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Spatial-temporal patterns and driving factors for industrial wastewater emission in China

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ABSTRACT

China's extraordinary economic growth, industrialization and urbanization coupled with inadequate investment in basic water supply and treatment infrastructures, have resulted in increasing industrial water pollution. However, due to imbalanced development, industrial wastewater emissions present significant regional disparity. Industrial wastewater management disparity requires more in-depth study on both spatial and temporal patterns across different regions for identification of appropriate and effective mitigation policies while considering practical and localized realities. This paper addresses this issue and contributes to new knowledge by analyzing the spatial-temporal characteristics and driving forces of industrial wastewater emission variations in China's 31 provinces during the years 1995–2010. Using the Logarithmic Mean Divisia Index (LMDI) method, the results show that economic factors are the main driving factors of industrial wastewater emission changes in all provinces during the study period. It is also found that technology improvement considerably offsets emission increases. Using these research findings, both general and specific measures for controlling industrial wastewater emissions are offered so that the overall industrial water efficiency can be improved, in China and potentially elsewhere.

经济最重要，技术能够平衡排放

1. Introduction

With globally increasing population, urbanization and industrialization, wastewater emissions have become a major environmental concern (Kundzewicz et al., 2008). These wastewater emissions contain high levels of heavy metals, organic compounds and pathogens (Shannon et al., 2008). The rapid urbanization in developing countries has further exacerbated negative health and environmental consequences (Wu et al., 2011).

As the largest developing country China faces serious water shortages and pollution issues (Geng et al., 2007). 45% of China's major rivers have become seriously polluted in the past couple decades, resulting in over half of China's 1.3 billion people consuming water contaminated with chemical and biological wastes such as petroleum, ammonia, nitrogen, volatile phenols, and mercury (Ministry of Environmental Protection, 2009). Nearly 700 million people continue to consume water containing excessive amounts of the e-coli bacterium. It is estimated that 180 million people drink water with a variety of organic pollutants (Feng et al., 2008).

Evidence has been found that increasing industrial wastewater emission is the main culprit of much of China's water pollution (Kendy et al., 2004). Total wastewater emission reached 58.9 billion tons in 2010, about 175% more than in 1990. Over 40% of this emission emanated from industrial sources (National Bureau of Statistics of China).

Fig. 1 depicts the detailed industrial wastewater emissions at provincial levels during 1995–2010. It is clear that the total amounts of industrial wastewater emissions in eastern regions (such as Jiangsu, Zhejiang, Shandong and Guangdong provinces) are much larger than those in western China (such as Tibet, Qinghai and Xinjiang). This regional disparity requires more detailed study and analysis, especially identifying the factors driving this industrial wastewater discharge.

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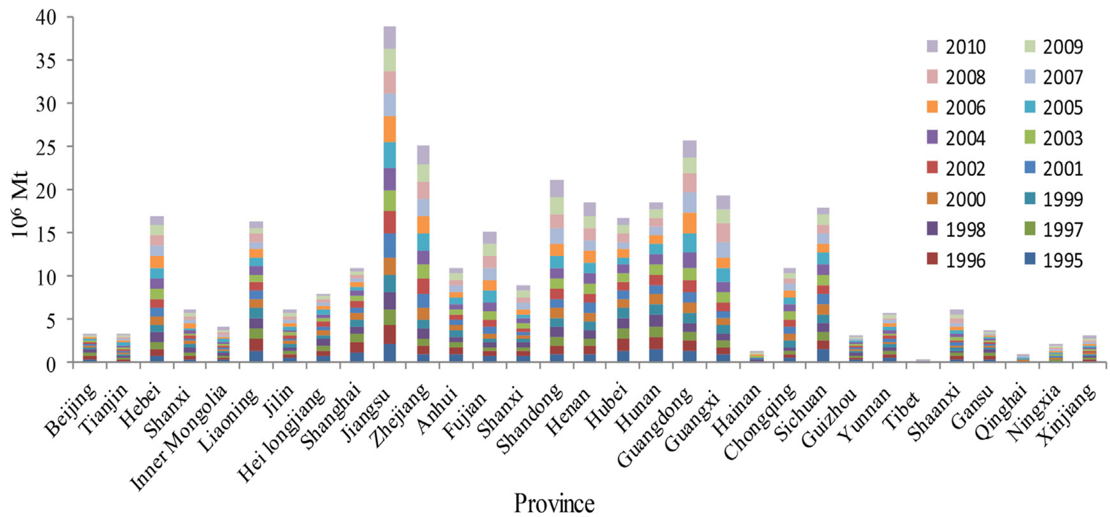

Fig. 1. Total amount of the industrial wastewater discharge at provincial level during 1995–2010 (MEP and NBSC, 1996–2011).

Studies on wastewater problems have traditionally been conducted from hydrological (Duarte et al., 2002), chemical (Mendas et al., 2008) and physical perspectives (Jia et al., 2012), mainly focusing on the supply side of water resources and water quality (Cochran and Logue, 2011). However, few studies have sought to identify the antecedent factors of industrial wastewater discharge, especially in developing countries. Studies on antecedent factors can help decision-makers develop more effective policies for controlling industrial wastewater emissions, especially in situations where regional disparities exist. These disparities point to challenges that may be unique to different regions. Hence, this study contributes to this body of knowledge by identifying antecedent factors contributing to China's wastewater emissions and their regional variations and disparities.

To meet the objectives of this study we first present our methodology, including research method, data sources and treatment details. We then present our research outcomes and provide an in-depth analysis on four specific regions. Finally, we clarify policy implications so as to provide appropriate mitigation policies that can be prepared by considering the regional (spatial) disparities.

