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Drivers of virtual water flows on regional water scarcity in China

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ABSTRACT

Previous studies had shown that the virtual water flows had intensified local water scarcity of China. There is an urgent need to identify the drivers of virtual water flows and provide the potential options to reduce the impact of virtual water flows on regional water scarcity. Based on the multi-regional input-output model and structural decomposition analysis, we evaluated the redistribution of water withdrawal within China in 2002, 2007 and 2012, and then revealed the hidden driving forces of the changes in virtual water flows. For a specific province, the drivers had been divided into local and the rest of China. Here we found that: (1) The share of virtual water flows in interregional trade to total water withdrawal had increased (from 20.1% to 40.5%) during the study period. (2) The direction of virtual water flows has reversed between some Chinese regions. Northwest and Northeast regions have become the major virtual water exporters. (3) The virtual water flows hidden in traded products of agriculture, electricity and the chemical industry accounted for more than 83% of total virtual water flows. (4) Local efficiency gains and consumption pattern changes in other provinces were the main drivers for changes in virtual water flows. The water-scarce Northwest and Northeast of China had further increased virtual water export to the water-rich provinces in southern China. This trend could be curbed by improving water use efficiency and restraining water-intensive consumption. Our results could pinpoint areas to invest in water use efficiency and provide guidance for areas to restrain water-intensive consumption.

1. Introduction

China's regions have been facing serious water scarcity driven by a mismatch between available water resources and water demand, a trend that has been getting worse over the years (Jiang, 2009; Liu and Yang, 2012). The arid Northern China shows the most severe levels of water scarcity and used 19.1% of regionally available water resources to satisfy the water demand for close to half of China's population (Cai et al., 2017b). In response, China's government developed more than 20 physical water transfer projects including the South–North Water Transfer Project (SNWTP) which is the world's largest such scheme (Liu et al., 2013).

Compared with the physical water transfer projects like SNWTP which cost approximately 17 billion US dollars (Berkoff, 2003) and potentially negative impacts on ecosystems, there is another solution to mitigate regional water scarcity (Vorosmarty et al., 2015). Ideally, water scarce regions would import water-intensive products to satisfy the domestic production and consumption instead of producing them locally and by doing so conserve their domestic water resources (Allan, 1998; Hoekstra and Hung, 2002). In this case, water resources required along the entire production chain are being virtually transferred from the exporting to the importing

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region through trade between regions (Hoekstra, 2003). This water consumption along supply chains of goods traded between countries or regions is referred to as virtual water flows (Hoekstra and Mekonnen, 2012). Some scholars argue that virtual water flows are a potential solution for the spatial mismatch between available water resources and water demand in China. That is, the northern regions with poor water resources should import water-intensive products from the water-rich southern regions instead of producing them by themselves (Antonelli and Sartori, 2015; Hoekstra, 2003; Ma et al., 2006).

The problem of unequal water distribution is closely related and receives additional complexity due to unequal economic development. To address regional economic inequality, China's government launched a number of national development strategies such as the “Western Development” in 2001, “Revitalization of the Northeast” in 2004 and “Rise of Central China” in 2003. Given the close linkages between economic activities and water consumption (Suweis et al., 2013), these national development strategies will also impact virtual water flows as well as regional water use. Highly water-intensive sectors such as the chemical industry and power sectors have been moved from rich coastal areas to inland areas which is reflected in changes in interprovincial virtual water flows from the water-scarce northwest to the water-rich southeast (Jiang et al., 2015; Wu et al., 2017; Zhang and Anadon, 2014) and thus aggravating water shortage in water-exporting regions (Zhao et al., 2015).

While most virtual water flow studies in China had focused on a specific year such as 2002 (Guan and Hubacek, 2007), 2005 (Dalin et al., 2014) or 2007 (Cai et al., 2017a; Dong et al., 2014; Feng et al., 2014; Jiang et al., 2015; Zhang and Anadon, 2014; Zhao et al., 2015) or a short term like 2002–2007 (Zhang et al., 2016b), the fast pace of development, demographic and lifestyle changes as well as regional and national policies especially after 2007 (like financial crisis in 2008 (Mi et al., 2017b) and implication of 12th Five-Year Plan) requires a temporal comparative approach that allows identifying changes and their drivers. However, these variations and drivers of virtual water flows have been largely neglected in previous research. This leads to the open question whether direction and quantity of virtual water flows have changed and potentially intensified regional water scarcity; and how to mitigate such intensified water scarcity triggered by interprovincial trade in China.

Although there are a number of studies that evaluated the drivers of virtual water flows at the global scale these have seldom been evaluated at the national level (Carr et al., 2012; S. Tamea et al., 2014; Suweis et al., 2012). Moreover, many of these studies are based on virtual water flows calculation using bottom-up methods. Most of the virtual water flows calculation based on bottom-up methods only include agricultural products trade (Dang et al., 2015; Zhuo et al., 2016). These bottom-up methods can only trace bilateral trade rather than the whole supply chain and thus fails to identify the final consumer of water resources in more complex supply chains (Feng et al., 2011; Hoekstra and Mekonnen, 2012; Hubacek and Feng, 2016). For example, China has been identified as a net virtual water importer based on the bottom-up methods (Dalin et al., 2012), however, when taking into account complete supply chains, China becomes a net virtual water exporter (Zhang and Anadon, 2014; Zhao et al., 2015). As a result, the assessment of drivers of virtual water flows based on the bottom-up methods may not be accurate. On the other hand, multiregional input-output model (MRIO) has a comprehensive system boundary avoiding the mistake of incomplete supply chains and thus allows to link resource extraction and environmental impacts along complex supply chains (Wiedmann, 2009). Thus, MRIO is widely used in the calculation of virtual water flows (Guan et al., 2014; Lenzen et al., 2013; Qu et al., 2017; White et al., 2015; Zhao et al., 2015). The structural decomposition analysis (SDA) has often been combined with the MRIO to analyze the drivers of emissions and resources consumption, respectively (Cheng et al., 2017; Mi et al., 2017b).

