

# Demand-driven water withdrawals by Chinese industry: a multi-regional input-output analysis

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**Abstract** With ever increasing water demands and the continuous intensification of water scarcity arising from China's industrialization, the country is struggling to harmonize its industrial development and water supply. This paper presents a systems analysis of water withdrawals by Chinese industry and investigates demand-driven industrial water uses embodied in final demand and interregional trade based on a multi-regional input-output model. In 2007, the *Electric Power, Steam, and Hot Water Production and Supply* sector ranks first in direct industrial water withdrawal (DWW), and *Construction* has the largest embodied industrial water use (EWU). Investment, consumption, and exports contribute to 34.6%, 33.3%, and 30.6% of the national total EWU, respectively. Specifically, 58.0%, 51.1%, 48.6%, 43.3%, and 37.5% of the regional EWUs respectively in Guangdong, Shanghai, Zhejiang, Jiangsu, and Fujian are attributed to international exports. The total interregional import/export of embodied water is equivalent to about 40% of the national total DWW, of which 55.5% is associated with the DWWs of *Electric Power, Steam, and Hot Water Production and Supply*. Jiangsu is the biggest interregional exporter and deficit receiver of embodied water, in contrast to Guangdong as the biggest interregional importer and surplus receiver. Without implementing effective water-saving measures and adjusting industrial structures, the regional imbalance between water availability and water demand tends to intensify considering the water impact of domestic trade of industrial products. Steps taken to

improve water use efficiency in production, and to enhance embodied water saving in consumption are both of great significance for supporting China's water policies.

**Keywords** water withdrawal, embodied water use, Chinese industry, interregional trade, multi-regional input-output analysis

## 1 Introduction

Water is recognized as the most critical natural resource (Cai et al., 2009). China is one of the 13 countries in the world with the most limited water resources, and its annual per capita available amount of renewable freshwater is only a quarter of the global average (Hu and Cheng, 2013). Along with rapid industrialization and fast economic growth since the 1980s, China's water demands have increased drastically (Hubacek et al., 2009). Meanwhile, its physical water supply remains essentially the same in recent decades (Ministry of Water Resources, 2012). Ever increasing water demands coupled with uneven spatial distribution of water resources have posed severe pressure on China's limited freshwater resources (Lin et al., 2012). For instance, more than half of the renewable water resources are withdrawn for direct uses in most river basins of North China (Ministry of Water Resources, 2012). Most cities in the northern and western parts of China are facing serious water problems, and their rising water demands have been met largely by increasing the uses of underground water resources and from water courses. Excessive water withdrawals have resulted in significant damage to the freshwater and estuarine ecosystems in China.

Traditional economic and energy analysis rarely takes

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water resources into consideration, and water is usually not recognized as an important factor of industrial production (Guan and Hubacek, 2008). But in reality, water is related to all industrial activities either directly or indirectly (Yang et al., 2013). Water demands by Chinese industry nearly tripled between 1980 and 2007 (Ministry of Water Resources, 2008), and about a quarter of the country's water uses are allocated to industrial production and related activities. In some developed coastal provinces such as Guangdong, Jiangsu, Shanghai, and Zhejiang, the industrial sectors generally account for more than 30% of their overall water use. Although a large fraction of the water withdrawn by the industrial sectors can be finally returned to its original water bodies, water qualities may be largely impaired and even polluted compared to other water-use sectors. Given the increasing proportion of freshwater allocated to industrial production, the gap between supply and demand of qualified water resources will become wider with continued industrial growth in China (Cheng and Hu, 2011; Zhang and Anadon, 2013).

In order to evaluate the water requirements of the economic and industrial sectors, an input-output model is a useful tool for capturing the economic interaction between water users. The application of an input-output approach can not only identify the direct and on-site immediate water withdrawal by an economic sector, but also reveal the embodied and off-site water use induced by final demand (Guan and Hubacek, 2008; Chen and Chen, 2013b). The patterns of demand-driven water uses and water reallocation mechanisms between economic sectors can then be identified (Llop, 2013). Scholars have carried out a large number of input-output analyses regarding embodied water for global, national, and regional economies (e.g., Hoekstra and Chapagain, 2007; Chen and Chen, 2011, 2013b; Feng et al., 2011; Chen et al., 2012; Cazcarro et al., 2013; Lenzen et al., 2013; Mubako et al., 2013). For the research of water footprint or virtual water flows in China, some studies have focused on the country totally (e.g., Zhao et al., 2009; Chen and Chen, 2010; Chen et al., 2010; Wang et al., 2013a), the water-deficient regions (Zhao et al., 2010; Dong et al., 2013; Wang et al., 2014), and some cities (Okadera et al., 2006; Wang et al., 2009; Wang et al., 2013b), on the basis of the single regional input-output models.