2. Research method

2.1. Decomposition analysis

Decomposition analysis is a useful method for identifying key sustainable development driving factors (Ang, 1994; Shao et al., 2014). This methodology has been widely employed within China, for example to identify key factors for regional sustainable development (Geng et al., 2011). Decomposition analysis has also been successfully applied to identifying key driving forces on energy-related greenhouse gas (GHG) emissions in Chinese mega cities (Liu et al., 2012a), and uncovering China's GHG emissions from regional and sectoral perspectives (Liu et al., 2012b).

There are two typical decomposition analysis methods, namely, the index decomposition analysis (IDA) method and the structural decomposition analysis (SDA) method. IDA method uses index number concept in decomposition analysis and has advantages in temporal analysis due to its adaptability and simplicity (Liu et al., 2012a), while SDA method has its advantages in analyzing detailed industrial sectoral emissions but requires the complete input–output table (Diakoulaki et al., 2006). Due to a lack of a complete input–output table, IDA was selected for this study. Among various IDA approaches, the logarithmic mean divisa index (LMDI) approach has become the most popular one due to its path independency, consistency in aggregation and easily interpreted results (Ang, 1994). Another advantage of this approach is that it can absolutely eliminate residuals and tackle the zero value issue that conventional IDA methods are facing (Ang, 2004). It cannot only undertake multiplicative decomposition and chain development index analysis which cannot be achieved by Laspeyres index decomposition method, but also conduct continuous-time link relative analysis which cannot be achieved by structural decomposition analysis due to the limitation of the input–output table (Ang, 2004). For instance, a practical LMDI application was conducted for investigating Canada's industrial energy consumption and CO_2 emissions (Ang, 2005). Consequently, given these advantages, the LMDI approach was selected in this study in order to identify the antecedent factors influencing China's industrial wastewater emissions.

In order to observe spatial patterns of industrial wastewater emissions, a GIS (Geographical Information System)-based database was established. GIS is especially adept at forming a spatial database for regional industrial wastewater discharge, identifying the current distribution, the amounts, densities, and historical (temporal) changes of industrial wastewater discharge, serving as a powerful decision and policy tool to effectively manage industrial wastewater. In order to observe temporal patterns of industrial wastewater discharge, time series decomposition analysis was conducted. The original application of time series decomposition analysis can be traced to the early 1990s (Ang and Lee, 1994), in which decomposition analysis was completed between year t and $t+1$ (here t varies from the first year to the last year of the study period). Most previous studies undertook their temporal analysis by using a period-wise approach and comparing indices between the first and the last year of a given period. However, results of a period-wise decomposition analysis are sensitive to the choices of the baseline year and the final year. This approach is often unable to uncover detailed evolutionary effects of the decomposed factors over the whole study period (Liu et al., 2012a). The LMDI approach can be applied in both a period-wise and a time series manner. Therefore, LMDI's flexibility makes it suitable to conduct a comprehensive time series analysis and can provide a holistic picture of China's industrial wastewater emissions.

Referring the previous LMDI approach (Ang, 2005), total industrial wastewater discharge can be expressed by the following Equation (1):

$$W^t = \sum_i^n W_i^t = \sum_i^n \left[\left(\frac{W_i^t}{V_i^t} \right) \cdot \left(\frac{V_i^t}{G_i^t} \right) \cdot \left(\frac{G_i^t}{P_i^t} \right) \cdot P_i^t \right] \quad (1)$$

Where W^t represents the total amount of industrial wastewater emitted in year t across the whole country; W_i represents the total industrial wastewater emission in province i; V_i represents added industrial value in province i; G_i represents gross domestic product in province i; P_i represents total population in province i; n represents the total number of studied provinces.

Thus, based on Equation (1), four potential antecedent factors could be identified as the driving forces of regional level industrial wastewater emissions, which can be indicated as technology improvement (T), industrial structure (S), economic development (E) and regional population (P), and can be shown in Equation (2):

$$T_i^t = \frac{W_i^t}{V_i^t};\quad S_i^t = \frac{V_i^t}{G_i^t};\quad E_i^t = \frac{G_i^t}{P_i^t}; \quad (2)$$

By substituting Equation (2) on the right of Equation (1), then we can get the Equation (3):

$$W^t = \sum_i^n \left(T_i^t \cdot S_i^t \cdot E_i^t \cdot P_i^t \right) \quad (3)$$

According to the LMDI approach, the change of industrial wastewater emissions between a base year m and a target year t, denoted byΔW_m^t, can be decomposed into the following determinant factors: (a) technology improvement effect (denoted as ΔW_{Tec}), (b) industrial structure effect (denoted as ΔW_{Str}), (c) economic development effect (denoted as ΔW_{Eco}), and (d) population effect (denoted as ΔW_{Pop}). Thus, the difference ΔW_m^t is decomposed into its components in additive forms, as illustrated in Equation (4):

$$\Delta W_m^t = W^t - W^m = \Delta W_{\mathrm{Tec}}^{t-m} + \Delta W_{\mathrm{Stc}}^{t-m} + \Delta W_{\mathrm{Eco}}^{t-m} + \Delta W_{\mathrm{Pop}}^{t-m} \quad (4)$$

Each effect in the right side of Equation (4) can be computed by the following Equations (5)–(8):

$$\Delta W_{\mathrm{Tec}}^{t-m} = \sum_i \frac{W^t - W^m}{\ln W^t - \ln W^m} \ln \left(\frac{T_i^t}{T_i^m} \right) \quad (5)$$

$$\Delta W_{\mathrm{Str}}^{t-m} = \sum_i \frac{W^t - W^m}{\ln W^t - \ln W^m} \ln \left(\frac{S_i^t}{S_i^m} \right) \quad (6)$$

$$\Delta W_{\mathrm{Eco}}^{t-m} = \sum_i \frac{W^t - W^m}{\ln W^t - \ln W^m} \ln \left(\frac{E_i^t}{E_i^m} \right) \quad (7)$$

$$\Delta W_{\mathrm{Pop}}^{t-m} = \sum_i \frac{W^t - W^m}{\ln W^t - \ln W^m} \ln \left(\frac{P_i^t}{P_i^m} \right) \quad (8)$$

