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Virtual water embodied in the export from various provinces of China using multi-regional input–output analysis

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Abstract

China is a large exporter and consumer of water embodied in export products. In addition, there is much trade among regions within China, and exports from various provinces consume not only local water but national non-local water. However, former calculations of the water consumption embodied in the exports of various provinces do not reflect the sources of the water consumption. Previous studies on virtual water in China's exports have focused on national aggregate analyses and have paid little attention to the inter-regional water consumption transfer driven by exports. We used a multi-regional input–output model of thirty provinces to examine the virtual water export. The results show that the total virtual water in China's exports was 106.3 billion m^3, and 77.0% of the embodiment was from exports from the eastern provinces, where over 90% of China's exports occur. However, the virtual water driven by per unit of export in the eastern regions is far less than that in the central and western regions. Moreover, the central and western provinces, whose exports are small, indirectly export much virtual water by supporting eastern China's exports via inter-regional economic linkages. The results yield important implications for China's export and virtual water export control policy.

Keywords: Inter-provincial trade; Multi-regional input–output; Provinces of China; Regional water transfer; Virtual water export

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1. Introduction

According to studies on agricultural water management by Mohammad (Valipour, 2015; Valipour *et al.*, 2015), we believe that it is essential for China to have a water policy due to the unpromising state of water resources. China is plagued with severe water shortages, and its fresh water resources comprise 2,800 billion m^3, accounting for 6% of global freshwater resources. However, China contains 21% of the world's population, resulting in a per capita water availability of only 2,200 m^3. This availability represents a quarter of the world's average, one-fifth of the United States' availability, and ranks 121 in the world. China is one of the thirteen countries that lack per capita water resources. Regional water shortages will not only lead to pressure for water use, but will also negatively affect the water supply sector, resulting in a deterioration of the quality of the water supplied to the residents (Sadiq *et al*., 2007; Petkovic *et al*., 2011; Lindhe *et al.*, 2012; Boryczko & Tchórzewska-Cieślak, 2014). In addition, China is a major exporter according to figures released by the General Administration of Customs. China's national total export reached ¥14.39 trillion in 2014, continuing as the largest exporter in the world. Such large commodity exports will drive significant virtual water outflow. Virtual water refers to the water resources that the production of goods and services require, an innovative concept put forward by Allan (1993) in the early 1990s. Much virtual water export undoubtedly exacerbates the shortage of water resources and the deterioration of the quality of the water supplied to the residents. However, China remains a country with large regional differences, which not only manifest in its level of economic development but also reflect its endowment of water resources. Due to the extensive division of labor in manufacturing processes and trade contacts among provinces, provinces produce different quantities of export products at different stages. Any given province indirectly exports the water resources of other relevant provinces when exporting commodities, which leads to the redistribution of water resources in various regions with exportation from various provinces.

Previous studies have generally only considered the trade flow of virtual water between China and other countries or the virtual water export in various industries across the country. They have not used appropriate methods and data to embody the export of virtual water in various industries in various provinces to assess their differences. Furthermore, previous studies on virtual water export in China have failed to evaluate the virtual water export in each province that is indirectly driven by the exports of the other domestic provinces. Addressing these issues will provide reasonable policy basis recommendations and suggestions to relieve the shortage of water resources in China and, in particular, ease the issue of unevenly distributed water resources.

2. Literature review

Many scholars have studied virtual water, although the depth and methods of research are different. For example, Sun *et al*. (2013) studied water footprint intensity spatial distribution patterns and evolution trends over 15 years via an exploratory spatial data analysis based on the water footprint calculation of China's thirty-one provinces (cities, districts) from 1995–2009. Liu *et al.* (2011) developed a general model and an improved model of agricultural virtual water domestic trade gravity of time and space based on the classical gravity model and the time gravity model. They analyzed the panel data of China's twenty-nine provinces (cities, districts) and the influencing factors on China's agricultural virtual water net domestic outflow. Xu *et al.* (2011) developed mathematical analysis models from the technology level, the industry level and the district level and demonstrated how to promote a water shortage region's economic growth via virtual water trade. They also illustrated the contribution of virtual water trade on the economic growth in China based on China's international agricultural virtual water flow patterns from 2005 to 2009. However, among the previously reported studies on virtual water, the input–output method is the most common and most effective method used in China and abroad. When analyzing the problems related to virtual water using the input–output method, scholars have primarily used the methods and levels discussed below.

Studies on the water footprint and virtual water problems in some regions use a single regional input–output model to measure and analyze the total water footprint or industry strength of virtual water and occasionally involves the virtual water trade with other regions. Cai *et al.* (2012) calculated and analyzed the intensity of virtual water and the water footprint of primary industries, secondary industries and tertiary industries of the Gansu province in 1997, 2002 and 2007 based on the single regional input–output method. They found that the intensity of virtual water of primary industries was the highest and decreased year-by-year. They also analyzed the virtual water trade of the Gansu province and showed that Gansu is a net exporter of virtual water. Wang *et al.* (2013) used an adjusted single regional input–output method to measure the total water use of all departments in Beijing in 2002 and 2007 to analyze the total water consumption and its change in primary water consumption departments. The results showed that the intensity of the water for agriculture and industries was decreasing. Yu *et al.* (2010) also used a single regional input–output method to explore the virtual water trade patterns in England. The authors found that the water-poor southeast area's water footprint was 22% higher than the water-rich northeast area. The total water footprint of the southeast area was two times that of the northeast. Mubako *et al.* (2013) used this method to study the state of virtual water of California and Illinois and found that the two states are net exporters of virtual water and that most of the virtual water outflow was due to the high water consumption intensity and low value-added departments.

The multi-regional input–output (MRIO) model primarily focused on virtual water trade and transfer between a region and the remaining areas. This method creates a new category that differs from the method described above. When studies involve multiple regions, it is necessary to introduce a MRIO model, which is the primary method to evaluate inter-regional virtual water trade and transfer. To estimate the virtual water trade between Shanxi and other provinces and to reveal the spatial pattern of Shanxi's virtual water trade, Li *et al.* (2012) applied a MRIO model in their study. By combining the trade data of other provinces in China, both the degrees of agriculture and industry virtual water trade were calculated. Shanxi primarily imported virtual water from western and northeast China, and exported virtual water to eastern coastal provinces. This is contrary to the traditional virtual water strategy. Based on MRIO model and the socio-economic data of 2007, Tan *et al.* (2013) studied the water footprint and the composition of its origin in the Guangdong province, revealing how each province contributed to the water footprint of the Guangdong province. In addition, using the MRIO model, Zhang *et al.* (2011) studied the water footprint composition and the virtual water transfer of Beijing.