Compared with the single regional input-output model, the multi-regional input-output model can not only present the interactions among industrial sectors within an economy, but also provide the spatial linkages of industries between any two regions in the system, and distinguish the production technologies between domestic and other regions based on a more comprehensive data foundation of the intraregional and interregional economic flows (Wiedmann, 2009; Wiedmann et al., 2011; Zhang et al., 2011a). Subsequently, the impacts of interregional trade on domestic resources use and environmental emissions can be estimated (e.g., Feng et al., 2013; Meng et al., 2013;

Zhang et al., 2013; Su and Ang, 2014; Tian et al., 2014; Zhang et al., 2014a, b; Zhong et al., 2015). Some studies have integrated embodied water accounting for China's regional economies in multi-regional input-output frameworks. Guan and Hubacek (2007) assessed the virtual water trade between North and South China based on an extended regional input-output model for eight hydro-economic regions. Zhang et al. (2011a) applied China's interregional input-output table to evaluate the water footprint and virtual water trade of Beijing in 2002. Feng et al. (2012) developed a multi-regional input-output model to assess the regional virtual water flows between the three reaches of the Yellow River Basin and the rest of China. Recently, Zhang and Anadon (2014) reported consumption-based water footprints at the provincial level in China by combining a multi-regional input-output model, though the authors used simplified water withdrawal inventories for the industrial sectors by province. Till now, few researchers have specified the water uses by the industrial sector of regional economies in China and investigated the virtual water flows across provinces through interregional trade of industrial products.

Taking account of the region-specific characteristics is important to customize and prioritize water policy recommendations, especially for the water-deficient regions. This paper presents a systems analysis of water withdrawals by Chinese industry for the year of 2007 and investigates the industrial water uses embodied in final demand and interregional trade with the recently available 2007 multi-regional input-output table. The evaluation of water embodiments can track both direct and indirect industrial water uses via taking the overlooked causal relationships into account and reflect the impact of China's interregional trade of industrial products on regional water uses. The results are critical for evaluating the structures and driving forces of the water uses by Chinese industry, and identifying where water savings and effective water management can be achieved.

The remainder of this paper is organized as follows. In Section 2, the algorithms for multi-regional input-output analysis and data sources are introduced. The direct industrial water withdrawals are analyzed in Section 3. In Section 4, the results of industrial water uses embodied in final demand and interregional trade are presented. The embodied water transfers associated with the direct water withdrawals of the *Electric Power, Steam, and Hot Water Production and Supply* sector are also discussed in this section. Concluding remarks will be drawn in the ending section.

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## 2 Methodology and data

### 2.1 Input-output analysis and water embodiment

The main data foundation of this study is the China multi-



If we introduce the following denotations

$$E^* = \begin{bmatrix} \left( \begin{matrix} \varepsilon_1^1 \\ \vdots \\ \varepsilon_{30}^1 \end{matrix} \right) \\ \vdots \\ \left( \begin{matrix} \varepsilon_1^{30} \\ \vdots \\ \varepsilon_{30}^{30} \end{matrix} \right) \end{bmatrix}, W^* = \begin{bmatrix} \left( \begin{matrix} w_1^1 \\ \vdots \\ w_{30}^1 \end{matrix} \right) \\ \vdots \\ \left( \begin{matrix} w_1^{30} \\ \vdots \\ w_{30}^{30} \end{matrix} \right) \end{bmatrix},$$