2.2. Data sources

Given that we are focusing on the size of China, a large amount of data are required for such a complicated and comprehensive study. The data were obtained from different sources, making it critical to ensure that most reliable data be collected. Our data acquisition effort includes China's official statistical database, published papers, and governmental reports. The data on industrial wastewater emissions, added industrial values, regional gross domestic products and regional populations were collected from the China Statistical Yearbooks for the years of 1996–2011 (National Bureau of Statistics of China), China Statistical Yearbooks on Environment for the years of 1996–2011 (Ministry of Environmental Protection and National Bureau of Statistics of China), and Chongqing Statistical Yearbooks for the years of 1996–1997 (Chongqing Statistics Bureau). The reason for using the Chongqing statistical yearbooks is that this city was originally a part of Sichuan province until 1997, then it became a standalone provincial region (mega city) separate of Sichuan province. On the basis of these data, panel data at the provincial level were constructed for further analysis. Due to data availability, 31 provinces and 4 province leveled mega cities (Beijing, Shanghai, Tianjin and Chonqing) were considered in this study, while Taiwan, Hong Kong and Macau were not included. Fig. S1 in the supplementary file of this paper provides raw data on both industrial wastewater amounts and industrial output values in all study provinces.

3. Results

By conducting a time series LMDI decomposition analysis, antecedent factors for industrial wastewater emission in China have been quantified. Fig. 2 presents our decomposition analysis results of industrial wastewater emission in China during 1995–2010, in which it is clear that regional economic development (ΔW_{Eco}) is the main driver for industrial wastewater emission, followed by technology improvement (ΔW_{Tec}), regional industrial structure (ΔW_{Str}) and population (ΔW_{Pop}). Supporting Figs. S2–S5 show comparative results of the average values for the four antecedent factors at provincial level and national average values. These four figures indicate that these antecedent factors are stronger in eastern regions relative to western regions. This is especially true for industrial structure effect. The average industrial structure effect values of eastern areas (such as Guangdong, Jiangsu, and Shandong) are higher than the national average, while the average industrial structure effect values of western regions (such as Tibet, Qinghai, and Xinjiang) are lower than the national average.

Industrial wastewater emission in Jiangsu province is the largest in China. It also has the largest technology effect, economic development effect and population effect. From the whole country point of view, the functions of these four antecedent factors are different. While economic development effect (ΔW_{Eco}), industrial structure effect (ΔW_{Str}) and population effect (ΔW_{Pop}) induced the growth of industrial wastewater emission during the study period, technology improvement effect (ΔW_{Tec}) offset increases of total industrial wastewater emission. The following sections provide and discuss the details of these effects on China's industrial wastewater discharge.

3.1. Regional economic development effect

Regional economic development was the most important antecedent factor resulting in increasing industrial wastewater emission over the period 1995–2010. Fig. 3 shows the comparison of economic development effect in different regions within the whole study period. It is clear that regional disparity exists and economic development effect in eastern regions is much higher than those in western regions. For instance, economic development effect in Jiangsu, Zhejiang, Shandong and Guangdong (the four richest provinces in east China) contributed 5136.9 Mt

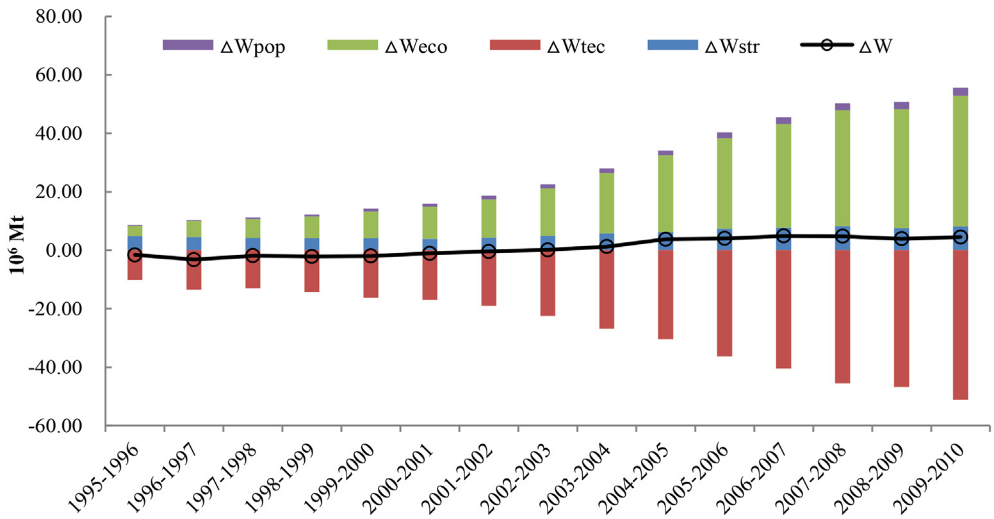

Fig. 2. Decomposition analysis results of industrial wastewater discharge in China during 1995–2010.