Using the MRIO model, scholars have studied the water footprint of each province in China and have measured the virtual water transfer due to regional trade. They have also utilized the MRIO model in the same manners as described above. The difference is the research object, which extends from a single region to all parts of the country. Wang (2014) studied regional virtual water trade space distribution law and change tendency in China from 2002 to 2007 based on the regional input–output model to identify whether regional trade in China truly played a role in relieving the pressure of water deficiencies. According to the results, the current trade adjusting tend among the various regional departments in China and the changes in regional virtual water trade patterns were both not conducive to relieve the water resources shortage problem caused by uneven distributions. Zhou & Shi (2008) presented an improved input–output table calculation model of water resources, bringing fresh water usage and wastewater discharge into the national economic industry value input–output table to construct a mixed input–output table of value-entity type. Then, the volume of inter-regional virtual water trade was obtained intuitively and accurately using the method and the authors put forward various problems that should be urgently addressed when China implements a regional virtual water strategy. Guan & Hubacek (2007) divided China into eight regions and designed a corresponding MRIO model to measure and evaluate China's inter-regional trade structure and virtual water transfer. The results showed that the current structure of China's trade is not conducive for the rational allocation of water resources. In the north, water scarcity outflowed 5% of their available water, whereas the south is rich in water resources, but instead imported water from other regions. Dong *et al.* (2014) used the model to study the water footprint and virtual water trade of each province in China. The results showed that the water footprint was closely related to the gross domestic product (GDP) of the province, as developed provinces tended to import virtual water and the north and west provinces with poor water exported the most virtual water.

Using a single regional input–output model, we can study virtual water net exports of various industries in the development of China's external trade. Because China has become the largest exporting country in the world, many merchandise exports cause loads on the virtual water outlets. This type of research utilizes a single regional input–output model, computing the coefficient of water usage, calculating the virtual water net export quantity based on foreign trade data, and then providing ideas for foreign trade strategies from water-saving point of view. He *et al.* (2011) computed virtual water input and output quantities of seventeen industries across the entire country of China for 2002, 2005, and 2007. The results showed that China was a virtual water net export country, and the quantity was still increasing. They also provided a detailed instruction of the primary regions and industries of virtual water export. Zhao *et al.* (2009) reported a computational model for the water footprint by summarizing the virtual trade based on input–output analysis technics and the consumption calculation model. They computed the direct water usage coefficient, the final consumed virtual water quantity, the water footprint and the import and export of virtual water using the input–output table of 2002. The result showed that the direct water consumption coefficient and the volume of virtual water in agriculture and power, heat, and water were bigger than that in other departments in China, and other departments consumed much water indirectly. China is a net exporter of virtual water, which is primarily concentrated in the light industries and services. Zhu & Gao (2009) also used the single regional input–output method and calculated the foreign trade of virtual water from 2002 to 2007. They performed an empirical analysis of the problems in the current structure of China's foreign trade in light of water resource conservation.

In summary, previous studies generally include the following two deficiencies in their input–output method for studying the issue of China's virtual water:

(1) When studying the issue of China's virtual water, previous studies have adopted MRIO model but only studied the situation of transferring virtual water among various regions of China due to inter-provincial trade. They failed to extend their research to foreign export and did not calculate and analyze the export quantity of virtual water to foreign countries.

(2) When combining studies on the issue of virtual water with foreign export, previous studies applied the single regional input–output model and usually considered the entire nation of China as the research object. Thus, they did not evaluate virtual water export from various provinces in detail. As a result, the direct export of local virtual water and the indirect export of non-local virtual water due to the export products of the each province are neglected. In addition, studying the foreign export of China's virtual water with the single regional input–output model utilized the national average water use coefficients of various industries to measure the export quantity of virtual water. Such studies neglect different industrial structures and the different water-use efficiency of products among various provinces of China. Therefore, the virtual water export from China cannot be accurately measured and calculated to show differences in the virtual water export among various regions of China.

Hence, the MRIO model is more appropriate for comprehensively evaluating the source of actual water consumption of export products among various provinces of China. Its advantages lie in combining the model with the input–output data, water-use data, and foreign trade data of various provinces and calculating the export quantity of virtual water from various provinces due to the exports from each industry in each province.

3. Methodology and data

3.1. MRIO model

The input–output method was first proposed in the 1930s by the economist Leontief and was used to reflect the relationship between the various sectors (industry) of the economy. As a MRIO table is an extension of single region input–output tables in that it reflects the inter-regional trade of commodities and services. It is more comprehensive and systematically reflects the economic relations among multiple regions in contrast to the single regional input–output table. Chenery (1953) and Moses (1955) put forward the MRIO model. The model assumes that the composition and sources of regional goods that have different uses (intermediate input, final consumption and investment of the different departments) are indiscriminate. Therefore, we only need to obtain the data for each department product flow in each region and do not need to develop a regional product flow matrix. Compiling a MRIO table that contains the volume of water consumption can aid in finding the physical and technical connection of water consumption among different departments in different regions. The specific methods and calculation steps are as follows.

Assume that there are n regions, and each region is divided into m sectors (each sector produces a homogeneous product). The balance of production activities in region r can be expressed as Equation (1), that is, the total output in each sector equals the output used as the intermediate input plus the output used as the final consumption:

$$x_i^r = \sum_{s=1}^{n}\sum_{j=1}^{m} x_{ij}^{rs} + \sum_{s=1}^{n} f_i^{rs} + e_i^r \tag{1}$$

where x_{ij}^{rs} is the intermediate sector monetary flow from sector i in region r to sector j in region s (r, s = 1, 2…m; i, j = 1, 2…n), f_i^{rs} is the final demand of region s for products in sector i from region r, e_i^r is the export of sector i in region r, and x_i^r is the total output of sector i in region r.

a_{ij}^r is the direct consumption coefficients of region r, which indicates that sector j in region r produces per unit of product in demand of sector i in the national regions. We define it as:

$$a_{ij}^r = \frac{x_{ij}^r}{x_j^r} \tag{2}$$

According to the product-flow origin and destination (O-D) matrix, we can calculate the proportion of product i used in region r that comes from region s and the proportion of product i used in region r that comes from region r, as follows:

$$c_i^{sr} = \frac{z_i^{sr}}{d_i^r},\ c_i^{rr} = \frac{z_i^{rr}}{d_i^r} \tag{3}$$

where z_i^{sr} is the monetary flow of product i from region s (the origin) to region r (the destination) and d_i^r is the total shipments of product i into region r from all regions (see Table 1).