While there are a few provincial level MRIO/SDA study such as Qian et al. (2018) with a focus on Yunnan, a comprehensive study on China assessing variation of virtual water flows and its driving forces is still lacking. Moreover, the SDA method used by Qian et al. has not distinguished local and external driving factors. The interpretation of internal and external driving forces of changes in virtual water flows is essential for setting the regional water use target and can provide more accurate policy objectives for the water resources managers (Zhao et al., 2016). In this study, we quantify virtual water flows between provinces in China for the years 2002, 2007 and 2012 using MRIO for 30 provinces with 29 sectors, and analyze the drivers of change using SDA. In our SDA framework, for a specific province, the drivers have been divided into two categories: local and the rest of China (Xu and Dietzenbacher, 2014).

2. Materials and method

2.1. Using multi-regional input-output analysis (MRIO) to calculate interprovincial virtual water flows

The multiregional input–output model (MRIO) has been widely used for uncovering the virtual water flows between regions (Feng et al., 2014; Lenzen et al., 2013; Zhao et al., 2015). In a MRIO framework, different regions are connected through inter-regional trade. The technical coefficient submatrix A^{rs} is composed of $a_{ij}^{rs} = z_{ij}^{rs}/x_j^s$ elements, where z_{ij}^{rs} is the inter-sector monetary flow from sector i in region r to sector j in region s and where x_j^s is the total output of sector j in region s. The final demand matrix y includes [$yrs\ i$] elements, where $yrs\ i$ denotes the final demand in region s for goods produced in region r. Therefore, the MRIO analysis can be written as:

$$\begin{bmatrix} x_1 \\ \vdots \\ x_r \\ \vdots \\ x_n \end{bmatrix} = \begin{bmatrix} A_{11} & \cdots & A_{1r} & \cdots & A_{1p} \\ \vdots & \ddots & \vdots & & \vdots \\ Ar1 & \cdots & Arr & \cdots & Arp \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ An1 & \cdots & Anr & \cdots & Ann \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_r \\ \vdots \\ x_n \end{bmatrix} + \sum_{n} \begin{bmatrix} y_{11} + \sum_{s \neq 1} y_{1s} \\ \vdots \\ y_{rr} + \sum_{s \neq r} y_{is} \\ \vdots \\ y_{nn} + \sum_{s \neq n} y_{ns} \end{bmatrix} \quad (1)$$

Using familiar matrix notation and dropping the subscripts, equation (1) can be written as $x = Ax + y$ or $x = (I\text{-}A)^{-1}y$, where $(I\text{-}A)^{-1}$ is the Leontief inverse matrix that captures both direct and indirect inputs required to satisfy one unit of final demand in monetary value and I is the identity matrix (Miller and Blair, 2009). The MRIO used in this study included 29 sectors in 30 Chinese provinces at the year of 2002, 2007 and 2012. The MRIO table used in this paper are based on each province's single Input-output table (IOT) in 2002, 2007 and 2012 released by National Statistics Bureau (NSB). The method to compile the MRIO table we used is also scientific and reasonable, which is widely used to the compilation of China's MRIOT in 2002 and 2007 in published paper or book (Chen et al., 2015; Zhang et al., 2012, 2018a; Zhang and Qi, 2012).

In this study, virtual water flow is defined as the water withdrawal associated with the production of goods and services traded between regions. To calculate virtual water flows between regions, the MRIO table was extended with the sector-specific water withdrawal:

$$WW_i = f_i x_i = f_i (I - A_i)^{-1} y_i \tag{2}$$

where WW_i is the vector of water withdrawal for each sector of region i due to the final consumption, x_i is the total economic output of region i, f_i is the vector of direct water intensity which shows the direct water withdrawal per unit of output in each sector, y_i is the vector of final demand, A_i is the matrix of technical coefficients and I is the unit matrix (Wiedmann, 2009). The impact of trade on environment has often been estimated by the Emissions Embodied in Trade' (EET) method as its arguably better for analysis of trade (Peters, 2008; Peters et al., 2011). In this study, the similar 'water embodied in trade' (WET) to has been used. According to the framework of EET or WET, the bilateral trade between regions to intermediate and final consumption will be combined and reallocated to final consumption (Peters and Hertwich, 2008; Zhao et al., 2015). In equation (1), for each region i, the A_{is} has been made to 0 $A_{is} = 0$ $(i \neq s)$, and let $eir = Ais + yis (i \neq s)$ to replace $y_{is,}$ then we can get the basic formulation of 'WET' (Zhao et al., 2015).

$$\begin{bmatrix} x_1 \\ \vdots \\ x_r \\ \vdots \\ x_n \end{bmatrix} = \begin{bmatrix} A_{11} & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & & \vdots \\ 0 & \cdots & Arr & \cdots & 0 \\ \vdots & & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & Ann \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_r \\ \vdots \\ x_n \end{bmatrix} + \sum_{n} \begin{bmatrix} y_{11} + \sum_{s \neq 1} e_{1s} \\ \vdots \\ y_{rr} + \sum_{s \neq r} e_{is} \\ \vdots \\ y_{nn} + \sum_{s \neq n} e_{ns} \end{bmatrix} \tag{3}$$

For the total output of region i, (x_i):

$$x_i = A_{ii} x_i + y_{ii} + \sum_{r \neq i} e_{ir} \tag{4}$$

where A_{ii} is the domestic technical coefficients, and y_{ii} shows the domestically produced products to fulfill final demand. The export from region i to region r $(e_i = \sum_{r \neq i} e_{ir})$ is the total bilateral trade (Weber and Matthews, 2007). Thus, equation (2) can be shown as:

$$WW_i = f_i x_i = f_i (I - A_{ii})^{-1} \left(y_{ii} + \sum_{r \neq i} e_{ir} \right) \tag{5}$$

Based on equation (5), the quantity of virtual water export and import for region i can be calculated as:

$$VWE_{ir} = f_i (I - A_{ii})^{-1} \sum_{r \neq i} e_{ir} \tag{6}$$

$$VWI_{ir} = f_1 (I - A_{11})^{-1} e_{1i} + f_2 (I - A_{22})^{-1} e_{2i} + \cdots + f_r (I - A_{rr})^{-1} e_{ri} (i \neq r) \tag{7}$$

where $VWE_{ir}$and VWI_{ir}shows the total virtual water export and import from region i to region r. We calculated the virtual water flows through the same methods for the year of 2002, 2007 and 2012. All values in 2007 and 2012 MRIO tables had been changed to 2002 constant prices using a GDP deflator derived from the China Statistic Yearbook (State Statistics Bureau., 2014). The virtual water flows are composed by $VWE_{ir}$and VWI_{ir}, and they were equated to each other within the nation.