$$Z^* = \begin{bmatrix} \left( \begin{matrix} z_{11}^{11} & \cdots & z_{301}^{11} \\ \vdots & \ddots & \vdots \\ z_{130}^{11} & \cdots & z_{3030}^{11} \end{matrix} \right) & \cdots & \left( \begin{matrix} z_{11}^{301} & \cdots & z_{301}^{301} \\ \vdots & \ddots & \vdots \\ z_{130}^{301} & \cdots & z_{3030}^{301} \end{matrix} \right) \\ \vdots & \ddots & \vdots \\ \left( \begin{matrix} z_{11}^{130} & \cdots & z_{301}^{130} \\ \vdots & \ddots & \vdots \\ z_{130}^{130} & \cdots & z_{3030}^{130} \end{matrix} \right) & \cdots & \left( \begin{matrix} z_{11}^{3030} & \cdots & z_{301}^{3030} \\ \vdots & \ddots & \vdots \\ z_{130}^{3030} & \cdots & z_{3030}^{3030} \end{matrix} \right) \end{bmatrix},$$

and

$$X = \begin{bmatrix} \left( \begin{matrix} \sum_{s=1}^{30} \sum_{j=1}^{30} z_{1j}^{1s} + p_1^1 \\ \vdots \\ \sum_{s=1}^{30} \sum_{j=1}^{30} z_{30j}^{1s} + p_{30}^1 \end{matrix} \right) \\ \vdots \\ \left( \begin{matrix} \sum_{s=1}^{30} \sum_{j=1}^{30} z_{1j}^{30s} + p_1^{30} \\ \vdots \\ \sum_{s=1}^{30} \sum_{j=1}^{30} z_{30j}^{30s} + p_{30}^{30} \end{matrix} \right) \end{bmatrix},$$

then the above simultaneous equations can be expressed in a compressed matrix form of

$$W^* + Z^* \times E^* = X \times E^*. \tag{4}$$

If  $W, Z,$  and  $E$  are introduced as the transposes of  $W^*, Z^*,$  and  $E^*$ , then Eq. (4) can be transformed into

$$E = W(X - Z)^{-1}. \tag{5}$$

To get the value of  $E$ , the elements of  $W$ , i.e.,  $w_i^f$ , can be extracted from the direct water withdrawals of sector  $i$  in region  $f$ ; the elements of  $Z$ , i.e.,  $z_{ij}^s$ , can be extracted from the intermediate matrix of the MRIO table; and the elements of  $X$ , i.e.,  $\sum_{s=1}^{30} \sum_{j=1}^{30} z_{ij}^{fs} + p_i^f$ , can be calculated

based on the data extracted from the economic intermediate and final demand matrixes of the MRIO table, shown in Table 1.

Thus the embodied water uses  $W_{\text{EMBODIMENT}}$  of any given set of commodities  $P^* = [p_1, p_2, \dots, p_{900}]$  ( $p_i$  indicates the output of Entry  $i$  contained in the commodities set, and  $P$  is the transpose of  $P^*$ ) can be obtained as

$$W_{\text{EMBODIMENT}} = E \times P. \tag{6}$$

Thereafter, concrete analyses can be accomplished in

terms of embodied water flows related to specific economic activity, and the embodied water uses (EWU) induced by the final demand of all 30 regions (or 30 sectors), such as consumption, can be calculated by multiplying the embodied water use intensity matrix  $E$  by the corresponding final-use vector directly.

As to the calculation of water uses embodied in interregional trade, we resort to the method provided in Meng et al. (2013), in which the interregional trade in intermediate goods and services are treated as endogenous variables. The water use embodied in interregional trade measures a region's water withdrawals caused by other regions' total final demand through interregional supply chains or one region's water spillover to other regions in the processes of domestic trade outflow.

For instance, the water uses embodied in interregional exports (WEIE) of Region 1 can express as

$$\begin{aligned} \text{WEIE}^1 &= W^1(X - Z)^{-1} \left( \sum_{s=2}^{30} \sum_{t=1}^2 d_t^s + e^s + o^s \right) \\ &= \sum_{s=2}^{30} \text{WEIT}^{1s}, (s \neq 1), \end{aligned} \tag{7}$$

$$W^1 = [(w_1^1, \dots, w_{30}^1), (0, \dots, 0), \dots, (0, \dots, 0)],$$

$$d_t^{2*} = [(d_{1,t}^{1,2}, \dots, d_{30,t}^{1,2}), (d_{1,t}^{2,2}, \dots, d_{30,t}^{2,2}), \dots, (d_{1,t}^{30,2}, \dots, d_{30,t}^{30,2})], (s = 2)$$