Substituting Equation (2) and Equation (3) into Equation (1) yields the following equation:

$$x_i^r = \sum_{s=1}^{n}\sum_{j=1}^{m} c_i^{rs} a_{ij}^s x_j^s + \sum_{s=1}^{n} c_i^{rs} f_i^s + e_i^r \tag{4}$$

Converting the above formula to matrix form yields:

$$X = CAX + CF + E \tag{5}$$

where X is the output matrix, A is the technical coefficient matrix, and C is the trade coefficient matrix, F is the final demand matrix, and E is the export matrix.

x_i^r is the output of sector i in region r.

Table 1. O-D matrix.

		Destination		
		1	…	n
Origin	1	$z_i^{1,1}$	$z_i^{1,s}$	$z_i^{1,1}$
	…	…	…	…
	n	$z_i^{n,1}$	$z_i^{n,s}$	$z_i^{1,n}$
	Total	d_i^1	d_i^s	d_i^n

Let

$$C = \begin{bmatrix} C^{11} & \cdots & C^{1n} \\ \cdots & \cdots & \cdots \\ C^{n1} & \cdots & C^{nn} \end{bmatrix}, \ C^{rs} = \begin{bmatrix} c_1^{rs} & 0 & 0 & 0 \\ 0 & c_2^{rs} & 0 & 0 \\ & & \ddots & \\ 0 & 0 & & 0 \\ 0 & 0 & 0 & c_m^{rs} \end{bmatrix}$$

in which the elements show the proportion of the total amount of each product used in region s that comes from region r.

Let

$$A = \begin{bmatrix} A^1 & 0 & 0 & 0 \\ 0 & A^2 & 0 & 0 \\ & & \ddots & \\ 0 & 0 & & 0 \\ 0 & 0 & 0 & A^n \end{bmatrix}, \ A^r = \begin{bmatrix} a_{11}^r & \cdots & a_{1m}^r \\ \cdots & \cdots & \cdots \\ a_{m1}^r & \cdots & a_{mm}^r \end{bmatrix},$$

where A^r is the technical coefficient matrix indicating the intermediate inputs of region r from both within the region and outside regions (including imports).

$F = \begin{bmatrix} F^1 \\ F^2 \\ \vdots \\ F^{\mathrm{n}} \end{bmatrix}$ and $F^r = \begin{bmatrix} f_1^r \\ f_2^r \\ \vdots \\ f_{\mathrm{m}}^r \end{bmatrix}$, where f_i^r is the final consumption demand of sector i in region r.

$E = \begin{bmatrix} E^1 \\ E^2 \\ \vdots \\ E^{\mathrm{n}} \end{bmatrix}$ and $E^r = \begin{bmatrix} e_1^r \\ e_2^r \\ \vdots \\ e_{\mathrm{m}}^r \end{bmatrix}$, where e_i^r is the export demand of sector i in region r.

Rewriting Equation (5), we can obtain Equation (6),

$$CAX + CF + E \Rightarrow (I - CA)X = CF + E \Rightarrow X = (I - CA)^{-1}(CF + E) \quad (6)$$

To remove CF from Equation (6), we obtain Equation (7),

$$XE = (I - CA)^{-1}E \quad (7)$$

where XE is the output driven by the exports of the entire nation. We can further obtain the production in region s driven by the exports of region r:

$$X_{EX^r} = (I - CA)^{-1}E^r \tag{8}$$

$$X_{EX^r} = \begin{bmatrix} x^1_{EX^r} \\ x^2_{EX^r} \\ \vdots \\ x^s_{EX^r} \\ \vdots \\ x^n_{EX^r} \end{bmatrix}$$

in which the element represents the production in region s driven by the exports of region r.

Thus, we can further obtain the virtual water in region s induced by the exports of region r:

$$W_{EX^r} = \widehat{W}X_{EX^r} = \widehat{W}(I - CA)^{-1}E^r \tag{9}$$

$$W_{EX^r} = \begin{bmatrix} w^1_{EX^r} \\ w^2_{EX^r} \\ \vdots \\ w^s_{EX^r} \\ \vdots \\ w^n_{EX^r} \end{bmatrix}, \widehat{W} = \begin{bmatrix} \widehat{W}^1 & & & & \\ & \ddots & & & \\ & & \widehat{W}^s & & \\ & & & \ddots & \\ & & & & \widehat{W}^n \end{bmatrix} \text{ and}$$

$$\widehat{W}^s = \begin{bmatrix} w^s_1 & & & & \\ & \ddots & & & \\ & & w^s_i & & \\ & & & \ddots & \\ & & & & w^s_m \end{bmatrix},$$

where w^s_i is the direct water use coefficient of sector i in region s, $\widehat{W}^S$ is the diagonal matrix of the direct water use coefficient in region s, $\widehat{W}$ is the diagonal matrix of the direct water use coefficient in the national various regions, and $w^s_{EX^r}$ is the virtual water in region s induced by the exports of region r.

Thus, we can calculate the total virtual water induced by exports from region r using the following equation:

$$w^{Tot}_{EX^r} = \sum_{s=1}^{n} w^s_{EX^r} \tag{10}$$

In addition, we can calculate the virtual water in region s induced by the national exports:

$$w^s_{EX^{tot}} = \sum_{r=1}^{n} w^s_{EX^r} \quad (11)$$

3.2. Data sources and processing methods

In this article, we used the 2007 MRIO tables (Xu & Li, 2008) for China developed by the State Development Research Center and the State Statistical Bureau. Until now, the 2007 MRIO table for China has been the latest regional input–output table for China. These MRIO tables include thirty provinces (all provinces of China except Tibet, Taiwan, Hong Kong and Macao), and each province includes forty-two sectors. For convenience, this study merged forty-two sectors into thirteen sectors. Moreover, the flows of bulk commodities supplied by service sectors was poorer compared to other industrial sectors, and the data of water use was difficult to obtain. Furthermore, the water use coefficient was very low, and the quantity of virtual water in exports is very small, this study only analyzed the cases of nine sectors (except for four service sectors) among the thirteen sectors.

The water consumption of each province and that of the relevant industrial sectors of China in 2007 were obtained from the *China Environment Yearbook* (National Bureau of Statistics, 2008) and *China Water Resources Bulletin* (Ministry of Water Resources People 's Republic of China, 2008). The data of agricultural water use in various regions were obtained directly from the water resources bulletin. To calculate the industrial water use coefficient of various departments of each province, first, we calculated the national average water use coefficient of each industrial department w_i, and then made $W = [w_i]$. For province r, the output matrix of industrial departments was $X^r = [x_i^r]'$. Second, we made $S^{r'} = WX^r$, which means the pending revision of total water consumption of all industrial departments in province r, it was calculated by the national average water use coefficient. After that, we made S^r the real water consumption of all industrial departments in province r, and made $\delta^r = S^r/S^{r'}$, which means the correction factor of province r. Finally, the revised water use coefficient matrix of industrial departments in province r was $W^r = \delta^r W = [\delta^r W_i]$.

