Journal of Cleaner Production 228 (2019) 1401–1412

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Regional water footprints and interregional virtual water transfers in China

Shidong Zhang [a], Morteza Taiebat [a, b], Yu Liu [c, d], Shen Qu [a, *], Sai Liang [e], Ming Xu [a, b]

[a] School for Environment and Sustainability, University of Michigan, Ann Arbor, MI, 48109-1041, United States
[b] Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI, 48109-2125, United States
[c] Institutes of Science and Development, Chinese Academy of Sciences, Beijing, 100190, China
[d] School of Public Policy and Management, University of Chinese Academy of Sciences, Beijing, 100049, China
[e] State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing, 100875, China

ARTICLE INFO

Article history:
Received 1 November 2018
Received in revised form
31 March 2019
Accepted 23 April 2019
Available online 29 April 2019

Keywords:
Multi-regional input-output model
Virtual water
Water stress
China

ABSTRACT

China faces increasingly severe water stress from its limited, unevenly distributed water resources and rapid economic growth. Interregional trade of goods and services within China further leads to a redistribution of water resources through virtual water transfers. Such virtual transfers are subject to constant changes due to the temporal variabilities in driving factors such as production efficiency, consumption patterns and population. Here we use the most recent public data to measure the water footprints of 31 provincial-level regions in China and virtual water transfers among these regions in 2012. We find that virtual water transfer plays a significant role in regional water footprints and greatly changes the allocation of water resources towards regional consumptions. Already water-scarce north China regions benefit from virtual water transfer by outsourcing water-intensive products from other regions. However, the water-scarce Northwest China suffers from virtual water transfer by exporting water-intensive products. We suggest policy makers pay attention to demand-side measures to incentivize parties to improve water efficiency in their production and reduce the consumption of water-intensive goods. Policymaking should consider economic policy and water conservation policy together to alleviate regional water stress through virtual water transfers.

1. Introduction

Water resources are fundamental and strategic assets for human survival and socio-economic development. Recent studies on water resource management have focused on complementing technical and managerial solutions to problems such as water scarcity, water pollution, and ecosystem degradation with public policy and interregional cooperation on water resource governance.

In China, rapid economic growth has caused increasing conflicts between limited water supply and intensive water demand (Yu, 2011). Water resource endowment in China is spatially distributed unevenly across China. Water-rich regions are often less developed, while more developed regions have relatively less local water endowment (Zhang & Anadon, 2014). Furthermore, the production and consumption of water-intensive products are also spatially separated within China.

To alleviate the mismatch between water supply and demand in China, the Chinese government has built more than 20 large-scale projects to physically transfer water from one region to another region, including the South-to-North Water Diversion Project (Liu et al., 2013). On the other hand, virtual water transfer has been recognized as an alternative way to match the demand for water-intensive products with water resources in water-rich regions. Virtual water refers to the volume of water used in the production of a product (or provision of a service), also known as water embodied in products (Allan, 1993). Virtual water transfer happens when products made in one region using its local water resources are exported to another region for consumption. Through trade of goods and services, water resources are virtually redistributed across regions. However, the desirability of such redistribution is subject to scrutiny under the perspective of sustainability.

The concept of virtual water is closely related to water footprint which is an accounting method to measure water resource requirement based on the consumption of goods and services. In

* Corresponding author.
E-mail address: shenquin@umich.edu (S. Qu).

https://doi.org/10.1016/j.jclepro.2019.04.298
0959-6526/

particular, water footprint refers to the total volume of water resources required for all products and services consumed by a country, region, or individual over some time (Hoekstra and Chapagain (2007)). Virtual water transfer is essentially the water footprint of the goods or services that are imported from other regions for consumption. Both water footprint and virtual water trade are useful accounting methods to demonstrate the relationship between water resource endowment, water use in production, consumption patterns, and trade. At the national or subnational level, water footprint and virtual water transfer can be measured using environmentally extended input-output (EEIO) models (Hubacek et al., 2009).

A large number of studies have revealed the relationship between the structure of local consumption and its water footprint through virtual water transfer in some countries including, but not limited to, Italy (Ali et al., 2017), France (Ercin et al., 2013), and United Kingdom (Yu et al., 2010). Other studies have established a comprehensive understanding of the water footprints of countries at the global scale (Dalin et al., 2012; Han et al., 2018; Mekonnen and Hoekstra, 2011; Ridoutt and Pfister, 2010). These studies on water footprint and virtual water transfer have impelled academics and policy-makers to pay more attention to demand-side measures to manage water resources (Zhao et al., 2015).

Existing studies for China mainly focus on water footprint accounting for cities (Wang et al., 2013; Zhang et al., 2012), provinces (Dong et al., 2013; Liu et al., 2018; Tan et al., 2013), watersheds (White et al., 2015; Zhao et al., 2010), regions (Guan and Hubacek, 2007; Wang et al., 2014), and the nation (Chen et al., 2018; Hubacek et al., 2009; Zhang et al., 2011a; Zhao et al., 2009). However, limited studies exist on virtual water transfers among various regions in China through the trade of goods and services. For example, Zhang et al. (2011b) calculated water footprint of Beijing in 2002 using a multi-regional input-output (MRIO) model for China. Using a different MRIO model, Feng et al. (2012) analyzed the virtual water flows among the upper, middle, and lower sections of the Yellow River Basin and the rest of China in 2007. More recently, scholars started to quantify the provincial consumption-based water footprints and showed scale and structure of virtual water trade in China in 2007 without evaluating their impacts on water scarcity(Chen et al., 2017; Jiang et al., 2015; Zhang & Anadon, 2014). In addition of quantification of water footprints and virtual water transfer, Deng et al. (2016) adopted the Structural Decomposition Analysis (SDA) approach to exploring the driving forces behind the changes of multi-regional water footprints from 2002 to 2007. Similarly, Yang et al. (2016) employed SDA to investigate the reasons for the growing water use in China during 1997–2007.

These previous studies on water footprint and virtual water transfer for China suffer from the following limitations: 1) using single-regional input-output models which cannot capture the full water footprint and virtual water transfer of the economic system; 2) using MRIO models for full water footprint accounting, but those MRIO models have coarse spatial resolution or incomplete water use inventory; 3) focusing only on water footprint and virtual water transfer accounting without considering the impact of virtual water transfer on regional water stress; and 4) lacking significant policy implications due to the mismatch between outdated data and fast changing economic structures. To address these research gaps, this study uses the latest MRIO model for China in 2012 to quantify the water footprint and virtual water transfer of 31 provinces and examine the impact of virtual water transfer on regional water stress.

2. Methods and data

2.1. Environmentally extended multi-regional input-output (EE-MRIO) model

The input-output (IO) model is an economic model to analyze the interdependencies of sectors in an economy (Miller and Blair, 1985). The core of an IO model is an IO table which describes the flows of goods and services among economic sectors in the economy during a particular period, usually a year. Each entry in the *i*th row and *j*th column of the IO table represents the flow of goods or services from the *i*th sector to the *j*th sector. For a single region IO model, the gross output (X) of the economy can be expressed as:

$$X = (I - A)^{-1} Y \quad (1)$$

Where I is the identity matrix, A in the technical coefficient matrix representing the input of each sector required per unitary output of another sector, $(I - A)^{-1}$ is the Leontief inverse matrix, and Y represents the vector of final demand including household consumption, government expenditures, investment, and net export. Readers are referred to (Miller and Blair, 1985) for the basics of the IO model.

A multi-regional Input-output (MRIO) model contains IO tables from different regions connected by interregional flows of goods and services, fully reflecting the economic connections between different sectors in the same and different regions.