$$e^{2*} = [(0, \dots, 0), (e_1^2, \dots, e_{30}^2), (0, \dots, 0), \dots, (0, \dots, 0)], (s = 2)$$

$$o^{2*} = [(0, \dots, 0), (o_1^2, \dots, o_{30}^2), (0, \dots, 0), \dots, (0, \dots, 0)], (s = 2)$$

where  $WEIE^1$  is the total water use embodied in interregional exports of Region 1 ( $s \neq 1$ );  $(w_1^1, \dots, w_{30}^1)$  in  $W^1$  is the  $1 \times 30$  row vector of direct water withdrawals by sector for Region 1;  $d_t^s$  represents the domestic final consumption of region  $s$ , and  $(d_{1,1}^{1,2}, \dots, d_{30,1}^{1,2})$  in  $d_t^{2*}$  (the transposes of  $d_t^2$ ) is the  $1 \times 30$  row vector representing the consumption ( $t = 1$ ) in Region 2's final demand supplied by Region 1;  $(e_1^2, \dots, e_{30}^2)$  in  $e^{2*}$  is the  $1 \times 30$  row vector representing the exports of Region 2;  $(o_1^2, \dots, o_{30}^2)$  in  $o^{2*}$  is the  $1 \times 30$  row vector representing the other balance item of Region 2; and  $WEIT^{1s}$  is the transfer of embodied water flows from Region 1 to Region  $s$  ( $s \neq 1$ ). Therefore, the direct water withdrawals in Region 1 caused by the final demand in other regions can be identified.

Similarly, the total water use embodied in interregional imports (WEII) of Region 1 can be expressed as

$$WEII^1 = \sum_{s=2}^{30} WEIT^{s1}, \quad (8)$$

where  $WEII^1$  is the total water use embodied in interregional imports of Region 1; and  $WEIT^{s1}$  is the transfer of embodied water flows from Region  $s$  ( $s \neq 1$ ) to Region 1. The  $WEIE$  and  $WEII$  indicators can avoid double counting in measuring bilateral trade balance and associated water uses across regions since the intermediate products may flow through a region's borders multiple times to produce final products (Meng et al., 2013).

The net embodied water use of interregional trade balance (WEIB) can then be determined according to the difference between  $WEII$  and  $WEIE$ . The regions with negative  $WEIB$  are deficit receivers of embodied water from interregional trade, while those with positive  $WEIB$  are identified as surplus receivers. The concerned regional  $WEIB$  can also be served as an indicator to measure the difference between regional DWW and EWU. The net transfers of embodied water flows represent the direct water withdrawals in each region to produce interregional exported goods and services minus the water withdrawals in other regions to produce interregional imported goods and services.

Detailed introduction of the MRIO table and multi-regional input-output modeling method can be referred to Feng et al. (2013) and Meng et al. (2013), respectively.

## 2.2 Data sources and preparation

Water is either withdrawn directly from natural water

bodies or recycled from other stages and reused. In this paper, water withdrawals by Chinese industry are the direct fresh water intakes in the industrial production processes to meet the demand for industrial production, including normal industrial production, auxiliary production, and municipal use in those industries, excluding the recycled and reused water within the systems. Under the current Chinese statistical system, it is impossible to directly obtain the industrial water withdrawal data for the regional economy at the sectoral level in 2007. Fortunately, the China Economic Census Yearbook 2008 (National Bureau of Statistics, 2010) as the only public source, provides such data for the year of 2008 in detail including surface water, underground water, tap water, and other sources of water. We assume that the industrial water use efficiency is relatively stable within a one year time period, and then the 2007 water withdrawal data can be estimated based on the ratio of regional industrial value added between 2007 and 2008 (CSY, 2009). Since the industry by regional economy in the MRIO table covers 22 sectors (Nos. 2–23 in Appendix Table A1), all the water data from 38 industrial sectors in the China Economic Census Yearbook 2008 are accordingly aggregated into these 22 sectors. Particularly, the water withdrawals of the *Water and Gas Production and Supply* sector (S23) only refer to those of the gas production and supply industry, according to the statistical explanation and sectoral classification.