4. Results and discussion

Obvious differences among the eastern, central, and western regions of China exist in the level of development and water resource potential (the eastern region includes eleven provinces – Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan; the central region includes eight provinces – Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei, and Hunan; the western region includes eleven provinces – Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang). Therefore, in this paper we analyzed the state of virtual water export of thirty provinces and the three macro-regions (that is, the eastern, central, and western regions) in China.

4.1. An analysis of the pulling effect of export from various regions on the export of national virtual water

For each province, the total national virtual water induced by the province's exports includes the water consumption of export commodities locally and in other provinces. This indicator can reflect the impact of each region's exports on the water consumption of the entire country. Table 2 not only presents data from all provinces but also the commodity export data of the provinces, so the relationship

Table 2. Export quantity of various regions and the export situation of the national virtual water pulled by exports from various regions in 2007.

Region (r)	$W_{EX^r}^{Tot}$ (10^9 m^3)*	EX^r (10^9 ¥)**	$100\left[W_{EX^r}^{Tot}/\sum_r W_{EX^r}^{Tot}\right]$ (%)***	$100[EX^r/\sum_r EX^r]$ (%)****
Eastern provinces	81.9	8,420.0	77.0	92.2
Western provinces	15.7	312.8	14.8	3.4
Central provinces	8.7	400.9	8.2	4.4
Guangdong	23.1	2,870.0	21.7	31.4
Jiangsu	18.7	1,350.0	17.6	14.8
Zhejiang	9.8	959.0	9.2	10.5
Shandong	9.7	676.5	9.1	7.4
Xinjiang	9.4	27.8	8.9	0.3
Shanghai	7.0	1,120.0	6.6	12.3
Fujian	5.8	382.9	5.4	4.2
Liaoning	2.4	246.6	2.3	2.7
Heilongjiang	2.2	38.3	2.1	0.4
Beijing	2.1	436.3	2	4.8
Hebei	1.5	138.8	1.4	1.5
Tianjing	1.4	224.8	1.3	2.5
Anhui	1.3	65.0	1.2	0.7
Hubei	1.2	59.9	1.2	0.7
Guangxi	1.2	43.5	1.1	0.5
Ningxia	1.2	12.2	1.1	0.1
Jiangxi	1.1	40.8	1	0.4
Gansu	1.0	44.2	0.9	0.5
Jilin	0.9	27.4	0.8	0.3
Hunan	0.9	44.8	0.8	0.5
Henan	0.8	67.9	0.7	0.7
Sichuan	0.7	49.7	0.6	0.5
Inner Mongolia	0.5	26.8	0.5	0.3
Hainan	0.4	18.4	0.4	0.2
Chongqing	0.4	30.4	0.3	0.3
Yunnan	0.4	18.2	0.4	0.2
Shaanxi	0.4	38.6	0.4	0.4
Qinghai	0.4	6.8	0.3	0.1
Shanxi	0.3	56.9	0.3	0.6
Guizhou	0.2	14.6	0.2	0.2

*$W_{EX^r}^{Tot}$ represents the total national virtual water induced by exports from region r.
**EX^r represents the quantity of production exports from region r.
***$100\left[W_{EX^r}^{Tot}/\sum_r W_{EX^r}^{Tot}\right]$ represents the proportion of the total national virtual water induced by exports from region r.
****$100\left[EX^r/\sum_r EX^r\right]$ represents the proportion of quantity of production exports from region r.

between the national virtual water driven by exports from each province and local exports can be analyzed.

First, the national virtual water exports are mainly driven by exports in eastern China due to the high volume of exports from the eastern region, but the virtual water export driven by each export in the eastern region is less. According to Table 2 and from the perspective of the eastern, central and western parts, the eastern region exported commodities worth ¥8,420 billion, which comprised 92.2% of the total national export. However, the export quantity of the national virtual water driven by the exports from the eastern region only occupied 77.0% of the total export quantity of national virtual water. The exports from the western region accounted for 3.4% of the national export, promoting 14.8% of the export of national virtual water. The central region, whose exports accounted for 4.4% of national exports, pulled 8.2% of the export of national virtual water. Accordingly, the unit export commodity of the eastern region consumed one-fifth of the water used by the unit export commodity of the western part and half of the water used by the unit export commodity of the central part. There were two main reasons for this result. First, the eastern region used water more efficiently when producing the same export commodity compared to the central and western regions. Second, the respective export commodities of the eastern, central and western regions presented huge differences. Specifically, the eastern region focused on exporting commodities characterized by low water consumption, whereas the central and western regions primarily exported commodities characterized by high water consumption.

Second, provinces with small exports are likely to pull a large amount of the national virtual water exports. The Guangdong province ranked highest according to the array of the export quantity of national virtual water driven by export from various provinces. In 2007, the exports from the Guangdong province boosted export to 23.1 billion m^3 of virtual water across the country, accounting for 21.7% of the total export of national virtual water. The major cause was that the Guangdong province had a large amount of exports and exported a total of ¥2,870 billion in 2007, which accounted for 31.4% of the national exports. Ranking second in export quantity, the Jiangsu province, with 14.8% of export quantity, propelled 17.6% of the export of national virtual water. The export quantity of virtual water pulled by the export of the Jiangsu province was also second in the country. The eight top-ten provinces in pulling the export quantity of the national virtual water were in the eastern region, and the export quantity of these provinces ranked top throughout the country. Xinjiang and Heilongjiang accounted for 8.9% and 2.1%, respectively, of the export quantity of national virtual water, but their export quantities only held a small proportion of the national export quantity, namely 0.3% and 0.4%, respectively. This is because the two provinces are typical provinces exporting agricultural products, and agricultural sectors belong to typical sectors with low prices and high water consumption. The virtual water export driven by agricultural from Xinjiang and Heilongjiang respectively reached 12.95 billion m^3 and 3.72 billion m^3. Moreover, a great deal of virtual water was exported by the mining industry, the petrochemical industry and power, heat, and water industries in the Heilongjiang province. These sectors were also characterized by high water consumption and exported 1.06 billion m^3 virtual water.

