



Drivers of dynamic evolution in provincial production water usage: perspective of regional relevance

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Abstract

With the advancement of industrialization and urbanization, the issue of water shortage has become a bottleneck for China's economic development. Based on the structural decomposition analysis and multi-regional input–output tables of China in 2002 and 2012, this paper explores the drivers of the change in China's production water usage from the regional relevance perspective. Results show a significant increase in China's production water usage during the study period. The relationship between production water usage and per capita GDP shows an inverted U-shaped curve, and the economic scale by provinces has been improved, while the trend of production water usage differs. There are rapid increases in production water usage in economically developing provinces, while it is falling sharply in developed provinces. The crucial factors promoting its growth are changes in consumption level, population scale, and regional economic patterns. The technical effect is the most important factor in curbing the growth, followed by effects of final demand sectoral and distribution structure. The provinces and sectors with more production water usage shows higher technical and final demand effects. Therefore, it is necessary to promote water-saving activities, enhance the water-saving technical effect, and optimize final demand structure to promote economic growth with low-water usage.

Keywords Regional economic pattern · Structural decomposition analysis · Multi-regional input–output model · Production water usage

JEL Classification Q25 · R58 · L95

Introduction

With the comprehensive advancement of industrialization and urbanization, the contradiction between supply and demand of water resources in China has further intensified. The lack of water resources has become a bottleneck for the development

of China's regional economy (Mou et al. 2019). Recent years have shown a clear upward trend in water use in China, enabling a high rate of production in different sectors (as shown in Fig. 1a). On the one hand, to alleviate China's water resource problems, the government has introduced a series of policies on water resource management. The "13th Five-Year Plan for National Economic and Social Development of the People's Republic of China" and the report of the 19th National Congress of the Communist Party of China emphasize the implementation of its most stringent water resource management system. By 2020, the total water usage in the country will be within 670 billion tons. The controlling indicators of total water usage for each province are defined by government according to the specific conditions of each province. On the other hand, many local governments, represented by the Guangdong and Shandong Ministry of Water Resources, have introduced water resource management plans to control total water usage, while ensuring both quality and quantity.

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It is particularly noteworthy that water resources in China are very scarce, with a prominent mismatch between water use structure and regional economic development.¹ In Fig. 1b, the economically developed regions, such as BT,² have a relatively low share of water usage, while CR and other economically underdeveloped regions have a higher share of water usage. Simultaneously, owing to the close economic interaction between regions, economic activities in one region may have an important impact on production water usage in other regions. Therefore, when implementing a water resource management system, it is necessary to focus on the interaction between regions. To coordinate the imbalance between water use structure and regional economic development, this study attempts to decompose the changes in China's production water usage from the perspective of regional relevance.

In recent years, scholars have conducted extensive research on water consumption and drivers of its evolution in China. Prior literatures primarily analyze the quantification of water footprint and virtual water trade. They also analyze the factors influencing changes, estimation of water usage, and the driving factors behind changes. Studies that measure the water footprint and virtual water trade often use input–output methods (I–O) (Zhou et al. 2019) that reflect inter-sectoral linkages and even inter-regional linkages. The following studies use single-region I–O methods to quantify water usage. Zhao et al. (2009) measured China's water footprint and the water footprint intensity of 23 sectors in 2002 and measured virtual water trade in import and export in China. Zhang et al. (2011) and Wang et al. (2013) measured the water footprint of various sectors in Beijing in 2002 and 2007, while Yang et al. (2015a) measured the water footprint of various sectors in Xinjiang in 2007. Among studies based on multi-regional input–output tables, Feng et al. (2012) assessed inter-regional virtual water flows by constructing a four-region input–output model. Dong et al. (2014), Feng and Chen (2016), and Chen et al. (2017) used the multi-regional input–output table in 2007 to measure the water footprint and inter-provincial virtual water trade in China. Many studies have quantified China's water footprint and virtual water trade

based on the input–output model, providing detailed calculations for the provincial level.

Studies investigating the driving factors of changes in water footprint in China commonly use structural decomposition analysis (SDA) (Magacho et al. 2018; Zhou et al. 2020) and index decomposition analysis (IDA) (Hang et al. 2019). Studies using the IDA method for a single region include Xu et al. (2015), Zhao et al. (2017), Kang et al. (2017), Xie and Su (2017), and Zhao and Chen (2014). The IDA method can reflect only the direct effect, whereas the SDA method, based on I–O analysis, can quantify not only the direct economic and technical links between provinces by sectors, but also the indirect links. Therefore, scholars use the SDA method more often (Hoekstra and Van den Bergh 2003; Okushima and Tamura 2011; Li et al. 2020).

At present, the research scope of the study region in most studies using the SDA method is either the whole of China (Yu et al. 2019) or a single region within China. Among studies analyzing the factors affecting changes in water usage at the national level, Zhang and Liu (2015) used the SDA method to identify the factors influencing China's water usage during 1999–2007. Yang et al. (2015b) and Yang et al. (2016) used the dynamic SDA model to analyze the drivers by sector, during 1997–2007. Wang et al. (2016) analyzed the drivers of changes in water footprints by sectors across China, during 1997–2007. Zhang et al. (2020) quantified the socio-economic factors to China's water use changes during 2002–2017, based on the environmentally extended I–O analysis and the SDA method. Guan and Chen (2020) explored the drivers of the water-energy nexus in China from 1990 to 2014 and decomposed the water consumption of different consumers into six energy-related factors.

Among studies considering a single region of China (Beijing, Zhangye, Haihe River Basin, and so on), Zhang et al. (2012) and Zhao et al. (2016) analyzed the factors influencing changes in Beijing's water footprint in different periods. Zhi et al. (2015) examined these drivers in Beijing, during 1987–2020, based on the IO-IPAT-SDA model. Most of these studies showed that the primary impetus of growth in water use is economic growth and the reduction in water intensity. Zhi et al. (2014) and Feng et al. (2017) identified the driving factors of changes in the water footprint in the Haihe River Basin during 2002–2007 and Zhangye during 2001–2011. Some scholars also studied the changes of water use at the multi-regional level. Liang et al. (2020) quantified the water withdrawals driven by the provincial final demand of energy products and explored the driving factors of the provincial energy-water nexus in China from 2007 to 2012. Most of these studies indicated that the technical effect inhibited the growth of water footprint, while the final demand effect promoted it. Therefore, the improvement in water-saving technology is a crucial factor in inhibiting further increase in water usage. However, these studies rarely consider

¹ The Council Information Office of China held a press conference on February 16, 2012, and invited Hu Siyi, vice minister of the Ministry of Water Resources, to introduce the background and main contents of the "Opinions of the National Council on Implementing the Most Stringent Water Resources Management System."

² According to Zhang (2012), the mainland in China mainly consists of the following eight regions: northeast (NE, including Heilongjiang, Jilin, and Liaoning), Beijing-Tianjin region (BT, comprising Beijing and Tianjin), northern coast (NC, including Hebei and Shandong), eastern coast (EC, including Shanghai, Jiangsu, and Zhejiang), southern coast (SC, including Fujian, Guangdong, and Hainan), central region (CR, including Shanxi, Henan, Anhui, Hubei, Hunan, and Jiangxi), northwest (NW, including Inner Mongolia, Shaanxi, Ningxia, Gansu, Qinghai, and Xinjiang), and southwest (SW, including Sichuan, Chongqing, Guangxi, Yunnan, Guizhou, and Tibet).

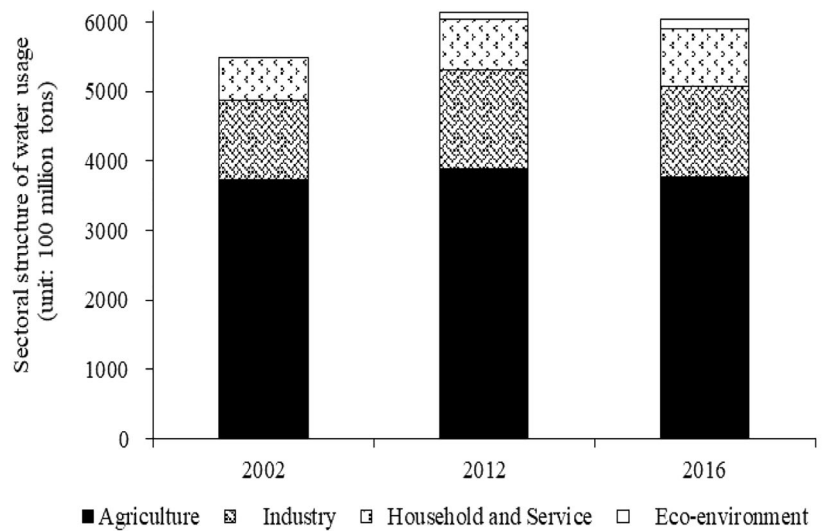
inter-regional interactions and, thus, fail to identify the factors influencing dynamic evolution in water usage from the perspective of regional relevance.

