Water Policy 23 (2021) 310–326

Decomposing drivers of changes in productive and domestic water use based on the logarithmic mean Divisia index method: a regional comparison in Northern China

Wenfei Lyu[a,b], Yuansheng Chen[a,*], Zhigang Yu[a,b], Weiwei Yao[a] and Huaxian Liu[a,b]

[a]*Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China*
**Corresponding author. E-mail: chenys@igsnrr.ac.cn*
[b]*College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China*

Abstract

It is crucial to consider regional heterogeneity while analyzing drivers of changes in sectoral water use for developing differentiated and effective demand-regulation strategies in China. By using the logarithmic mean Divisia index method, this study compares dynamic influences of intensity, structure and scale factors on changes in productive and domestic water use during 2003–2017 between Tianjin (a socio-economic developed region) and Hebei (less-developed). The results show that the scale effect stimulated the growth of productive water use in both regions, while structure and intensity effects restrained such growth. The three effects all stimulated the growth of domestic water use in most years in both regions. In both regions, the largest contributor to changes in productive and domestic water use was the scale and intensity effect, respectively. However, in the two regions, the synergies of three effects resulted in different change trends of productive water use, and cumulative contributions of sub-sectors to the intensity, structure and scale effects were not exactly the same. Tianjin and Hebei need to keep on adjusting industrial structure and lowering water-use intensity to control future growth of productive water use and take strict measures to tackle the increasing trend of domestic water use but should have different policy implementation focuses.

Keywords: Comparison; Domestic water use; LMDI model; Northern China; Productive water use; Water-demand management

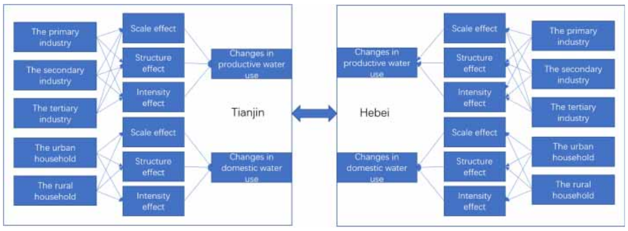
Highlights

- The drivers of water-use changes of regions at different socio-economic development stages were compared.
- The forces of driving-factors of productive and domestic water use changed with time.

doi: 10.2166/wp.2021.137

- The root cause of changes in productive and domestic water use was not exactly the same in the two regions.
- The results are helpful for formulating differentiated water-demand management policies.

Graphical Abstract



Introduction

Water scarcity occurs in many regions of the world (Jovanovica *et al.*, 2020). Water-demand management (WDM), which aims to regulate water demand and seek efficient use of water resources (Brooks, 2007; Wang *et al.*, 2014b), is essential for adaptation to the increasing incidence of water scarcity (Brown *et al.*, 2019). In past decades, China has witnessed rapid socio-economic development, accompanied with unprecedented pressure on water resources and water supply. The Chinese government has realized the importance of WDM to address water scarcity problems and achieve sustainable development. The Water Law of the People's Republic of China, revised in 2002, explicitly puts forward the requirement of building a water-saving society (Standing Committee of the National People Congress (SCNPC), 2002). Since 2002, China has introduced a series of policies to regulate water demand in agricultural, industrial, service sectors and cities. The recent top-level plans have emphasized joint efforts of water-saving in processes of production, living and consumption (National Development and Reform Commission (NDRC) *et al.*, 2016); and differentiated goals, directions and key tasks of water-saving according to local conditions of different regions (NDRC *et al.*, 2017). These plans urge water authorities in China to pursue more comprehensive and fine-grained practices of WDM. To make effective and more targeted WDM strategies, it is necessary to analyze the influencing factors of water use and consider regional and sectoral heterogeneity. Given this background, this study makes a comparative analysis of drivers of sectoral water use in regions at different stages of socio-economic development and provides WDM policy suggestions for different regions.

In this study, 'water use' refers to water withdrawal, which means water removed from a source and used for human needs (Gleick, 2003), and total water use encompasses different types of sectoral water use, e.g. industrial, agricultural and residential (Wang *et al.*, 2015). Extensive research has been carried out to explore the factors influencing water use at the regional level using econometric or regression models. For example, many researchers conduct a Kuznets curve (i.e. an inverted U-shaped curve) analysis to investigate the relationship between economic development and water use (Duarte *et al.*, 2013) or sectoral water use (Jia *et al.*, 2006; Katz, 2015) using econometric models. Sohn (2011) identified water price policies, type of water management, city size and density, and precipitation to be significant factors influencing urban water use quantity using a regression model (Sohn, 2011). Khanji (2017) explored the impact of various socio-economic factors on agricultural and nonagricultural water withdrawal also by conducting an econometric model. In his results, population density, arable land per capita, trade openness and employment significantly influenced agricultural water withdrawal. Food production index, trade openness, GDP per capita, industrial structure and employment significantly influenced nonagricultural water withdrawal (Khanji, 2017).

Furthermore, some empirical studies have quantified the contributions made by multiple drivers to changes in water use by decomposition analysis. Structural decomposition analysis (SDA) is a kind of decomposing techniques. Wang *et al.* (2014a) allocated changes in U.S. industrial water withdrawals in 1997–2002 to changes in population, GDP per capita, water-use intensity, production structure, and consumption patterns by using SDA based on the 1997 U.S. economic input–output (EIO) table and found that consumption pattern change was the largest net contributor to changes in water withdrawals (Wang *et al.*, 2014a). Zhang *et al.* (2020) also adopted SDA and EIO tables to quantify the relative contributions of changes in five influencing factors to changes in China's water use (Zhang *et al.*, 2020). SDA is scientific but is difficult to use for time-series analysis and region comparisons because of its dependency on EIO tables (Wang & Li, 2018). However, the other decomposing technique, i.e. index decomposition analysis (IDA), can apply time-series data and panel data easily (Ang *et al.*, 2016). Among the IDA methods, the Laspeyres and Divisia index methods are most widely used (Shang *et al.*, 2016). Shang *et al.* (2017) introduced the Laspeyres index method to decompose changes in industrial water use in Tianjin. Zhang *et al.* (2015) quantified yearly the contributions of underlying factors to changes in water use in Urumchi by a refined Divisia index method, i.e. the logarithmic mean Divisia index (LMDI) method. Zhang *et al.* (2018) also employed the LMDI to calculate contributions of drivers to agricultural water use in the Heihe River basin. After comparing different models linked to Laspeyres and Divisia indices, Ang (2004) recommended LMDI models due to their desirable properties, such as perfect decomposition, theoretical foundation and adaptability.