2.2. *Structural decomposition analysis (SDA) for the variation of virtual water flows during 2002–2012*

The SDA methods have been widely used to assess the driving forces of changes in emission or resources use embodied in trade, like CO_2 (Mi et al., 2017a, 2018) or water resources (Qian et al., 2018). Under the SDA framework, five factors have often been considered (population, efficiency, production structure, consumption patterns and consumption volume) (Mi et al., 2017b). In this study, as equations (6) and (7) shows that the *VWE* and *VWI* are determined by water intensity or water use efficiency (E), the Leontief inverse (L) (production structure) and final demand F. The matrix F is determined by composition of final products S (consumption pattern) and the demand matrix of final consumption. The demand matrix of final consumption is depended on population P and per capita final demand D (consumption volume) (Mi et al., 2017b). We distinguish the different effects between local and the rest of China (ROC) by dividing each factor into two parts based on previous study. For example, the $E^{(r)}$ shows the effect of local water intensity of province r, while the $E^{(-r)}$ represents the effect of the ROC (the remainder of China without province r) water intensity (see Table 1). The relationships of VWE^r and VWI^r with these factors can be shown by:

$$VWE^r = u^r \left(E^{(r)}, E^{(-r)}, L^{(r)}, L^{(-r)}, D^{(r)}, D^{(-r)}, P^{(r)}, P^{(-r)}, S^{(r)}, S^{(-r)} \right) \tag{8}$$

$$VWI^r = g^r \left(E^{(r)}, E^{(-r)}, L^{(r)}, L^{(-r)}, D^{(r)}, D^{(-r)}, P^{(r)}, P^{(-r)}, S^{(r)}, S^{(-r)} \right) \tag{9}$$

For the decomposition analysis, there is no unique way to do a decomposition as previous study shows (Dietzenbacher and Los, 1998). In the case of k variables, the number of alternative decompositions is $k!$ In this study the alternatives would be 3,628,800 as we have $k = 10$. It's too complex to get the implementation in practice. The average of two polar decomposition forms is approximately equal to the results of all possible decomposition forms according to the previous studies (Dietzenbacher and Los, 1998; Xu and Dietzenbacher, 2014; Zhang et al., 2015). Thus, we used the two polar decomposition forms in this study. For the first polar form, the decomposition is started by changing the first variable first, and then by changing the second and followed by changing the third variables, etc. The second polar form is derived in the opposite manner. To be specific, the decomposition of second polar form starts by changing the last variable first, followed by changing the second-to-last variable and so forth. Based on this, after calculating the geometric average of u^r_{polar1} and u^r_{polar2}, we can

Table 1
Description of structural decomposition components.

Factors	Description
$\Delta E^{(r)}$	Local water intensities or water use efficiency
$\Delta E^{(-r)}$	Water intensities or water use efficiency of the ROC
$\Delta L^{(r)}$	Local production structure
$\Delta L^{(-r)}$	Production structure of the ROC
$\Delta D^{(r)}$	Local per capita final demand or economic development
$\Delta D^{(-r)}$	Per capita final demand or economic development of the ROC
$\Delta P^{(r)}$	Local population
$\Delta P^{(-r)}$	Population of the ROC
$\Delta S^{(r)}$	Local trade structure of final products
$\Delta S^{(-r)}$	Trade structure of final products of the ROC

get the changes in *VWE* from *t* year to *t-1* year. Moreover, the same procedure had been used for *VWI*. The equations can be shown by:

$$\Delta VWE^r_{t-1,t} = \frac{\Delta vwe^r_t}{\Delta vwe^r_{t-1}} = \sqrt{u^r_{polar1} \times u^r_{polar2}} \tag{10}$$

$$\Delta VWI^r_{t-1,t} = \frac{\Delta vwi^r_t}{\Delta vwi^r_{t-1}} = \sqrt{g^r_{polar1} \times g^r_{polar2}} \tag{11}$$

We had taken the changes in virtual water export (*VWE*) as an example, the changes caused by each separate component got the following relationship (Xu and Dietzenbacher, 2014):

$$\Delta VWE + 1 = \left(\Delta E^{(r)} + 1\right) \times \left(\Delta E^{(-r)} + 1\right) \times \left(\Delta L^{(r)} + 1\right) \times \left(\Delta L^{(-r)} + 1\right) \times \ldots \left(\Delta S^{(r)} + 1\right) \times \left(\Delta S^{(-r)} + 1\right) \tag{12}$$

Additionally, more details about the SDA used in this study can be found in SI.

2.3. Water use data and water scarcity assessment

Water use is defined as the quantity of water withdrawal in this study. The water withdrawal data for each sector at provincial level mainly came from the Water Resources Bulletin (WRB) for each province and the China Environmental Statistics Database (CESD). The quantity of water withdrawal for agriculture, services sector and households for each province are based on the data from WRB for each province. Water withdrawal data for services sectors are aggregated at the provincial level, and we assume that water withdrawal intensity for each service sector are the same in each province based on other research studies (Feng et al., 2014; Zhang and Anadon, 2014). The quantity of water withdrawal for industrial sectors of each province was based on the data from CESD and it was calculated based on the following processes (more detailed description about CESD can be found in previous studies (Zhang et al., 2018a; Zhang et al., 2018b).

First, we collected the water withdrawal data for each enterprise from the CESD, and then we summed the water withdrawal data for sector *i* of province *j*.

$$\mathrm{WW}^*_{ij} = \sum_{j-n} \mathrm{W}_{ij} \tag{13}$$

where WW^*_{ij} is the quantity of water withdrawal for sector *i* in province *j* based on the data of CESD. W_{ij} is the quantity of water withdrawal for each industrial enterprise of sector *i* in province *j*. We had to adjust the quantity of water withdrawal for each industrial sector in a province for the CESD only covered the enterprises which quantity of pollution discharge represents 80%~90% of the total instead of all the industrial enterprises for each province (Cai et al., 2017a; Wang et al., 2017).

$$\mathrm{WW}_{ij} = \mathrm{WW}^*_{ij} \times \mathrm{I}_j \tag{14}$$

where the WW_{ij} is the final quantity of water withdrawal for sector *i* in province *j* used in the virtual water flows calculation, the I_j is the adjustment coefficient for province *j* which is calculated by equation (15). We have multiplied the quantity of water withdrawal derived from CESD by I_j to get the final quantity of water withdrawal for each industry sector in a province.