In summary, this study attempts to examine the factors influencing the dynamic changes in production water usage from the perspective of regional relevance, which few other studies in the literature do. As the main component of total water usage, production water usage is the key to controlling total water usage. Based on the SDA method and multi-regional input–output tables of China in 2002 and 2012, this study examines the drivers of change in China’s production water usage. This study is significant for implementing China’s most stringent water resource management system and accelerating the development of a water-saving society.

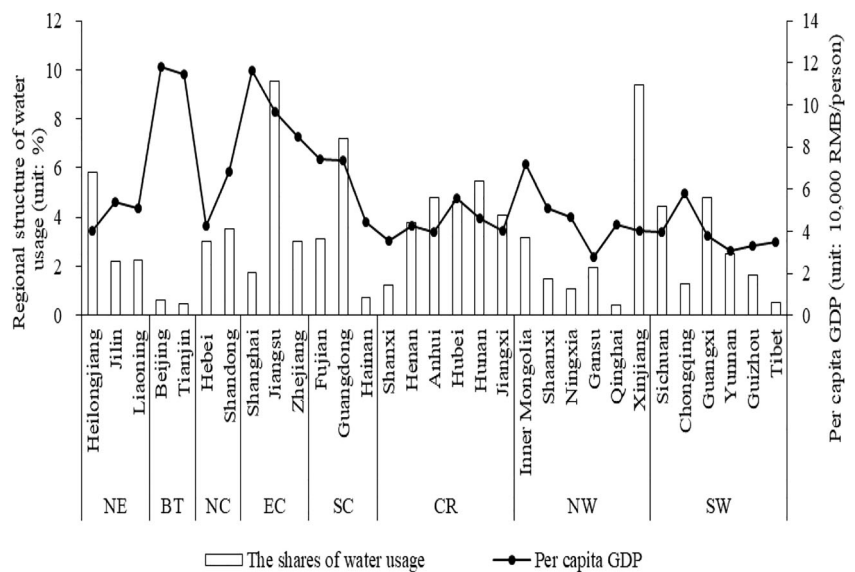
The main contributions of this study are as follows: (1) It constructs multi-regional water usage–economy I–O tables based on input–output tables of China and the direct water-use data of provinces by sectors in 2002 and 2012. (2) Using the SDA method, considering the spatial heterogeneity of the final demand, it analyzes the factors influencing the dynamic changes in China’s production water usage. (3) Analyzing the empirical results, it puts forth some suggestions for developing a water-saving society in China, from the perspective of regional coordination.

The rest of the paper is organized as follows. The “[Methods and data](#)” section outlines the theoretical derivation of the SDA model considering the spatial heterogeneity of the final demand; it also briefly describes the data. The “[Regional and](#)

Fig. 1 **a** Sectoral structures of water usage. **b** Regional structures of water usage and per capita gross domestic production (GDP) in 2016



(a)



(b)

Table 1 The multi-regional water usage–economy input–output table in China

	Intermediate Demand						Final Demand			Exports	Total Outputs
	P^1		...		P^n		P^1	...	P^n		
	S^1	...	S^m	...	S^1	...					
	S^1										
	P^1	⋮	Z^{11}	...	Z^{1n}	F^{11}	...	F^{1n}	E^1		X^1
	S^m										
Intermediate inputs	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
	S^1										
	P^n	⋮	Z^{n1}	...	Z^{nm}	F^{n1}	...	F^{nm}	E^n		X^n
	S^m										
Imports			M^1	...	M^n						
Value-added			V^1	...	V^n						
Total inputs			X^{1t}	...	X^{nt}						
Water usage			W^1	...	W^n						

P province, S sector. n number of provinces, m number of sectors

' indicates that the vector or matrix is transposed

sectoral structures of changes in production water usage in China” section discusses the regional and sectoral structure of dynamic changes in production water usage, while the “Drivers for dynamic changes in production water usage” section discusses the results of the SDA. The last section presents the conclusions and policy implications.

Methods and data

Methods

The models in this study are based on a multi-regional water usage–economy I–O table with the assumption of competitive imports, as presented in Table 1. Z^{rs} is the intermediate demand matrix for each sector in province r for the production in each sector in province s , and its dimension is $m \times m$; F^{rs} represents the matrix of final demand from province s for each sector in province r , with dimension of $m \times 1$. X^r and E^r are the total output and the export vectors of province r , respectively, and their dimension is $m \times 1$. M^r , V^r , and W^r are imports, value

added, and water usage vectors in province r , respectively, with dimension of $1 \times m$.

The total output for each sector in province r comprises three parts: intermediate demand, final demand, and export, which can be written as follows:

$$X^r = \sum_s Z^{rs} u + \sum_s F^{rs} + E^r = \sum_s Z^{rs} u + F^r + E^r, \tag{1}$$

where u is a $m \times 1$ column vector, and F^r represents the final demand from all provinces in each sector to province r , with $F^r = \sum_s F^{rs}$. The direct consumption coefficients matrix A^{rs} , expressed as $A^{rs} = Z^{rs} (\hat{X}^s)^{-1}$, represents the intermediate input from each sector in province r for the production of one unit of product in each sector in province s , and \hat{X}^s is the diagonal matrix with total outputs of each sector in province s , X^s . Then Eq. (1) can be rewritten as follows:

$$X^r = \sum_s A^{rs} X^s + F^r + E^r, \tag{2}$$

Eq. (2) can be written in matrix form as follows:

$$X = AX + F + E, \tag{3}$$

where X , F , and E are the total output, final demand, and

$$X = \begin{bmatrix} X^1 \\ \vdots \\ X^n \end{bmatrix}_{mn \times 1}, \quad F = \begin{bmatrix} F^1 \\ \vdots \\ F^n \end{bmatrix}_{mn \times 1}, \quad E = \begin{bmatrix} E^1 \\ \vdots \\ E^n \end{bmatrix}_{mn \times 1}, \quad A = \begin{pmatrix} A^{11} & \cdots & A^{1n} \\ \vdots & \ddots & \vdots \\ A^{n1} & \cdots & A^{nn} \end{pmatrix}_{mn \times mn}.$$

According to the Leontief model, Eq. (3) can be further rewritten as follows:

$$X = (I - A)^{-1}(F + E) = B(F + E), \tag{4}$$

In Eq. (4), B is the Leontief inverse matrix, that is, the complete demand coefficient matrix:

$$B = \begin{pmatrix} I - A^{11} & L & -A^{1n} \\ M & O & M \\ -A^{n1} & L & I - A^{nn} \end{pmatrix}^{-1} = \begin{pmatrix} B^{11} & L & B^{1n} \\ M & O & M \\ B^{n1} & L & B^{nn} \end{pmatrix}_{mn \times mn}$$

Assuming W^r is the direct water-use vector of province r , the direct water-use coefficient vector of province r is $w^r = u' \widehat{W}^r (\widehat{X}^r)^{-1}$, where u is a $m \times 1$ column vector, and \widehat{W}^r is the diagonal matrix with the direct water-use vector of province r , \widehat{X}^r is the diagonal matrix with the total outputs of sectors in province r , X^r . Therefore, the production water usage W^r of province r is

$$W^r = w^r X^r = w^r B^r (F^r + E^r), \tag{5}$$

Based on the models of Zhang (2018) and Yang et al. (2015c), the final demand $Y = F + E$ can be further expressed in the following form, in which the final demand sectoral structure S , final demand distribution structure U , final demand regional structure R , population scale P , and consumption level C are multiplied. Eq. (5) can be further rewritten as follows:

$$W = wBSU'RPC, \tag{6}$$

Based on Eq. (5), the effects of various factors on changes in production water usage are determined using the two-polar decomposition method recommended by Dietzenbacher and Los (1998).³ In this study, changes in the production water usage $\Delta W = W_t - W_0$ between time t and time 0 are decomposed as follows:

³ This method takes into account the “non-uniqueness problem” in structural decomposition and has the advantage of simplified operation. It is a structural decomposition method, which is very suitable for empirical analysis (Zhang 2010).

export vectors in all provinces by sectors, respectively, and $Y = F + E$. In addition, A is the direct consumption coefficient matrix for each sector in all provinces. They can be written as follows:

$$\Delta W = f(\Delta w) + f(\Delta B) + f(\Delta(F + E)), \tag{7}$$

where $W_0 = w_0 B_0 (F_0 + E_0)$ and $W_t = w_t B_t (F_t + E_t)$. Each effect in Eq. (7) can be formulated as follows:

$$f(\Delta w) = (\Delta w B_t (F_t + E_t) + \Delta w B_0 (F_0 + E_0))/2, \tag{8}$$

$$f(\Delta B) = (w_0 \Delta B (F_t + E_t) + w_t \Delta B (F_0 + E_0))/2, \tag{9}$$

$$f(\Delta(F + E)) = (w_0 B_0 \Delta(F + E) + w_t B_t \Delta(F + E))/2, \tag{10}$$

The technical effect in Eq. (8) reflects the impact of changes in the direct water-use coefficients on changes in production water usage. In the production process, with the improvement of water-saving technologies, the water-use coefficients will reduce. The inter-regional intermediate input structural effect in Eq. (9) represents the impact of changes in the intermediate input structure between regions. The final demand effect in Eq. (10) represents the impact of changes in the regional final demand.

Based on Eq. (6), changes in production water usage $\Delta W = W_t - W_0$ between time t and time 0 are further decomposed as follows:

$$\Delta W = f(\Delta w) + f(\Delta B) + f(\Delta S) + f(\Delta U') + f(\Delta R) + f(\Delta P) + f(\Delta C), \tag{11}$$

where $W_0 = w_0 B_0 S_0 U'_0 R_0 P_0 C_0$ and $W_t = w_t B_t S_t U'_t R_t P_t C_t$. Effects in Eq. (11) can be formulated as follows:

$$f(\Delta w) = (\Delta w B_t S_t U'_t R_t P_t C_t + \Delta w B_0 S_0 U'_0 R_0 P_0 C_0)/2, \tag{12}$$

$$f(\Delta B) = (w_0 \Delta B S_t U'_t R_t P_t C_t + w_t \Delta B S_0 U'_0 R_0 P_0 C_0)/2, \tag{13}$$

$$f(\Delta S) = (w_0 B_0 \Delta S U'_t R_t P_t C_t + w_t B_t \Delta S U'_0 R_0 P_0 C_0)/2, \tag{14}$$

$$f(\Delta U') = (w_0 B_0 S_0 \Delta U' R_t P_t C_t + w_t B_t S_t \Delta U' R_0 P_0 C_0)/2, \tag{15}$$

$$f(\Delta R) = (w_0 B_0 S_0 U'_0 \Delta R P_t C_t + w_t B_t S_t U'_t \Delta R P_0 C_0)/2, \tag{16}$$

$$f(\Delta P) = (w_0 B_0 S_0 U'_0 R_0 \Delta P C_t + w_t B_t S_t U'_t R_t \Delta P C_0)/2, \tag{17}$$

$$f(\Delta C) = (w_0 B_0 S_0 U'_0 R_0 P_0 \Delta C + w_t B_t S_t U'_t R_t P_t \Delta C)/2, \tag{18}$$

The technical effect in Eq. (12) is the same as that in Eq. (8). The inter-regional intermediate input structural effect in Eq. (13) is the same as that in Eq. (9). The final demand effect in Eq. (10) is the sum of the final demand sectoral structural effect in Eq. (14), the final demand distribution structural effect in Eq. (15), the final demand regional structural effect in Eq. (16), the population scale effect in Eq. (17), and the consumption level effect in Eq. (18). The sectoral structural effect reflects the impact of sectoral structural changes in the final demand provided by each province. The distribution structure effect reflects the impact of changes in shares of various final demand categories in the final demand of each region. The regional structure effect reflects the impact of changes in shares of the final demand for each province in the whole country. The population scale effect reflects the impact of changes in each region’s population. The consumption level effect reflects the impact of the per capita final demand on the changes in production water usage.

Data

The data used in this study consist of two parts: the multi-regional I–O tables (2002, 2012) in China and the amounts of direct water usage in each province, by sectors. The multi-regional I–O tables are compiled by the Institute of Geographic Sciences and Natural Resources Research of Chinese Academy of Sciences. They include 30 major provinces (excluding Tibet, Hong Kong, Macau, and Taiwan) subdivided into 42 sectors. To match the water usage of the 30 provinces by sectors, we merge the 42 sectors of the multi-regional I–O tables into 30. The 30-sector classification is given in Table 3 in the Appendix. The water usage of the first industry in each province is derived from the information published by the China Statistical Yearbook in 2003 and 2013 (National Bureau of Statistics of China 2003, 2013a), which corresponds to the first sector in the multi-regional I–O tables and includes agriculture, forestry, animal husbandry, and fishery.

We follow several steps to obtain industrial water usage by provinces and sectors in 2002 and 2012. First, we retrieve the total amounts of industrial water usage for each province from the China Statistical Yearbook in 2003 and 2013 (National Bureau of Statistics of China 2003, 2013a). Second, we derive the water usage of industrial sub-sectors in 13 provinces (Jiangxi, Anhui, Henan, Xinjiang, Hebei, Chongqing, Hunan, Tianjin, Shanxi, Guangxi, Guangdong, Gansu, and Shaanxi) for 2002 and 2012 from the Statistics Yearbooks of each province in 2003 and 2013, the China Statistical Yearbook in 2003 and 2013 (National Bureau of Statistics of China 2003, 2013a), the 2013 China Economic Census Yearbook (National Bureau of Statistics of China 2013b), and the 2010 Hunan Energy Statistical Yearbook. We then adjust in accordance with the shares of industrial sub-sectors water usage in the total output of the industry. Thus, we obtain

the adjusted coefficients of water use together with the industrial water usage by sectors. Finally, owing to the similarity in water-use coefficients of provinces geographically adjacent or located in the same water resource basin, we consider the coefficients of 13 provinces by sectors and the output values of the other 18 provinces in 2002 and 2012 (obtained from the multi-regional I–O tables) to measure water usage by sectors in the other 18 provinces. We then adjust water usage as per the total amounts of water usage by sector (National Bureau of Statistics of China 2003, 2013a).

We adopt the following process for water usage in construction and tertiary industries in each province (Zhao et al. 2019). Firstly, to obtain the total amount of water usage in these sectors for 2002 and 2012, we assume that the proportion of households, tertiary industries, and construction in water usage related to households and services in 2002 and 2012 is the same as that in 2011, using the Bulletin of First National Census for Water (National Bureau of Statistics of China 2013c). Secondly, according to the proportions of the output value in the construction sector for each province, to the national output value in 2002 and 2012, we allocate the total amount of water usage in the sector. Thirdly, to calculate water usage in the tertiary industry by sector, we adopt the water-use coefficients of tertiary industries (Research Group of Chinese Input–Output Association 2007) and assume that its proportion in 2012 is the same as that in 2002. Finally, according to the output proportion in each province by sectors, in the tertiary industry corresponding to the national output, we allocate water usage in the tertiary industry by sectors and obtain water usage for each province in sub-sectors of tertiary industries.