4.2. An analysis on the water consumption intensity of unit export commodities of various provinces

We divided the national virtual water in exports from each region by the volume of the exports of each region to produce the water consumption per unit of export commodities. This value can reflect the differences in the efficiency of water use in the production processes of exports in the various regions of China and it can aid in the analysis of the different types of exports and different water technologies in the various regions.

As shown in Figure 1, the export quantity of the national virtual water driven by the unit export of Xinjiang reached 0.339 m^3/¥, which exceeded all other provinces. Xinjiang was followed closely by Ningxia, with a unit export value of 0.098 m^3/¥. Guangdong, Tianjin, Shanghai, Shanxi, and Beijing ranked the lowest. Except for Shanxi, these provinces made up regions with relatively developed economies and that focused on exporting low water consumption and high value-added commodities. Furthermore, the proportion of tertiary industries in these provinces far exceeded the proportion of secondary industries, whose production links primarily consumed little water. Among the top ten-ranking provinces in pulling the export quantity of national virtual water by virtue of their unit export, only the Hainan province with a relatively underdeveloped economy is in the eastern part; the other provinces are in central and western parts. Moreover, several traditional agricultural provinces, such as Xinjiang, Heilongjiang, Jilin, Jiangxi and so on, have unit exports with high water consumption, which indicated the primary cause for the large differences in the export quantity of national virtual water pulled by the unit export of various provinces was that the export commodities among the various provinces were highly different.

4.3. An analysis on the pulling effect of national exports on the virtual water export of various provinces

For each province, the pulling effect of national exports on the local virtual water export is the export volume of local virtual water that is driven by local exports and exports from other regions; specifically, the local virtual water embodied in China's total exports. It can reflect the impact of China's exports on the water consumption of each region. Table 3 presents the results of this analysis. We analyzed the data together with the export volume of each region to take the water consumption into account when evaluating the benefits created by the exports of various provinces. Each region is presented in

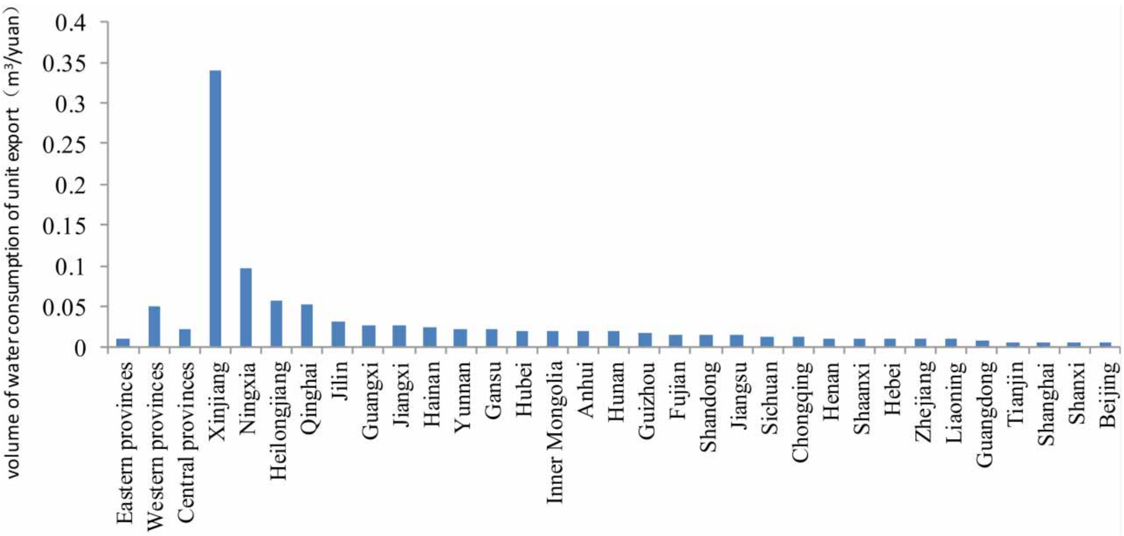

Fig. 1. Export quantity of the national virtual water pulled by the unit exports of various provinces.

Table 3. Export quantity of various regions and the export situation of the virtual water pulled by national exports in 2007.

Region (r)	$W^r_{EX^{Tot}}$ (10^9 m^3)*	EX^r (10^9 ¥)	$100\left[W^r_{EX^{Tot}}/\sum_r W^r_{EX^{Tot}}\right]$ (%)**	$100\left[EX^r/\sum_r EX^r\right]$ (%)
Western provinces	27.4	312.8	25.8	3.4
Central provinces	20.4	400.9	19.2	4.4
Eastern provinces	58.5	8,420.0	55.0	92.2
Xinjiang	13.1	27.8	12.4	0.3
Ningxia	1.4	12.2	1.3	0.1
Heilongjiang	4.9	38.3	4.6	0.4
Inner Mongolia	2.6	26.8	2.4	0.3
Guangxi	3.5	43.5	3.3	0.5
Hunan	3.2	44.8	3	0.5
Yunnan	1.2	18.2	1.1	0.2
Jilin	1.6	27.4	1.5	0.3
Guizhou	1.1	14.6	1	0.2
Jiangxi	2	40.8	1.9	0.4
Anhui	3.4	65	3.2	0.7
Qinghai	0.4	6.8	0.4	0.1
Hubei	2.8	59.9	2.6	0.7
Hainan	0.6	18.4	0.6	0.2
Henan	1.9	67.9	1.8	0.7
Sichuan	1.3	49.7	1.2	0.5
Gansu	1.3	44.2	1.2	0.5
Shaanxi	0.9	38.6	0.9	0.4
Hebei	3.3	138.8	3.1	1.5
Chongqing	0.6	30.4	0.6	0.3
Fujian	5.3	382.9	5	4.2
Jiangsu	17.6	1,350	16.6	14.8
Shanxi	0.6	56.9	0.6	0.6
Liaoning	2.4	246.6	2.2	2.7
Shangdong	5.2	676.5	4.9	7.4
Zhejiang	5.4	959	5.1	10.5
Guangdong	13.5	2,870	12.7	31.4
Shanghai	4.3	1,120	4	12.3
Tianjing	0.4	224.8	0.4	2.5
Beijing	0.5	436.3	0.5	4.8

*$W^r_{EX^{Tot}}$ represents the virtual water export in region r induced by the total national exports.
**$100\left[W^r_{EX^{Tot}}/\sum_r W^r_{EX^{Tot}}\right]$ represents the proportion of the virtual water export in region r induced by the total national exports.

descending order of the ratio of the local virtual water embodied in China's total exports to the local export volume.