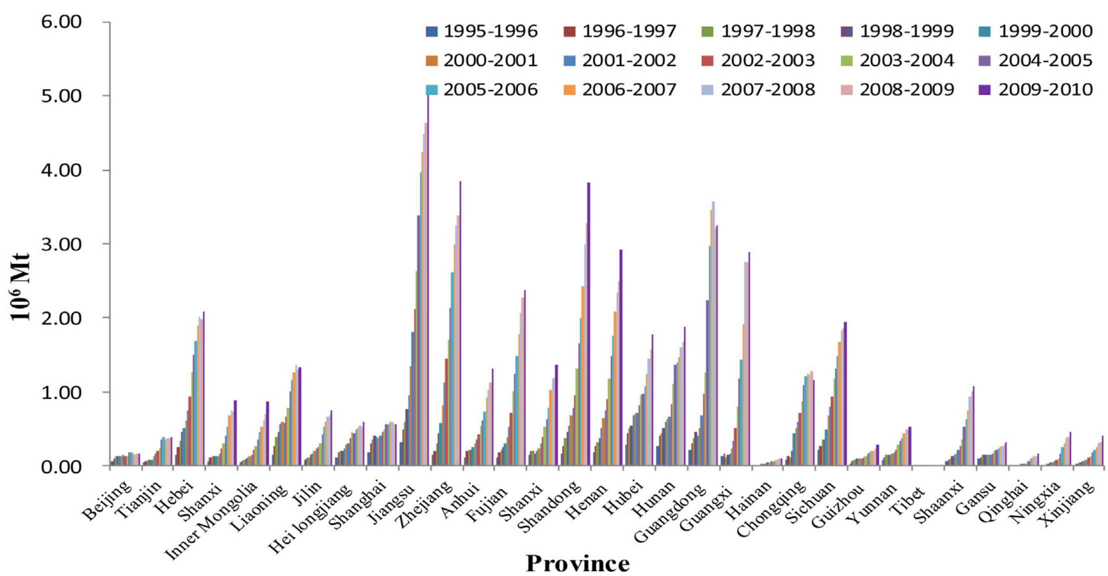

Fig. 3. Comparison of economic development effect in different regions.

(million tons), 3850.5 Mt, 3828.3 Mt and 3245.8 Mt industrial wastewater emissions in 2010, respectively; while the economic development effect in Tibet, Qinghai, Xinjiang, Ningxia (all located in west China) contributed only 16.5 Mt, 169.2 Mt, 396.8 Mt and 454.3 Mt industrial wastewater emissions in 2010, respectively.

3.2. Regional industrial structure effect

Regional industrial structure effect was another antecedent factor causing increasing industrial wastewater emission over the period of 1995–2010, but with a much lesser influential magnitude. Fig. 4 shows the comparison results of industrial structure effects in different regions. In particular, the industrial structure effects in Guangdong, Jiangsu, Zhejiang, Shandong, Guangxi and Sichuan were more significant than other regions.

Such results were based upon the fact that these provinces had rapidly developed their manufacturing sectors during the study period. However, industrial wastewater emissions decreased in several regions, namely in Beijing during 2001–2010, in Shanghai during 2000–2002 and 2007–2010, and in Chongqing during 1996–2008. The main reason is that these three cities had reduced their total investment in manufacturing sectors during the study period, while at the same time increased their investment in service sectors, which are typically less water-consuming.

3.3. Technology improvement effect

Technology improvement is the main antecedent factor for reducing total industrial wastewater emission in all the provinces except for Chongqing. Fig. 5 shows the comparison results of technology improvement effects in different regions within the whole study period.

Technology improvement effect increased the total industrial wastewater emission in Chongqing over the periods 1995–1996 and 1998–2002. Increased industrial wastewater emissions are 245.3 Mt, 253.6 Mt, 153.6 Mt and 20.8 Mt during 1998–1999, 1999–2000, 2000–2001, 2001–2002 periods, respectively. The main reason is that this city allowed some water inefficient industries to

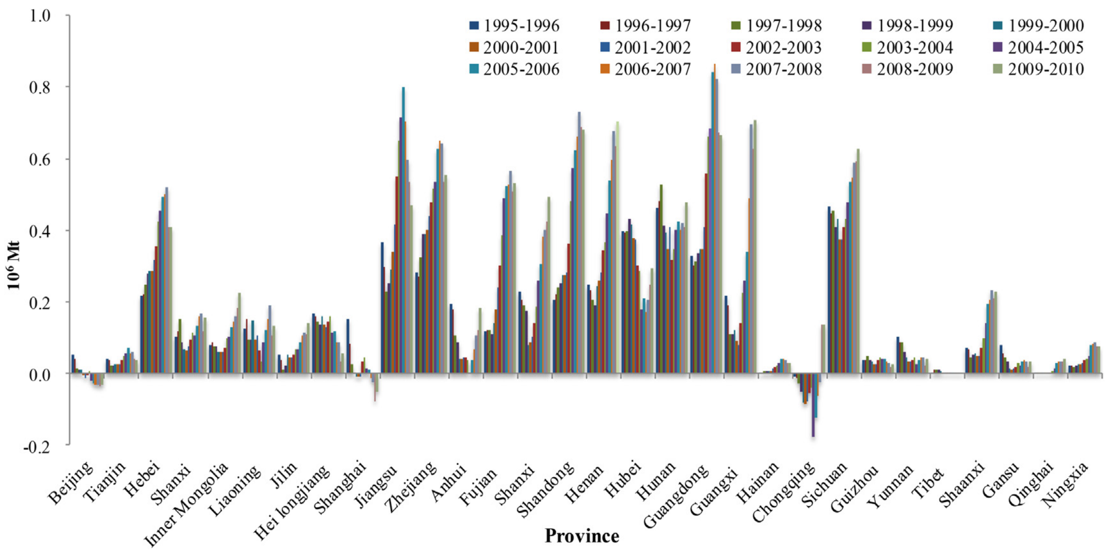

Fig. 4. Comparison of industrial structure effect in different regions.