The I_j is calculated through dividing the water withdrawal data of industry from WRB by data from CESD for province *j*.

$$\mathrm{I}_j = \frac{\mathrm{WR}_{idj}}{\mathrm{WW}^*_{idj}} \tag{15}$$

where WR_{idj} is the total quantity of water withdrawal for industry of province *j* which derived from WRB for each province; the WW^*_{idj} is the quantity of water withdrawal for industry of province *j* which was calculated by the sum of WW^*_{ij} based on the data from CESD.

To make the assessment of virtual water flows on regional water scarcity, we also estimated the water scarcity of each province in 2002, 2007 and 2012. The water scarcity assessment had been evaluated through the water scarcity index (WSI). The WSI used in this study is the ratio of the quantity of annual freshwater withdrawal to the renewable freshwater availability. Moreover, the water scarcity has been classified, the moderate, severe, and extreme water scarcity would occur when the value of WSI is 20–40%, 40–100%, and over 100%, respectively (Liu et al., 2017; Oki and Kanae, 2006; Vörösmarty et al., 2000).

Fig. 1 shows the flow of our methods. We first compile the MRIO table based on the provinces' single IOT and collect the water withdrawal data from WRB and CESD to establish the water withdrawal inventory of each sectors at province level. Then, we made the estimation of virtual water flows and their impacts on regional water scarcity in 2002, 2007 and 2012 based on the corresponding year of MRIO, water withdrawal inventory and WSI. Finally, we analyzed the driving forces of the changes in virtual water flows through the SDA method which distinguish the effects of local and the ROC.

3. Results

3.1. Variation of virtual water flows during 2002–2012

Virtual water flows played an increasingly important role in water use in China during 2002–2012. Virtual water flows amounted to 110.3 Gm^3/y, i.e., 20.1% of the total water withdrawal in China in 2002, which increased to 209.5 Gm^3/y or 36% in 2007, which is similar to findings in other studies (Dong et al., 2014; Jiang et al., 2015; Zhang and Anadon, 2014; Zhao et al., 2015), and further increased to 248.1 Gm^3/y or 40.5% in 2012. In other words, during that decade, the quantity of virtual water flows increased by more than 124%, and the share of virtual water related withdrawals increased. In addition, the direction of virtual water flows between regions also changed during the same period. A larger share of virtual water was exported from the less developed regions such as Northwest and Northeast regions to the developed areas in the East, North and South coast regions. Fig. 2 shows this direction change from 2a to 2c. Whereas virtual water was mainly exported from the Central and Northeast regions and South Coast and Beijing-Tianjin regions being the major virtual water importers in 2002, by 2007, the Northwest regions had replaced the Central regions and became the major virtual water exporters; and the East Coast changed from the major virtual water exporter in 2002 to importer in 2007. By 2012, the position of major virtual water exporter of the Northwest and Northeast regions further strengthened and the major importers changed from East coast to South and North coast regions.

3.2. Impact of virtual water flows on regional water scarcity

Following economic and population growth, water withdrawal continuously increased during the study period. The number increased by 12% from 545.5 Gm^3/y in 2002 to 578.2 Gm^3/y in 2007 and 611.2 Gm^3/y in 2012 (Fig. 3). Almost all provinces show an

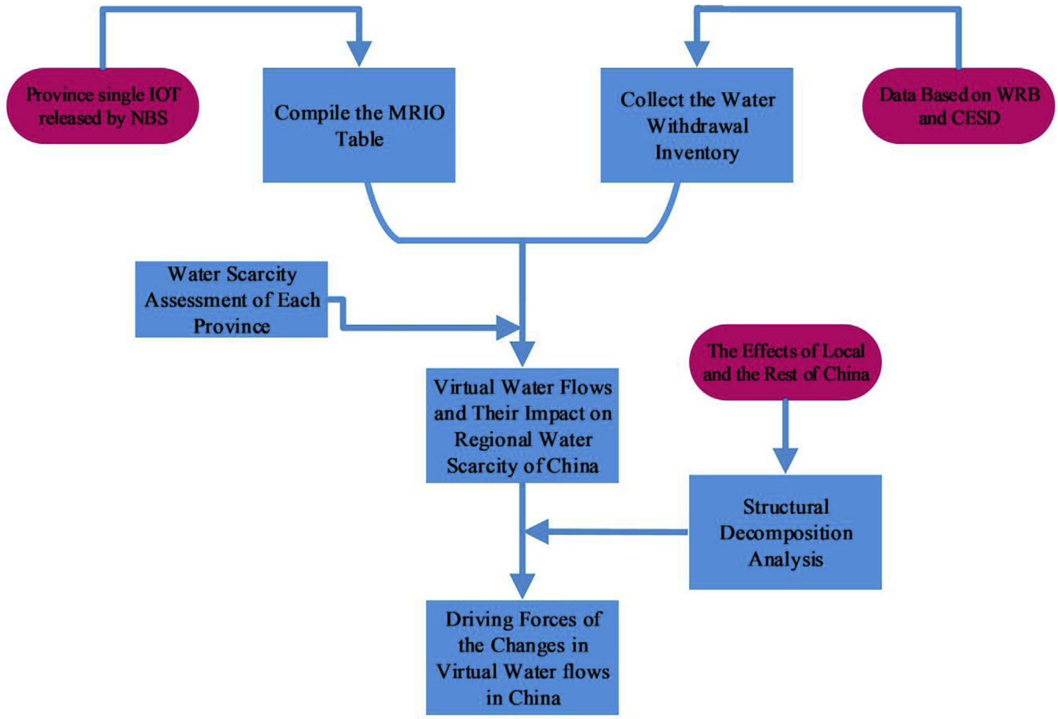

Fig. 1. The method flow chart of our study.

