structure was significantly optimized. The growth of traditional textile, chemical, and agricultural industries slowed down, while the information technology, metallurgy, and automobile industries rapidly developed and emerging industries, including new energy, made progress. From 2003 to 2012, the output proportion of the textile industry fell by 80% and the chemicals and chemical products manufacturing sector by 35%, while that of the ferrous metal smelting and rolling processing industry rose by 33%.

Tianjin began with a textile industry, and after nearly 100 years of reform and development, has recently fostered six industrial pillars, namely aerospace, petrochemicals, equipment manufacturing, electronic information, biological medicine, new energy and new materials, and national defense (Statistical Bureau of Tianjin, 2013). Industrial clusters centered in TBNA have also gradually grown. However, the contrast between water shortages and rapidly growing industrial water demand due to the rapid expansion of the industrial scale has become increasingly prominent, and it has been difficult to meet this demand with Tianjin's water supply. In 2013, water use totaled 2.52 billion m^3 in Tianjin, of which 540 million m^3 or 21.3% served industrial purposes. In general, 47% of external water and 25% of deep groundwater is used for industrial production. Moreover, in recent years, the serious over-exploitation of groundwater has resulted in a series of ecological consequences, including land subsidence and seawater intrusion. Thus, the Chinese government is

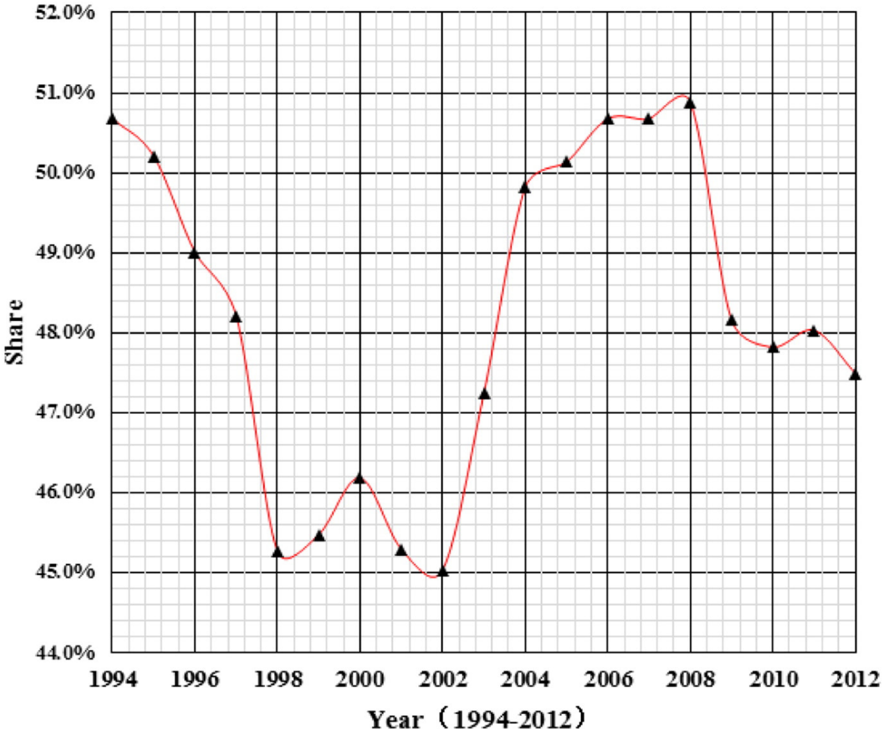

Fig. 2. Change in the share of Tianjin's industrial output in GDP (1994–2012).

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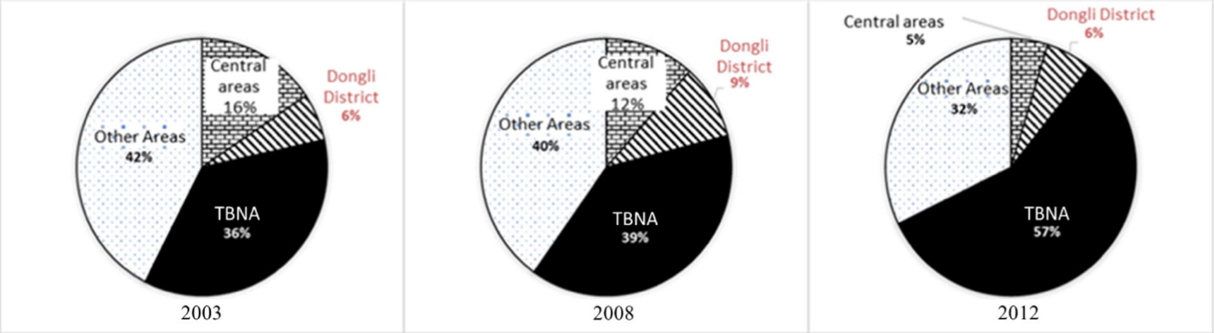