Regional and sectoral structures of changes in production water usage in China

In Fig. 2, the relationship between production water use and per capita GDP in 2002 and 2012 is comparatively analyzed

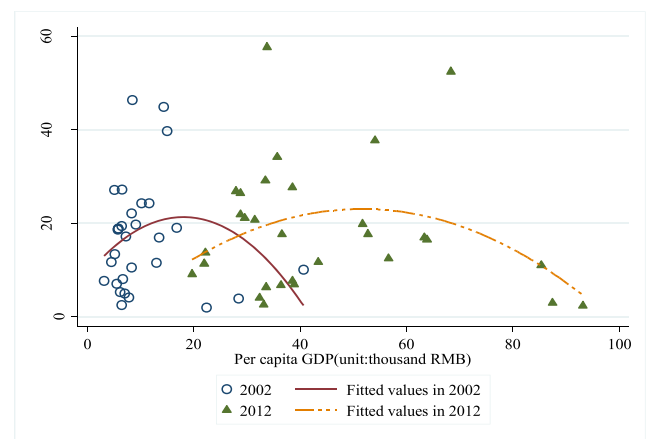


Fig. 2 Environmental Kuznets curves in 2002 and 2012

using the well-known environmental Kuznets curve. The vertical axis shows the amounts of production water use, and the abscissa represents per capita GDP, while each point corresponds to one province. Figure 2 shows that the relationship of production water use and per capita GDP is an inverted U-shaped curve in both 2002 and 2012. At the left side of the apex, the more developed the province, the greater the amount of production water use. And at the right side of the apex, the more developed the region, the smaller the amount of production water use. Whether the expansion of economic scale is conducive to reducing production water use depends on whether it is on the right side of the inverted U-shaped environment Kuznets curve. The expansion of economic scale has a very close relationship with the change of production water use. On the one hand, economic growth depends on the expansion of production scale, which leads to an increase in production water usage. On the other hand, economic growth can promote technological innovation, help optimize industrial layout, and improve water efficiency, which reduces production water usage. In addition, compared with 2002, the inverted U-shaped environment Kuznets curve in 2012 shifted to the right along the abscissa axis, indicating that the economic scale of each province has been significantly improved. However, there are significant differences in the trends of production water usage in various provinces.

Analysis of regional structure

During 2002–2012, the growth rate of China's production water usage is 9%, and the water usage in two-thirds of the provinces has increased. The changes in the production water usage in China mainly occur in CR, Xinjiang and Inner Mongolia in NW, and NC. Figure 3 shows, in comparison with 2002, that the direct water-use coefficients of all provinces in China show a downward trend in 2012, indicating a gradual decrease in water usage per unit output. In recent years, the government's water-saving policy has shown a

positive impact. In NC, where both the final demand share and the direct water-use coefficients have declined, production water usage has decreased significantly. The direct water-use coefficient in Inner Mongolia has decreased, but its share of final demand has increased, and its production water usage shows a downward trend. However, the direct water-use coefficients in Xinjiang and CR have decreased, but their shares of final demand have increased, while production water usage shows an upward trend. Therefore, in many regions, the water-saving effects of technological progress cannot offset the scale effect of water use induced by economic growth.

During 2002–2012, the production water usage in economically underdeveloped regions has increased rapidly, and that in economically developed regions has declined sharply. The pulling effect of the rapid growth in China's per capita gross domestic production (GDP) on production water usage is significantly greater than the inhibition effect of decline in direct water-use coefficients. Therefore, China's production water usage shows a growth trend. Figure 4 shows that as per capita GDP have increased by 3.77 and 4.33 times, respectively, the growth rates of production water usage in Jiangsu and Hunan, where such use is mainly concentrated, are higher than the national average (9%). In Xinjiang, where the growth rate of per capita GDP is close to 300% and the direct water-use coefficient has declined slowly, the growth rate of the production water usage is as high as 17.51%, which is about twice the growth rate of the national average. For Guangdong, the growth rate of per capita GDP is low, while the direct water-use coefficient has decreased significantly, and the production water usage has decreased by 7.92%.

Analysis of sectoral structure

During 2002–2012, the changes in the production water usage in China are mainly concentrated in agriculture (S01), gas and water production and distribution (S23), and electricity and heat production and supply (S22). The sectors list is detailed

Fig. 3 Regional structures of changes in production water usage, direct water-use coefficients, and shares of final demand during 2002–2012

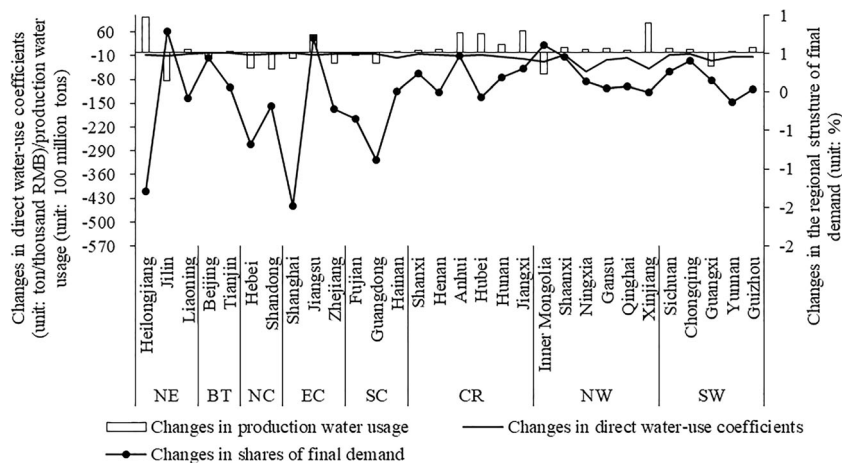
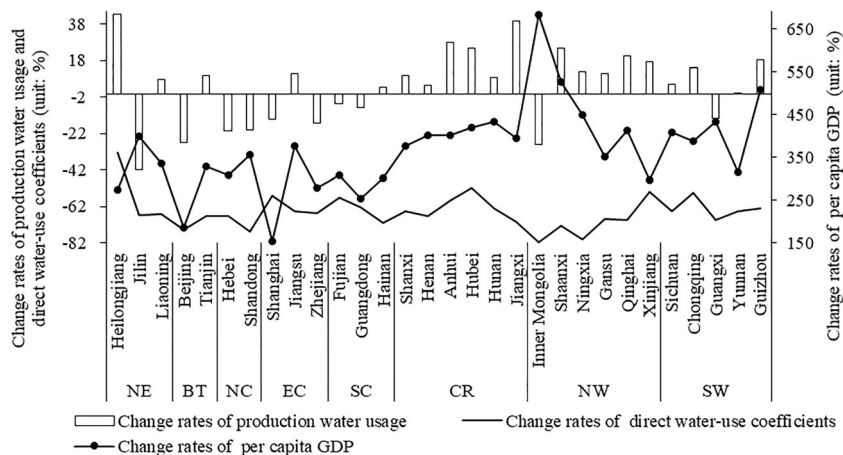


Fig. 4 Regional structures of change rates in the production water usage, direct water-use coefficients, and per capita GDP during 2002–2012



in Table 3 in the Appendix. In comparison with 2002, the direct water-use coefficients of all sectors in China show a downward trend in 2012. Figure 5 shows a large decline in the direct water-use coefficients and production water usage of S01 and S22. This indicates that changes in water-saving technology have a significant impact on the sectoral structure of production water usage in China. The direct water-use coefficient in S23 has decreased, while its share of the final demand has increased, and its production water usage shows an upward trend.

S01, S23, and S22 are the key sectors that cause changes in China’s production water usage. They are the main sectors for increasing production water usage in most regions with increased usage and for reducing usage in regions with reduced production water usage. Table 2 shows that S01 is primarily responsible for the increase in the production water usage in NE (except Jilin), Sichuan and Chongqing in SW, Shanxi and Jiangxi in CR, and NW (except Inner Mongolia). It is also the main sector responsible for the reduction of the production water usage in NC, SC (except Hainan), and parts of SW (including Guangxi, Guizhou, and Yunnan). Among them, the reduction in the production water usage in S01 of

Yunnan is 16.60 times the total change in the production water usage in that province. S23 is the key sector for the increase in the production water usage in EC (except Shanghai), SC (except Hainan), Henan and Anhui in CR. It is also the critical sector for the decrease in the production water usage in Hainan, Shanghai, and Tianjin. The reduction of production water usage in S23 of Hainan is 1.50 times the total change in the production water usage in that province. S22 is the crucial sector for the increase in production water usage in Hubei, Guizhou, and Inner Mongolia and for the decrease in the production water usage in NW (including Gansu, Qinghai, and Xinjiang) and Jiangsu in EC.

Drivers for dynamic changes in production water usage

Based on the SDA decomposition results obtained from Eqs. (7) and (11), this section discusses and analyzes the contribution of each factor influencing the changes in production water usage.