The mainland of China (excluding the Hong Kong Special Administrative Region, the Macau Special Administrative Region, and the Taiwan Province) consists of 31 regions at the provincial level, including 22 provinces, 5 autonomous regions (Inner Mongolia, Guangxi, Xinjiang, Ningxia, and Tibet) and 4 municipalities (Beijing, Shanghai, Tianjin, and Chongqing), which can be further divided into eight areas (i.e., Northeast, Beijing-Tianjin, North, Central, Central Coast, South Coast, Northwest, and Southwest) (Feng et al., 2013; Meng et al., 2013). The coverage of each area associated with corresponding regional information in this study is listed in Appendix Table A2 (Tibet is not included).

## 3 Direct water withdrawals

The estimated total direct water withdrawals (DWWs) by Chinese industry in 2007 amount to  $59.3 \times 10^9$  m<sup>3</sup>, of which surface water, ground water, tap water, and others account for 70.1%, 12.4%, 15.7%, and 1.8% of the national total, respectively. Figure 1 presents the DWW distribution by region. On a regional basis, Jiangsu has the largest DWW of  $12.6 \times 10^9$  m<sup>3</sup>, accounting for 21.3% of the national total, followed by Shanghai of  $6.1 \times 10^9$  m<sup>3</sup>, Guangdong of  $3.7 \times 10^9$  m<sup>3</sup>, Hunan of  $3.3 \times 10^9$  m<sup>3</sup>, Shandong of  $2.8 \times 10^9$  m<sup>3</sup>, Hubei of  $2.8 \times 10^9$  m<sup>3</sup>, Zhejiang of  $2.8 \times 10^9$  m<sup>3</sup>, and Hebei of  $2.4 \times 10^9$  m<sup>3</sup>. The aforementioned 8 regions among all the 30 regions

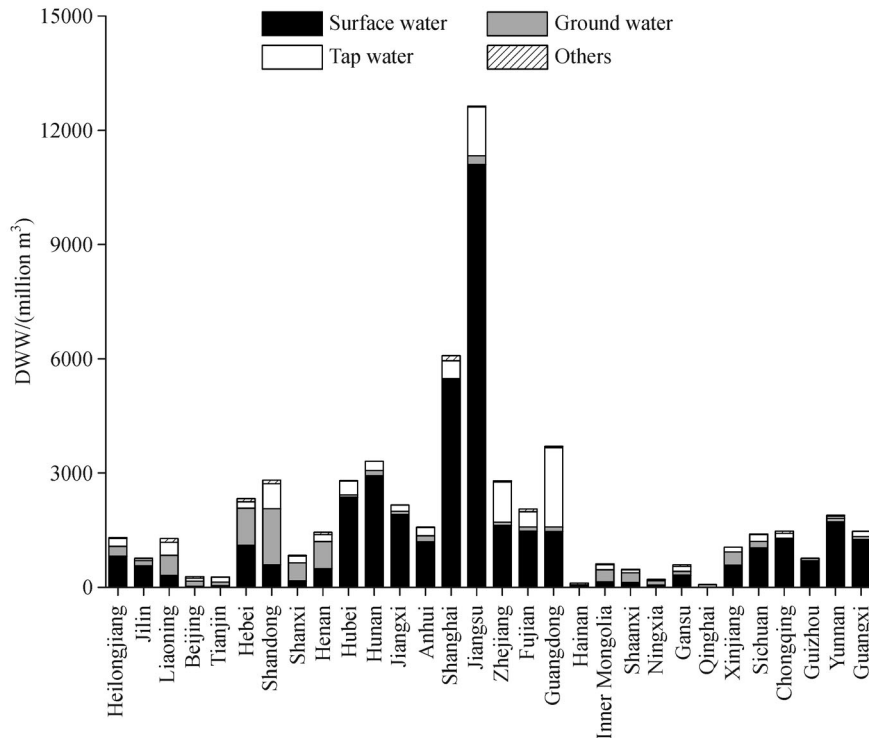


Fig. 1 Direct industrial water withdrawals by region.

contribute to 61.9% of the nationwide total. On the contrary, the industrial water uses of Qinghai, Hainan, Ningxia, Beijing, Tianjin, and Shaanxi are respectively less than 1.0% of the national total. Regarding the regional DWW composition, surface water is the dominating water type in 19 regions, which contributes to 46.7%–90.0% of the regional DWWs. In another 9 regions, ground water is the leading type. Some western and northern regions such as Shandong, Beijing, Shanxi, and Inner Mongolia have a high proportion of ground water in the DWW composition. Tap water also contributes a large proportion to the DWWs of some regions, such as 43.2% for Tianjin and 55.7% for Guangdong. Detailed information for industrial water withdrawals by region is shown in Table A2.