This study utilizes the LMDI method to quantitatively analyze and compare the contributions of influencing factors to changes in sectoral water use in different regions in China. Sectoral water use in this study includes productive water use, which refers to water used in the production process, and domestic water use, which refers to water used for indoor and outdoor household purposes (Sohn, 2011). Table 1 shows the specific scope of productive and domestic water use, and their sub-sectoral water use. We select two provincial-level administrative regions at different stages of socio-economic development in China, i.e. Tianjin and Hebei as the study area. The influences of economic scale, industrial structure, water-use intensity, urbanization and population size on water use are comprehensively studied. Firstly, the changes in productive and domestic water use in Tianjin and Hebei during 2003–2017 are analyzed.

Table 1. Specific scope of productive and domestic water use.

Sectoral water use	Sub-sectoral water use	Scope
Productive water use	Primary industry water use	Water use for agriculture, forestry, animal husbandry, fishery and livestock
	Secondary industry water use	Industrial and construction water use
	Tertiary industry water use	Water use for various service industries, such as merchandise trade, catering and accommodation, transportation, warehousing, post and telecommunications, culture, education and health, and government organizations
Domestic water use	Urban domestic water use	Indoor and outdoor water use for urban household
	Rural domestic water use	Indoor and outdoor water use for rural household

Secondly, the drivers of changes in productive and domestic water use are temporally decomposed for each region. The results obtained are compared indirectly to investigate the similarities and differences between the two regions. Finally, some differentiated policy suggestions are put forward for improving regional WDM. The results of this study are conducive to provide an analytical basis for the formulation of more targeted and comprehensive WDM policies.

Materials and methods

Factor decomposition using the LMDI model

The aim of this study is to quantify the impact of economic scale, industrial structure and productive water-use intensity on regional productive water use, and the impact of population size, urbanization and domestic water-use intensity on regional domestic water use. Economic scale and population size can be summarized as the scale factor, and changes in sectoral water use caused by the scale factor are defined as the scale effect. Industrial structure and urbanization can be summarized as the structure factor, and changes in sectoral water use caused by the structure factor are defined as the structure effect. Productive and domestic water-use intensity can be summarized as the intensity factor, and changes in sectoral water use caused by the intensity factor are defined as the intensity effect.

We adopt the LMDI method to quantitatively decompose changes in sectoral water use into scale, structure and intensity effects. The LMDI is an improvement of the traditional Divisia index by leaving no residual and effectively handling the zero value in the data set (Ang & Choi, 1997). This method can be divided into eight models in temporal decomposition analysis based on the nature of an aggregate indicator (quantity indicator versus intensity indicator), a decomposition procedure (additive versus multiplicative decomposition) and a weight formula (LMDI-I versus LMDI-II) (Ang, 2015). The application scenarios for each model vary. The aggregate indicator in this study is sectoral water use, which is a quantity one. The additive decomposition procedure is more suited when used in conjunction with a quantity indicator (Ang, 2015). In addition, the weight formula of LMDI-I has a simpler and more intuitive form than LMDI-II. For the above reasons, we choose the quantity indicator decomposition model based on the LMDI-I weight equation and an additive decomposition procedure.

The relationship between the aggregate sectoral water-use and influencing factors can be expressed by the following identity:

$$W_p = \sum_{i=1}^{n} \frac{W_{pi}}{\mathrm{GDP}_i} \times \frac{\mathrm{GDP}_i}{\mathrm{GDP}} \times \mathrm{GDP} \tag{1}$$

$$W_h = \sum_{i=1}^{m} \frac{W_{hi}}{\mathrm{POP}_i} \times \frac{\mathrm{POP}_i}{\mathrm{POP}} \times \mathrm{POP} \tag{2}$$

where W_p is the total quantity of productive water use, that is, the sum of water use of primary, secondary and tertiary industries. W_h is the total quantity of domestic water use, that is, the sum of urban and rural domestic water use. GDP is the gross regional product; GDP_i is the *GDP* (*value-added*) of productive sub-sector i; W_{pi} is the water use of productive sub-sector i; POP is the total population of a region; POP_i is the population of domestic sub-sector i; W_{hi} is the water use of domestic sub-sector

i; and n and m indicate the number of productive sub-sectors and domestic sub-sectors, respectively. Equations (1) and (2) can be further expressed as:

$$W_p = \sum_{i=1}^{n} E_{pi} \times Q_{pi} \times S_p \tag{3}$$

$$W_h = \sum_{i=1}^{m} E_{hi} \times Q_{hi} \times S_h \tag{4}$$

with $E_{pi} = W_{pi}/\text{GDP}_i$, $Q_{pi} = \text{GDP}_i/\text{GDP}$, $S_p = \text{GDP}$, $E_{hi} = W_{hi}/\text{POP}_i$, $Q_{hi} = \text{POP}_i/\text{POP}$, $S_h = \text{POP}$, where E_{pi}, Q_{pi}, S_p, E_{hi}, Q_{hi} and S_h represent the productive water-use intensity, industrial structure, economic scale, domestic water-use intensity, urban–rural structure and population scale, respectively.

Using the additive decomposition procedure, we define productive and domestic water use in the base year as W_p^0 and W_h^o, respectively, and in the tth year as W_p^t and W_h^t, respectively. Then, the difference between the two is:

$$\Delta W_p = W_p^t - W_p^0 = \Delta W_{Ep} + \Delta W_{Qp} + \Delta W_{Sp} \tag{5}$$

$$\Delta W_h = W_h^t - W_h^0 = \Delta W_{Eh} + \Delta W_{Qh} + \Delta W_{Sh} \tag{6}$$