Fig. 3. Transfer of industrial output in Tianjin.

gradually restricting groundwater exploitation. Additionally, with accelerating urbanization and sharp urban population growth, increased domestic water demand is now competing with that of industries, reducing the share of industrial water within the overall water distribution. Facing this grim situation, Tianjin has responded appropriately to adjust its industrial structure and improve water use efficiency. Over the past two decades, water-consuming projects in the papermaking, textile, metallurgy, and chemical industries have been phased out, with numerous water-saving, high-tech projects given priority.

3. Qualitative analysis of industrial water use in Tianjin

3.1. General analysis

According to the history of developed countries, industrial water use in an area will not continue to increase. More specifically, when the economy develops to a certain stage, industrial water use will stop growing and will exhibit a downward trend. For example, industrial water use began to decline in Sweden in 1964, Japan in 1974, and the United States in 1981. The relationship between industrial water use and economic development can be depicted by the Kuznets curve. China is experiencing rapid industrialization and has experienced a decline in industrial water use in some of its economically developed areas, including Tianjin.

Fig. 4 depicts Kuznets curves based on the relationship between industrial water use and per capita GDP from 1990 to 2012. The changes in industrial water use in Tianjin differed from those in other economically developed regions. Water use peaked in Tianjin when the per capita GDP reached 15,000 yuan, lower than that in Beijing (20,000 yuan). Beijing is the capital of China, and China has heavily invested in Beijing to promote water-saving measures and technology. Currently, in terms of industrial water use per 10,000 yuan, Tianjin is performing similarly to Beijing. However, the funds invested in water-saving in Tianjin are much less than in Beijing. In other words, without favorable economic conditions, Tianjin achieved a decline in industrial water use before Beijing by adopting more stringent water control measures and more advanced water-saving technologies. Nevertheless, the potential for additional water savings is rather limited without more financial support.

Tianjin's industrial water use increased more gradually after the rapid growth and slow decline stages compared with that of developed areas such as Beijing. In 2008, Tianjin's industrial water use reached its lowest level of 380 million m^3. As Tianjin entered a stage of rapid economic development and the per capita GDP maintained an annual growth rate of 14.2% from 2008 to 2012, industrial water use began to rise owing to the rapid expansion of the industrial scale. Given that the demand for water owing to socioeconomic development far exceeds supply, industrial water use is bound to increase in Tianjin. Long-term zero growth is unlikely in water-rich areas such as the United States and Japan.

3.2. Driving force analysis

Tianjin's industrial water use is subject to change within multiple constraints, including industrial scale expansion, water-saving technological upgrades, and available water resources. This study focuses on the period of 2001 to 2012, with particular attention given to industrial adjustments during the second round of reforms (2003–2012). To better grasp the law of long-term industrial development in Tianjin, we also analyze data from the first round (1994–2002).

3.2.1. Output-driven force

We introduce industrial output as an indicator to describe the scale of industrial development in Tianjin, producing output-driven force. Increasing output is the most direct driving force of the upward trend of water use. In the absence of other driving forces, industrial water use is directly proportional to industrial output. To facilitate longitudinal comparisons, the industrial output values for all years are converted using the constant price index of 1990. The *Tianjin Statistical Yearbook* (Statistical Bureau of Tianjin, 1995–2013) and *Tianjin Water Resources Bulletin* (Tianjin Water Authority, 1995–2013) provide the total industrial output from 1994 to 2012, according to which the industrial water use and total industrial output chart are provided in Fig. 5.

Although there is no obvious linear relationship between industrial output and water use, three distinct correlation stages are apparent in Fig. 5 based on industrial output. As shown in Fig. 5, when industrial output is low, it is negatively correlates with water use amid industrial restructuring. In the intermediate stage, when the industrial output appears to be increasing, the amount of water use does not significantly change owing to improvements in water use efficiency and the industrial scale. In the final stage, water use positively correlates with industrial output, mainly owning to the expansion of the industrial scale, indicating no room for improvement in water savings.