The distribution of the DWWs at the sectoral level is shown in Fig. 2. Sector 22 (*Electric Power, Steam, and Hot Water Production and Supply*) contributes the largest fraction of 55.8% to the national total DWW, amounting to  $33.1 \times 10^9 \text{ m}^3$ , followed by Sectors 12 (*Chemical Industry*) of 9.6%, 14 (*Smelting and Pressing of Ferrous and Nonferrous Metals*) of 6.6%, 10 (*Papermaking and Paper Products, Printing and Record Medium Reproduction, Cultural, Educational and Sports Articles*) of 4.0%, 7 (*Textile*) of 3.6%, and 6 (*Food Production, Food Processing and Tobacco Processing*) of 3.6%. The six sectors mentioned above out of all the 22 industrial sectors are responsible for 83.2% of the national total DWW. As to the water source, tap water comprises the largest share in

most manufacturing sectors. In the extraction sectors such as Sector 2 (*Coal Mining and Dressing*), ground water is an important water source for industrial production. Meanwhile, surface water accounts for 30%–60% of the DWWs in some industrial sectors. This is particularly evident in Sector 22, where surface water accounts for 93.5% of the sectoral DWW. In 2007, 83.0% of China's electricity power is generated by thermal power plants, most of which are coal-fired (CSY, 2008). Water is mainly used as feed water to circulating cooling systems and ash water in coal-fired power plants (Pan et al., 2012). Since coal-fired power generation consumes large volumes of water, the power industry as the major industrial water user has the greatest potential for direct water savings among all the industrial sub-sectors (Gu et al., 2014).

## 4 Embodied water uses

### 4.1 EWUs in final demand

Figure 3 shows the embodied industrial water uses (EWUs) in the final demand of all the 30 regions. The geographic distribution of EWUs has significant regional differences. Jiangsu holds the top EWU volume of  $8.8 \times 10^9 \text{ m}^3$  (14.8% of the national total), followed by Shanghai of  $6.2 \times 10^9 \text{ m}^3$  (10.5%), Guangdong of  $6.1 \times 10^9 \text{ m}^3$  (10.3%), and Zhejiang of  $4.8 \times 10^9 \text{ m}^3$

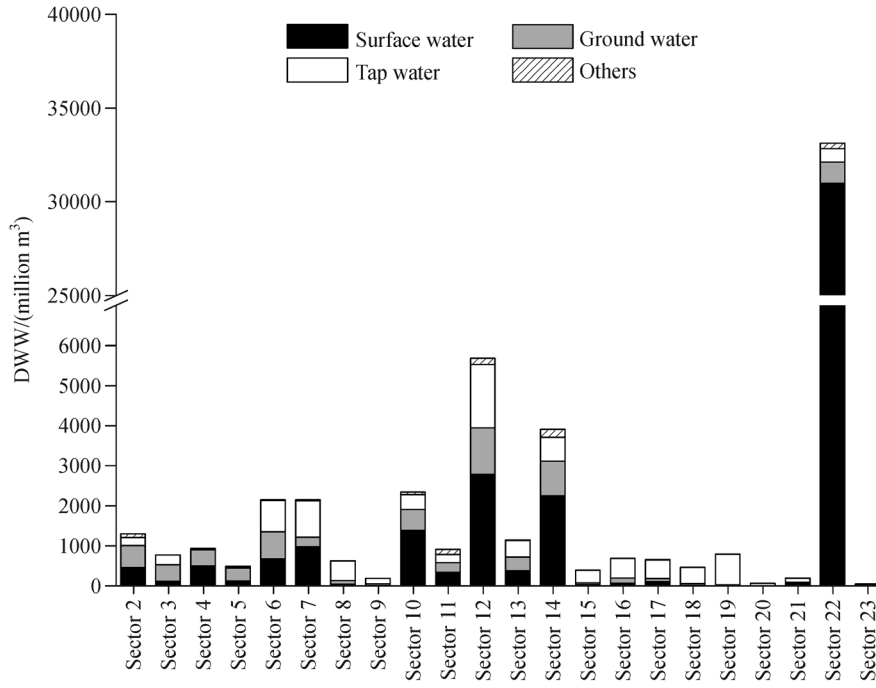


Fig. 2 Direct water withdrawals by industrial sub-sector.