We define ΔW_p and ΔW_h as the total effect or synergies, representing the total change of productive and domestic water use in the time period [0, t], respectively. ΔW_{Ep}, ΔW_{Qp} and ΔW_{Sp} represent the intensity, structure and scale effect in productive water-use decomposition, respectively. ΔW_{Eh}, ΔW_{Qh} and ΔW_{Sh} represent the intensity, structure and scale effect in domestic water-use decomposition, respectively. The LMDI method is perfect in decomposition and gives no residual, so the right-side of Equations (5) and (6) do not contain a residual term. Supplementary Material, Appendix A provides the proof of LMDI's perfect decomposition. The driving effects can be expressed as:

$$\Delta W_{Ep} = \sum_{i=1}^{n} \omega_{ji}^t \times \text{In} \frac{E_{pi}^t}{E_{pi}^0} \tag{7}$$

$$\Delta W_{Qp} = \sum_{i=1}^{n} \omega_{ji}^t \times \text{In} \frac{Q_{pi}^t}{Q_{pi}^0} \tag{8}$$

$$\Delta W_{Sp} = \sum_{i=1}^{n} \omega_{ji}^t \times \text{In} \frac{S_p^t}{S_p^0} \tag{9}$$

$$\Delta W_{Eh} = \sum_{i=1}^{m} \omega_{ji}^t \times \text{In} \frac{E_{hi}^t}{E_{hi}^0} \tag{10}$$

$$\Delta W_{Qh} = \sum_{i=1}^{m} \omega_{ji}^t \times \text{In} \frac{Q_{hi}^t}{Q_{hi}^0} \tag{11}$$

$$\Delta W_{Sh} = \sum_{i=1}^{m} \omega_{ji}^t \times \text{In} \frac{S_h^t}{S_h^0} \tag{12}$$

ω_{ji}^t stands for the LMDI-I weight of sub-sector i in sector j ($j = p$, h; p and h stand for the productive and domestic sectors, respectively) and can take the following form:

$$\omega_{ji}^t = \begin{cases} \dfrac{W_{ji}^t - W_{ji}^0}{(W_{ji}^t / W_{ji}^0)}, & W_{ji}^t \neq W_{ji}^0; \\ W_{ji}^t, & W_{ji}^t = W_{ji}^0 \neq 0; \\ 0, & W_{ji}^t = W_{ji}^0 = 0 \end{cases} \tag{13}$$

The detailed mathematical derivation is available in Supplementary Material, Appendix B. The sign of the decomposition results ($\pm$) indicates driving-force direction: positive represents the stimulation of water use and negative the inhibition of water use. The absolute value of the decomposition results indicates the magnitude of the driving forces.

Data and processing

The water-use data in this study are derived from the Tianjin Water Resources Bulletin (2003–2017) (Tianjin Water Authority (TWA), 2004–2018) and the Hebei Water Resources Bulletin (2003–2017) (Hebei Water Resources Department (HWRD), 2004–2018), except for the data of Hebei's urban and rural domestic water use, sourced from the Hebei Water Resources Research Institute. The economic and demographic data are derived from the Tianjin Statistical Yearbook (2004–2018) (Statistical Bureau of Tianjin (SBT), 2004–2018), Hebei Economic Yearbook (2004–2018) (General Office of Hebei Provincial People Government *et al.*, 2004–2018) and New Hebei 60 years 1949–2009 (Statistical Bureau of Hebei (SBH), 2009).

Productive water use is subdivided into water use of primary, secondary and tertiary industry (Table 1), but the data in the Hebei Water Resources Bulletin are not aggregated like this. Hebei's construction water use is incorporated into public service water use. As construction water use accounts for a small amount of secondary industry water use, we take industrial water use as secondary industry water use and public service water use as tertiary industry water use in the data calculation of Hebei. To avoid the impact of price fluctuations, the economic data are converted according to the 2003 constant price, unless there are notes about exceptions.

The study area

Tianjin and Hebei are located in the North China Plain which lacks water resources (Figure 1) and are components of the Capital Economic Circle (the political and cultural center and one of the economic centers of modern China) with large demand for water resources. The two regions are at different stages of socio-economic development. Tianjin is a socio-economically developed region, while Hebei is less developed. The detailed differences are described below.

Population size and population growth are different between the two regions. Hebei has a larger population than Tianjin, but Tianjin is more densely-populated. In 2017, the population density of Tianjin reached 1,378 people per square kilometer which was 3.7 times higher than that of Hebei. Both regions saw overall steady population growth in 2003–2017, but the growth rate in Tianjin was faster. The average

Fig. 1. Location of the study area.

annual growth rate of permanent residents of Tianjin and Hebei was about 3 and 1%, respectively (Supplementary Material, Figure A1). Notably, however, negative population growth occurred for the first time in Tianjin in 2017.

Tianjin is a highly urbanized area, but Hebei is less urbanized. The urbanization level of Tianjin was far higher than that of the national average, ranking third among the provincial-level administrative regions in China. Since 2011, Tianjin's urbanization rate has remained above 80%, but the growth rate has slowed down. The urbanization rate of Hebei was lower than the national average in 2003–2017. After 2015, the urbanization rate only reached over 50% but grew rapidly (Supplementary Material, Figure A2).

The economy of Tianjin has registered a higher level of development than that of Hebei at a greater speed of growth. GDP per capita can be used to measure the level of economic development in a region. The GDP per capita of Tianjin was about 2.5–2.8 times higher than that of Hebei in 2003–2017 (although the GDP in absolute terms of Hebei was higher than that of Tianjin due to Hebei's larger population). Besides, in the study period, the average annual growth rate of GDP of Tianjin and Hebei was about 13 and 10%, respectively (Supplementary Material, Figure A1), indicating that Tianjin developed faster than Hebei.

The structural differences of the three major industries can also be found in the two regions. Firstly, the internal structure of secondary industry in the two regions is quite different. Tianjin has established an industry pattern underpinned by electronic information, automobiles, metallurgy, chemical, medical, new energy and environmental protection industries (Shang *et al*., 2017). The industry in Hebei is dominated by traditional industries with high resource consumption such as equipment manufacturing, steel, petrochemical and building materials (Yu, 2018). Secondly, the proportion of primary industry to GDP in Tianjin has gradually decreased to an extremely low level (1–4% in 2003–2017), but that in Hebei still keeps a certain proportion (7–15% in 2003–2017), far higher than the national average (Supplementary Material, Figure A3). The relatively large proportion of primary industry in Hebei results from its natural and geographical attributes, and the division of work in the coordinated development of Beijing–Tianjin–Hebei (a modern agricultural base in the Beijing–Tianjin–Hebei region). Finally, in terms of the industrial structure upgrading process, Tianjin's upgraded level of industrial structure is higher than Hebei's. The ratio of the value-added of tertiary industry to that of secondary industry (TS ratio) could reflect the upgrading level of industrial structure to some extent. The TS ratio in Tianjin was higher than that in Hebei throughout the study period (Supplementary Material, Figure A4).

The distinct social and economic characteristics of the two regions would probably make the influences of driving-factors on water-use changes different.