3.2.2. Technology-driven force

Technology-driven force refers to the reduction of water use per unit of product caused by the advancement of water-saving technologies, use of water-saving devices, water-saving publicity, and system development. It manifests from improvements in water use efficiency and is generally expressed by water use per 10,000 yuan of industrial output. Improvements in water use efficiency can restrict of the increase in industrial water use. In the absence of other driving forces, water use efficiency is inversely proportional to industrial water use. Fig. 6 shows the correlation of industrial water use with water use per 10,000 yuan of output in Tianjin from 1994 to 2012.

There is a significant linear correlation between water use per 10,000 yuan of output and industrial water use in Tianjin, with the positive correlation coefficient reaching 0.83. As shown in Fig. 6, the correlation can be divided into three stages. First is the rapid increase in water use efficiency and rapid decline in industrial water use. From 1994 to 2001, water use per 10,000 yuan of output plummeted from

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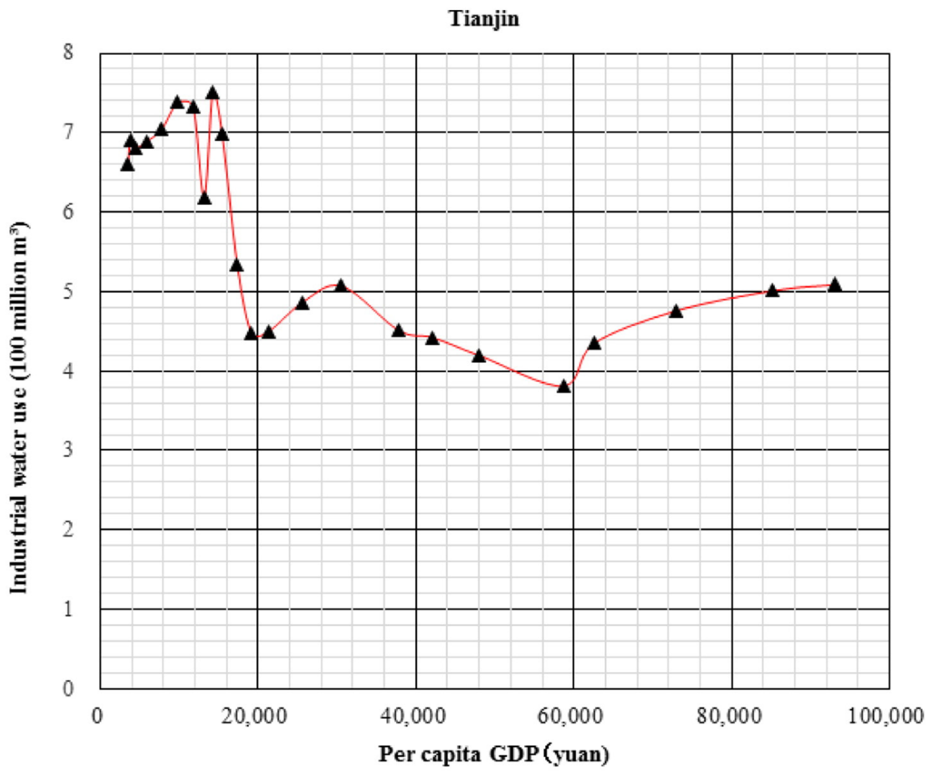