First, the central and western regions have contributed a large amount of water to the exports of eastern region. As shown in Table 3, the pulled export quantity of virtual water in various provinces of the eastern part is the largest, namely 58.5 billion m^3, followed by 27.4 billion m^3 in the western regions, and 20.4 billion m^3 in the central regions. The pulled exports of the virtual water of the three regions correspond to 55.0%, 25.8% and 19.2%, respectively. When these data are compared with the proportion of total national virtual water induced by exports from these three regions (see Table 2), the following findings are quite striking, namely, the eastern region, with 92.2% of national export quantity, boosted 77.0% of the total export of national virtual water (as in Table 2), but the quantity of the virtual water export pulled by the national exports in this region only made up 55.0% of the total export quantity of the national virtual water. In other words, the export quantity of the virtual water pulled by the exports of the eastern region in other regions made up at least 22% of the total export quantity of the national virtual water (55.0% of the export quantity of the virtual water in the eastern region was partly driven by other regions). In contrast, the western region exported only 3.4% of the national commodities, but the pulled export of the virtual water in the western provinces accounted for 25.8% of the total export quantity of the national virtual water. The central region exported only 4.4% of the national export quantity, but its export quantity of virtual water amounts to 19.2%.

The central and western regions had small export quantities. However, the central and western regions contributed a good deal of water to national (mainly eastern region) exports. Without doubt, this situation will intensify the problem of the shortage of water resources in the central and western regions. In addition to the above-mentioned differences in the export commodities of the various regions in water consumption intensity, there were two additional reasons for this situation. First, the central and western regions primarily undertook the upstream links of producing export commodities due to geographic and technical differences. These links usually consume a large amount of water. The eastern region primarily undertook technology-intensive links and consumed less water. Second, the central and western provinces primarily exported high water consumption and low value-added products to the eastern provinces in the process of provincial import and export. Inversely, the eastern provinces exported low water consumption and high value-added products to the central and western provinces.

Second, most central and western provinces export a large amount of local virtual water but less products. The distinct confines of 'west, central, and east' among various provinces run from the top to the bottom of Table 3. Six of the top ten provinces are from the western region, and four from the central region. However, the ten provinces at the bottom of the list are all in eastern region except for Hebei and Hainan, which indicates that the exports of most of the central and western provinces play a lesser role in promoting their economies, but they consumed a relatively large amount of local water resources due to the national exports, and the opposite occurred in the eastern provinces. For example, Xinjiang consumed 13.1 billion m^3 of virtual water due to China's total exports while receiving economic benefits of only ¥2.78 billion from local exports. The ratio of these two quantities was up to 0.5, while this ratio for Beijing was only 0.0011, indicating that while the same benefit was received from exports, the cost of water consumption in Xinjiang was much higher than that in Beijing by supporting China's total exports. However, in the past, the evaluation of the export activities of the provinces only encompassed the economic benefits without considering the differences in the cost of water consumption in the provinces, or the need for relevant support and compensation in the central and western provinces.

4.4. A comparative analysis on pulling and pulled export quantities of virtual water of various provinces

Respective discussions were held regarding the national virtual water driven by the export of various provinces and the virtual water export in various provinces driven by national exports, and an analysis was conducted by combining the export quantity of the various provinces above. However, the above two datasets of various provinces were not displayed and analyzed comparatively. For each province, if the former is greater than the latter, the province has a net import of virtual water from other provinces, if the former is less than the latter, the province has a net export of virtual water to other provinces. In addition, we added the indicator of local embodied virtual water to the local exports, and compared it with the above two indicators to reflect the local virtual water from non-local exports and the non-local virtual water from local exports (Figure 2).

First, individual eastern provinces provide large amounts of water to support the export of the other regions, whereas the export of the eastern provinces pulls a large export of the virtual water of other provinces. According to Figure 2, the national virtual water embodied in the local exports in the eastern region, including Beijing, Tianjin, Shanghai, Zhejiang, Shandong and Guangdong, was much higher than the local virtual water embodied in the national exports in these provinces. Thus, the export quantity of the virtual water in these provinces was pulled by their own exports, which indicated that the export of these provinces consumed much of the water resources of other regions in addition to using their own water resources. Except for consuming the plentiful water resources of other provinces for its export, Jiangsu also expended significant local water resources due to the influence of national exports. Hebei is a water-shortage region, and the local virtual water embodied in national exports was much larger than in local exports, as Hebei provided abundant water resources to support the economic development of Beijing and Tianjin.

Second, the export quantity of national virtual water pulled by the export of the central and western provinces is derived locally and these provinces provide a certain amount of water consumption for the exportation of products in other regions. For each province in central and western regions, the total export quantity of national virtual water in local exports was less than that of the local virtual water in total national exports, which was in contrast to the state of the eastern provinces. In addition, this finding was more obvious in Heilongjiang, Anhui, Hunan, Inner Mongolia, Guangxi and other provinces, which further illustrated that the central and western regions offered plenty of water to the exports of the eastern region. Additionally, in terms of the central and western provinces, the local

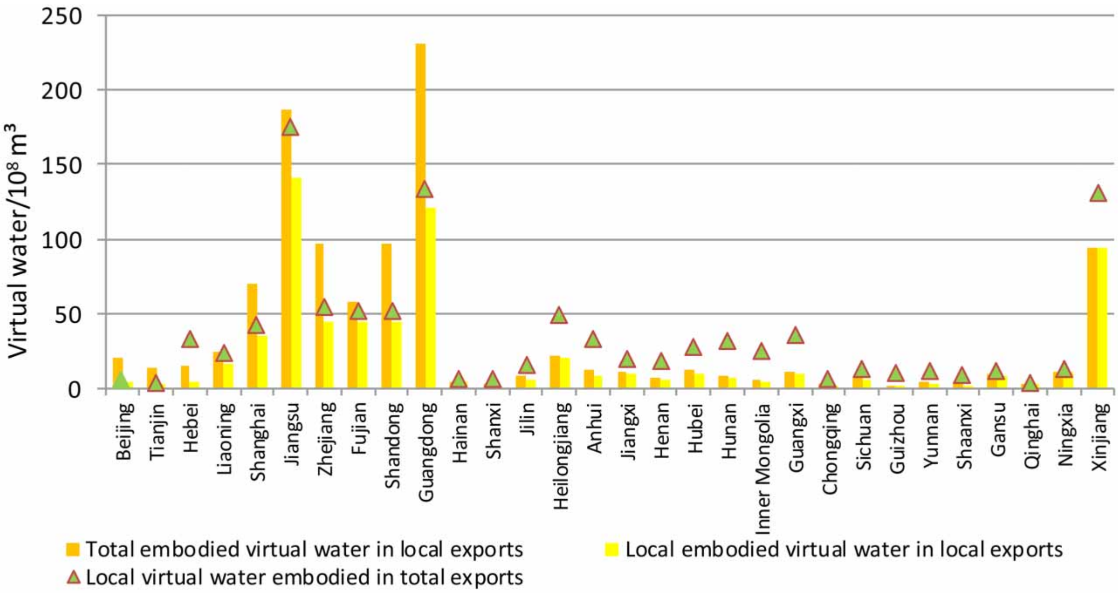

Fig. 2. Detailed information of the quantity of virtual water export in various provinces.

virtual water embodied in local exports was roughly equal to the national virtual water embodied in local exports. Namely, the exports of these provinces consumed almost no water resources of other provinces.