Results and discussion

Water-use changes in the study area 2003–2017

Figure 2 demonstrates the water use of Tianjin and Hebei in 2003–2017. Regarding the total productive water use, the two regions exhibited different trends that productive water use of Tianjin fluctuated and increased by 4.7% overall in 2003–2017 (Figure 2(a)), while that of Hebei increased slightly in 2003–2006, and decreased after 2006, with an overall decrease of 13.0% (Figure 2(b)). Among the three major industries, primary industry was the largest water user in both regions, but its water use presented a declining trend during the study period, with that of Tianjin and Hebei decreased by 5.3 and 17.9%, respectively. Tertiary industry used the least water in both regions, but its water use grew sharply, with that in Tianjin and Hebei increasing by 56.1 and 90.1%, respectively. Secondary industry water use showed different trends in the two regions: increasing overall by 16.6% in Tianjin (from decreasing to increasing with the turning point at 2008) and however, declining overall by 22.5% in Hebei.

The total domestic water use of both regions presented an upward trend in 2003–2017, with that of Tianjin and Hebei increasing overall by 45.3 and 28.0%, respectively. Regarding sub-sectorial domestic water use, the urban domestic water use of both regions also showed an increasing trend, with that of Tianjin and Hebei increasing by 102.4 and 65.6%, respectively, while the rural domestic water use of both regions exhibited different trends. The rural domestic water use of Tianjin decreased by 54.7%, but that of Hebei fluctuated in a small range and stayed stable overall. In Tianjin, the domestic water use of urban residents was greater than that of rural residents throughout the study period, but in Hebei that of urban residents had been smaller than that of rural residents until 2015.

It can be seen from the above analysis that during the study period, the growth rate of total productive and total domestic water use in Tianjin was greater than that of Hebei and the change trends of water use of sub-sectors had some resemblances and distinctions between the two regions. Besides, compared with the change trend of productive water use, that of domestic water use had its own features. Briefly, productive water use was better controlled than domestic water use in the study area, because productive water use did not increase significantly under the rapid growth of regional economy, while domestic water use grew a great deal with regional population growth during the study period.

Decomposition of changes in productive water use

Figure 3 and Table 2 present factor decomposition results of changes in productive water use in each region from 2003 to 2017. Figure 3 depicts the annual variations of different driving-factors (the yearly

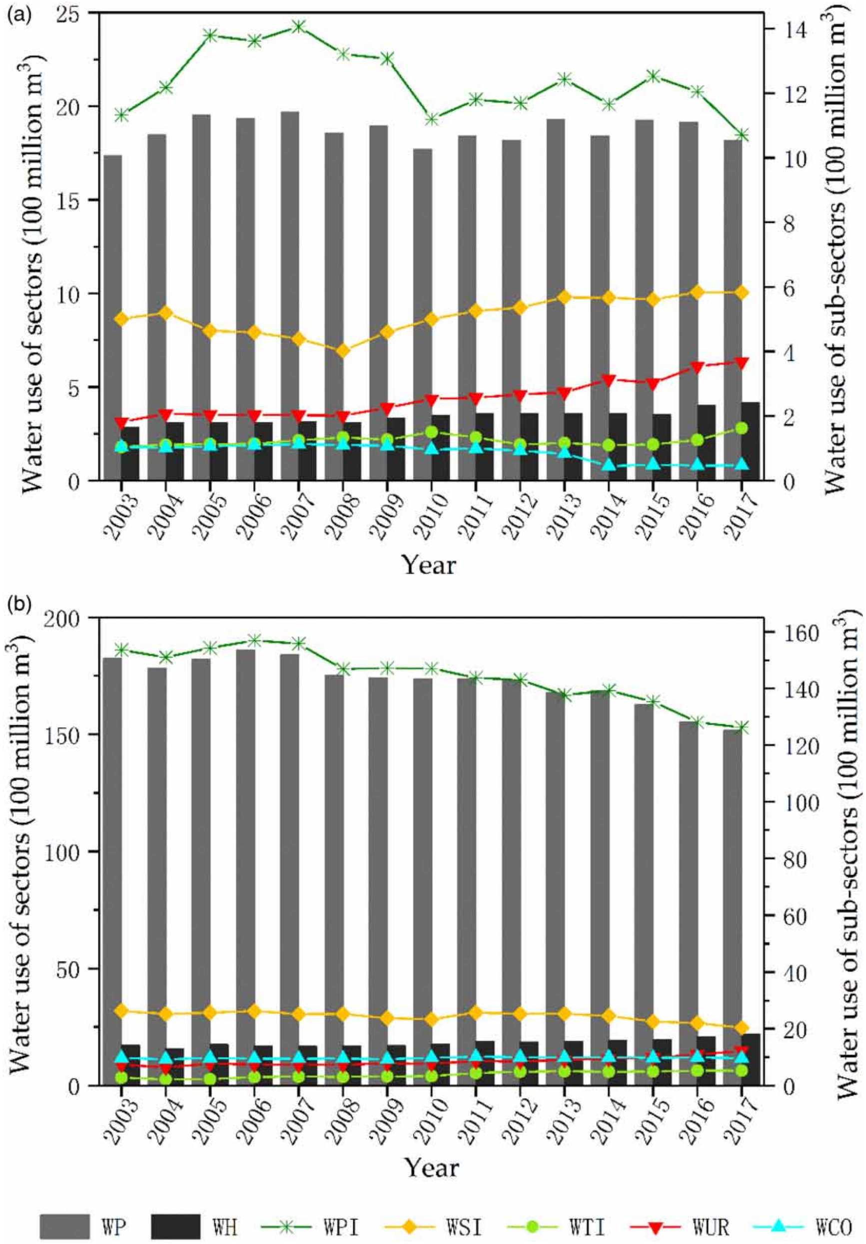


Fig. 2. Water use in the study area during 2003–2017. (a) Tianjin; (b) Hebei. WP: productive water use; WH: domestic water use; WPI: primary industry water use; WSI: secondary industry water use; WTI: tertiary industry water use; WUR: urban domestic water use; WCO: rural domestic water use.

decomposition results in table form are also available in Supplementary Material, Appendix D) and Table 2 the cumulative contributions sorted by each sub-sector.