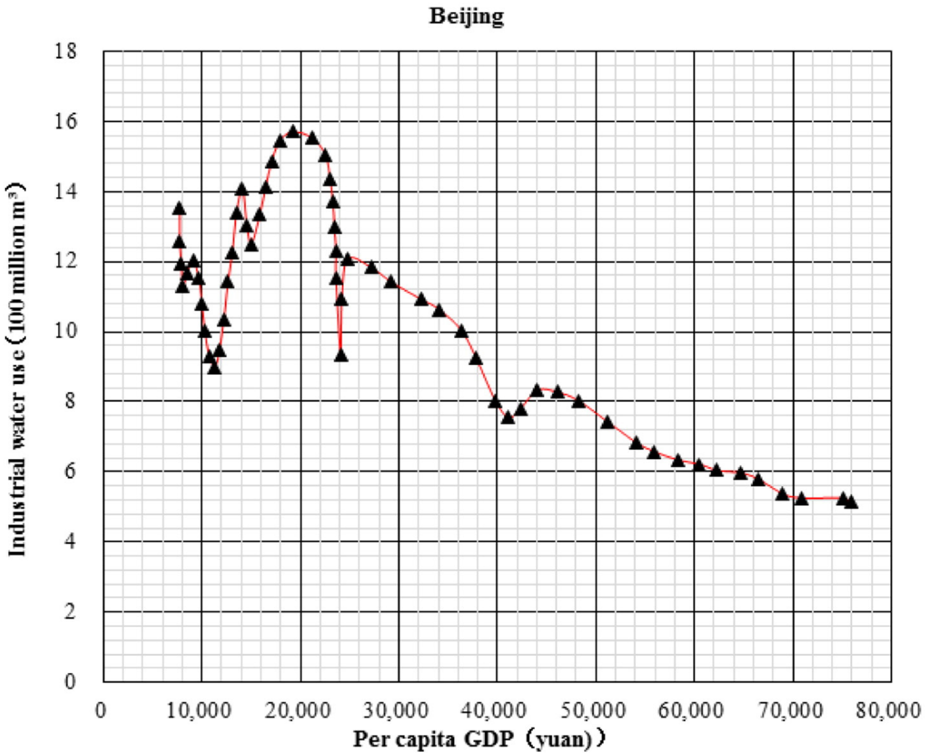

Fig. 4. Industrial water use changes with per capita GDP in Tianjin and Beijing.

40 to 13 m^3, with an average annual decline of 3.8 m^3, implying rapid improvements in water use efficiency. Industrial water use also fell sharply to 450 million from 700 million m^3. This means that, among all driving forces, technology played a key role and significantly curbed the rise of industrial water use. Second are the slow increase in water use efficiency and the slight decline in industrial water use. From 2002 to 2008, water use efficiency gradually improved with water use per 10,000 yuan of output, which dropped by 1.5 m^3 annually, while industrial water use dropped from 450 million to 380 million m^3. Although the technology-driven force began to weaken, it was not overshadowed by the others. Last is the stagnation of water use efficiency and increasing industrial water use. There was little room for improvement in water use efficiency after water use per 10,000 yuan of output reached 3 m^3 in 2008. With the expansion of the industrial scale, industrial water

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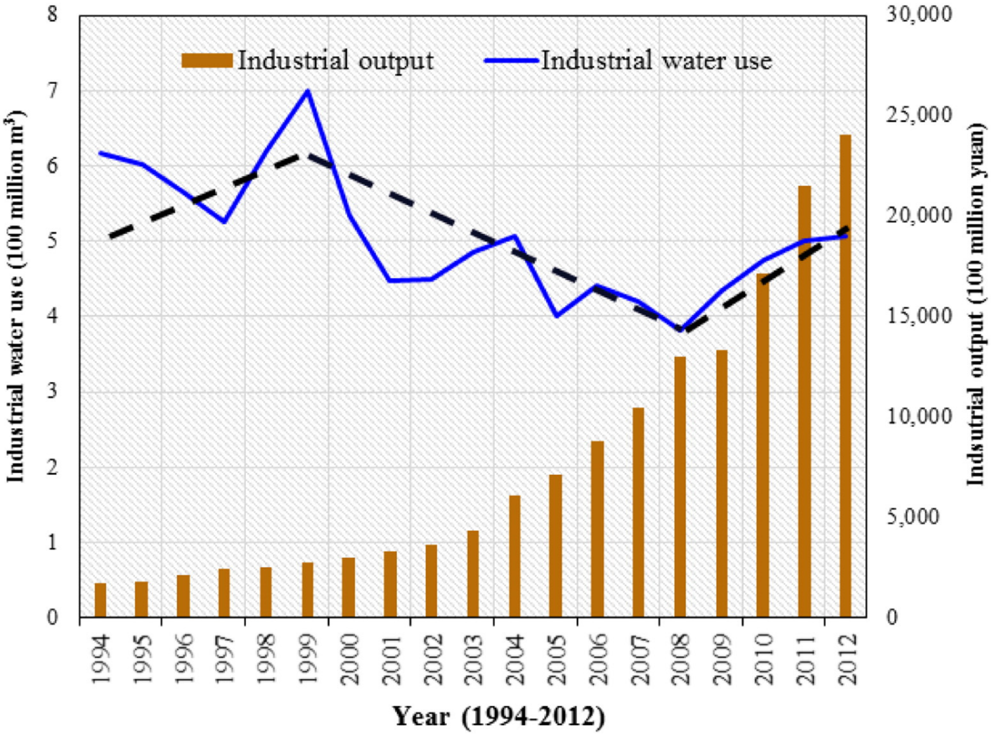