An environmentally extended MRIO (EE-MRIO) model extends

Table 1
Water resource-extended MRIO table.

			Intermediate consumption							Final consumption			Export	Gross output
			Region 1			…	Region m			Region 1	…	Region m		
			Sector 1	…	Sector n		Sector 1	…	Sector n					
Intermediate Input	Region 1	Sector 1	x_{11}^{11}	…	x_{1n}^{11}	…	x_{11}^{1m}	…	x_{1n}^{1m}	F_1^{11}	…	F_1^{1m}	E_1^1	X_1^1
		…	…	…	…	…	…	…	…	…	…	…	…	…
		Sector n	x_{n1}^{11}	…	x_{nn}^{11}	…	x_{n1}^{1m}	…	x_{nn}^{1m}	F_n^{11}	…	F_n^{1m}	E_n^1	X_n^1
	…	…	…	…	…	…	…	…	…	…	…	…	…	…
	Region m	Sector 1	x_{11}^{m1}	…	x_{1n}^{m1}	…	x_{11}^{mm}	…	x_{1n}^{mm}	F_1^{m1}	…	F_1^{mm}	E_1^m	X_1^m
		…	…	…	…	…	…	…	…	…	…	…	…	…
		Sector n	x_{n1}^{m1}	…	x_{nn}^{m1}	…	x_{n1}^{mm}	…	x_{nn}^{mm}	F_n^{m1}	…	F_n^{mm}	E_n^m	X_n^m
	Import		AM_1^1	…	AM_n^1	…	AM_1^m	…	AM_n^m	FM^1	…	FM^m		
Primary input			V_1^1	…	V_n^1	…	V_1^m	…	V_n^m					
Gross input			X_1^1	…	X_n^1	…	X_1^m	…	X_n^m					
Water withdrawal			W_1^1	…	W_n^1	…	W_1^m	…	W_n^m					

the MRIO which describes only economic activities of an economy by including data on environmental flows of each sector. The additional data characterize resource use and waste and emissions generated by each sector during the same period which the MRIO describes. These data are located adjacent to the MRIO table as an environmental satellite account.

Focusing only on water withdrawal, a water resource-extended MRIO model can comprehensively characterize the relationship between local water resources and economic sectors for a system with sub-system regional economies. It can be used to quantify water footprints of each region in consumption of specific goods or services, as well as the transfer of virtual water through interregional trade. In the EE-MRIO table, water withdrawal of each sector is included as an additional row adjacent to the original MRIO table (Table 1).

The Chinese MRIO for 2012 has 31 regions (provinces) and 42 sectors in each region. Define $W = \begin{bmatrix} W^1 & W^2 & \ldots & W^{31} \end{bmatrix}$ in which W_i^r represents direct water use of sector i in region r. Moreover, direct water use coefficients of each province are calculated as:

$$Q = \begin{bmatrix} Q^1 & Q^2 & \ldots & Q^{31} \end{bmatrix} = \begin{bmatrix} W^1 & W^2 & \ldots & W^{31} \end{bmatrix} \cdot \begin{bmatrix} (X^1)^{-1} & 0 & \ldots & 0 \\ 0 & (X^2)^{-1} & \ldots & 0 \\ \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & \ldots & (X^{31})^{-1} \end{bmatrix} \tag{2}$$

where Q^r is the vector of direct water use coefficients in region r; and $q_i^r = w_i^r / x_i^r$ is the direct water use coefficient of sector i in region r, which means the volume of direct water used in sector i in region r. Therefore, water footprints of regional consumption can be calculated as:

$$\begin{bmatrix} H^{11} & H^{12} & \ldots & H^{1\cdot31} \\ H^{21} & H^{22} & \ldots & H^{2\cdot31} \\ \ldots & \ldots & \ldots & \ldots \\ H^{31\cdot1} & H^{31\cdot2} & \ldots & H^{31\cdot31} \end{bmatrix} = \begin{bmatrix} Q^1 & 0 & \ldots & 0 \\ 0 & Q^2 & \ldots & 0 \\ \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & \ldots & Q^{31} \end{bmatrix} \cdot \left[I - \begin{bmatrix} A^{11} & A^{12} & \ldots & A^{1\cdot31} \\ A^{21} & A^{22} & \ldots & A^{2\cdot31} \\ \ldots & \ldots & \ldots & \ldots \\ A^{31\cdot1} & A^{31\cdot2} & \ldots & A^{31\cdot31} \end{bmatrix} \right]^{-1} \cdot \begin{bmatrix} F^{11} & F^{12} & \ldots & F^{1\cdot31} \\ F^{21} & F^{22} & \ldots & F^{2\cdot31} \\ \ldots & \ldots & \ldots & \ldots \\ F^{31\cdot1} & F^{31\cdot2} & \ldots & F^{31\cdot31} \end{bmatrix} \tag{3}$$

where F^{rs} means final consumption of goods and services in region s imported from region r; and H^{rs} represents the water footprint of final consumption in region s in region r. When $r \neq s$, H^{rs} represents the virtual water transfer from region r to region s. The sum of all virtual water transfers from other region ($\sum_{r,r \neq s} H^{rs}$) is the virtual water import of region s; and $\sum_{s,s \neq r} H^{rs}$ is the virtual water export of region r.

2.2. Water footprint intensity (WFI)

Based on the water footprint accounting obtained from the water resource-extended MRIO model, we develop a water footprint intensity (*WFI*) index to evaluate the efficiency of water use of a specific sector relative to other sectors. Our intuition is that, if the water footprint of the unitary final product in a sector is higher than those in other sectors, the water efficiency of this sector is relatively low. In particular, water footprint intensity (*WFI*) of sector j is shown as:

$$WFI_j = \frac{WF_j}{X_j} \tag{4}$$

where WF_j denotes the water footprint of the jth sector and X_j represents the output of the jth sector. To facilitate the comparison of different sectors, the *WFI* is normalized into an *WFI* index ρ_j:

$$\rho_j = \frac{WF_j}{X_j} \Big/ \frac{\sum WF_j}{\sum X_j} = \frac{WF_j}{\sum WF_j} \times \frac{\sum X_j}{X_j} \tag{5}$$

Larger *WFI* index means that water footprint of the final consumption of goods and services from a particular sector is greater than the average of all sectors, indicating relatively low water use efficiency of this sector.

2.3. Water stress index (WSI)

Water stress index (*WSI*) refers to water stress due to water withdrawal from available local water resources (U) (Zhao et al., 2015), expressed as:

$$WSI = \frac{WW}{U} = \frac{WU - PW_{net,im}}{U} \tag{6}$$

where WW is the local water withdrawal, which is equal to water use (WU) minus net physical water import ($PW_{net,im}$); WU is the gross volume of water distributed to users including water lost in the distribution; and U is renewable freshwater availability. The value of *WSI* can be used to categorize water stress levels as shown in Table 2 (Zhao et al., 2015).

To consider the impact of virtual water transfer on local water stress, we modify *WSI* by adding virtual water import in the equation:

$$WSI^* = \frac{WU + VW_{net,im}}{U} = \frac{WW + PW_{net,im} + VW_{net,im}}{U} \tag{7}$$

where WSI^* measures the level of water stress caused by the final consumption of a region for both locally produced and imported goods and services. Greater WSI^* than *WSI* in a region indicates that the region is a net importer of physical and virtual water, which is useful to alleviate the local water stress (Zhao et al., 2015).