4.5. An analysis of virtual water export of each sector in the provinces

We calculated and analyzed the proportion of virtual water exports in various industrial sectors in each region driven by China's exports (Figure 3), to comprehensively identify the key sectors of virtual water export in each province and explore the internal reasons for the disparity between the provinces.

First, the export of virtual water in each province mainly arises from agriculture and power, heat and water. The proportion of virtual water export from these two sectors accounted for 61.4% and 21.9% of the nation's total virtual water exports. Especially in Xinjiang and Ningxia, where the contribution of agriculture was greater than 90%. On the other hand, the construction industry and building material production are sectors with less virtual water export, and their proportion of virtual water export accounted for only 0.26% and 0.03% of the national's total virtual water export. These phenomena result from the high water consumption by agriculture and power, heat and water and the low water consumption and lower export volume by the construction and building material industries.

Second, a considerable difference in the proportion of virtual water export exists in each sector among the provinces. For example, agriculture and power, heat and water in Shanghai are responsible for only 48% of Shanghai's total virtual water exports, while the percentage for other provinces was greater than 68%. In addition, the proportion of virtual water exports from the food, wood, paper, textiles and clothing industries in several of the eastern provinces (that is, Shanghai, Jiangsu, Zhejiang, Fujian and Guangzhou) is higher than in the central and western regions. However, the mining industry in the

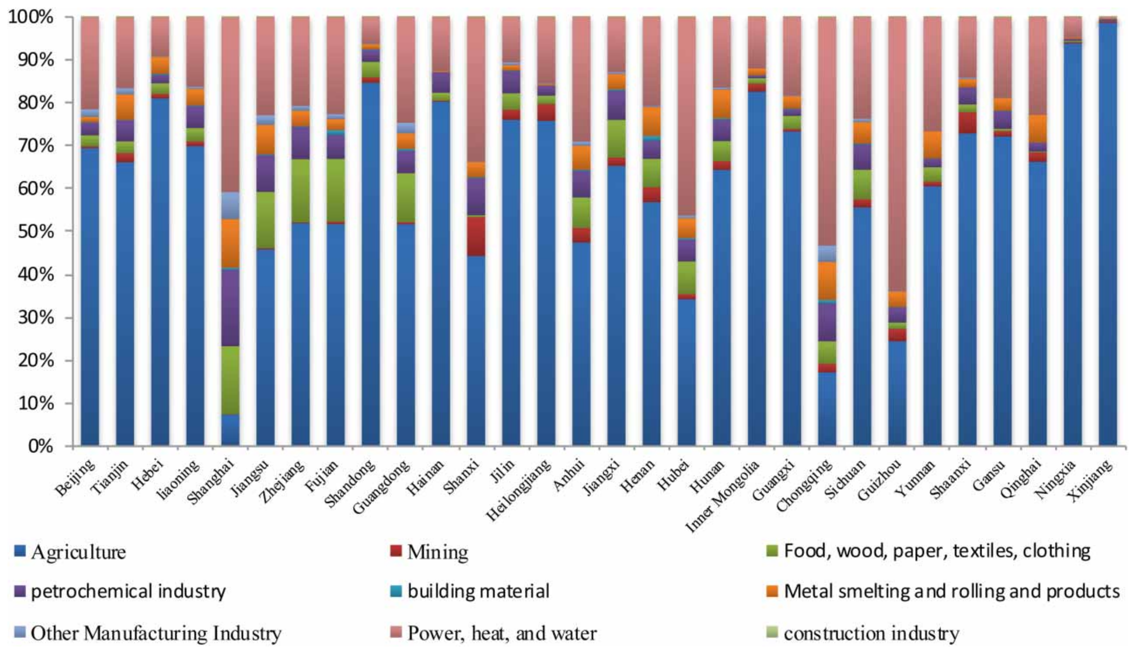

Fig. 3. Proportion of virtual water exports of each sector in the provinces.

central and western provinces was responsible for a higher percentage of virtual water exports than in the eastern provinces. This is closely related to the marked differences in the industrial structure of the provinces.

5. Conclusions and recommendations

According to previous studies, exports from China contain significant virtual water export. However, in this study, using MRIO, we found that our exports not only caused significant virtual water outflow, but that exports from eastern China contributed more than 90% of the total exports and generated around 77% of China's virtual water outflow, the central and western provinces accounted for less than 10% of exported goods, nonetheless, pulled approximately 23% of China's virtual water outflow.

In addition, this study found that, due to the differences in water use efficiency of production, export commodity groups, and production division of labor, economically developed regions, such as the eastern provinces, generally export commodities of low water consumption intensity, whereas the central and western provinces generally export commodities of high water consumption intensity.

Finally, by comparing the volume of exports and virtual water export, we found that, although the eastern region exports many products, its local virtual water export driven by its own exports is low. In contrast, the central and western regions contributed to significant virtual water exports for the eastern region export. In addition, virtual water induced by China's exports in the central and western regions is greater than that in the eastern regions but the same economic benefit is derived from the exports. Regarding the central and western regions, the national virtual water export driven by their own exports are derived almost completely from local sources; that is, the product exports of the central and western regions consume scarce water resources from other regions. This shows that in the provincial trade of high water consumption products, primarily central and western regions export to the eastern region, and most products from the eastern region export to the central and western regions for the export-oriented products. Furthermore, the volume of the virtual water exports from agriculture and power, heat and water in the various provinces were usually large, while the construction and building materials industries exported less virtual water. Because there are differences in various provinces in terms of industrial structure and the division of labor, the volumes of virtual water export in each sector from each province are distinctly different.

In terms of policy recommendations, firstly, we should prompt the central and western regions to improve the production process and technical level and to improve water use efficiency, especially for high water consumption industries in the water-shortage provinces.

