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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.