Fig. 5. Industrial water use and total industrial output in Tianjin for 1994–2012.

use began to increase gradually. In this case, the technology-driven force was overshadowed by the others.

3.2.3. Structure-driven force

The structure-driven force mainly refers to the effects that changing structures of different industrial sectors exert on industrial water use. To characterize this impact visually, Shang et al. (2016a) introduced the indicator of partiality (p) of the industrial structure to high water use. A p-value closer to 1 indicates greater partiality to high water use, while a value closer to 0 denotes greater partiality to low water use. The calculated results of the partiality for the second round of industrial adjustments are shown in Fig. 7.

As shown in Fig. 7, Tianjin had a partiality of below 0.5 throughout the reform period, indicating that the industrial structure was mostly water efficient during that period. However, a changing trend is also evident in Fig. 7, in which partiality first declined by 27.3% from 2003 to 2006 and then increased by 26.1% during the second set of reforms from 2006 to 2012, reaching its pre-reform level. This indicates that

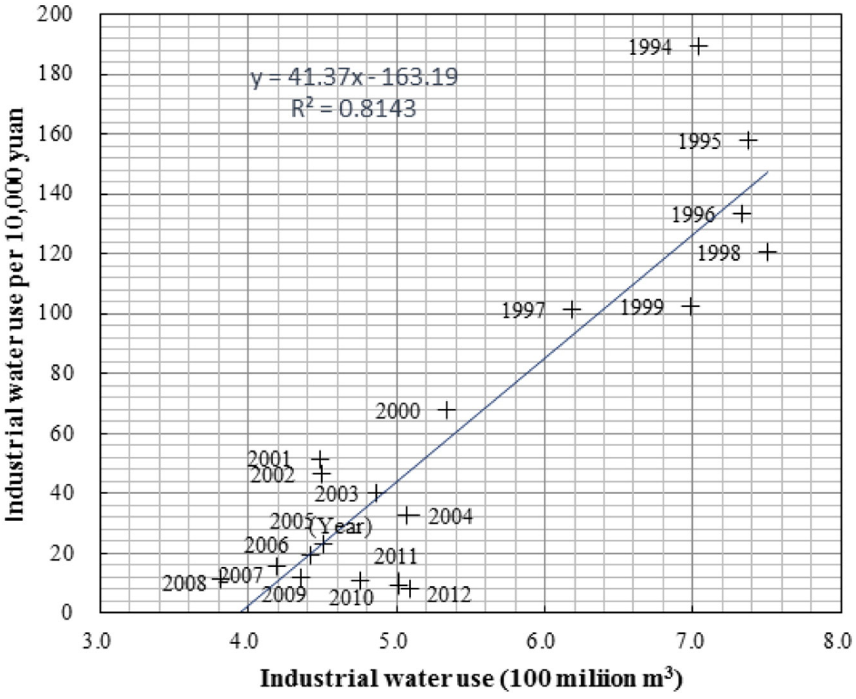

Fig. 6. Correlation between water use per 10,000 yuan of output and industrial water use in Tianjin (1994–2012).