Fig. 5 Sectoral structures of changes in production water usage, direct water-use coefficients, and shares of final demand during 2002–2012

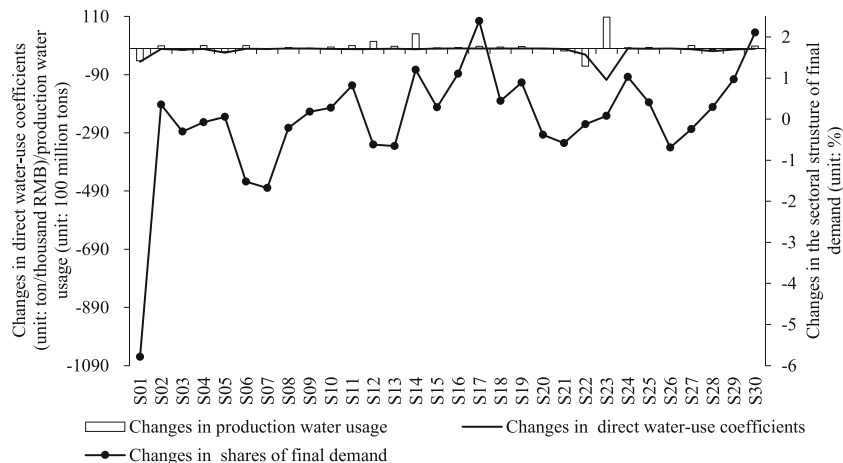


Table 2 The three sectors with the highest proportion of the changes in production water usage in all provinces (unit: %)

Region	Province	Sector (ratio)			
NE	Heilongjiang	S01 (117)	S03 (- 6)	S22 (- 4)	
	Jilin	S01 (- 99)	S05 (- 5)	S13 (1)	
	Liaoning	S01 (84)	S28 (11)	S27 (- 11)	
BT	Beijing	S01 (- 56)	S23 (- 22)	S27 (11)	
	Tianjin	S23 (- 85)	S05 (72)	S27 (49)	
NC	Hebei	S01 (- 95)	S05 (- 8)	S14 (7)	
	Shandong	S01 (- 64)	S05 (- 14)	S28 (- 7)	
EC	Shanghai	S23 (- 106)	S28 (39)	S27 (- 3)	
	Jiangsu	S22 (- 143)	S23 (117)	S01 (47)	
	Zhejiang	S01 (- 97)	S28 (- 23)	S23 (17)	
SC	Fujian	S01 (- 338)	S23 (78)	S07 (30)	
	Guangdong	S01 (- 91)	S23 (10)	S28 (9)	
Hainan	Hainan	S01 (337)	S23 (- 170)	S28 (- 50)	
	Shanxi	S01 (44)	S27 (26)	S22 (11)	
CR	Henan	S01 (- 176)	S23 (173)	S22 (- 123)	
	Anhui	S23 (64)	S22 (- 42)	S01 (36)	
	Hubei	S22 (61)	S01 (20)	S23 (- 18)	
	Hunan	S14 (39)	S22 (36)	S01 (- 32)	
	Jiangxi	S01 (70)	S10 (10)	S21 (- 13)	
	NW	Inner Mongolia	S01 (- 124)	S22 (7)	S14 (5)
NW	Shaanxi	S01 (88)	S10 (- 7)	S03 (7)	
	Ningxia	S01 (75)	S22(14)	S05 (- 4)	
	Gansu	S01 (95)	S14 (13)	S22 (- 17)	
	Qinghai	S01 (132)	S22(- 27)	S14 (- 2)	
	Xinjiang	S01 (100)	S22 (- 4)	S23 (3)	
	SW	Sichuan	S01 (164)	S23 (61)	S12 (- 28)
	Chongqing	S01 (32)	S23 (31)	S28 (- 16)	
SW	Guangxi	S01 (- 111)	S23 (- 17)	S14 (7)	
	Yunnan	S01 (- 1660)	S23 (1004)	S28 (237)	
	Guizhou	S22 (96)	S02 (15)	S01 (- 38)	

The ratio in brackets is equal to the amounts of the changes in the production water usage of the certain sector, divided by the amounts of the changes in production water usage for the corresponding province S sectors

The technical effect

During 2002–2012, the technical effect led to a reduction in the production water usage in all provinces and sectors. The technical effect is a key factor in curbing the growth of China’s production water usage, and the provinces and sectors that use more water for production show higher technical effects. Figure 6 shows that the technical effect has the greatest inhibitory effect on the growth of the production water usage in Xinjiang, Jiangsu, Guangdong, and Hunan. The technical effects of these provinces account for about 27% of the total technical effect. Figure 7 shows that the technical effect has the greatest inhibitory effect on the growth of production water usage in S01, S23, and S22. The technical effects of these sectors account for about 80% of the total technical effect. With increasing awareness of water conservation (Du et al. 2018) and improvement in water-saving technologies, the amount of water directly used by per unit of product (i.e., direct water-use coefficients) has been reduced. The more the provinces and sectors use water in their production processes, the greater their technical effect. Overall, the technical effect has reduced the total production water usage in China by 437.8 billion t.

The inter-regional intermediate input structural effect

During 2002–2012, the change in inter-regional intermediate input structure has a weak inhibitory effect on the growth of China’s production water usage. This article describes the impact of changes in the intermediate input structure on production water usage from regional and sectoral perspectives. Figures 8 and 9 show the regional and sectoral structures of changes in the intermediate inputs from 2002 to 2012, respectively. The total shares of intermediate input in 12 provinces, such as Gansu, Chongqing, and Xinjiang, have decreased by 6.73%. Their weighted average direct water-use coefficients in 2002 and 2012 (weighted by their shares of intermediate inputs) are 6.19 t/thousand RMB and 2.25 t/thousand RMB.

Fig. 6 SDA results and direct water-use coefficients for each province

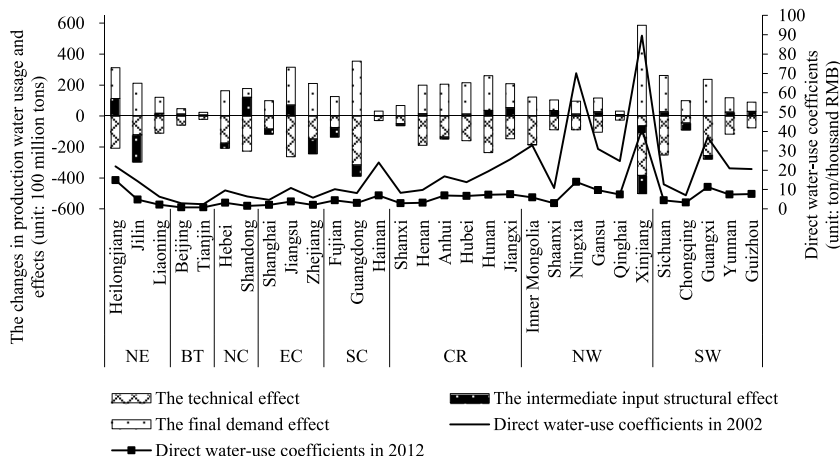
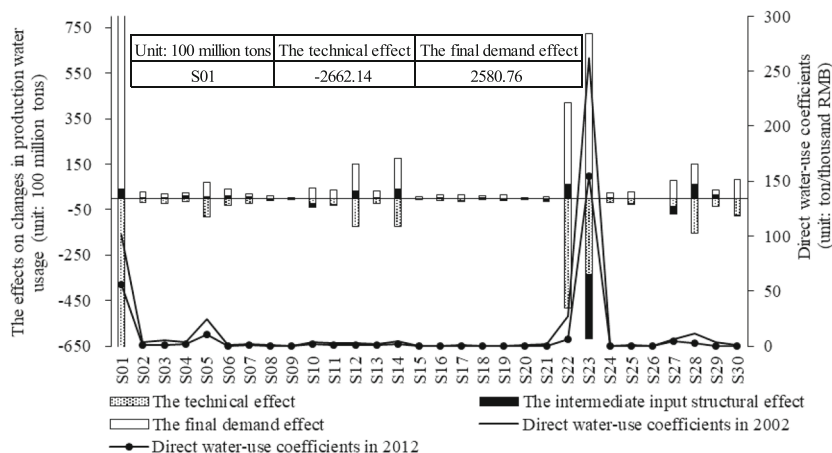


Fig. 7 SDA results and direct water-use coefficients for each sector



While the weighted direct water-use coefficients of other provinces are 5.81 t/thousand RMB and 2.08 t/thousand RMB, respectively. Since the former is always higher than the latter, the regional structural change of the intermediate input is generally beneficial in reducing the production water usage in China.