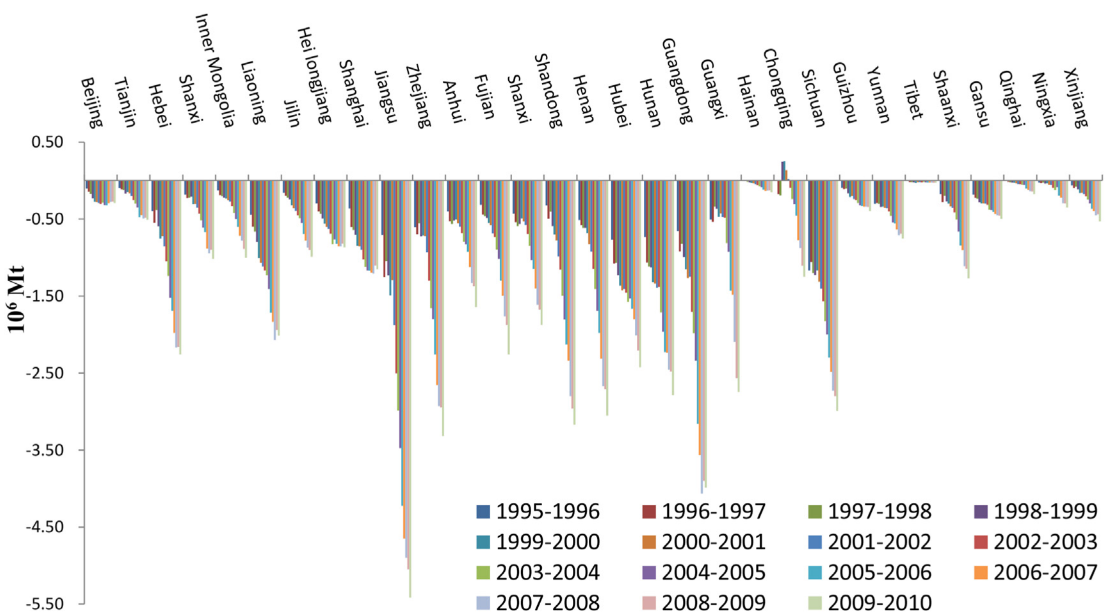

Fig. 5. Comparison of technology improvement effect in different regions.

operate their businesses during 1995–1996 and 1998–2002 in order to encourage their economic development. But then the city government realized this problem and changed their economic policy and stopped this relationship trend after 2002, with similar and not contrary to other provinces.

In general, Jiangsu, Guangdong, Shandong, Henan, Hunan and Sichuan provinces had the most significant technology improvement effects, while Tibet had the least technology improvement effect. For instance, technology improvement effect in Jiangsu was 18 times as large as in Tibet in 2010, with figures of 541.7 Mt and 29.4 Mt in reducing industrial wastewater emissions, respectively. Thus, it is clear that the western regions need to pay more attention to improving their technology levels.

3.4. Population effect

Population factor has a minor effect on the industrial wastewater emission. Fig. 6 shows the comparison results of population effects in different regions within the whole study period. Compared with other provinces, population effects in Zhejiang and Guangdong were more significant and contributed 787.2 Mt and 497.9 Mt, respectively. The reason is that these two provinces have more immigration workers due to their booming economy. On the contrary, population effects in Chongqing and Sichuan showed different trends for industrial wastewater emissions during the period of 2004–2010, in which they reduced 21.7 Mt and 33.9 Mt industrial wastewater emissions, respectively. This matched the fact that these two provinces had the largest emigration populations with a substantial migration and most of them moved to Guangdong and Zhejiang. For instance, there were 16.79 emigration populations in Sichuan and 12.08 million emigration populations in Chongqing in 2012, while 9.6 million immigration populations in Guangdong were from Sichuan and Chongqing and 1.82 million immigration populations in Zhejiang were from Sichuan and Chongqing in 2012 (Jiang, 2013; Wang et al., 2013).

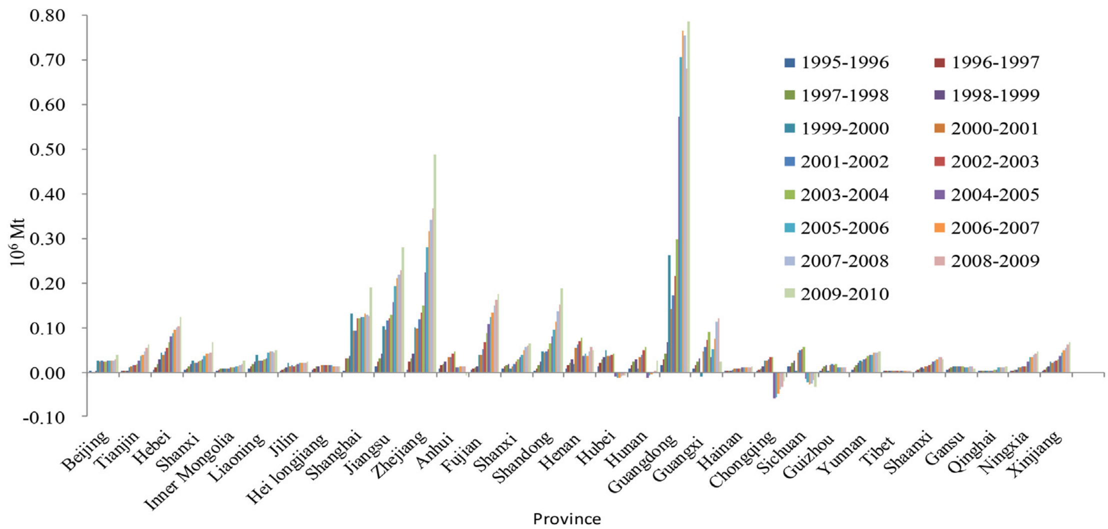

Fig. 6. Comparison of population effect in different regions.