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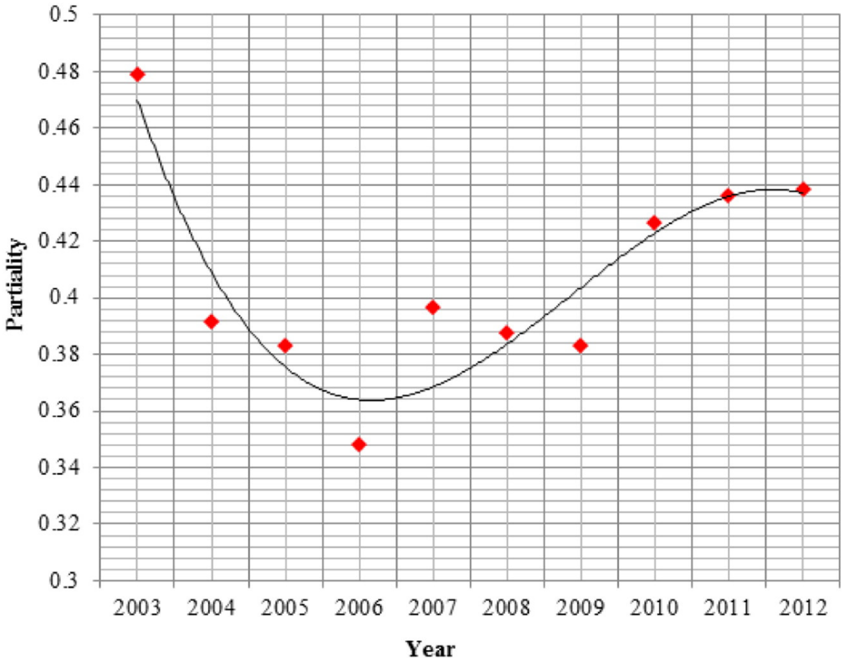

Fig. 7. Partiality of Tianjin's industrial structure to high water use (2003–2012): Data are adapted from Shang et al. (2016a).

Tianjin's industrial restructuring was not necessarily directed toward water conservation. The reforms may have included other targets such as energy savings, improving efficiency, and economic development. Noticeably, water-intensive industries exhibited an expanding trend after 2007.

4. Quantitative analysis of industrial water use in Tianjin

4.1. Methodology

Mahony (2013) used an extended Kaya identity to describe the relationship between CO_2 emissions and policy, population, and the economy. By extending this concept to industrial water use, we decomposed its driving forces into output, technological, and structural forces to characterize the contributions of industrial scale expansion, water-saving technologies, and industrial restructuring, respectively. Therefore, the change in industrial water use for the *t*th year can be written as follows:

$$\Delta Q = \Delta Q_M + \Delta Q_\mu + \Delta Q_q \tag{1}$$

where ΔQ represents the change in industrial water use, and ΔQ_M, rΔQ_q and ΔQ_μ represent those owing to output, technology, and industrial structure respectively.

The formulae for calculating the items of Eq. (1) using the Laspeyres and LMDI models are given below:

4.1.1. Laspeyres model

$$\Delta Q_M = \sum_{i=1}^{n} M^0 q_i^0 \Delta\mu_i + \frac{1}{2}\Delta\mu_i\left(q_i^0 \Delta M + M^0 \Delta q_i\right) + \frac{1}{3}\Delta\mu_i \Delta M \Delta q_i \tag{2}$$

$$\Delta Q_\mu = \sum_{i=1}^{n} \mu_i^0 q_i^0 \Delta M + \frac{1}{2}\Delta M (q_i^0 \Delta\mu_i + \mu_i^0 \Delta q_i) + \frac{1}{3}\Delta\mu_i \Delta M \Delta q_i \tag{3}$$

$$\Delta Q_q = \sum_{i=1}^{n} \mu_i^0 M^0 \Delta q_i + \frac{1}{2}\Delta q_i\left(M^0 \Delta\mu_i + \mu_i^0 \Delta M\right) + \frac{1}{3}\Delta\mu_i \Delta M \Delta q_i \tag{4}$$

4.1.2. LMDI model

$$\Delta Q_M = \sum_{i=1}^{n} \frac{Q_i^t - Q_i^0}{lnQ_i^t - lnQ_i^0} \ln \frac{M_t}{M_0} \tag{5}$$

$$\Delta Q_\mu = \sum_{i=1}^{n} \frac{Q_i^t - Q_i^0}{lnQ_i^t - lnQ_i^0} \ln \frac{q_i^t}{q_0^t} \tag{6}$$

$$\Delta Q_q = \sum_{i=1}^{n} \frac{Q_i^t - Q_i^0}{lnQ_i^t - lnQ_i^0} \ln \frac{q_i^t}{\mu_0^t} \tag{7}$$

where $M^0$is the value of industrial output in the previous year, $q_i^0$is water use per 10,000 yuan of industrial added value in industrial sector *i* in the previous year, and μ_i^0 is the proportion of Tianjin's total industrial output value that came from industrial sector *i* in the previous year. ΔM, Δq_t, and $\Delta \mu_i$ refer to the changes in industrial output value, water use per 10,000 yuan, and the output proportion of industrial sector *i*, respectively;Q_i^0 is the water use of industrial sector *i* in the previous year; and Q_i^t is the water use of industrial sector *i* in the *t*th year.