Secondly, when evaluating the benefits created by the exports of various provinces, the water consumption caused by export should also be taken into account. The central and western regions contributed a large amount of virtual water for the eastern regions' exports; therefore, because they received great economic benefits from these exports, the eastern regions should provide appropriate financial compensation and technical support to the appropriate water supply regions, so as to alleviate water shortages in these regions. According to the analysis above, the current industrial structure in China will worsen the condition of water shortages in the water-short regions, and the water-rich regions consume little water at present, which means that the current industrial structure in China is not conducive to balance the unevenly distributed water resources in China. Promoting nationwide industrial restructuring by transferring the high water-consuming export industries from the western region to the eastern region will effectively ease the water shortage in China's central and western regions. In addition, the water-short regions should reduce the production and export of high water-consuming products, especially for those with low added value that are useless for stimulating the local economy.

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References

Allan, J. A. (1993). *Fortunately there are substitutes for water otherwise our hydro-political futures would be impossible*. In: *Priorities for Water Resources Allocation and Management,* Vol. 13, p. 26.

Boryczko, K. & Tchórzewska-Cieślak, B. (2014). Analysis of risk of failure in water main pipe network and of delivering poor quality water. *Environment Protection Engineering 40*(4), 77–92.

Cai, Z. H., Shen, L. X., Liu, J. G. & Zhao, X. (2012). Applying input-output analysis method for calculation of water footprint and virtual water trade in Gansu Province. *Acta Ecologica Sinica 32*(20), 6481–6488 (in Chinese).

Chenery, H. B. (1953). Regional analysis. In: *The Structure and Growth of the Italian Economy.* Chenery, H. B., Clark, P. G. & Pinna, V. C. (eds). US Mutual Security Agency, Rome, pp. 97–129.

Dong, H. J., Geng, Y., Fujita, T., Fujii, M., Hao, D. & Yu, X. M. (2014). Uncovering regional disparity of China's water footprint and inter-provincial virtual water flows. *Science of the Total Environment 500–501*, 120–130.

Guan, D. & Hubacek, K. (2007). Assessment of regional trade and virtual water flows in China. *Ecological Economics 61*, 159–170.

He, X. B., Zhang, H. W., Wang, Y. & Ma, S. Y. (2011). Analysis of Chinese international virtual water trade in an input-output method. *Environmental Science and Management 36*(3), 7–10 (in Chinese).

Li, F. Y., Liu, W. D. & Liu, H. G. (2012). Inter-regional virtual water trade model and its application in Shanxi Province. *Resources Science 34*(5), 802–810 (in Chinese).

Lindhe, A., Norberg, T. & Rosén, L. (2012). Approximate dynamic fault tree calculations for modelling water supply risks. *Reliability Engineering & System Safety 106*, 61–71.

Liu, H. M., Li, G. J. & Wang, K. Q. (2011). Analysis on the influencing factors of China's agricultural virtual water domestic trade based on gravity model. *Chinese Rural Economy* (5), 21–32 (in Chinese).

Ministry of Water Resources People's Republic of China (2008). *China Water Resources Bulletin 2008.* China Water & Power Press, Beijing (in Chinese).

Moses, L. N. (1955). The stability of interregional trading patterns and input-output analysis. *American Economic Review 45*, 803–832.

Mubako, S., Lahiri, S. & Lant, C. (2013). Input–output analysis of virtual water transfers: case study of California and Illinois. *Ecological Economics 93*, 230–238.

National Bureau of Statistics of China (2008). *China Environment Yearbook 2008.* China Statistical Publishing House, Beijing (in Chinese).

Petkovic, S., Gregoric, E., Slepcevic, V., Blagojevic, S., Gajic, B., Kljujev, I., Žarković, B., Djurovic, N. & Draskovic, R. (2011). Contamination of local water supply systems in suburban Belgrade. *Urban Water Journal 8*(2), 79–92.

Sadiq, R., Rodriguez, M. J., Imran, S. A. & Najjaran, H. (2007). Communicating human health risks associated with disinfection by-products in drinking water supplies: a fuzzy-based approach. *Stochastic Environmental Research and Risk Assessment 21*(4), 341–353.

Sun, C. Z., Chen, S. & Zhao, L. S. (2013). Spatial correlation pattern analysis of water footprint intensity based on ESDA model at provincial scale in China. *Journal of Natural Resources 28*(4), 571–582 (in Chinese).

Tan, S. L., Liu, Z. F., Xiong, Y. J., Liao, C. & Chen, Z. H. (2013). Evaluation of water footprint for Guangdong province in an interregional input-output framework. *Ecology and Environmental Sciences 22*(9), 1564–1570 (in Chinese).

Valipour, M. (2015). A comprehensive study on irrigation management in Asia and Oceania. *Archives of Agronomy and Soil Science 61*(9), 1247–1271.

Valipour, M., Ziatabar Ahmadi, M., Raeini-Sarjaz, M., Gholami Sefidkouhi, M. A., Shahnazari, A., Fazlola, R. & Darzi-Naftchali, A. (2015). Agricultural water management in the world during past half century. *Archives of Agronomy and Soil Science 61*(5), 657–678.

Wang, X. N. (2014). Research on distribution and tendency of virtual water trade in China based on inter-regional input-output model. *Management Review 26*(7), 46–54 (in Chinese).

Wang, Z. Y., Huang, K., Yang, S. S. & Yu, Y. J. (2013). An input-output approach to evaluate the water footprint and virtual water trade of Beijing, China. *Journal of Cleaner Production 42*, 172–179.

Xu, X. C. & Li, S. T. (2008). *Preparation and Analysis of Regional Input-Output Table of China.* Journal of Tsinghua University, Beijing (in Chinese).

Xu, C. X., Ma, C., Tian, G. L. & Xie, W. X. (2011). Study on mechanisms of virtual water trade and its contribution to regional economic growth. *China Soft Science* (12), 110–119 (in Chinese).

Yu, Y., Hubacek, K., Feng, K. & Guan, D. (2010). Assessing regional and global water footprints for the UK. *Ecological Economics 69*, 1140–1147.

Zhang, Z. Y., Yang, H. & Shi, M. J. (2011). Analyses of water footprint of Beijing in an interregional input–output framework. *Ecological Economics 70*, 2494–2502.

Zhao, X., Yang, Z. F. & Chen, B. (2009). Study on Chinese virtual water trade and consumption in an input-output framework. *Journal of Natural Resources 24*(2), 286–294 (in Chinese).

Zhou, J. & Shi, A. N. (2008). Method for calculating virtual water trade and demonstration. *China Population Resources and Environment 18*(4), 185–188 (in Chinese).

Zhu, Q. R. & Gao, J. F. (2009). Study on the issue of foreign trade and virtual water in China by input-output model. *China Soft Science* (5), 40–46 (in Chinese).

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