4. In-depth study in four case regions

There are some idiosyncratic patterns to antecedents of industrial wastewater emissions within different Chinese provinces. Generally, the four antecedent factors are stronger in eastern regions than in western regions. These results are especially true with respect to industrial structure effect, where the average values of eastern regions (such as Guangdong, Jiangsu, and Shandong) were higher than the national average and the western region average values (such as in Tibet, Qinghai, and Xinjiang) were lower than national average.

Industrial wastewater discharge in Jiangsu province was the largest in China, while industrial wastewater discharge in Tibet was the least. Beijing and Chongqing as provincial leveled cities had some unique characteristics. They were characterized by decreasing trends in terms of industrial structure effect while other provinces had increasing trends. Therefore, Jiangsu (eastern region), Beijing (mega-city), Chongqing (western region and mega-city) and Tibet (western region) were chosen as the case regions to have an in-depth study.

These four regions presented different industrial wastewater emission trends during the period of 1995–2010. Beijing decreased its industrial wastewater emission from 369.9 Mt in 1995 to 81.9 Mt in 2010, Jiangsu increased its industrial wastewater emission from 2201.8 Mt in 1995 to 2637.6 Mt in 2010, Chongqing increased its industrial wastewater emission from 440.0 Mt in 1995 to 451.8 Mt in 2010, and Tibet decreased its industrial wastewater emission from 21.6 Mt in 1995 to 7.4 Mt in 2010, respectively.

Fig. 7 shows the proportion of industrial wastewater emission from the four antecedent factors in the four case regions over the period of 1995–2010. Clearly technology improvement effect and economic development effect were two main antecedents for industrial wastewater emission, followed by industrial structure effect and population effect. The proportion of economic development effect in the four regions had a sharp increase. Economic development effect increased from 25% in 1995 to 30% in 2010 in Beijing, from 23% in 1995 to 45% in 2010 in Jiangsu, from 34% in 1995 to 45% in 2010 in Chongqing, and from 22% to 33% in 2010 in Tibet. This result indicates that China had significantly expanded its economic scale across the whole country during the study period and this rapid development resulted in higher industrial wastewater emission.

We also observed that rapid development was not balanced across the regions. For example, as one of the richest provinces, Jiangsu's economy developed rapidly over the period of 1995–2010, as its GDP increased from 515.5 billion RMB in 1995–4142.5 billion RMB in 2010 (1USD = 6RMB). Although industrial structure effect decreased from 26% in 1995 to 4% in 2010, the total industrial wastewater emission still inordinately increased due to rapid economic development. As China's main manufacturing base, it is expected that Jiangsu province will continue to develop manufacturing industry over the next few decades. The commensurate industrial wastewater emission will most likely not be significantly reduced if this development pattern continues. More importantly, it is also the type of manufacturing industry that seeks to locate in this region. Many chemical processors locate in Jiangsu. It is well known that these types of companies contribute to the notorious algal bloom in Taihu lake (Guo, 2007). Although significant efforts have been put forth and advances have been made, especially cleaner production in key polluting industries, this province still faces challenges in controlling the total emissions from these firms (Liu et al., 2012c).

Beijing, as the national capital, is home to China's political elite and thus wields substantial political power. As part of the economic development evolution, it has targeted and attracted relatively more service sector industries in the last two decades, especially high-tech, financial and education sector industries while simultaneously relocating many of its polluting industries outside its administrative territory. During the time of this study period, the city won and hosted the 2008 Olympic Games. This situation caused Beijing to receive many preferable environmental policies from the central government, one of which was industrial relocation of polluting industry. This industrial shift and relocation, much of it politically mandated and supported, resulted in decreased industrial wastewater emission. But a separate and opposite force also occurred, namely, rapid urbanization. Beijing had significantly increased its population during the study period. The contribution from this population increase (from 1% in 1995 to 7% in 2010) was the most significant of these four case regions. However, in general, the Beijing pattern is quite unique and has not been replicated in other regions. Possibilities do exist to learn from their unique policies and examples, at least for mega cities.

Chongqing, also a provincial leveled mega city, should be regarded as a more representative mega city that does not enjoy the