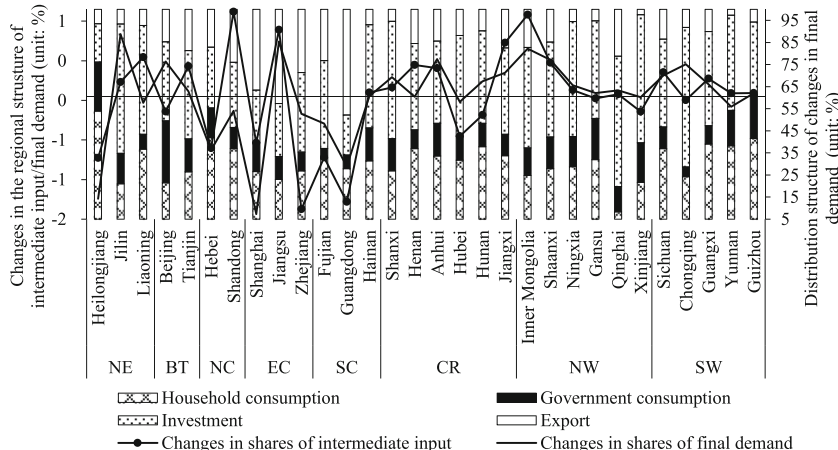
The change in the sectoral structure of the intermediate inputs can better explain the weak inhibitory effect of the intermediate input structure effect on the growth of China’s production water usage. Figure 9 shows that the total shares of intermediate input in 17 sectors, such as S11, S03, and S23, have decreased by 12.07%. Their weighted average direct water-use coefficients in 2002 and 2012 (weighted by their shares of intermediate inputs) are 8.05 t/thousand RMB and 2.80 t/thousand RMB, respectively. While the weighted direct water-use coefficients of other sectors are 1.32 t/thousand RMB and 0.61 t/thousand RMB, respectively. Because the former is always higher than the latter, that is, the weighted average direct water-use coefficient of the sectors with the decreased intermediate input share is greater than the weighted average direct water-use coefficient of the sectors with the increased intermediate input share, the sectoral

structure change of intermediate input results in a reduction of the production water usage in China.

The final demand effects

The final demand effect is the main reason for the rapid growth of China’s production water usage, and the final demand effect on the provinces or sectors with higher production water usage is far greater than on provinces or sectors with lower usage. The final demand effect has led to an increase in the production water usage in all provinces and sectors; therefore, it is the most critical factor in promoting the production water usage in China. Figure 6 shows that the final demand effect has the greatest effect on the increase in the production water usage in Xinjiang, Jiangsu, Guangdong, and Hunan. The final demand effects of these provinces account for about 31% of the total final demand effect. Figure 7 shows that the final demand effect has the greatest effect on increase in production water usage in S01, S23, and S22. Their final demand effects account for about 80% of the total final demand effect. The industrialization and urbanization process in each province and sector have used massive water resources to support economic development and maintain production. Moreover,

Fig. 8 The distribution structure of changes in the final demand, changes in shares of intermediate inputs, and the final demand by provinces



the final demand effect has a greater impact on the provinces and sectors with more production water usage. In total, the final demand effect has increased the production water usage in China by 458.3 billion t.

The rapid expansion of final demand in most provinces is mainly driven by the sharp increase in investment and household consumption during 2002–2012. Export growth is the main reason for the rising final demand in the coastal regions. The increase in government consumption is the major cause of the rise in Beijing’s final demand. Figure 8 shows that the contribution rates of export changes to the final demand changes in Guangdong, Jiangsu, and Shanghai exceed 30%. The change in government consumption is one of the main drivers of Beijing’s final demand effect, contributing to 28.10%. Changes in investment and large increases in household consumption are the main reasons for the growth of the final demand in all provinces. Among them, the impact of investment changes on the final demand changes in remote and economically underdeveloped provinces is greater than in coastal and economically developed provinces. Investment changes have contributed more than 50% to changes in the final demand in remote and economically underdeveloped provinces, such as Chongqing, Qinghai, Jilin, Xinjiang, and Shanxi, while contribution rates in coastal economically developed provinces such as Guangdong, Shanghai, Jiangsu, Hebei, and Shandong are no more than 30%. The contribution rates of household consumption changes to the final demand changes of various provinces are less volatile, with a contribution rate in the range of 20–40%.

The rapid expansion of the final demand in most sectors is mainly driven by changes in investment and large increases in household consumption. Export growth is the main reason for the increase in the final demand in S13, S7, and S20. The change in government consumption is the main driver of the increase in the final demand in S29. Figure 9 shows that the contribution rates of the export expansion to the final demand changes in S13, S7, and S20 exceed 120%. The change in government consumption is one of the main drivers of the

final demand effect for S29, with a contribution rate of 81.66%. Changes in investment and large increases in household consumption are the main reasons for the growth of final demand in sectors with large production water usage. The changes in household consumption have contributed more than 90% to changes in the final demand in S1, S23, and S22. The decline in investment significantly affects the change in the final demand of S01, with a contribution rate of 108.76%.

The above analysis shows that the final demand effect is the most important factor in increasing the production water use in China. From the part of “Methods,” we observe that the final demand effect can be further decomposed into the effects of the final demand sectoral structural, final demand distribution structural, final demand regional structural, population scale, and the consumption level. In the next subsection, we examine the effects of various factors affecting the final demand on the changes in production water usage.

The final demand sectoral structural effect

The change in the sectoral structure of final demand is conducive to reducing China’s production water usage. The inhibitory effect of the change in the final demand sectoral structure on the growth of China’s production water usage is about a quarter of the technical effect. In S01, the final demand sectoral structural effect has mainly inhibited the growth of production water usage. Furthermore, the final demand sectoral structural effect of S01 is 1.20 times that of the whole country. Figure 10 shows that the change in the sectoral structure of the final demand has greatly inhibited the growth of production water usage in S01. Furthermore, its inhibitory effect on S01 and other sectors is greater than its enhancing effect on other sectors. Therefore, the changes in the sectoral structure of the final demand are conducive to reducing the amount of production water usage in China.

The changes in the sectoral structure of the final demand are mainly reflected in the decline of the final demand share of

Fig. 9 The distribution structure of changes in the final demand, changes in shares of intermediate inputs, and the final demand by sectors

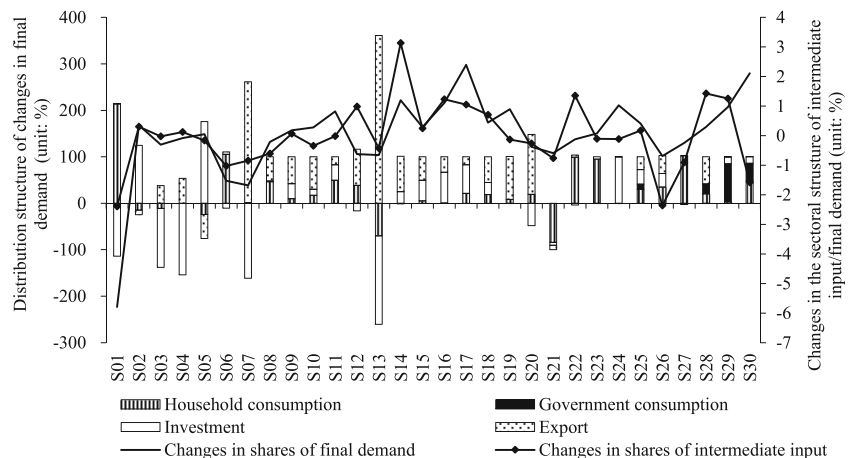
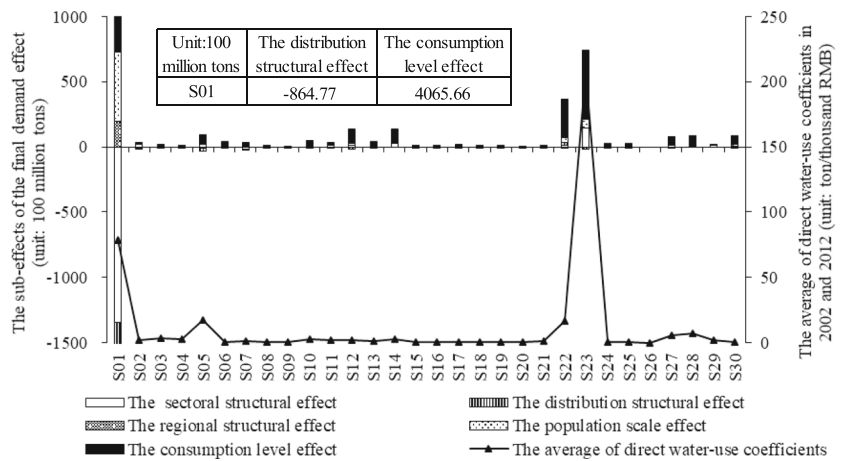