4.2. Data management

In this study, water use data for Tianjin are sourced from the *Tianjin Water Resources Bulletin* (Tianjin Water Authority, 1995–2013). The statistics on water use by industrial sectors are adopted from the *Tianjin Industrial Energy Efficiency Guide* (Tianjin Development and Reform Commission, 2004–2013) and Tianjin Municipal Bureau of Statistics and those on output are from the *Tianjin Statistical Yearbook* (1995–2014) (Statistical Bureau of Tianjin, 1995–2013).

Industrial water refers to the water supply for plant workers and water used in (or during) the industrial production process, for example, in boilers and manufacturing, processing, cooling, air conditioning, and washing. Industrial water mainly consists of surface water, groundwater, recycled water, and desalinated water and does not include directly used seawater. Furthermore, we converted industrial output data for all years using the constant price index of 1990 to avoid errors caused by price fluctuations between years.

4.3. Results and analysis

From 2003 to 2012, Tianjin's industrial water use exhibited a decline-rise trend. More specifically, industrial water use declined by 21.5% from 48.6 million to 381.30 million m^3 from 2003 to 2008, but later rebounded to 508.87 million m^3 in 2012. In this section, we use the refined Laspeyres and LMDI models to decompose Tianjin's industrial water use from 2003 to 2012, and the decomposition results for output, technology, and structure are shown in Fig. 8. The two models produce consistent decomposition results with difference within 5%, except for some particular years (Specifically, 2009, 2010, 2011 and 2012). Such exceptions can attributed to drastic changes in the share of individual industrial sectors or water use efficiency, which may be related to statistical errors.

With the Laspeyres decomposition results, we conducted a driving force analysis of this time span. As shown in Fig. 8, industrial output stimulated industrial water use in Tianjin and accounted for an average annual growth of 77 million m^3 over the study period, averaging 76 million m^3 before 2008 and 79 million m^3 after. This means that, driven by fast industrial scale expansion, industrial water use grew intensely after 2008, which is consistent with the results obtained in Section 3.2.1.

Technology, on the other hand, inhibited industrial water use in Tianjin and contributed to an average annual reduction of 79 million m^3. In particular, the technology-driven reduction registered at 90 million m^3 before 2008 and 67 million m^3 after, implying that industrial improvement of water use efficiency slowed down and became stagnant after 2008, in line with the correlation analysis results (Fig. 6).

The effect of structure on industrial water use was not stable, i.e., it served as a promoting factor in some years and an inhibiting one in others. Within the study period, promotion and inhibition alternated, but promotion dominated after 2008, indicating the increasing partiality of the industrial structure to high water use, as described in Section 3.2.3. Overall, structural adjustments did not exert much of an effect on industrial water use, as little change was observed.

5. Discussion and conclusion

As analyzed above, industrial water use is subject to multiple driving forces, shaped by combinations of industrial scale expansion, technological advances, industrial restructuring, and water availability. At different times, these driving forces vary in intensity, leading to complex trends in industrial water use. Only by decomposing the driving forces can we accurately grasp these trends and make scientific predications. In this study, we decomposed the driving forces of industrial water use in Tianjin using the refined Laspeyres model and LMDI model and compared the results of the two. The decomposition results of the two models agree, with some difference in particular years. We therefore can conclude that the two models are applicable to the quantitative analysis of industrial water use changes.

In this study, we analyzed factors driving industrial water use in Tianjin from 2003 to 2012 and described changes in their impacts at different stages while clarifying the contributions of the industrial scale and structure and water use efficiency. There were two distinct stages on temporal scales. Prior to 2008, technology was the primary factor in industrial water use, hindering growth sufficiently to overcome the stimulating effect of output. Structure additionally inhibited water use, which, as a whole, exhibited a downward trend. After 2008, however, output became the main factor influencing industrial water use, with a stimulating effect overshadowing technology-caused inhibition. At the same time, improper adjustments to the industrial structure increased water use. As a whole, industrial water use exhibited an upward trend during this stage.