2.4. Structural decomposition analysis of provincial water footprint

For each province, the change in water footprint can be decomposed in to the effects of five driving factors (suppressing the index for the province):

$$\varDelta WF = \varDelta\left(QL\left(\frac{F}{y}\right)\left(\frac{y}{p}\right)p\right) = \underbrace{\varDelta QL\left(\frac{F}{y}\right)\left(\frac{y}{p}\right)p}_{Effect\ of\ water\ efficiency} + \underbrace{Q\varDelta L\left(\frac{F}{y}\right)\left(\frac{y}{p}\right)p}_{Effect\ of\ economic\ structure} + \underbrace{QL\varDelta\left(\frac{F}{y}\right)\left(\frac{y}{p}\right)p}_{Effect\ of\ consumption\ pattern} + \underbrace{QL\left(\frac{F}{y}\right)\varDelta\left(\frac{y}{p}\right)p}_{Effect\ of\ affluence} + \underbrace{QL\left(\frac{F}{y}\right)\left(\frac{y}{p}\right)\varDelta p}_{Effect\ of\ population} \quad (8)$$

where $\varDelta WF$ is the change in provincial water footprint, Q is a row vector containing the water use per unit economic production for all the province-sectors, L is the Leontief inverse, F is a column vector of final demand by the province, y is total final demand by the province, and p is population.

There is uncertainty resulting from the above decomposition. Specifically, for n driving factors, there can be $n!$ decompositions (Dietzenbacher and Los, 1998). Therefore, this analysis computes and reports all the $5! = 120$ possible results.

2.5. Data sources

Due to the data availability and its relevance to local water stress, only "blue water" is considered in this study, which refers to the surface and groundwater used for production and consumption activities.

There is no direct source of data on sectoral water withdrawal in each province for China. The Chinese Water Resources Bulletin provides data on 2007 and 2012 aggregate water withdrawal for agriculture, industry, and service sectors for each province. We further disaggregate the data by sectors in proportion to sectoral water withdrawal data in 2008 (Chinese Economic Census Yearbook, 2008). The sources of water are categorized as surface water, groundwater, and transferred water. Both surface water and groundwater belong to water supply within a region, therefore defined as water withdrawal.

Water use data for 2012 are from China Statistical Yearbook 2013 on Environment (National Bureau of Statistics of China, 2013). Water use here refers to the volume of water distributed to users including water lost in distribution.

The 2012 Chinese MRIO table includes 31 provinces, specifically 22 provinces, 5 autonomous regions, and 4 provincial level megacities (Beijing, Shanghai, Tianjin, and Chongqing), each with 42 sectors. This MRIO table was estimated based on single regional input-output tables for each region in China. Methodological details can be found in our previously published study (Zhang et al., 2018).

3. Results

3.1. Water footprint at the sector level

The total water withdrawal in China in 2012 was 562.2 billion m^3. Water footprints of the aggregated agriculture, industry, and service sectors are 59.5%, 27.8%, and 12.7% of the total water withdrawal, respectively. Fig. 1 shows the top 10 sectors concerning their water footprints. The *Farming, Forestry, Animal Production and Fishery* sector has the most significant water footprint among all sectors, followed by the *Production and Supply of Electricity and Steam* sector. Because these two sectors directly use a significant amount of water in their production, their large water footprints mainly come from such direct water use.

In addition to sectors that directly use a large amount of water, there are also sectors that do not necessarily use a significant amount of water ranked in the top 10, such as *Education*, *Public Management, Social Security and Social Organizations*, and *Health Care and Social Work Activities*. These sectors surpass most of the sectors in the manufacturing industry, indicating a large amount of water withdrawal-induced by the consumption of intermediate goods and services in these sectors. This indicates the importance of the service industry on water resource management from the footprint perspective, although the service industry does not necessarily consume a large amount of water directly. Given the rapid growth of the service industry in China, demand-side measures have become increasingly essential to instigate the full water conservation of the economic system by targeting the consumption of goods and services.

Table 3 shows China's sectors with the *WFI index* greater than 1 in 2012. As expected, top sectors in *WFI index* are also those sectors ranked top in absolute water footprints. The ranking of sectors, however, is different. Three sectors in the service industry rank higher with significantly larger *WFI index* compared to other sectors, including Health Care and Social Work Activities, Education, and Public Management, Social Security and Social Organization. The high *WFI index* values for these service sectors indicate significant low water efficiency comparing with other sectors from the perspective of the whole economic system, even though they do not necessarily consume much water.

3.2. Provincial water footprints

There are significant differences in water footprints among provinces in China in 2012 (Fig. 2). Among all 31 provinces included in our study, Guangdong (79.9 billion m^3), Jiangsu (53.9 billion m^3), Zhejiang (40.7 billion m^3), and Shandong (35.0 billion m^3) have the largest water footprints. Moreover, the water footprints of

Table 2
Levels of water stress.

Level of water stress	*WSI*
Extreme	>1
Severe	0.4-1
Moderate	0.2-0.4
No stress	<0.2

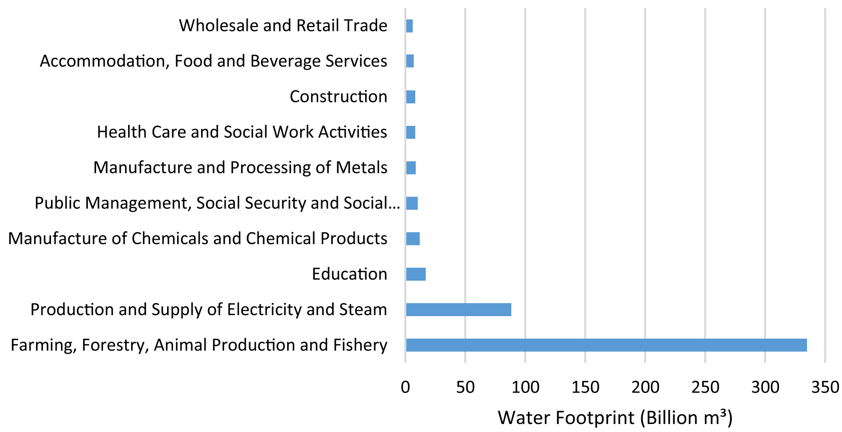

Fig. 1. Top 10 sectoral water footprints (billion m^3) in China in 2012.

Table 3
Sectors with *WFI index* greater than 1 in China in 2012.

Sectors	*WFI index*
Production and Supply of Electricity and Steam	644.2
Health Care and Social Work Activities	54.4
Education	47.2
Public Management, Social Security and Social Organization	20.3
Farming, Forestry, Animal Production and Fishery	19.8
Construction	4.7
Mining and Washing of Coal	2.2
Accommodation, Food and Beverage Services	1.9
Manufacture of Nonmetallic Mineral Products	1.4
Finance	1.1

provinces in the coastal areas are generally higher than those in other areas. The spatial distribution of water footprints of provinces is closely related to the difference in the development status of each province. On the one hand, coastal regions generally have more population with higher household expenditure. These regions are also the main hubs of manufacturing for exported goods in China. High household expenditure and large exports together drive the production of consumption goods or intermediate goods as well as water footprint. On the other hand, coastal regions specialize in high-end manufacturing and services comparing to inland regions in China. These sectors generally consume consumption goods or use intermediate goods, meaning they have driven the production of goods which leads to large water footprint.