The scale effect has positive values throughout the study period, while the intensity effect and the structure effect have negative values (Figure 3), indicating in both regions the economic growth

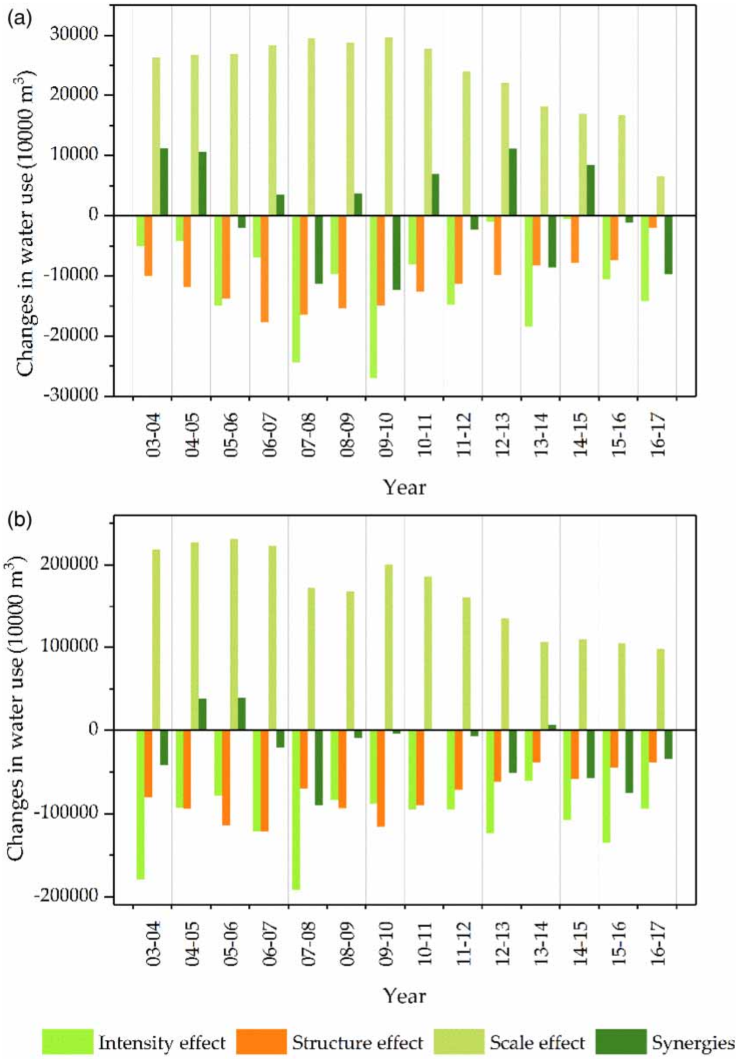


Fig. 3. Annual variations of driving effects of changes in productive water use. (a) Tianjin; (b) Hebei.

Table 2. Cumulative contribution and contribution rate of sub-sectors of productive water use with respect to the three effects.

		Contribution (100 million m^3)				Contribution rate (%)			
Region	Effect	Primary industry	Secondary industry	Tertiary industry	Synergies	Primary industry	Secondary industry	Tertiary industry	Synergies
Tianjin	Intensity	−6.17	−8.44	−1.43	−16.04	38.5	52.6	8.9	100.0
	Structure	−16.40	0.57	−0.14	−15.97	102.7	−3.5	0.8	100.0
	Scale	21.97	8.71	2.15	32.82	66.9	26.5	6.5	100.0
Hebei	Intensity	−111.36	−40.76	−2.88	−155.00	71.8	26.3	1.9	100.0
	Structure	−112.16	1.80	0.62	−109.74	102.2	−1.6	−0.6	100.0
	Scale	196.09	33.04	4.73	233.87	83.8	14.1	2.0	100.0

stimulated productive water use; however, industrial structure adjustment and changes in productive water-use intensity reduced productive water use. The absolute value of synergies shows that the contribution of the scale effect was the greatest and that of the structure effect the smallest in both regions (Table 2). Therefore, economic growth was the dominant reason for the changes in productive water use in Tianjin and Hebei. This is consistent with the literature, concluding rapid growth of regional economy has a strong pulling effect on resources and energies (Li *et al*., 2015; Shang *et al*., 2017; Liu *et al*., 2018). A difference between the two regions is that during the study period, in Tianjin the stimulating effect of economic growth was greater than the inhibiting effects of water-use intensity decreases and industrial structure adjustments, eventually leading to the increase of productive water use; while in Hebei the opposite occurred, eventually leading to the decline of productive water use. This indicates that the economically developed Tianjin with faster economic growth may face greater pressure to control the growth of productive water use than the less-developed Hebei.

The forces of driving-factors changed with time (Figure 3). Overall, the scale and structure effects in the two regions experienced a process of gradual strengthening and then weakening. The scale effect's trend was consistent with the trend of economic growth. Notably, the economic growth of Tianjin and Hebei slowed down further after 2013 and 2011, respectively (before the turning point, the average annual economic growth rate of Tianjin and Hebei was as high as 16 and 12%, respectively, but after the turning point, dropped to 8 and 7%, respectively), and the scale effect exhibited a clear, associated reduction. The reason for the weakening trend in the structure effect, in the later part of the study period, was that the decline in the proportion of the value-added of primary industry to regional GDP continued to shrink. Decreases of productive water use, caused by the adjustment of industrial structure from the high-water-use primary industry to the low-water-use secondary and tertiary industry, got smaller, which was more obvious in Tianjin. In contrast with the scale and structure effects, the intensity effect fluctuated greatly (Zhang *et al*., 2014), mainly because the marginal cost of water-saving would get increasingly high and it is difficult to continually improve water-use efficiency. When water-use efficiency arrives at a high level, greater efforts in water conservation and stronger policy measures are often required to further lower water-use intensity to enhance the inhibition of intensity effect. For example, after Tianjin started the pilot construction of a water-saving society in 2006 and applied 'the strictest water-resources management system' in 2012, the weakened intensity effect recovered to some extent.

The cumulative contributions of each sub-sector to the three effects in Table 2 explain the root cause of changes in productive water use. The negative values of the intensity effect contributed by the three industries in both regions reveal that the changes in productive water-use intensity of the three industries all reduced productive water use, while the positive values of the scale effect suggest that the changes in economic scale of the three industries all increased productive water use in both regions. The signs of the structure effect contributed by the three industries indicate that only changes in the proportion of primary industry to GDP reduced productive water use in both regions. In both regions, primary industry made the largest contribution to the total scale and total structure effects, although the growth rate of primary industry in 2003–2017 was lowest among the three industries (4 and 3% overall in Tianjin and Hebei, respectively) and the ratio of its value-added to regional GDP declined only slightly (that of Tianjin and Hebei dropped by 2 and 5%, respectively); in contrast, tertiary industry contributed least to the total scale and total structure effects. In terms of the contribution of the three industries to total intensity effect, secondary industry ranked first in Tianjin, indicating that secondary industry had the largest reduction in water-use intensity among the three industries (Wang & Li, 2018). However, primary industry ranked first in Hebei. The main reason for this inconsistency was that the two regions differed in their focus on water conservation. Tianjin, a historic industrial city, has attached great importance to water-saving in industrial production against the background of local water shortages. Since 2006, the industrial water-use efficiency of Tianjin has taken the lead in China (Shang *et al.*, 2016). A large agricultural province, Hebei, has paid more attention to the improvement of agricultural water-use efficiency, and its water-use efficiency in primary industry was relatively high compared to other regions in China. In addition, the tertiary industry contributed the least to total intensity effect in both regions and water-saving space of tertiary industry needs to be excavated, as its water use grew rapidly.