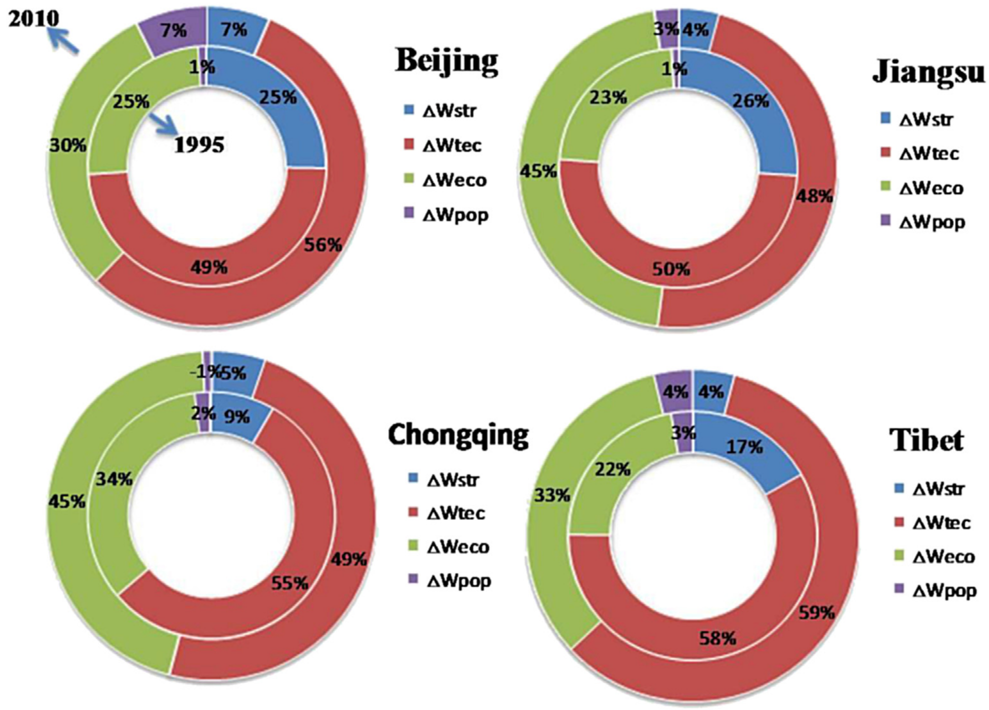

Fig. 7. Driving forces comparisons in Beijing, Jiangsu, Chongqing and Tibet (inner: year 1995; external: year 2010).

same preferable political situation as Beijing. For example, it is difficult for this city to recruit service oriented businesses and use mandates relocating its own polluting companies outside its territory. Thus, industrial structure effect did not make a significant impact during the study period (from 9% in 1995 to 6.5% in 2010). This lack of industrial structure influence is partially attributed to a weakened economic situation. In addition, many of their citizens moved to Guangdong and Zhejiang to seek jobs, thus, population effect decreased from 2% in 1995 to 1.5% in 2010.

Tibet is a special autonomous region in China. Located in the west, this region is also the original source of many international rivers, including the Ganges River, the Indus River, the Brahmaputra River, the Salween River and the Mekong River. Protecting these watersheds and its ecological environment is very critical. Polluting industries are strictly forbidden to operate within this region. This region has gradually ceased pollution firms' operations, contributing to the absolute reduction of industrial wastewater emissions. The industrial structure effect slumped from 17% in 1995 to 4% in 2010. The other three antecedent factors remained relatively stable between 1995 and 2010. In order to further protect its unique natural environment, more rigorous control measures will be implemented in Tibet, indicating that total industrial wastewater emission is expected to further decrease.

5. Policy implications

In general, our research outcomes reflect that significant regional disparity on industrial wastewater discharge exists, leading to significant socio-economic and political issues. Provinces in east China have higher industrial wastewater emissions due to their intensive industrial development and manufacturing-based industrial structure; while provinces in west China have less industrial wastewater emissions but may face more pressures with their rapid industrialization. Such a regional disparity indicates that region-specific policies on reducing industrial wastewater emissions should be initiated. Direct and indirect policy implications from this study suggest the following efforts, policy reform, economic instruments, technology improvement, and capacity-building.

First of all, current policies on industrial wastewater emission should be reformed with a consideration of regional disparity. On one hand, the relatively economically prosperous regions in eastern China have a genuine and regionally intrinsic interest in improving resource efficiency and environmental performance. They have the necessary economic development to provide them the 'luxury' to focus efforts on environmental improvements, including careful management of industrial wastewater emissions. These regions are more likely to feel pressures from communities and public stakeholders whose economic quality of life is at acceptable levels, but whose broader social and environmental quality of life is in need of improvement. It can be expected that internal policies, without national government regulatory instruments or cajoling through economic instruments, is required. On the other hand, the less prosperous western regions are facing different socio-economic forces such as needs to meet the basic economic, and in some cases survival, of their populations. Thus, they are more likely to be influenced through external policy instruments such as national financial subsidies (Geng, 2011). Although the Chinese central government set up a national emission reduction target (Geng and Sarkis, 2012), this target was allocated across provinces and provincial level cities based upon regional GDP totals, without considering variations in economic development level, industrial structure, water resource endowment, technology improvement level, or population effects. Therefore, such a target should be redesigned by considering the above factors. For instance, China's central government carefully monitors government officials' performance at all levels of government. Adding one environmental performance indicator, such as the total amount of industrial wastewater emission, for assessing the overall performance of local officials can be a potent policy initiative. Of course, such an indicator should be region-specific. It can be more rigorous in east China regions since they are eager to make more ambitious changes and have adequate funds and technologies, but can be relatively lower in west China regions where resources are limited. The appropriate set of this type of performance measure for local politicians can potentially increase enforcement of various existing environmental regulations, such as the water pollution prevention and control law, cleaner production promotion law and circular economy promotion law (Su et al., 2013). Also, industrial development policies should be based upon local water resource endowment. It is well-known that the northern China is facing serious water shortages. Thus, the central government should consider guiding water-consuming industries to southern regions where water resources are more available. For instance, a recent study on Liaoning (a heavy industrial province in northeast China)'s water footprint recognized that Liaoning is a net water export region through its trade (Dong et al., 2013), further exacerbating its water shortage issue and leading to that its main river (the Liao River) has become the most polluted of the seven largest national river systems (Wang et al., 2011). This situation requires quick action on phasing out these water-consuming and polluting industries.