Fig. 10 The decomposing result of the final demand effect and the average of direct water-use coefficient for each sector (The average of direct water-use coefficient is equal to the arithmetic mean of the direct water-use coefficients in 2002 and 2012)



sectors with high direct water-use coefficients and the increase in the final demand share of sectors with low direct water-use coefficients, resulting in a decrease in production water usage in China during 2002–2012. As shown in Fig. 10, the final demand shares of S01 and S22 with high average direct water-use coefficients have reduced significantly, and the decline of S01 is as high as 5.79 percentage points. The final demand share of S23 with high average direct water-use coefficient has increased slightly, while the increase is less than 0.1 percentage points. The increases in the final demand shares of the sectors with low average direct water-use coefficients do not exceed 2.4 percentage points. Consequently, the changes in the sectoral structure of final demand are generally conducive to the reduction of production water usage in China.

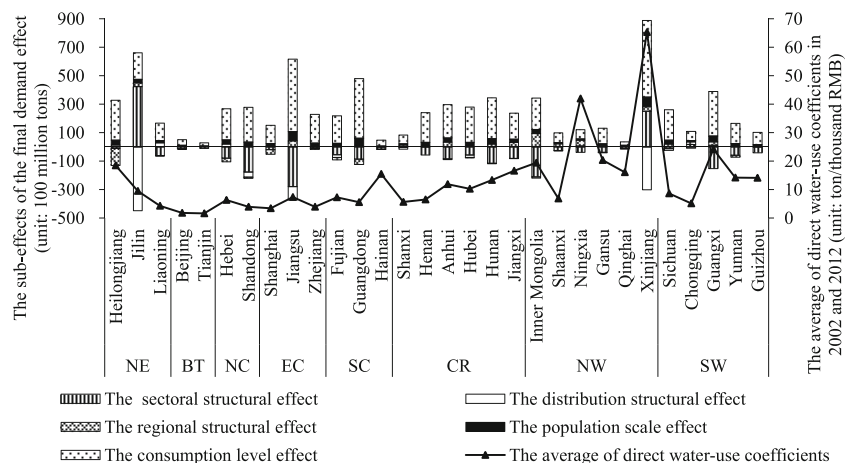
The changes in the sectoral structure of final demand have a greater inhibitory effect on provinces with more developed economies and more water usage than those with less developed economies and less water usage. Furthermore, it has a positive effect on the growth of production water usage in Jilin, Xinjiang, and Chongqing. Figure 11 shows that the final demand sectoral structural effect has a relatively weak inhibitory effect on the growth of production water usage in Beijing, Tianjin, and Shanghai, so that their reduction of

production water usage does not exceed 2 billion t. While the inhibitory effect in Jiangsu and Guangdong is larger, their reduction in the production water usage is 27.96 billion tons and 8.64 billion tons, respectively. However, it has increased the production water usage in Jilin, Xinjiang, and Chongqing by 42.33, 25.15, and 1.63 billion t, respectively.

The final demand regional structural effect

During the study period, the change in regional structure of final demand is not conducive to the reduction of the production water usage in China. This is because the average direct water-use coefficients of provinces where the final demand shares increase are greater than those of provinces where the final demand shares decline. Figure 8 shows that during 2002–2012, the total share of the final demand in 18 provinces such as Jilin, Jiangsu, Inner Mongolia, and Anhui increased by 5.38%, and the average direct water-use coefficient of these provinces in 2002 and 2012 is 13.33 tons/thousand RMB, while the average direct water-use coefficient of other provinces is 12.45 tons/thousand RMB. Since the average direct water-use coefficient of provinces where the final demand shares increase is greater than that of provinces where the final

Fig. 11 The decomposing result of final demand effect and the average of direct water-use coefficient for each province



demand shares decline, the change in the regional structure of final demand accelerates the growth of China's production water usage.

The direction of change in the regional final demand structure and that of the final demand regional structural effect has a positive relationship; that is, if the ratio of the final demand in the province to the total final demand increases, the final demand regional structural effect is positive; otherwise, it is negative. The final demand regional structural effect has contributed to the growth of production water usage in two-thirds of China's provinces, mainly because the proportion of the final demand for these provinces, except Xinjiang and Henan, has increased in the total final demand. This has an inhibitory effect on the remaining one-third provinces, primarily because of the decline in the proportion of final demand for these provinces in the total final demand. Figures 8 and 11 show that for Jilin, Jiangsu, Inner Mongolia, and Anhui, the shares of the final demand in the country have increased and that the final demand regional structural effect is positive. The shares of the final demand have decreased for most other provinces, and the final demand regional structural effect is negative. However, for Xinjiang and Henan, although the shares of final demand in the country have declined, the final demand regional structural effect is positive.

The consumption level and population scale effect

The consumption level effect is the most important factor driving the growth of China's production water usage, followed by the population scale effect, indicating that the increase in consumption levels and the expansion of population will increase production water usage. Similar to the final demand effect, their impacts on provinces and sectors with high production water usage are most significant. Figure 10 shows that during 2002–2012, the consumption level and population scale effects mainly affect S01, S23, and S22 with more water usage. Their total consumption level effect accounts for 86.20% of the total consumption level effect in China, while the population scale effect accounts for 86.51%. Figure 11 shows that the total consumption levels effect in Xinjiang, Jiangsu, Guangdong, and Hunan with large production water usage accounts for 30.90% of that in the country, and the population scale effect accounts for 30.69%. The consumption level effect generally has a great impact on the growth of production water usage. Although its contribution to the growth of production water usage in Hainan, Beijing, Qinghai, and Tianjin is weak, the consumption level effect of these provinces is also 4.10 billion t. The population size effect generally has a weaker effect on the growth of production water usage than the consumption level effect, which ensures that the increase in production water usage in each province does not exceed 7.00 billion t. Among them, it has

the weakest contribution to the increase in Hainan, Beijing, Qinghai, and Tianjin. The population scale effect has increased the production water usage of these provinces with less water usage by less than 0.60 billion tons.

The final demand distribution structural effect

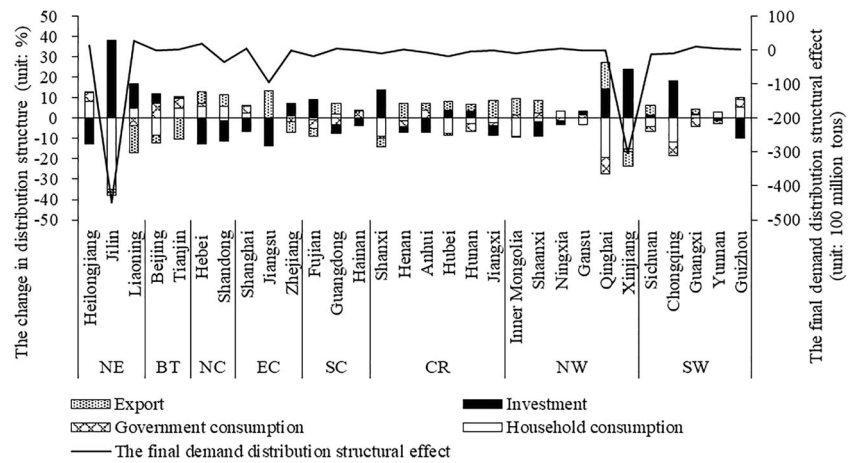
The change in the distribution structure of final demand has reduced the production water usage in China. The inhibitory effect of the final demand distribution structural effect is only second to the final demand sectoral structural effect. The change in the distribution structure of final demand has a significant inhibitory effect on the growth of production water usage in most provinces and has a weak promotion effect in some provinces. Figure 11 shows that the final demand distribution structural effect has an inhibitory effect on the growth of production water usage in nearly two-thirds of the provinces. It has the most significant inhibitory effect on Jilin and Xinjiang, which have reduced production water usage by 44.88 and 30.24 billion t, respectively. While the final demand distribution structural effect has a weak positive effect on another one-third of the provinces, with the greatest promotion effect on Liaoning; however, its increase caused by the final demand distribution structural effect is less than 2.3 billion t. Therefore, the change in the distribution structure of final demand generally contributes to the reduction of production water usage in China.