Decomposition of changes in domestic water use

Figure 4 and Table 3 present factor decomposition results of changes in domestic water use in each region from 2003 to 2017 (the yearly decomposition results in table form are also available in Supplementary Material, Appendix D).

In most years, the scale, structure and intensity effect have positive values in Tianjin and Hebei (Figure 4) and the synergies are also positive (Table 3). Therefore, the three effects all stimulated the growth of domestic water use in both regions in 2003–2017 overall. The cumulative contributions of the intensity, structure and scale effects to changes in domestic water use in 2003–2017 were 87, 5 and 36 million m^3, respectively, in Tianjin, and 258, 30 and 188 million m^3, respectively, in Hebei (Table 3). The intensity effect contributed the greatest and the structure effect the smallest to domestic water-use changes in both regions. This indicates that the increase in household water-use intensity was the dominant reason for the increase in domestic water use, while population growth and the development of urbanization had relatively little effect. The increase in water-use intensity is associated not only with the continual improvement of residents' living standards and water supply conditions, but also with the fact that local governments have not imposed strict restrictions on domestic water-use intensity, mainly resorting instead to water price policies and awareness campaigns to cultivate people's awareness of water conservation. Clearly, these voluntary water-saving measures cannot effectively curb the rising water demand caused by people's pursuit of high living standards.

The scale effect and structure effect in both regions changed gradually and smoothly, but the intensity effect in both regions changed greatly (Figure 4). The change trends of scale and intensity effects were roughly consistent with the trends of population growth and changes in domestic water-use intensity, respectively. For example, the stimulating role of the scale effect became strongest in Tianjin and Hebei in 2015 and 2010, when the growth rate of the regional population was largest. In Tianjin, due to the negative growth of the permanent residents in 2017, the scale effect turned to a weak inhibition of domestic water-use growth. However, the annual variations of structure effect were not exactly in line with the changes in the urbanization rate in the study area. This inconsistency occurred in Hebei where the structure effect demonstrated a weak inhibitory role after 2010 in spite of the ever-rising urbanization rate (Supplementary Material, Figure A2). It seems to go against the general conclusion that urbanization in China would bring about growth in water use (Bao, 2014; Jin *et al.*, 2018; Sun *et al.*, 2019), because with urbanization more residents move to cities and towns where improved water and energy-use conditions and living standards stimulate water demand. The general conclusion may not hold in less-urbanized areas where the increase in urban domestic water use caused by the rise in the proportion of urban residents cannot rival the decrease in rural domestic water use caused by the

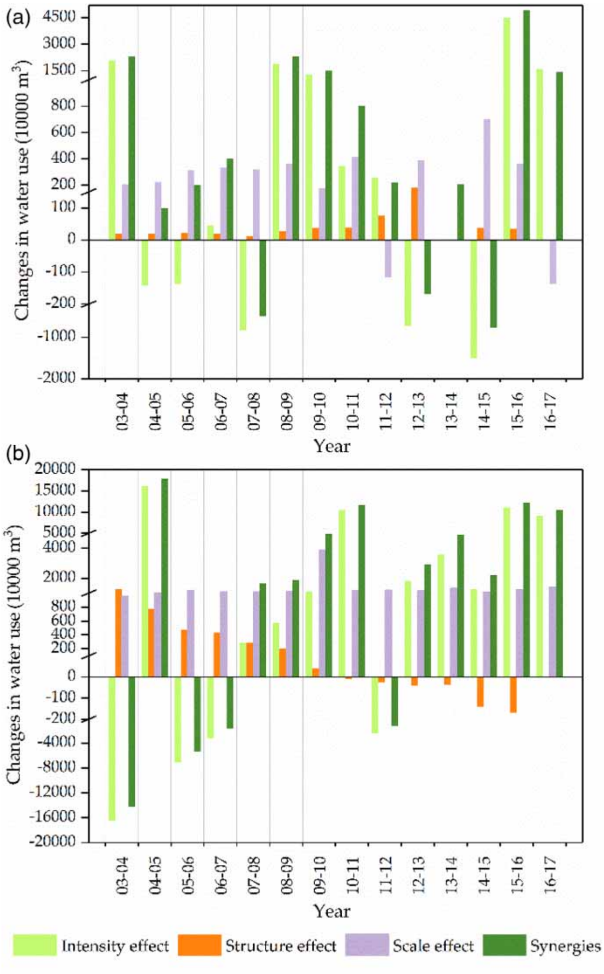


Fig. 4. Annual variations of driving effects of changes in domestic water use. (a) Tianjin; (b) Hebei. *Note*: The decomposition results between 2013 and 2014 in Tianjin are omitted because of an inconsistent statistical caliber.

Table 3. Cumulative contribution and contribution rate of sub-sectors of domestic water use with respect to the three effects.

		Contribution (100 million m^3)			Contribution rate (%)		
Region	Effect	Urban residents	Rural residents	Synergies	Urban residents	Rural residents	Synergies
Tianjin[a]	Intensity	1.04	– 0.17	0.87	120.0	– 20.0	100.0
	Structure	0.16	– 0.11	0.05	313.2	– 213.2	100.0
	Scale	0.26	0.10	0.36	72.8	27.2	100.0
Hebei	Intensity	– 0.12	2.70	2.58	– 4.5	104.5	100.0
	Structure	4.07	– 3.77	0.30	1,361.4	– 1,261.4	100.0
	Scale	0.87	1.01	1.88	46.2	53.8	100.0

[a]The cumulative contribution excludes the change between 2013 and 2014, because of an inconsistent statistical caliber.

decline in the proportion of rural residents. Therefore, the trend of structure effect is related not only to the trend of changes in the urbanization rate but also to the degrees of urbanization.

The cumulative contribution of each sub-sector to the three effects in Table 3 reveals the root cause of changes in domestic water use. Regarding the total structure effect, the contribution of urban sector was greater than that of the rural sector in both regions. However, the two regions differed in terms of the total intensity effect and the total scale effect. The contribution of the urban sector was greater than that of the rural sector in Tianjin, while the opposite was true in Hebei. This indicates that the stimulating effect of domestic water use intensity and population scale in Tianjin was mainly caused by the urban sector, but in Hebei by the rural sector.