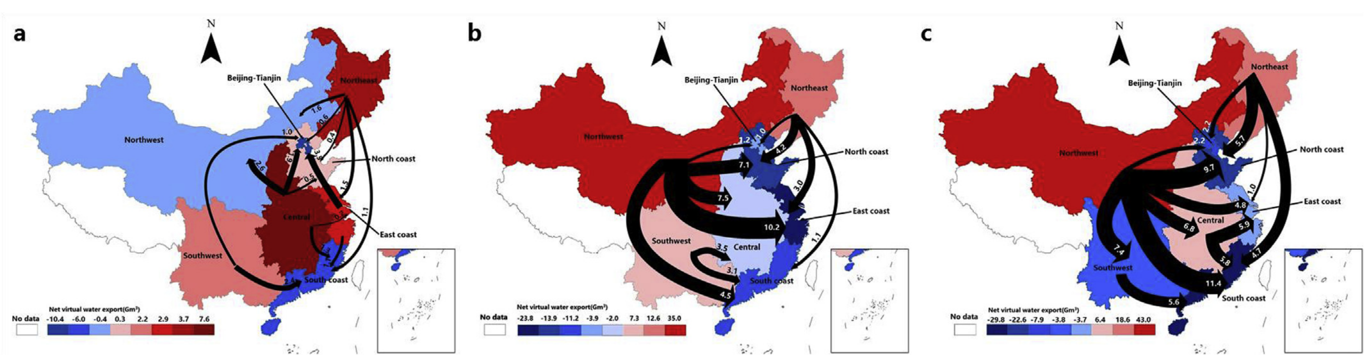

Fig. 2. Virtual water balance per economic region and the largest net virtual water flows are shown in China at 2002 (a), 2007 (b) and 2012 (c). Note that, only net water export of >0.2 Gm^3/y are labeled in (a) and >0.1 Gm^3/y are labeled in (b) and (c).

increase for water withdrawal with the rate of increase ranging from 2% to 42% during 2002–2012. Only five of the 30 provinces show a decrease (of less than 15%) in water withdrawal during the same period. Based on the water scarcity assessment (see section 2.3), we see in Fig. 3 that many regions in China faced severe water scarcity. There were 18 provinces facing water scarcity problems during 2002–2012 which included the highly developed east coast regions such as Shanghai, Jiangsu and Guangdong and the less developed regions of western China such as Inner Mongolia, Xinjiang and Ningxia.

The virtual water flows between different provinces during 2002–2012 intensified the water scarcity situation of the less developed central and western regions, which were also the major water exporters (as shown in Fig. 4). Water scarce provinces, Xinjiang and Heilongjiang, are two major virtual water exporters. These two exported 48.2% and 23.8% of the respective provincial water withdrawal in 2002 and the shares increased to respectively 64.6% and 78.3% in 2012. In addition, other water-scarce provinces such as Hubei, Hebei and Anhui were also major exporters in 2002, 2007 and 2012. In 2002, Beijing, Gansu and Hainan were the major virtual water importers and these three held about one-fifth of the total virtual water import. The major virtual water importers changed to Shandong, Zhejiang and Guangdong in 2007 and 2012 and these three accounted for more than 27% of the total virtual water import. There were more than eight provinces facing water scarcity that benefited from the virtual water flows during the study period (nine in 2002, eleven in 2007 and eight in 2012).

The main sources for virtual water flows were related to Agriculture, Electricity and Heating Power Production and Supply (Electricity sector for short) and Chemicals sectors (see Fig. 5). The virtual water flows related to the agriculture sector increased from 68.2 Gm^3/y in 2002 to 138.5 Gm^3/y in 2007 and 174.2 Gm^3/y in 2012 accounting for about 70% of total virtual water flows. The increase of virtual water flows from the agriculture sector may be explained by the increase in meat consumption (Cai et al., 2017a). Animal-based food needs more water than plant-based diets over the

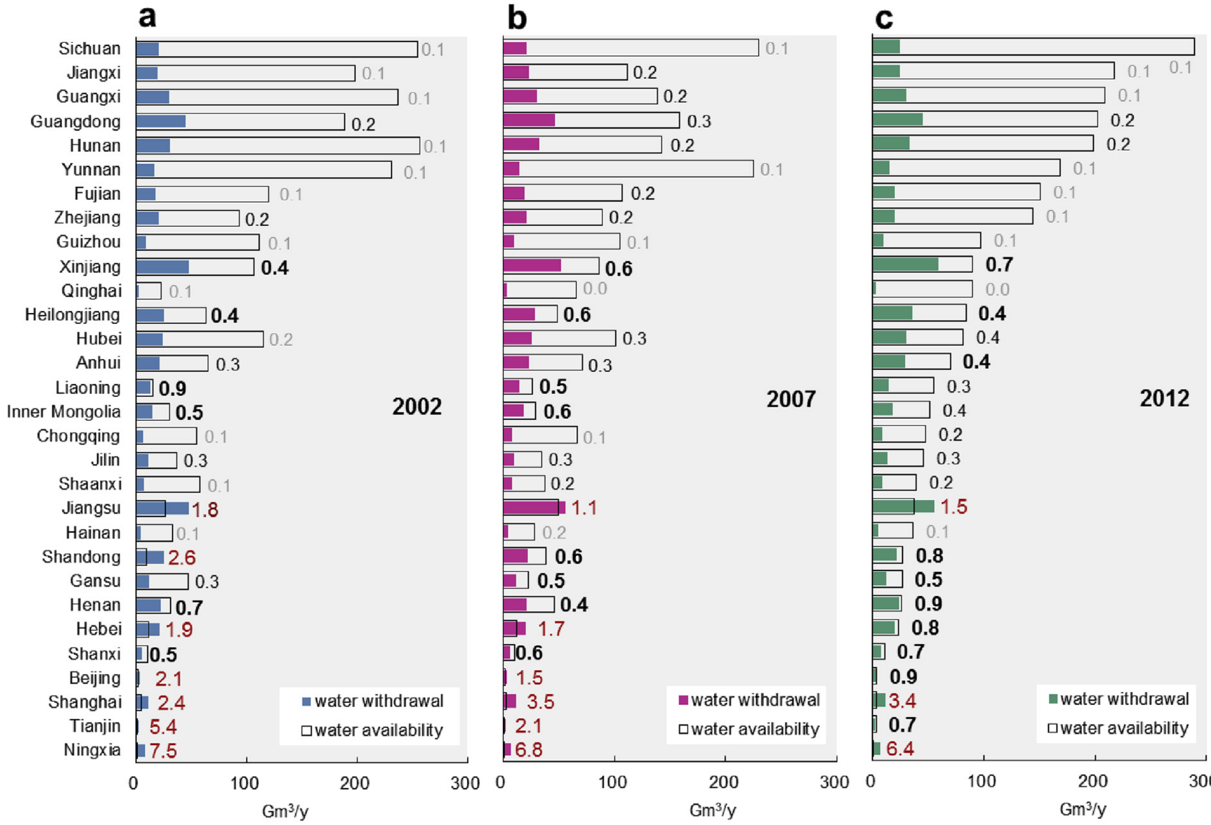

Fig. 3. Water withdrawal and water scarcity for China's each province at 2002(a), 2007(b) and 2012(c). The value for each province shows the water scarcity index, <0.2: without water scarcity (in grey); 0.2–0.4: moderate water scarcity (in black); 0.4–1.0: severe water scarcity (in bold black); >1: extreme water scarcity (in red). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