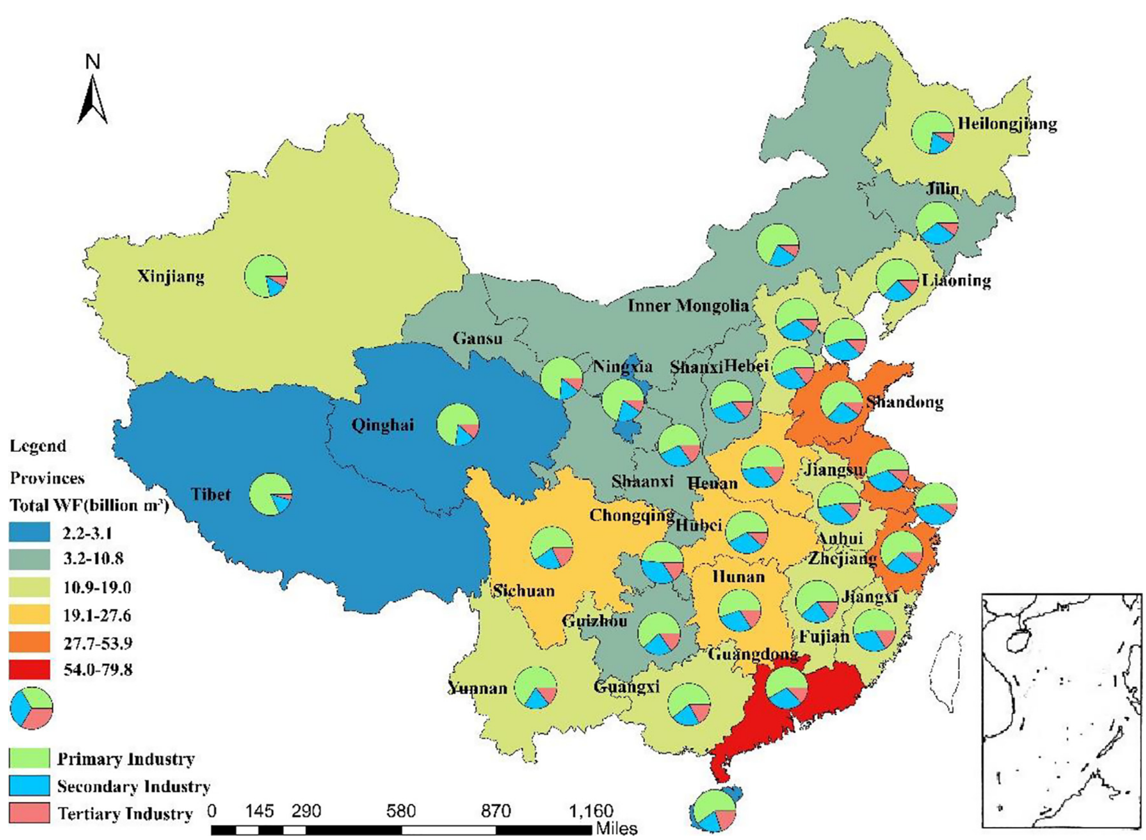

Fig. 2. Water footprints (billion m^3) of China's provinces in 2012.

Fig. 3 shows the water footprint per capita for each province in China in 2012. Unlike the distribution of the total provincial water footprints, per capita water footprints of a couple of inland provinces become higher. There are generally three types of provinces with high per capita water footprints. The first includes provinces in coastal areas such as Guangdong, Zhejiang, Shanghai, and Jiangsu. The high water footprints in these provinces are the primary driver of the high per capita water footprints, although they are also populous. The second category includes Xinjiang, Heilongjiang, Ningxia, and other agriculture-dominated areas. Relatively small populations with water-dependent agriculture lead to large per capita water footprints in these regions. The last category includes less populous provinces such as Tibet and Qinghai. Although their water footprints are not high, the size of population in these provinces makes per capita water footprints high.

Fig. 4 compares provinces in their water footprints per unit gross domestic product (GDP) generated in 2012. Less developed regions including west China, Guangxi, and Helongjiang generally have high water footprints per unit GDP. This is mainly due to their relatively low GDP levels. Guangdong and Shanghai both have high water footprints per unit GDP, mostly because of their considerable water footprints. Other Southern China provinces have less water footprint per unit GDP, while provinces in Northern China have the least water footprints per unit GDP. These provinces represent higher water efficiency from the perspective of whole economic system.

Fig. 5 decomposes water footprints of each province in China in 2012 by the four final demand categories including household consumption, government expenditure, investment, and export. Across all provinces, household consumption is the most significant driver in final demand for water footprint. The importance of household consumption in water footprint is the largest (more than 50%) in less developed regions where other types of final demand are relatively small. For developed regions, the shares of water footprint driven by household consumption are less than 50% of their total water footprints. In Shanghai, less than 40% of its water footprint is driven by household consumption. On the other hand, export contributes significantly (around 25%) to water footprints of more developed, coastal provinces including Shanghai, Jiangsu, Zhejiang, and Guangdong. These provinces are the main sources of China's export to the world. Regions undergoing rapid development such as Chongqing, Hubei, and Fujian have seen large portions of their water footprint driven by investment from urbanization and infrastructure development. Lastly, government expenditure drives the least amount of water footprint for most provinces except Beijing. As the capital of China, Beijing hosts much more government functions than any other provinces. Therefore, government expenditure contributes to more than 28% of Beijing's water footprint, while only about or less than 10% come from government expenditure for other provinces.

3.3. Virtual water transfer

The water footprint of a region includes two parts: water withdrawal from the region to produce products consumed in the same region and water withdrawal from other regions to produce products consumed in this region. The latter is essentially the virtual water import. Comparing virtual water import with the total water footprint of a region can reveal its dependency on water resources in other regions. As shown in Fig. 6, many the 31 provinces import more than 50% of their water footprints from other regions through virtual water transfer. Water footprints of the three provincial-level megacities, Beijing, Shanghai, and Tianjin mostly rely on virtual water import.