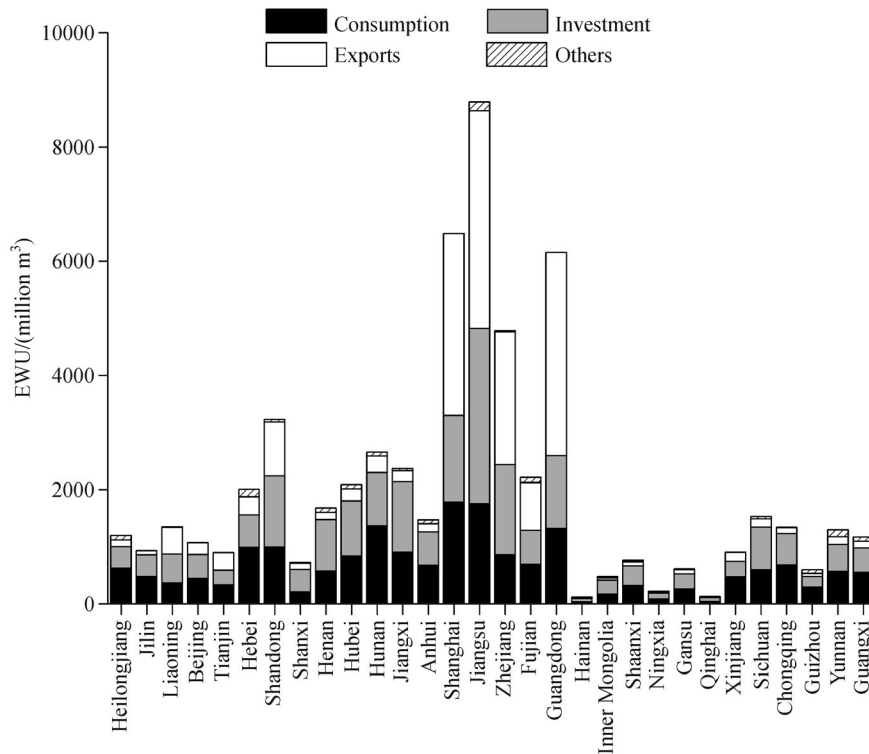


Fig. 3 Industrial water uses embodied in final demand by region.

(8.1%). The picture of regional EWU distribution is quite different from that of regional DWW distribution. The EWUs of 15 regions increase compared to the DWWs,

with the value of EWU/DWW larger than 1. Prominently, the EWUs in Beijing and Tianjin are 3.5 and 3.0 times the value of their DWWs, respectively.

As to the EWU composition in terms of final demand categories, the industrial water uses embodied in consumption, investment, and exports are 33.3%, 34.6%, and 30.6% of the national total, respectively. Investment accounts for 35%–55% of the EWUs in most regions, and is the leading final demand category in 12 regions. Consumption is the leading final demand category in 13 regions, which contributes an average fraction of 39.6% to all the 30 regions' EWUs. Also, the shares of exports are especially high in some eastern coastal regions' EWUs. For instance, 58.0%, 51.1%, 48.6%, 43.3%, and 37.5% of the EWUs respectively in Guangdong, Shanghai, Zhejiang, Jiangsu, and Fujian are attributed to exports. China is a net embodied water exporter (Zhao et al., 2009; Zhang et al., 2011b; Chen and Chen, 2013b), and the eastern coastal regions contribute a major share towards the country's export trade and embodied water exports due to their location advantages and great economic openness (Zhang et al., 2013).