Conclusions and policy suggestions

By using the LMDI method, the influences of intensity, structure and scale factors on the changes in productive and domestic water use in 2003–2017 were quantitatively decomposed in Tianjin and Hebei. Based on the results, the following conclusions are drawn.

The influences of scale, structure and intensity factors on changes in productive water use in Tianjin and Hebei had some similarities. Firstly, the structure and intensity effects restrained water-use growth on the whole, while the scale effect stimulated the growth. Secondly, economic growth was the dominant reason for the changes in productive water use. Thirdly, the scale and structure effects experienced a process of gradual strengthening and then weakening; however, the intensity effect fluctuated greatly. Lastly, changes in productive water-use intensity of the three industries all reduced productive water use, while changes in economic scale of the three industries all increased productive water use. Primary industry contributed the most to the scale and structure effects, and tertiary industry contributed the least to all the three effects. The difference between Tianjin and Hebei mainly lay in two aspects. In Tianjin, the stimulating effect of economic growth was greater than the inhibiting effects of water-use intensity decreases and industrial structure adjustments, eventually leading to the upward trend of productive water use; while in Hebei the opposite occurred, eventually leading to the downward trend of productive water use. Moreover, secondary industry contributed the most to intensity effect in Tianjin, while primary industry contributed the most to intensity effect in Hebei.

For changes in domestic water use, the influence of driving-factors of Tianjin and Hebei also had some similarities and differences. The similarities between the two regions were mainly that the three effects all stimulated water-use growth overall; that the increase in household water-use intensity was the dominant reason for changes in domestic water use; that the scale and structure effects changed gradually and smoothly, but the intensity effect fluctuated greatly; and that in terms of the cumulative contribution of each sub-sector to the structure effect, the urban sector contributed more than the rural sector in both regions. One of the important differences was that the stimulating effect of domestic water-use intensity and population scale was mainly caused by the urban sector in Tianjin, but by the rural sector in Hebei. The other one was that owing to the different degrees of urbanization in the two regions, the annual variations of structure effect in Tianjin were basically consistent with the changes in the urbanization rate, while those in Hebei were not exactly in line with the changes in the urbanization rate.

The future economy in China is expected to remain stable growth with a potential growth rate of 5.30–6.24% in 2020–2025 (Lu, 2019), which will still drive the growth of productive water use. Besides, with the development of society and economy, people's living standards will continue to improve. Therefore, domestic water-use intensity will probably keep increasing and the rising domestic water use will ensue. In the context of China's efforts to promote water conservation throughout society, the local governments of the study area should keep on adjusting industrial structure and lowering water-use intensity to consolidate the achievements in controlling productive water use and take more strict measures to tackle the increasing trend of domestic water use in the future. Based on our results, different regions should have different policy implementation focuses.

Hebei needs to accelerate the structural adjustment among the three industries, continuing to reduce the proportion of the high-water-use primary industry and promoting the development of the tertiary industry. Furthermore, in the secondary industry, the proportion of heavy and chemical industries should be gradually reduced, and the strategic emerging industries should be promoted. In terms of reducing the water-use intensity, the focuses of Hebei are on upgrading the traditional industries with new technologies and processes and eliminating the outdated production capacity to improve the water-use efficiency of secondary industry; and on vigorously promoting water-saving irrigation, optimizing the planting structure of crops, and exploring the trade of agricultural water rights to improve the water-use efficiency of primary industry. Tianjin may face greater pressure than Hebei to control the water-use growth due to its higher level of economic development. Tianjin should pay special attention to optimizing the internal structure within each industry, because the proportion of primary industry has limited room for declining. Specifically, in the primary industry, Tianjin needs to reduce the proportion of farming and develop modern urban agriculture; in the secondary and tertiary industries, to raise the proportion of industries with high value-added and low resources consumption. As for reducing the water-use intensity, the focus of Tianjin is mainly on improving the water-use efficiency of the primary and tertiary industries. Besides, since the water-use efficiency of the secondary industry has reached a high level, stronger measures like water-saving inspection should be taken in the future to ensure that the efficiency will not rebound.

The local governments of both regions should strengthen their existing measures to save domestic water use. Comprehensive water-condition education should be carried out, including not only cognition education (why to save water) but also skills education (how to save water); the priority should be given to the cultivation of students' and preschool children's water-saving habits and awareness; the form of education should be innovated to improve the effect of education. Water-efficient appliances in households need to be further promoted, especially in old urban residential communities and rural areas. In addition, incentive and constraint mechanisms should be developed for water-saving and water-wasting, respectively. Tianjin, as a highly urbanized region, should mainly focus on the urban sector, while Hebei, as a less-urbanized region, should pay attention to the rural sector as well as the urban sector.

Acknowledgement

This research was funded by the National Key Research and Development Program of China (Grant No. 2016YFC0401408).

Data availability statement

All relevant data are included in the paper or its Supplementary Information.

References

Ang, B. W. (2004). Decomposition analysis for policymaking in energy which is the preferred method. *Energy Policy 32*(9), 1131–1139.

Ang, B. W. (2015). LMDI decomposition approach: a guide for implementation. *Energy Policy 86*, 233–238.

Ang, B. W. & Choi, K.-H. (1997). Decomposition of aggregate energy and gas emission intensities for industry: a refined Divisia index method. *The Energy Journal 18*(3), 59–73.

Ang, B. W., Su, B. & Wang, H. (2016). A spatial–temporal decomposition approach to performance assessment in energy and emissions. *Energy Economics 60*, 112–121.

Bao, C. (2014). Spatio-temporal coupling relationships among urbanization, economic growth and water use change in China. *Acta Geographica Sinica 69*(12), 1799–1809 (in Chinese).

Brooks, D. B. (2007). An operational definition of water demand management. *International Journal of Water Resources Development 22*(4), 521–528.

Brown, T. C., Mahat, V. & Ramirez, J. A. (2019). Adaptation to future water shortages in the United States caused by population growth and climate change. *Earth's Future 7*(3), 219–234.

Duarte, R., Pinilla, V. & Serrano, A. (2013). Looking backward to look forward: water use and economic growth from a long-term perspective. *Applied Economics 46*(2), 212–224.

General Office of Hebei Provincial People's Government, Statistical Bureau of Hebei, & Hebei Academy of Social Sciences (2004–2018). *Hebei Economic Yearbook (2004–2018)*. China Statistics Press, Beijing (in Chinese).