Second, economic instruments can play a key role on reducing industrial wastewater discharge. For example, taxation policy can be a major player. By taxing the industrial wastewater discharged by industries, the funds received can be directly applied to cleaner production and other industrial water-saving initiatives. These taxes would internalize some of the externalities associated giving a true industrial cost for these wastewater emissions. These true social costs of industrial wastewater emission can provide greater incentives to manufacturers for reducing their wastewater emissions through the implementation of cleaner production, source reduction, process integration, and other technological efforts. Also, government can increase water prices so that companies can significantly reduce their water consumption. These surcharges could be used to support innovative industrial wastewater reduction initiatives. This measure will be significantly effective, especially for those small and medium enterprises as they usually have limited money on research investment. However, it will cost more to do business and may cause a migration of organizations to regions where there is either less enforcement or no regulations at all. The race-to-the-bottom and the search for pollution havens may cause organizations to relocate to other regions within China (particularly the west China) or internationally. A potential consequence is that the dirtiest companies will relocate to regions where economic development is so poor (i.e. western regions) that environmental regulation enforcement takes a blind eye. Unintended consequences should be carefully monitored. Having an LMDI based decompositional analysis to monitor these potential policy initiatives can provide insights into whether these detrimental shifts are occurring, whether it is in China or internationally.

Third, technology improvement efforts should be made. A previous study proved that the application of advanced cleaner production technologies at the corporate firm level can reduce both freshwater consumption and industrial wastewater discharge in Liaoning province (Geng et al., 2010). These efforts require significant resource allocation to increase wastewater reduction related research and development (R&D). Other technologies, especially the emerging industrial water management technologies, such as water pinch technology (Foo et al., 2005; Dakwala et al., 2009), can significantly reduce industrial wastewater emission and freshwater consumption for one individual company due to its process synthesis nature. In addition, efforts should be made to supplement individual company level R&D investment in these environmental technologies by encouraging broader collaboration among different organizations. In China, this may be easier to complete due to rapid development of industrial parks, in all regions of China, with over 6600 industrial parks currently in operation (Geng and Zhao, 2009). These industrial parks typically share their water related infrastructure. This close proximity industrial aggregation creates opportunities for industrial wastewater reuse and recycling collaborations. A collaborative industrial park case study in the Tianjin economic development area (TEDA) exemplifies the great potential for reducing total industrial wastewater emissions with a decrease of 45.6%, and a secondary economic benefit of reducing total costs by 10.37% (Geng et al., 2007). Another study further explored the effectiveness of appropriate pricing strategies on reducing total industrial wastewater emissions in TEDA (Geng, 2005). However, such initiatives only occurred in east China, not the west or inland regions, indicating that technology transfer should be undertaken so that more industrial parks in west or inland regions can benefit from such an application. Therefore, collaborative R&D efforts that provide more synergistic opportunities should be encouraged and implemented across the whole country.

Finally, capacity-building efforts should be initiated. Governmental agencies can effectively organize various capacity-building programs to, at minimum, increase industry's awareness. Industry would need to recognize that their licenses to operate and legitimacy may be called into question by their communities or even by their customers. Also, these various initiatives can provide business values from a variety of perspectives including cost efficiencies and potential revenue generation (e.g. through development and marketing of new technologies developed for wastewater management). The focus of these awareness raising programs should cover not only urban areas but also remote rural areas as many township or village owned enterprises are still employing obsolete equipment and technologies and feel reluctant to make changes due to their myopic perspectives. Sometimes awareness raising in these publicly owned enterprises can truly be eye-opening as communities begin to realize that they may be poisoning themselves for short-sighted economic development goals. The difficulty in many of these situations is the extreme poverty levels associated with these smaller, rural organizations. Even if awareness was raised concerning the impacts of wastewater emissions and the available mitigation technologies, the resources from these publicly, rural, owned companies may be severely limited. In addition, regional development imbalance further exacerbates this issue. Comparing with rich east Chinese regions, inland and west regions have relatively weak environmental awareness and lower capacity on applying advanced technologies and management practices. Consequently, a domestic collaboration mechanism should be established. Such broader regional collaborative initiatives can be fruitful programmatic and policy initiatives. For instance, super mega cities (such as Beijing and Shanghai) may continue to seek industrial relocation policies. But if these 'encouraged' relocations are to occur, it behooves the central government to 'encourage' these mega cities to provide technological, financial and capacity-building support to the hosting regions. As such, since most eastern regions have more advanced technologies than those existing in western regions, the central government should seek to facilitate the state-of-the-art technologies and information on industrial wastewater emission to be transferred from rich eastern regions to poor western regions. For instance, given the population shifts and migration trends, both Zhejiang and Guangdong provinces should actively engage in helping both Sichuan and Chongqing regions since both of them host a large amount of immigration workforces from Sichuan and Chongqing. The shifting population migration workforce is a real issue for other environmental concerns as well and should be carefully monitored through additional analyses.

6. Conclusions

China has experienced remarkable industrialization and urbanization over the past couple decades. Such a rapid development has wrought a serious industrial wastewater emission challenge. However, due to China's huge size and imbalanced development, different regions have different industrial wastewater emission patterns.

Our LMDI based decompositional analysis contributes to this improved understanding with significant policy insights. Overall we find that economic development factor is the dominating driving factor of industrial wastewater emission changes in all provinces during the study period, followed by industrial structure and population, while technology improvement offsets total industrial wastewater emissions.

Also, significant regional disparity on industrial wastewater emission exists. The more industrialized east regions have much higher industrial wastewater emissions, while the relatively backward west regions have less industrial wastewater emissions. Several mega cities even have decreased industrial wastewater emissions due to their industrial structure changes. Therefore, industrial wastewater management strategies should address environmental and social (sustainable development) issues through multiple dimensions. Efforts include policy reforms, economic instruments, technology improvement and improving public and industrial awareness of water usage policies for conservation and utilization.

Overall, we believe that these initiatives and the modeling approach presented in this paper can be replicated in other regions of the world, but significant political and regulatory controls will be needed if these policy initiatives are to truly overcome many of the economic, technological, industrial, and population limitations that exist, especially in developing nations.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2014.04.047.

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