The change in the distribution structure of the final demand in China from 2002 to 2012 is mainly reflected in the increase in household consumption and the decline in government consumption. The average direct water-use coefficient of the major provinces, where the share of household consumption has risen, is smaller than that of major provinces where the share of government consumption has fallen. This change in the distribution structure of final demand has led to a decline in production water usage. Figure 12 shows that household consumption increased more than the increase in China's overall household consumption share mainly in Shanghai, Guangdong, Tianjin, and Shandong. Their average direct water-use coefficient is 11.38 tons/thousand RMB during 2002–2012. While government consumption decreased by more than the decline in China's overall government consumption share mainly in Xinjiang, Ningxia, Guangxi, Jiangxi, etc., their average direct water-use coefficient is 15.49 tons/thousand RMB. Therefore, the final demand distribution structural effect has caused the production water usage in China to decline.

Conclusions and policy implications

From the regional relevance perspective, this study populates the input–output framework to measure China's production

Fig. 12 The change in distribution structure of the final demand and the final demand distribution structural effect for each province



water usage and adopts the SDA method to examine the impact of water-saving technology, regional economic pattern change, consumption level, and population scale changes on the change in China’s production water usage. The results of this study provide an important basis for China to achieve its total water usage control target and implement water conservation schemes in the future. The following conclusions are apparent.

First, China’s water use has increased significantly during 2002–2012, and the proportion of water use in the production sector, among total water use, remains very high. In addition, another prominent problem is the inconsistency between regional water usage and economic development. The relationship of production water usage and per capita GDP shows an inverted U-shaped curve in both 2002 and 2012. Compared with 2002, the inverted U-shaped environment Kuznets curve in 2012 has shifted to the right along the abscissa axis, indicating that the economic scale of each province has been significantly improved. However, there are significant differences in the trends of production water usage in various provinces. The production water usage in economically underdeveloped regions is rapidly increasing, while it is falling sharply in economically developed regions. S01, S23, and S22 are key sectors for changes in production water usage in these regions.

Second, the technical effect is a key factor in curbing the growth of China’s production water usage, while the final demand effect is a key factor in promoting it. And the provinces and sectors that use more water for production show higher technical and final demand effects. The rapid expansion of economic scale in most provinces or sectors in China is mainly driven by the substantial increase in investment and household consumption. Furthermore, export growth is the main reason for the expansion in economic scale in coastal regions. Among the factors affecting the final demand, the consumption level effect is the most important factor driving the growth of China’s production water usage, followed by the population scale effect.

Third, the change in the sectoral structure of the final demand is conducive to reducing China’s production water usage, which is about a quarter of the technical effect. The second is the final demand distribution structure effect. The inhibitory effect of the inter-regional intermediate input structure on the growth of production water usage is less than the positive effect of the final demand regional structure effect. Therefore, overall, the change in the regional economic pattern has led to an increase in China’s production water usage.

Therefore, this study makes the following policy recommendations:

Firstly, in order to promote water-saving activities, it is necessary to link the total amount of production water usage or direct water-use coefficients with the performance evaluation of local governments and industrial supervision. The rapid growth of China’s economy has increased the demand for products and services, resulting in a huge pulling effect on the growth of production water usage. To improve the efficiency of water use and accelerate the development of a water-saving society, it is necessary to regard underdeveloped regions, as well as key sectors, such as S1, S23, and S22, as crucial objects of assessment and supervision.

Secondly, it is essential to enhance the technical effect in a water-saving society. The production sectors, especially with large direct water-use coefficients (such as S01, S23, and S22), should improve efficiency in using water by introducing advanced water-saving technologies, upgrading equipment, or improving management. Simultaneously, it is necessary to encourage and supervise water-saving technical assistance to economically underdeveloped provinces from developed provinces. Furthermore, local governments could strengthen the exchange and sharing of water-saving experiences. In addition, the increase in consumption level has a huge pulling effect on the growth of production water usage. It should focus on advocating the use of low-water use products and increasing investment in projects conducive to water conservation.

Finally, it is important to optimize structures of the final demand to promote economic growth with low-water usage.

In addition, to reverse the unfavorable situation of economic pattern at the expense of massive growth in water usage, local governments could promote inter-regional coordinated development model. On the one hand, China could encourage the development of sectors with lower direct water-use coefficients and strengthen the supervision of sectors with higher direct water-use coefficients. The local government could encourage residents to adapt to water-saving lifestyles and improve investment efficiency. On the other hand, it is necessary to maintain a comparative advantage in provinces with higher water-use efficiency and increase their shares in intermediate inputs. Specifically, it is important to promote the final consumption of provinces with lower direct water-use coefficients, while curbing the share of provinces with higher direct water-use coefficient in final consumption.

In this article, from the regional relevance perspective, the impact factors of the changes in production water use in China during 2002–2012 are uncovered with the use of I–O and SDA model. If data are available, updated data at the city level can be used to do similar studies in following research. In addition, similar methods used in our article could be applied to water-use intensity, related indicators in energy, wastewater, waste, pollutants, and other fields.

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Authors' contributions Chao Gao contributed to data curation, formal analysis, and writing of the original draft. Rui Xie contributed to the conceptualization and methodology. Youguo Zhang contributed to the methodology, writing review, and editing. Kunfu Zhu contributed to the conceptualization, writing review, and editing.

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Data availability The datasets used and/or analyzed during the current study can be provided on reasonable request.

Compliance with ethical standards

Competing interests The authors declare that they have no competing interests.

Ethical approval All analyses were based on published data in yearbook or literature, and no ethical approval and patient consents are required. Authors confirm that we have permission of the use of software and data in our study.

Consent to participate There are no individual participants included in the study.

Consent to publish The authors confirm that the work described has not been published before (except in the form of an abstract or as part of a published lecture, review, or thesis), that it is not under consideration for publication elsewhere, and that its publication has been approved (tacitly

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Appendix. Sector classification

Table 3 The description table of 30 sectors of classification

Sector ID	Sector name/description
S01	Agriculture
S02	Mining and washing of coal
S03	Extraction of petroleum and natural gas
S04	Mining of metal ores
S05	Mining and processing of non-metal ores and other ores
S06	Manufacture of foods and tobacco
S07	Manufacture of textile
S08	Manufacture of textile wearing apparel, footwear, caps, leather, fur, feather and its products
S09	Processing of timbers and manufacture of furniture
S10	Papermaking, printing and manufacture of articles for culture, education and sports activities
S11	Processing of petroleum, coking, and nuclear fuel
S12	Chemical industry
S13	Manufacture of non-metallic mineral products
S14	Smelting and rolling of metals
S15	Manufacture of metal products
S16	Manufacture of general purpose and special purpose machinery
S17	Manufacture of transport equipment
S18	Manufacture of electrical machinery and equipment
S19	Manufacture of communication equipment, computer and other electronic equipment
S20	Manufacture of measuring instrument and machinery for cultural activity and office work
S21	Other manufacture
S22	Electricity and heat production and supply
S23	Gas and water production and distribution
S24	Construction
S25	Wholesale and retail trades
S26	Transportation, warehousing, and post
S27	Hotels and catering services
S28	Leasing and business services
S29	Research and technical services
S30	Other social services

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