Gleick, P. H. (2003). Water use. *Annual Review of Environment and Resources 28*, 275–314.

HWRD (2004–2018). *Hebei Water Resources Bulletin (2003–2017)*. Hebei Water Resources Department, Shijiazhuang (in Chinese).

Jia, S., Yang, H., Zhang, S., Wang, L. & Xia, J. (2006). Industrial water use Kuznets curve: evidence from industrialized countries and implications for developing countries. *Journal of Water Resources Planning and Management 132*, 183–191.

Jin, W., Zhang, H., Zhang, H., Kong, W., Mao, G., Zhang, C. & Yan, X. (2018). The influence of population structural change on water consumption in urbanization. *Resources Science 40*(4), 784–796 (in Chinese).

Jovanovica, N., Pereirab, L. S., Paredesb, P., Pôçasc, I., Cantored, V. & Todorovic, M. (2020). A review of strategies, methods and technologies to reduce non-beneficial consumptive water use on farms considering the FAO56 methods. *Agricultural Water Management 239*, 106267.

Katz, D. (2015). Water use and economic growth: reconsidering the Environmental Kuznets Curve relationship. *Journal of Cleaner Production 88*, 205–213.

Khanji, S. E. (2017). An exploration of the interaction between socio-economic productivity and water withdrawal. *Environment, Development and Sustainability 19*, 653–677.

Li, W., Sun, S. & Li, H. (2015). Decomposing the decoupling relationship between energy-related CO_2 emissions and economic growth in China. *Natural Hazards 79*(2), 977–997.

Liu, L., Wu, T., Xu, Z. & Pan, X. (2018). The water-economy nexus and sustainable transition of the Pearl River Delta, China (1999–2015). *Sustainability 10*(8), 2595.

Lu, Y. (2019). Economic outlook for the 14th five-year plan period. *China Finance 10*(10), 74–76 (in Chinese).

NDRC, Ministry of Water Resources, Ministry of Housing and Urban-Rural Development (2017). *The 13th Five-Year Plan for Building A Water-Saving Society*. National Development and Reform Commission, Ministry of Water Resources, Ministry of Housing and Urban-Rural Development, Beijing (in Chinese).

NDRC, Ministry of Water Resources, Ministry of Housing and Urban-Rural Development, Ministry of Agriculture, Ministry of Industry and Information Technology, Ministry of Science and Technology, Ministry of Education, General Administration of Quality Supervision, Inspection and Quarantine, National Government Offices Administration (2016). *Plan for National Water Conservation Action*. National Development and Reform Commission, Ministry of Water Resources, Ministry of Housing and Urban-Rural Development, Ministry of Agriculture, Ministry of Industry and Information Technology, Ministry of Science and Technology, Ministry of Education, General Administration of Quality Supervision, Inspection and Quarantine, National Government Offices Administration, Beijing (in Chinese).

SBH (2009). *New Hebei 60 Years 1949–2009*. China Statistics Press, Beijing (in Chinese).

SBT (2004–2018). *Tianjin Statistical Yearbook (2004–2018)*. China Statistics Press, Beijing (in Chinese).

SCNPC (2002). *Water Law of the People's Republic of China (Revised in 2002)*. China Water Power Press, Beijing (in Chinese).

Shang, Y., Lu, S., Shang, L., Li, X., Wei, Y., Lei, X., Wang, C. & Wang, H. (2016). Decomposition methods for analyzing changes of industrial water use. *Journal of Hydrology 543*, 808–817.

Shang, Y., Lu, S., Li, X., Sun, G., Shang, L., Shi, H., Lei, X., Ye, Y., Sang, X. & Wang, H. (2017). Drivers of industrial water use during 2003–2012 in Tianjin, China: a structural decomposition analysis. *Journal of Cleaner Production 140*, 1136–1147.

Sohn, J. (2011). Watering cities: spatial analysis of urban water use in the Southeastern United States. *Journal of Environmental Planning and Management 54*(10), 1351–1371.

Sun, Y., Li, P., She, S., Eimontaite, I. & Yang, B. (2019). Boosting water conservation by improving campaign: evidence from a field study in China. *Urban Water Journal 15*(10), 966–973.

TWA (2004–2018). *Tianjin Water Resources Bulletin (2003–2017)*. Tianjin Water Authority, Tianjin (in Chinese).

Wang, H., Small, M. J. & Dzombak, D. A. (2014a). Factors governing change in water withdrawals for U.S. industrial sectors from 1997 to 2002. *Environmental Science & Technology 48*, 3420–3429.

Wang, X., Zhang, J., Shahid, S., Bi, S., Yu, Y., He, R. & Zhang, X. (2014b). Demand control and quota management strategy for sustainable water use in China. *Environmental Earth Sciences 73*(11), 7403–7413.

Wang, H., Small, M. J. & Dzombak, D. A. (2015). Improved efficiency reduces U.S. industrial water withdrawals, 2005 – 2010. *Environmental Science & Technology Letters 2*, 79–83.

Wang, S. & Li, R. (2018). Toward the coordinated sustainable development of urban water resource use and economic growth: an empirical analysis of Tianjin City, China. *Sustainability 10*(5), 1323.

Yu, K. (2018). *Research on the Industrial Transfer Effects of Beijing-Tianjin-Hebei Region*. PhD Thesis, Technical Economy and Management Research Group, University of Science and Technology Beijing, Beijing, China (in Chinese).

Zhang, C., Zhang, H. & Gong, Y. (2014). Structural upgrading, technological progress and water resource consumption based on a refined LMDI method. *Resources Science 36*(10), 1993–2002 (in Chinese).

Zhang, Y., Yang, D., Tang, H. & Liu, Y. (2015). Analyses of the changing process and influencing factors of water resource utilization in megalopolis of arid area. *Water Resources 42*(5), 712–720.

Zhang, S., Su, X., Singh, V. P., Ayantobo, O. O. & Xie, J. (2018). Logarithmic Mean Divisia Index (LMDI) decomposition analysis of changes in agricultural water use: a case study of the middle reaches of the Heihe River basin, China. *Agricultural Water Management 208*, 422–430.

Zhang, P., Zou, Z., Liu, G., Feng, C., Liang, S. & Xu, M. (2020). Socioeconomic drivers of water use in China during 2002–2017. *Resources, Conservation & Recycling 154*, 104636.

Received 30 June 2020; accepted in revised form 21 January 2021. Available online 12 February 2021