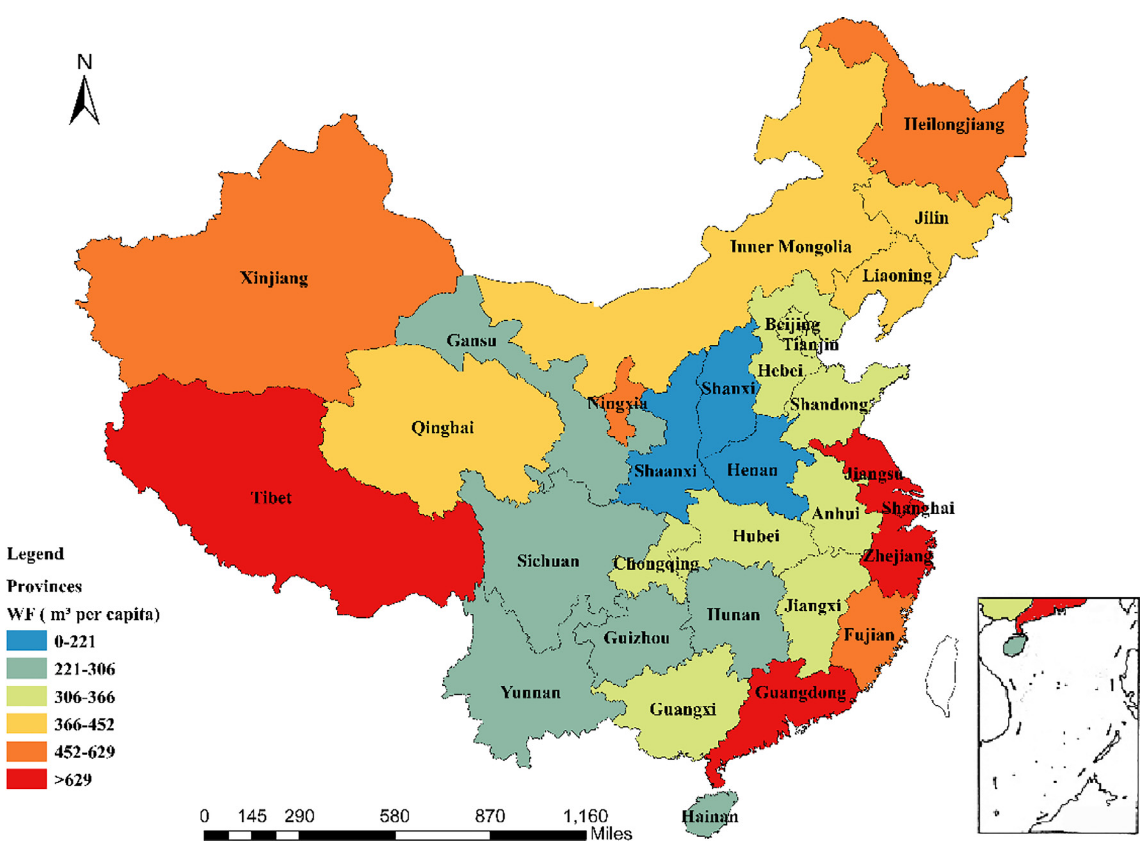

Fig. 3. Water footprint per capita (m^3 per capita) of China's provinces in 2012.

Fig. 4. Water footprint per unit GDP (m^3/thousand dollars) of China's provinces in 2012.

Based on development status, economic structure, and geographical proximity, following Zhang and Qi (2012), we divide China into eight regions: Beijing-Tianjin (Beijing and Tianjin), North Coast (Hebei and Shandong), Central (Shanxi, Henan, Anhui, Hubei, Hunan, and Jiangxi), Northwest (Inner Mongolia, Shaanxi, Ningxia, Gansu, Qinghai, and Xinjiang), Northeast (Heilongjiang, Jilin, and Liaoning), East Coast (Shanghai, Jiangsu, and Zhejiang), South Coast (Fujian, Guangdong, and Hainan), and Southwest (Sichuan,

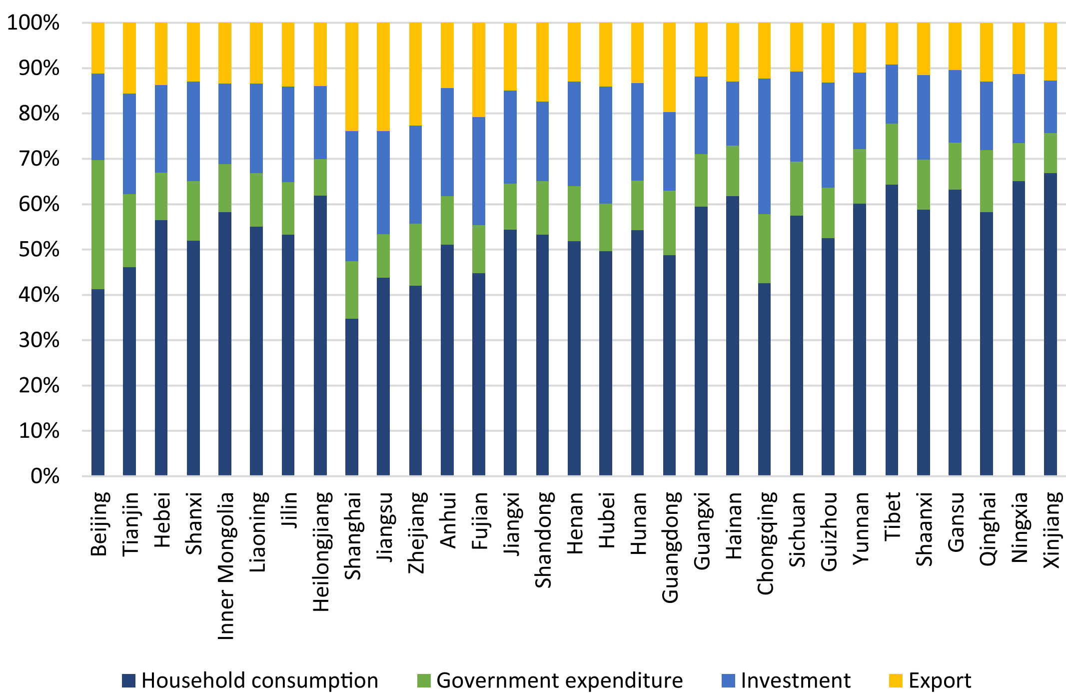

Fig. 5. Water footprint of China's provinces by final demand categories in 2012.

Fig. 6. Ratio of virtual water import to total water footprint of China's provinces in 2012.

Chongqing, Guangxi, Yunnan, Guizhou, and Tibet).

Table 4 and Fig. 7 show the virtual water transfers among these eight regions, while inter-province virtual water transfers are shown in Table S1. On average, more than 40% of water footprint in the 31 provinces in China in 2012 comes from virtual water transfers, indicating significant importance of interregional exchanges of goods and services on demand for water resources at both the national and subnational levels.

Overall, the Central, Northwest, Northeast, and Southwest regions are net exporters of virtual water, meaning their virtual water exports are larger than their virtual water imports. The other regions, on the other hand, are net virtual water importers. The virtual water transfers among regions can help alleviate the stress some regions face from scarce local water resources. For example, the Beijing-Tianjin region and North Coast region have 89.4% and 71.1% of their water footprint from virtual water import, the highest among all regions. These two regions are mainly located in the Haihe River Basin which is one of the most water-scarce basins in the world (Varis et al., 2014). Importing water-intensive products—virtually importing water—from other regions relieves the demand for water from the already stressed Haihe River Basin.

It is worth noting that virtual water transfer among the regions is predominately driven by the market. Water resource conservation plays little role. As a result, water-stressed regions such as Northwest or provinces such as Xinjiang become net exporters of virtual water. Essentially these regions or provinces use their already scarce water to produce for the consumption of other regions or provinces which have relatively abundant water. This finding calls for attention on the impact interregional virtual water transfer on local water stress which requires a synergy of decision-making for both economic policy and environmental policy.

3.4. Impact of virtual water transfer on regional water stress

Shows the level of water stress for each province in China in 2012 indicated by water stress index (*WSI*) which considers only

Table 4
Virtual water transfers among eight regions of China in 2012 (billion m^3). Rows represent sources and columns represent destinations.

	Beijing-Tianjin	North Coast	Central	Northwest	Northeast	East Coast	South Coast	Southwest	Total export
Beijing-Tianjin	2.29	0.5	0.4	0.2	0.3	0.6	0.4	0.2	5.0
North Coast	2.42	14.7	3.9	1.5	2.1	6.2	3.7	2.1	36.6
Central	4.40	10.2	61.5	5.8	5.5	22.9	19.1	8.8	138.0
Northwest	3.38	6.04	11.2	26.5	6.0	15.1	14.0	11.1	93.4
Northeast	2.62	4.49	5.4	2.3	23.6	8.2	5.8	3.0	55.3
East Coast	2.45	6.18	7.2	2.6	3.1	49.9	8.4	3.6	83.4
South Coast	1.54	3.61	6.2	2.2	2.4	8.9	37.0	3.9	65.7
Southwest	2.34	5.23	8.6	3.8	3.1	10.3	12.0	39.5	84.9
Total import	21.4	50.9	104.2	44.9	46.0	122.1	100.5	72.2	562.2