The water use per 10,000 yuan of industrial output is an important indicator of industrial water use efficiency. In 2013, this value deceased to 8.3 m^3 in Tianjin, which ranked first of all the administrative districts directed by the central government of China. It was, therefore, declared the “National Water-Saving City” by the Chinese central government, with hopes that other arid areas would learn from Tianjin to transform and upgrade their economic structure to achieve of “a water-based city and production.” This study revealed that reducing industrial water use is not the primary target, but rather, a product of industrial restructuring in Tianjin. Water resources are a major issue, but in many cases, various factors, including GDP growth, energy savings, and emissions reduction, are considered in industrial development. Hence, industrial restructuring is not necessarily oriented toward

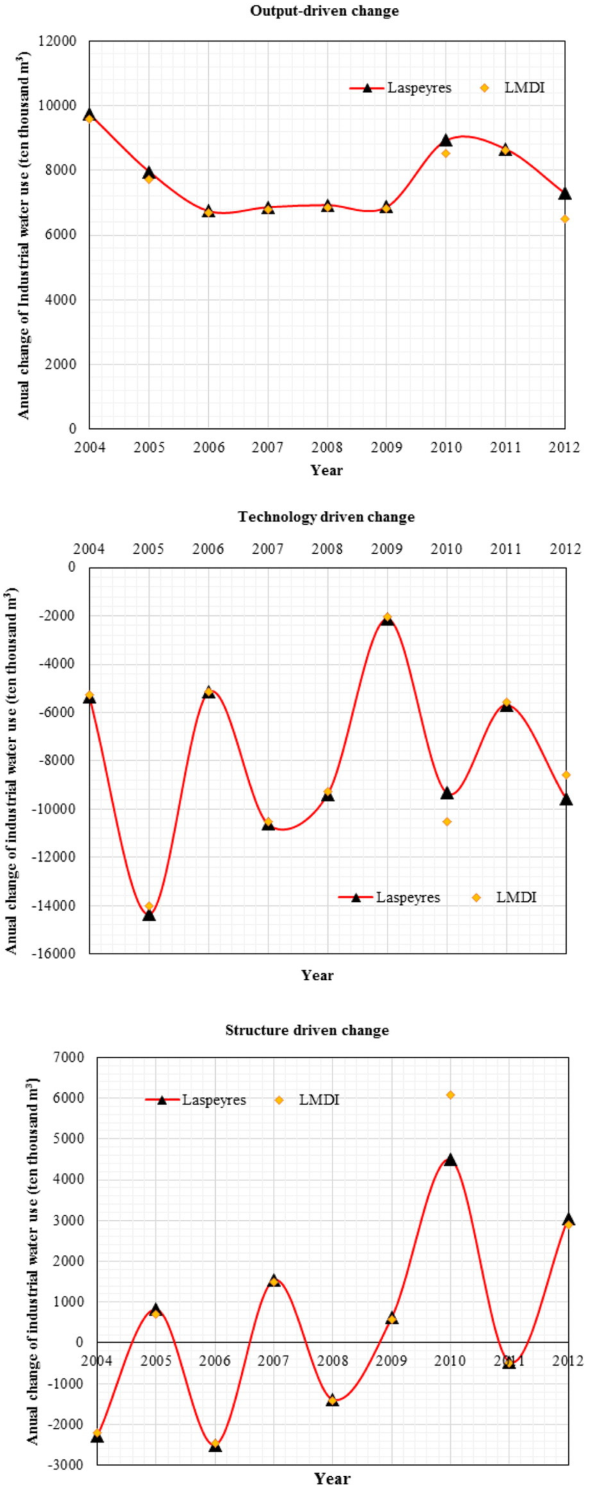

Fig. 8. Decomposition results of Laspeyres and LMDI models.

water-savings, and the local government does not use structure as a force to limit water use.

In China, industries have been responsible for as much as about 70% of all energy consumption over the years and are primarily responsible for mounting energy consumption in China. Industrial production entails large-scale water use. However, because of the complex relationship between water and energy systems, energy-saving does not simply mean water-saving, and the two are not always correlated. In some cases, energy-saving is conducive to water saving, while in others, it requires greater water use. In grim water and energy situations, the in-depth study of water-energy coupling and synergy is improtant for healthy industrial development.

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