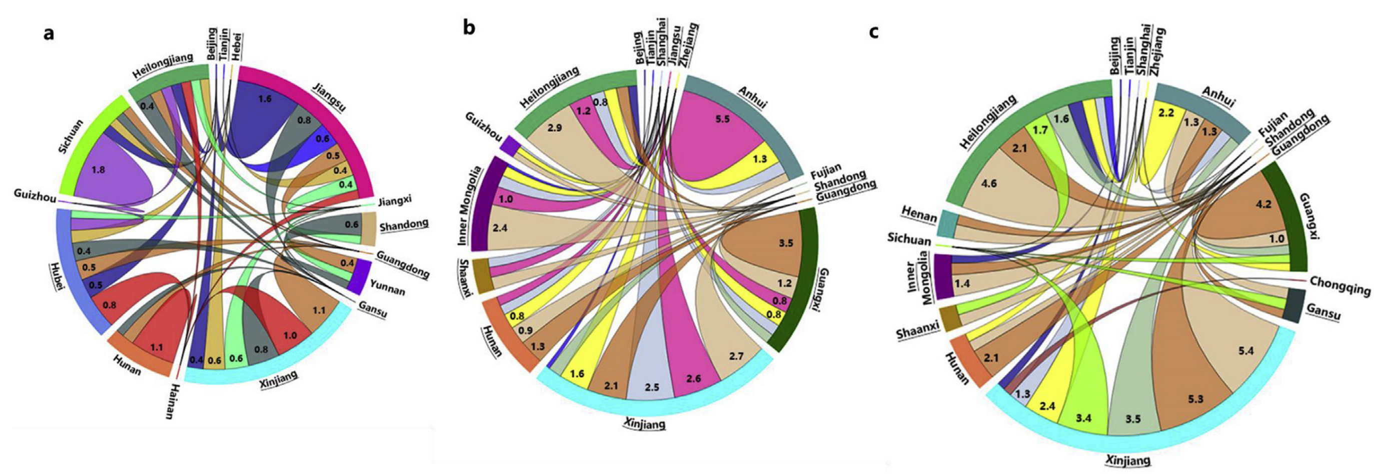

Fig. 4. Virtual water flows between provinces at 2002 (a), 2007 (b) and 2012 (c). The numbers refer to net virtual water exports in Gm^3. The regions with one color inside the circle are net importers, and the others are net exporters. The underlined regions faced water scarcity issues. Only net water export of >0.4, >0.6 and > 1.0 Gm^3/y are labeled in (a), (b) and (c) respectively. the whole pictures can be found in SI (Bostock, 2012). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

entire supply chain. As a result, for higher income regions, which were also the virtual water importers, meat-based diets contributed to higher virtual water import (Liu and Savenije, 2008). Following agriculture, the Electricity and Chemical Industry sectors made the second and third largest contribution to virtual water flows. Virtual water imports from these three sectors represented more than 75% of their total virtual water import of the major importers in 2002, 2007 and 2012.

3.3. Driving forces behind interprovincial virtual water flows

Based on Structural Decomposition Analysis of the changes in virtual water flows, we found that change in per capita final demand (a proxy for economic development) made the largest