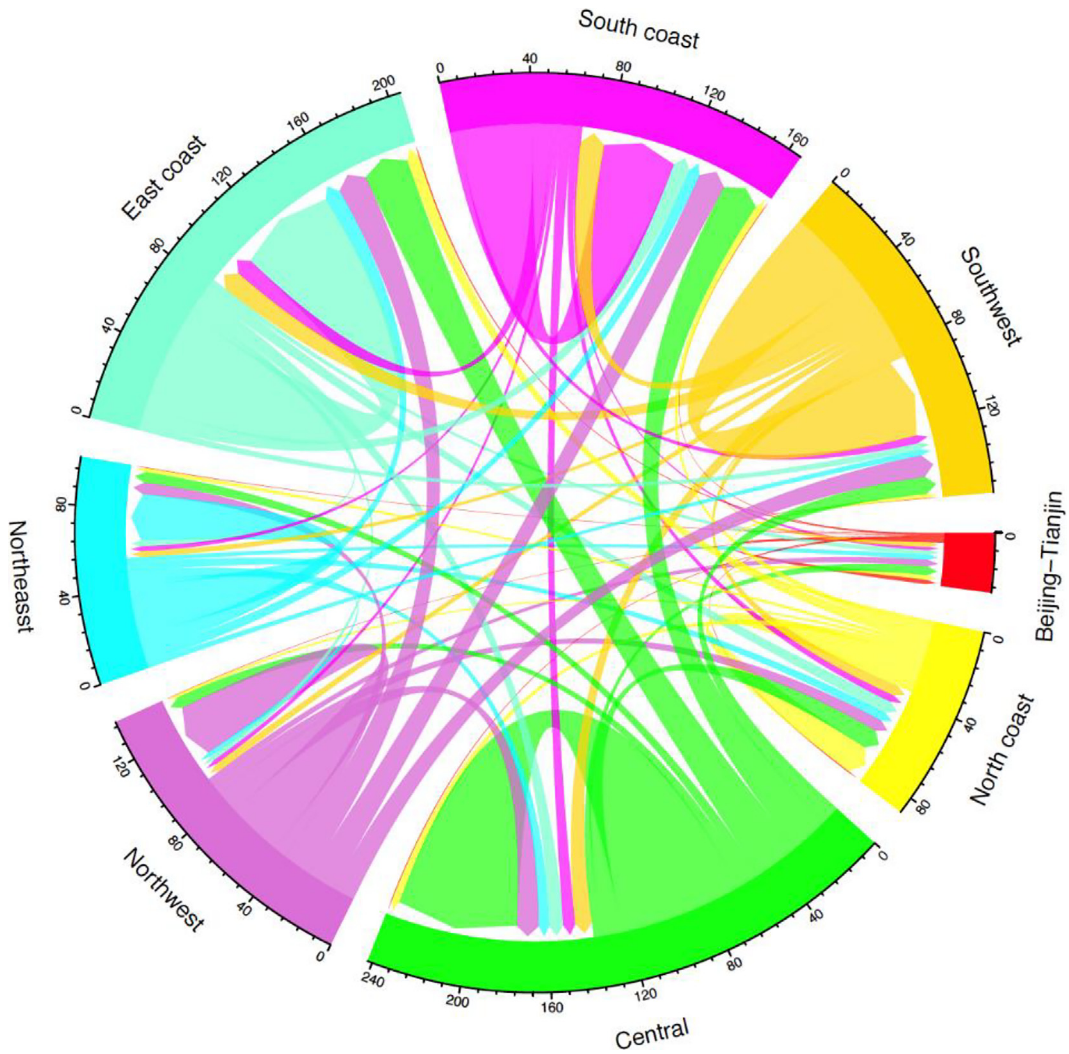

Fig. 7. Virtual water transfers among eight regions of China in 2012 (billion m^3). This figure reveals the directions and amounts of virtual water transfers among eight regions. For each region, the directions of the arrows represent the directions of virtual water flows and the width of the arrows stands for the amounts of virtual water flows. For each region, the inward arrows show the virtual water import and the outward arrows show the virtual water export.

local water withdrawal to fulfill regional consumption (Equation (6)). Shanghai, Ningxia, and Jiangsu face extreme water stress (*WSI*>1) and ten other provinces located in Northwest, Northeast, Central, and East Coast regions face severe water stress (0.4 < *WSI*<1). The other 18 provinces face either moderate water stress or have no water stress.

Considering each province's reliance on water resources from other regions through either physical import or virtual import, the modified *WSI* (*WSI**, Equation (7)) reveals that the actual severity of water stress in many provinces is larger than what the *WSI* indicates. (a) Shows that provinces with no water stress indicated by *WSI* remain as no water stress if evaluated using *WSI**, except for Zhejiang and Chongqing which both become moderate water stress. This change means that these two provinces' true water stress is more severe than what *WSI* indicates and they rely heavily on water from other regions. (b) Shows that moderate water stress regions will remain the same if using *WSI**, except Guangdong will become close to severe water stress, indicating its dependence on external water resources. For provinces facing severe water stress indicated by *WSI*, Beijing, Tianjin, and Shandong will become extreme water stress if measured by *WSI** ((c)). Beijing and Tianjin's *WSI** reach to close to 2.5 and 4, respectively. The consumption of these regions significantly relies on water resources in other regions through the imports of water-intensive products. Lastly, as indicated in (d), Shanghai will become more water stressed if measured by *WSI**, while Ningxia can become less water stressed.

3.5. Temporal changes in provincial water footprint and driving factors

It is necessary to use the most recent data for evaluating provincial water footprints. In contrast to direct water use, water footprints can be affected by a more extensive variety of factors, including production efficiency, consumer demand and population growth. All of these factors change continuously over time.

Fig. 8 shows changes in water footprint for six provinces from 2007 to 2012, and further decomposes water footprint changes into the five factors using structural decomposition analysis (Equation (8)): water efficiency, production structure, final demand structure, per capita final demand level and population. Fig. S3 presents such decompositions for all Chinese provinces. Provincial water footprint decreased in Shanghai, stayed nearly the same in Beijing and Jiangsu, increased moderately in Shandong and Zhejiang (less than 10 billion m^3) and significantly in Shandong (just above 10 billion

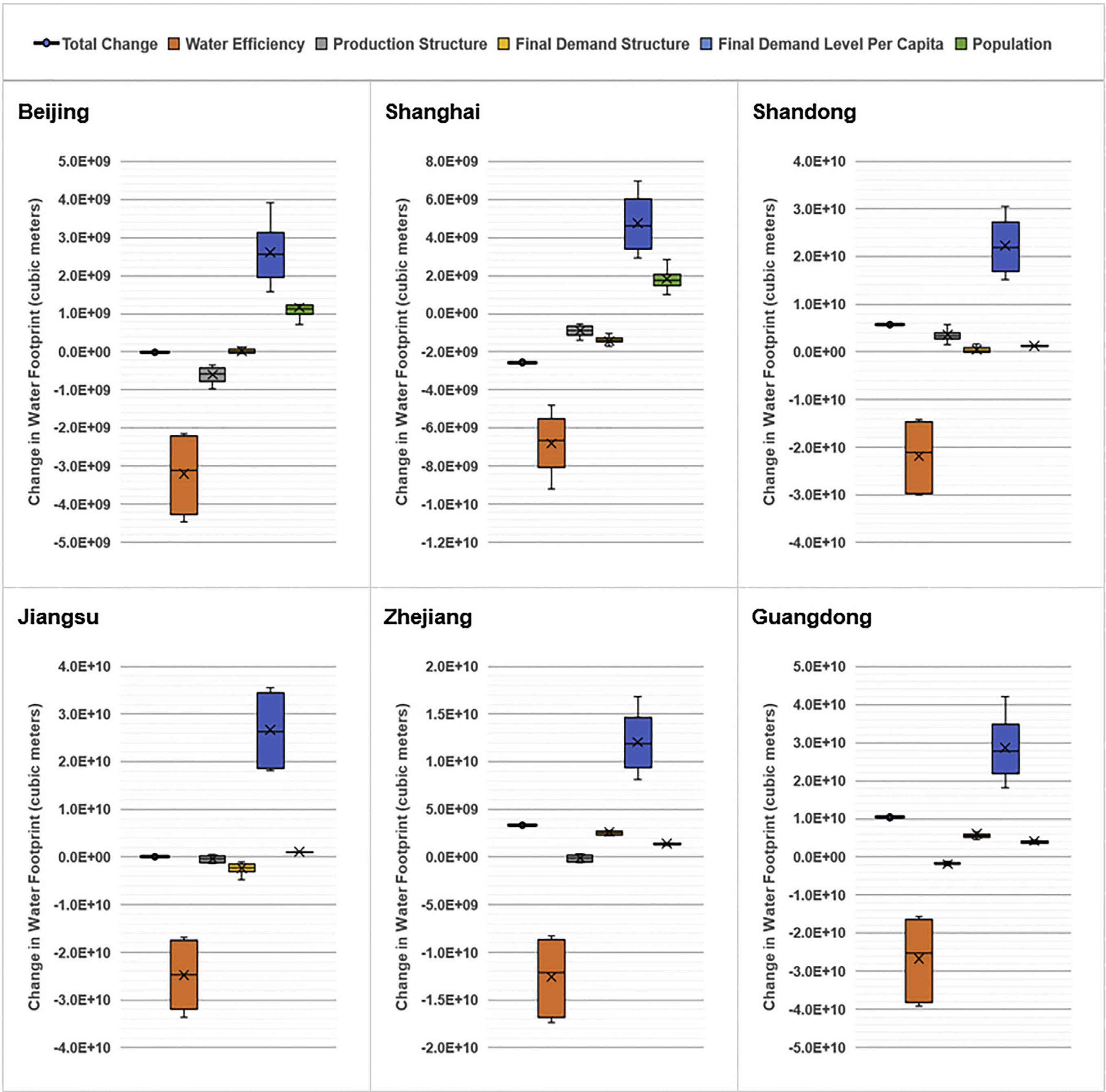

Fig. 8. Decomposition of provincial water footprint changes into five driving factors. For each driving factor, the box shows the upper and low quartiles of its contribution. The horizontal line and the cross marker in the box represent the median and the mean, respectively. The results for all the 30 provinces are listed in Fig. S3.

m^3). However, the apparent changes in water footprints mask the more dramatic changes in the underlying driving factors. The most important driver to increase water footprints is affluence: in all provinces, the average resident enjoyed a higher level of consumption of domestically produced goods and services, necessitating greater amounts of water use in production. On the other hand, the most critical factors driving down provincial water footprints is water efficiency, that is, water used to produce a unitary product in various sectors. The relatively small changes in provincial water footprints from 2007 to 2012 turn out to be the effects of these tow compensating factors (Fig. 8 and Fig. S3).

4. Conclusions and discussion

4.1. Patterns of provincial footprints and interprovincial virtual water transfers

Our study uses the most recent public data to examine the water footprints of Chinese provinces in 2012 and the associated virtual water transfers. Almost 60% of the water withdrawal in China in 2012 is attributed to agriculture, while industry and service use 27.8% and 12.7%, respectively. In addition to agricultural sectors and some manufacturing sectors such as *Production and Supply of Electricity and Steam* that directly use significant amounts of water in their production, our results also reveals that services sectors, such as *Education*, *Public Management, Social Security and Social Organization*, and *Health Care and Social Work Activities*, have large water footprints, given that they usually consume consumption goods or use intermediate goods. Using a *WFI index*, we further evaluate the water efficiency of each sector and identify sectors with below average water efficiency across the entire economy which are mostly sectors with high water footprints.

Significant differences in provincial water footprints exist. Coastal regions have higher water footprints because of their larger population, higher consumption, and dominance of manufacturing and service industries. However, on a per capita or per unit GDP basis, provinces in west China, Heilongjiang in the northeast, and Guangxi in the south rank top in water footprint due to lower population or GDP in these regions. Across all provinces, household consumption is the most significant driver for water footprint. Export contributes to about 25% of water footprint for more developed, coastal areas which are the main sources of China's export. Investment drives larger portion of water footprint in provinces undergoing rapid development, while Beijing sees government expenditure as an important driver for its water footprint.

Quantification of virtual water transfers among Chinese provinces indicates that Beijing, Shanghai, and Tianjin heavily rely on water resources in other regions for consumption. Interregional virtual water transfer helps alleviate water stress in areas that already face water scarcity such as Beijing, Tianjin, and the North Coast region. On the other hand, water-scarce regions such as Northwest become net virtual water exporters due to exporting water-intensive products to other regions, which further worsens their local water stress. Winners and losers resulted from the redistribution of water resources through virtual water transfers: some provinces' water stress is elevated if considering virtual water transfers due to importing water-intensive products from other regions, while others see alleviated water stress.

4.2. Timely water footprint evaluation for demand-side measures

It is critical to evaluate provincial water footprints timely, due to the temporal variability of the underlying driving factors such as water efficiency, production structure, consumption pattern, affluence and population. Not only does water footprints evolve constantly over time, but such changes can be the combined effects of even more dramatic changes in the driving factors. From 2007 to 2012, the improvements in water efficiency and production structure could barely compensate for the increases in affluence and population.

Therefore, our results clearly show the importance of demand-side measures in sustainable water resource management in China. Significant efforts and investment have been made to improve water use efficiency on the supply side, such as using more water efficient technology in agriculture and industrial production. However, limited attention has been paid on the demand-side approaches to drive water conservation in the production of consumption goods or intermediate goods. Such approaches include, but not limited to, pricing final products considering their water footprints, imposing consumer responsibility to internalize the cost associated with water footprint of products, taxation for the service industry based on their water footprint. These measures create economic incentives for consumers and industries consuming consumption goods or intermediate goods to purchase less water-intensive goods and services. As a result, each part of the whole economic system can be motivated to seek for water-efficient technology and non-technological ways to conserve water in their production. For the whole economy, water conservation and reduction of demand for water can be expected. Furthermore, decision-makers should consider economic policy and water conservation policy together, as economic policy affects how products are traded across regions and water conservation policy impacts how water is managed and used.

4.3. Limitations

Several key limitations exist in our study which represents crucial future research directions. First, our method is based on the environmentally extended input-output modeling framework which brings about some inherent limitations such as the assumption of homogeneous products in each sector, not considering the economy of scale, and significant time lag in data availability (Miller and Blair, 1985). Second, detailed data on China's water availability and consumption are limited. We must use data in 2008 to estimate sectoral water withdrawal for 2012. This data limitation calls for future efforts to develop more comprehensive accounting methods and system for water in China. Finally, our analysis focuses on the evaluation of a past situation. Any policy instrument will instigate complex changes in the economy. Significant rebound effects may exist when demand-side measures are implemented for water conservation, leading to the unintended consequence of increased water consumption(Berbel et al., 2015). New modeling methods are needed to understand the consequences of policy implementation for water footprint and virtual water transfer.

Acknowledgments

S.Z. acknowledges the financial support from the China Scholarship Council. M.T. acknowledges the support of Dow Sustainability Fellows Program at the University of Michigan Graham Institute. Y.L. acknowledges the support from the National Key Research and Development Program of China (Grant No. 2016YFA0602500), the Strategic Priority Research Program of Chinese Academy of Sciences (Grant No. XDA20100104) and the National Natural Science Foundation of China (Grant No. 71690242).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.04.298.