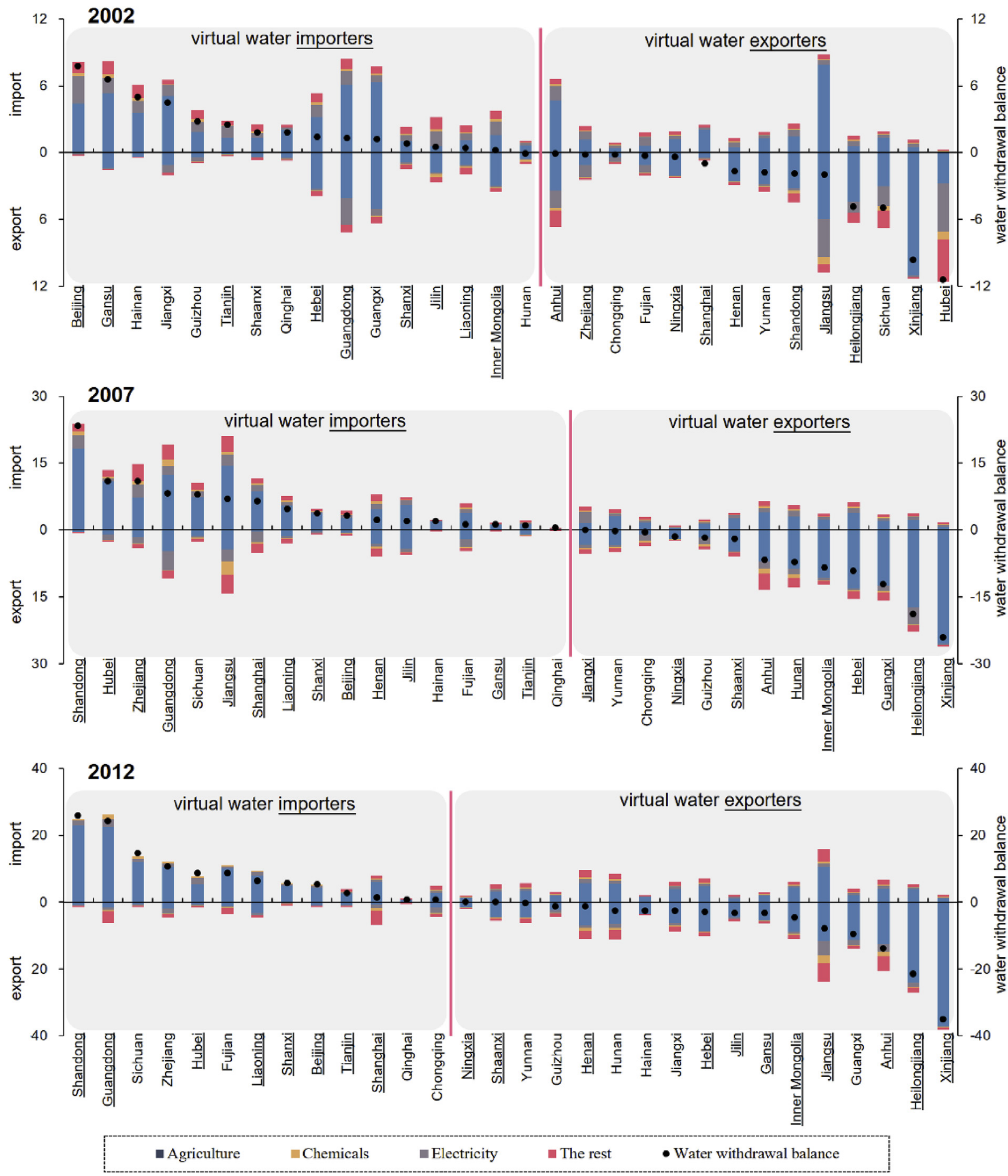

Fig. 5. Virtual water flows for different sectors during 2002–2012 (Gm^3/y). Notes that the regions with underline were faced with water scarcity.

contribution to the increase of virtual water flows between provinces. Economic development of the Rest of China (ROC) would have increased the total virtual water flows by 47.2% during 2002–2012 while keeping all other variables constant. Moreover, local economic development increased the total virtual water flows by 67.7%, everything else kept constant. Production structure change and trade structure of final products of the ROC would have increased the total virtual water flows by 44.0% and 20.9%, respectively. The population growth of the ROC contributed each less than 5% to the increase of the total virtual water flows. At the same time, efficiency gains, shown by the decline of local water intensity, would have reduced the total virtual water flows between provinces by 60.6% during 2002–2012. Efficiency gains in the ROC had no impact on virtual water flows.

At provincial level, economic development (shown by increase of per capita final demand) in the rest of China made the largest contribution to the increase of virtual water export of the major exporters, like Xinjiang and Heilongjiang. With other factors remaining the same, virtual water export of these two regions would increase by more than 25% (see Fig. 6). This indicates that the

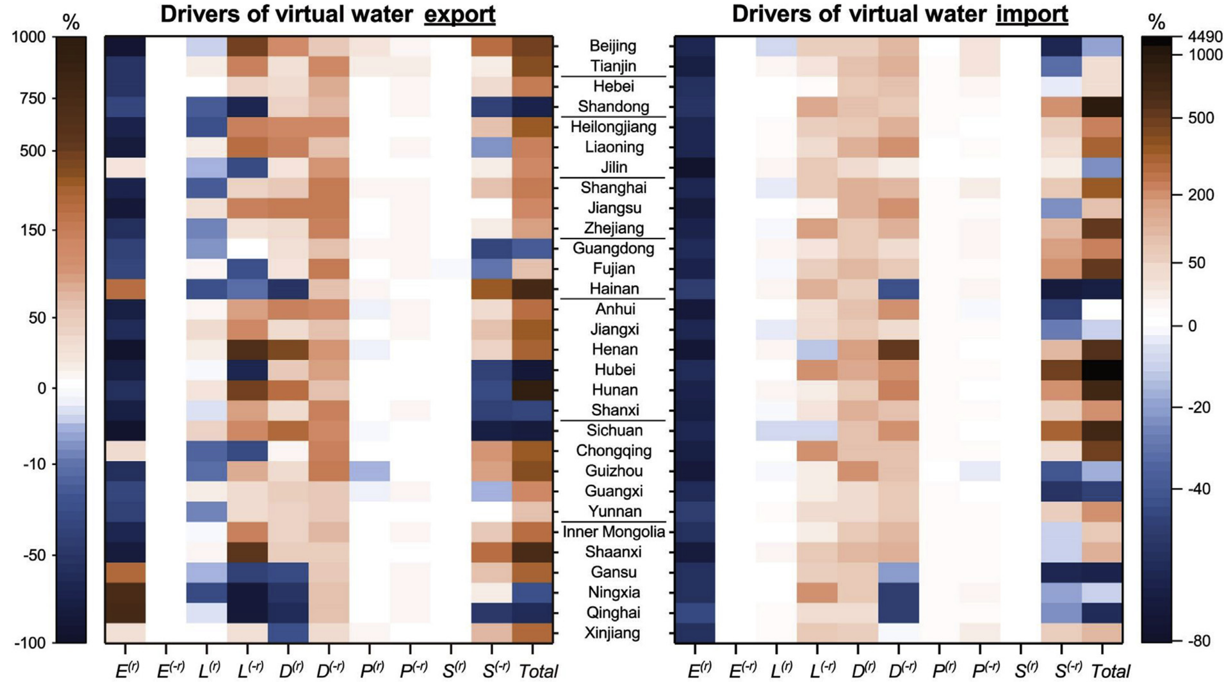

Fig. 6. Structure decomposition analysis of changes in virtual water export (*left*) and import (*right*)for each province during 2002–2012. The SDA results for 2002–2007 and 2007–2012 can be found in SI.

major importers use scarce water resources of exporters to achieve economic development. Production structure change of the ROC contributed 27% to the increase of virtual water export of the major exporters such as Anhui. This result indicates that the production structure of the major importers had changed to more water-intensive industries inquiring inputs of upstream supply chains located in exporting regions. While major exporters like Anhui also face water scarcity, the production structure change of the major importers had intensified the water scarcity of the major exporters. Trade structure of final products of the ROC also leads to more than 8% increase of the virtual water export of the major exporters like Xinjiang and Anhui, when other factors remain the same. This indicates that the major exporters sacrifice their scarce water resources to satisfy the major importers' increasing demand of water-intensive products like animal-based food and this partly verifies our hypothesis about the increasing virtual water import of higher income regions. Moreover, population growth of the ROC only made a small contribution (less than 3%) to the increase of virtual water export of the major exporters.

Local efficiency gains were the main driver for the decrease of virtual water exports. The decline of local water intensity reduced virtual water exports by 49.6%, 16.8% and 42.7% respectively for Xinjiang, Heilongjiang and Anhui, which were the major virtual water exporters. For the major virtual water importers, such as Guangdong, Shandong and Zhejiang, the decline of local water intensity in their own territories would have decreased the virtual water import by 41.4%, 38.1% and 39.2%, respectively, everything else kept equal. Therefore, there is a huge potential to reduce overall water demand by improving water use efficiency in both water rich and water poor regions.