References

Ali, Y., Pretaroli, R., Socci, C., Severini, F., 2017. Carbon and water footprint accounts of Italy: a Multi-Region Input-Output approach. Renew. Sustain. Energy Rev. 81, 1813–1824.
Allan, T., 1993. Fortunately There Are Substitutes for Water: Otherwise Our Hydropolitical Futures Would Be Impossible.
Berbel, J., Gutiérrez-Martín, C., Rodríguez-Díaz, J.A., Camacho, E., Montesinos, P., 2015. Literature review on rebound effect of water saving measures and analysis of a Spanish case study. Water Resour. Manag. 29 (3), 663–678.
Chen, W., Wu, S., Lei, Y., Li, S., 2017. China's water footprint by province, and interprovincial transfer of virtual water. Ecol. Indicat. 74, 321–333.
Chen, W., Wu, S., Lei, Y., Li, S., 2018. Virtual water export and import in China's foreign trade: a quantification using input-output tables of China from 2000 to 2012. Resour. Conserv. Recycl. 132, 278–290.
Dalin, B.C., Konar, M., Hanasaki, N., Rinaldo, A., Rodri, Ignacio, 2012. Correction for Dalin et al., Evolution of the global virtual water trade network, vol. 21, p. 8353.
Deng, G., Ma, Y., Li, X., 2016. Regional water footprint evaluation and trend analysis of China—based on interregional input–output model. J. Clean. Prod. 112, 4674–4682.
Dietzenbacher, E., Los, B., 1998. Structural decomposition techniques: sense and sensitivity. Econ. Syst. Res. 10 (4), 307–324.
Dong, H., Geng, Y., Sarkis, J., Fujita, T., Okadera, T., Xue, B., 2013. Regional water footprint evaluation in China: a case of Liaoning. Sci. Total Environ. 442 (1), 215–224.
Ercin, A.E., Mekonnen, M.M., Hoekstra, A.Y., 2013. Sustainability of national consumption from a water resources perspective: the case study for France. Ecol. Econ. 88 (7), 133–147.

Feng, K., Siu, Y.L., Guan, D., Hubacek, K., 2012. Assessing regional virtual water flows and water footprints in the Yellow River Basin, China: a consumption based approach. Appl. Geogr. 32 (2), 691–701. https://doi.org/10.1016/j.apgeog.2011.08.004.
Guan, D., Hubacek, K., 2007. Assessment of regional trade and virtual water flows in China. Ecol. Econ. 61 (1), 159–170.
Han, M., Chen, G., Li, Y., 2018. Global water transfers embodied in international trade: tracking imbalanced and inefficient flows. J. Clean. Prod. 184, 50–64.
Hoekstra, A.Y., Chapagain, A.K., 2007. Water Footprints of Nations: Water Use by People as a Function of Their Consumption Pattern. Springer Netherlands.
Hubacek, K., Guan, D., Barrett, J., Wiedmann, T., 2009. Environmental implications of urbanization and lifestyle change in China: ecological and Water Footprints. J. Clean. Prod. 17 (14), 1241–1248.
Jiang, Y., Cai, W., Du, P., Pan, W., Wang, C., 2015. Virtual water in interprovincial trade with implications for China's water policy. J. Clean. Prod. 87, 655–665.
Liu, J., Zang, C., Tian, S., Liu, J., Hong, Y., Jia, S., , et al.Miao, Z., 2013. Water conservancy projects in China: achievements, challenges and way forward. Glob. Environ. Chang. 23 (3), 633–643.
Liu, S., Han, M., Wu, X., Wu, X., Li, Z., Xia, X., Ji, X., 2018. Embodied water analysis for Hebei Province, China by input-output modelling. Front. Earth Sci. 12 (1), 72–85.
Mekonnen, M.M., Hoekstra, A.Y., 2011. National Water Footprint Accounts: the Green, Blue and Grey Water Footprint of Production and Consumption. UNESCO-IHE Institute for Water Education.
Miller, R., Blair, P., 1985. Input - Output Analysis Foundations and Extensions.
Ridoutt, B.G., Pfister, S., 2010. A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity. Glob. Environ. Chang. 20 (1), 113–120.
Tan, S., Liu, Z., Xiong, Y., Liao, C., Chen, Z., 2013. Evaluation of water footprint for Guangdong province in an interregional input-output framework. Ecology and Environmental Sciences 22 (9), 1564–1570.
Varis, O., Kummu, M., Lehr, C., Shen, D., 2014. China's stressed waters: societal and environmental vulnerability in China's internal and transboundary river systems. Appl. Geogr. 53, 105–116.
Wang, W., Gao, L., Liu, P., Hailu, A., 2014. Relationships between regional economic sectors and water use in a water-scarce area in China: a quantitative analysis. J. Hydrol. 515, 180–190.
Wang, Z., Huang, K., Yang, S., Yu, Y., 2013. An input–output approach to evaluate the water footprint and virtual water trade of Beijing, China. J. Clean. Prod. 42, 172–179. https://doi.org/10.1016/j.jclepro.2012.11.007.
White, D.J., Feng, K., Sun, L., Hubacek, K., 2015. A hydro-economic MRIO analysis of the Haihe River Basin's water footprint and water stress. Ecol. Model. 318, 157–167.
Yang, Z., Liu, H., Xu, X., Yang, T., 2016. Applying the water footprint and dynamic structural decomposition analysis on the growing water use in China during 1997–2007. Ecol. Indicat. 60, 634–643.
Yu, C., 2011. China's water crisis needs more than words. Nature 470 (7334), 307.
Yu, Y., Hubacek, K., Feng, K., Guan, D., 2010. Assessing regional and global water footprints for the UK. Ecol. Econ. 69 (5), 1140–1147.
Zhang, C., Anadon, L.D., 2014. A multi-regional input–output analysis of domestic virtual water trade and provincial water footprint in China. Ecol. Econ. 100 (2), 159–172.
Zhang, W., Liu, Y., Feng, K., Hubacek, K., Wang, J., Liu, M.-M., , et al.Zhang, P., 2018. Revealing Environmental Inequality Hidden in China's Inter-regional Trade. Environmental science & technology.
Zhang, Y., Qi, S., 2012. China Multi-Regional Input-Output Models: 2002 and 2007. China Statistics.
Zhang, Z., Shi, M., Yang, H., 2012. Understanding Beijing's water challenge: a decomposition analysis of changes in Beijing's water footprint between 1997 and 2007. Environ. Sci. Technol. 46 (22), 12373–12380.
Zhang, Z., Yang, H., Shi, M., 2011a. Analyses of water footprint of Beijing in an interregional input–output framework. Ecol. Econ. 70 (12), 2494–2502.
Zhang, Z.Y., Yang, H., Shi, M.J., Zehnder, A.J.B., Abbaspour, K.C., 2011b. Analyses of impacts of China's international trade on its water resources and uses. Hydrol. Earth Syst. Sci. 15 (9), 2871–2880.
Zhao, X., Chen, B., Yang, Z.F., 2009. National water footprint in an input-output framework - a case study of China 2002. Ecol. Model. 220 (2), 245–253.
Zhao, X., Liu, J., Liu, Q., Tillotson, M.R., Guan, D., Hubacek, K., 2015. Physical and virtual water transfers for regional water stress alleviation in China. Proc. Natl. Acad. Sci. Unit. States Am. 112 (4), 1031–1035.
Zhao, X., Yang, H., Yang, Z., Chen, B., Qin, Y., 2010. Applying the input-output method to account for water footprint and virtual water trade in the Haihe River basin in China. Environ. Sci. Technol. 44 (23), 9150–9156.