4. Discussion

4.1. Policy implications

Our results show that virtual water flows played an increasingly important role in water use in China between 2002 and 2012. In addition, the direction of flows had changed from Central China in 2002 whereas in 2012 most exports originated from Northeast and Northwest to the more developed coastal regions. This reflects that national development strategies like "Western Development" and "Revitalization of the Northeast" led to more virtual water export from Northeast and Northwest and intensified the regional water scarcity. Under the background of the implementation of these national development strategies, the Northwest and Northeast regions may have paid more attention to economic development than to environmental protection. In other words, these regions choose to sacrifice their scarce water resources in exchange for an increase in GDP and to satisfy the water demand of richer regions.

Based on the SDA results, we found that the economic development made the largest contribution to the increase of virtual water flows between regions. Per capita GDP had increased by more than 250% during the past decade and China has maintained a high economic development rate, the continuation of this growth rate would amplify the impact of virtual water flows on local water scarcity in future. Moreover, major importers had achieved economic development at the cost of scarce water resources in other provinces.

The SDA shows that this adjustment of industrial structure would lead to more virtual water export from the less developed regions face water scarcity through outsourcing from the developed coastal regions. This can be partly explained by the increase of water-intensive sectors such as Chemicals and Electricity sectors of the major importers requiring water-intensive inputs intensifying local water scarcity of the major exporters. The trade structure of final products of the ROC also led to more virtual water export of the major exporters. Based on the SDA results, the composition of household consumption, such as a higher share of high water-intensive meat-based food had significantly contributed to the increase in virtual water flows. This reflects the increase in the consumption animal-based food with increasing income (Hubacek and Sun, 2005), the consumption patterns are transitioning to higher water-intensive food items for the major importers and would lead to more virtual water import. A reduction of food-related water footprints would require educating consumers about health and environmental impacts of meat-based diets and promotion of lower water intensive and healthier plant-based diets (Vanham et al., 2013).

Based on the SDA result, we found that the efficiency gains made the largest contribution to the reduction of virtual water flows between regions. During the past decades, water use efficiency significantly increased (Jiang, 2015), but got still room to improve in future. For example, there is a big gap of irrigation water use efficiency between China and developed countries, the irrigation water use coefficients of developed countries are 40–60% more efficient than China's (Ministry of Water Resources., 2014). Given the importance of agriculture for water use this study emphasizes the urgency to implement water-saving measures in agriculture production. Economic incentives such as increasing the water price for water use in agricultural production can be taken as potential means to improve water use efficiency (Kang et al., 2017; Shi et al., 2014; Yang et al., 2003), but social consideration must be taken into account.

The Electricity sector was another major contributor to virtual water flows between regions. The electricity sector of the major virtual water exporters had held more than 15% of the total virtual water export from the electricity sector. Our results, similar with previous research (Zhang et al., 2017; Zhu et al., 2015), show virtual water export associated with electricity production from the water-scarce Northwest and Northeast regions to the coastal regions. During the past decade this trend had strengthened. Although water use efficiency of the electricity sector has improved during the past decade in almost all provinces, there is still a large room for power plants located in the Northwest and Northeast to improve the water use efficiency of electricity production. This can be achieved through measures such as the adaptation of air-cooling (the percent of air-cooling technology used was only about 40% in Northwest and Northeast) (Zhang et al., 2014, 2016a). Water saving technology should be promoted for major virtual water exporters in future to reduce the water withdrawal per unit of electricity production and decrease the quantity of virtual water export of the electricity sector. Similarly, water saving technologies should be promoted in other manufacturing sectors to help increase overall water efficiency.

Our results also provide policy implications of other regions or countries with uneven distribution of water resources and lots of trade between different places, like Africa (Konar and Caylor, 2013) USA (Dang et al., 2015) or Spain (Cazcarro et al., 2013). To get the sustainable water use of these regions, the impact of virtual water flows should be considered especially their impacts on regional water scarcity. Our results pointed out that the improvement of water use efficiency and constrain of water-intensive products should be the targeted opportunities to reduce the impact of virtual water flows on regional water scarcity.

4.2. Limitations and directions for future research

There are still some limitations in this study. First, virtual water flows were calculated based on relatively highly aggregated sectors potentially combining subsectors with high and low water intensity (Wiedmann, 2009). In this study, livestock and crop production were combined in an aggregated agriculture sector ignoring the respective shares and differences in water intensity between these two or more sub-sectors (Cai et al., 2017a). While this is frequently done in research due to data limitations, this level of aggregation inevitably leads to some level of error when calculating virtual water flows between regions. Second, we did not consider virtual water flows associated with international trade given the focus of this study on redistribution of water withdrawal within China through virtual water flows. Third, we did not consider the return flows which may contain pollutants (like nitrogen and phosphorus) (Mekonnen and Hoekstra, 2015, 2017) and would have influenced local water quality (Cai et al., 2017a).

To improve the accuracy of the results about the virtual water flows in China, the MRIO with more sectors especially for the agriculture should be used in the future research, like the MRIO of China with 135 industry sectors for each province (Wang et al., 2015). In order to get the whole picture about virtual water flows under the consideration of both domestic and international trade, future studies could connect the China MRIO with global MRIO models like GTAP (Liu et al., 2015). Moreover, as China also face severity of water quality deterioration, future studies should consider the impacts of interprovincial trade on water quality if data becomes available.

5. Conclusion

This paper analyzes both local and external drivers of virtual water flows associated with interprovincial trade in China, a topic which had not been explored in previous research. We found that the virtual water flows had played an increasingly important role in water use in China from 2002 to 2012 and the direction of virtual water flows has changed during the study period. For example, the Northwest and Northeast regions with scarce water resources have turned from net importers to virtual water exporters. We also found that the main factors explaining changes in virtual water flows were improvements in local water use efficiency and changes in consumption pattern in other provinces. Based on these results, we suggested that the target setting of future regional water use should consider the direction changes of virtual water flows and its impact on water scarcity. The water policy targeted to reduce the impact of virtual water flows on regional water scarcity should focus on the improvement of water use efficiency and disincentive the consumption of water-intensive products.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2018.10.077.

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