MRIO analysis can not only identify the economic links between regions, but also reveal the relationship between different sectors (Zhang et al., 2013). The EWU of each specific sector is obtained by summing the EWU of the same sector across all of the 30 regions. Displayed in Fig. 4 is the distribution of the EWUs in the final demand by sector. Sector 24 (*Construction*) ranks first in water use embodied in final demand, amounting to  $11.3 \times 10^9 \text{ m}^3$  and accounting for 19.0% of the national total EWU. The rapid development of transportation infrastructure and commercial and residential construction imposes a large amount of embodied water demands to Chinese industry, as con-

struction activities need a great deal of direct and indirect inputs of industrial products (e.g., cement, electricity and metal products) (Chen and Zhang, 2010). Sectors 30 (*Other Service Activities*), 22 (*Electric Power, Steam, and Hot Water Production and Supply*), 16 (*Ordinary Machinery and Equipment for Special Purposes*), 6 (*Food Production, Food Processing and Tobacco Processing*), 12 (*Chemical Industry*), 19 (*Electronic and Telecommunications Equipment*) and 17 (*Transportation Equipment*) are the next seven sectors in rank, contributing 11.4%, 7.5%, 6.6%, 5.8%, 5.4%, 5.2%, and 5.0% to the national total EWU, respectively.

As to the sectoral EWU composition, investment is the dominating final demand category in four extraction sectors (Sectors 2–5), two manufacturing sectors (Sectors 16 and 17), and Sectors 24 and 26. Prominently, investment contributes the share of 96.6% to the EWU of Sector 24. Most of the investment in China is flowed into infrastructure construction and heavy industry such as energy-intensive industrial production for iron and steel, cement, and electrolysis aluminum (CSY, 2008), which results in increasing embodied water uses. For most manufacturing industries such as Sectors 7–15 and 18–21, the shares of exports in the sectoral EWUs are especially high owing to China's exports of textile products, industrial raw materials, and primary machinery and equipment products. Consumption is found to be the leading final demand category for seven sectors such as Sectors 1 (*Agriculture*), 6, 22, and 30 associated with food, electricity, and service consumption in rural and urban households.

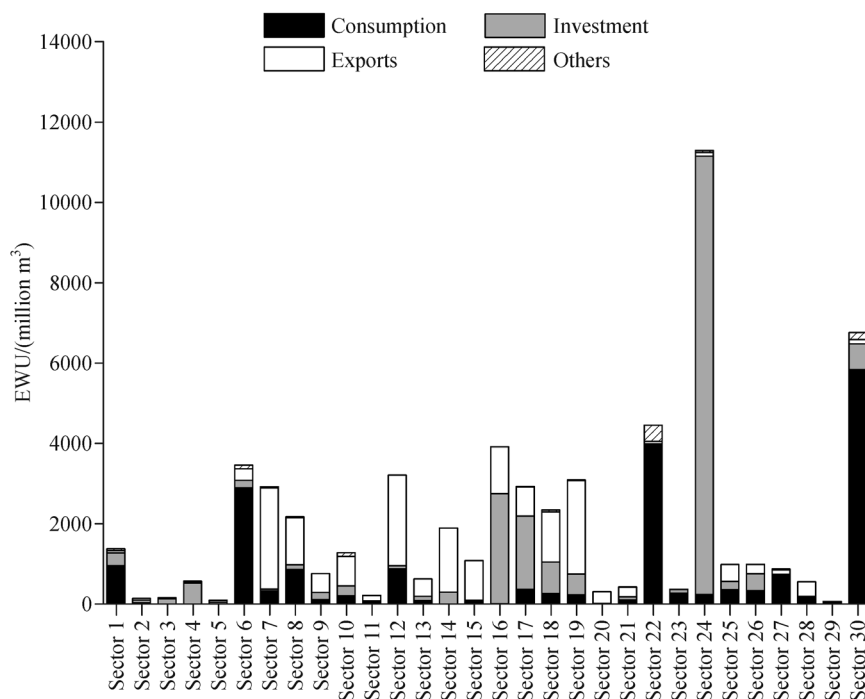


Fig. 4 Industrial water uses embodied in final demand by sector.

#### 4.2 EWUs in interregional trade

Listed in Table 2 is the distribution of industrial water uses embodied in interregional imports (WEII) and exports (WEIE) by region. The total WEII or WEIE sums up to  $23.9 \times 10^9 \text{ m}^3$ , in magnitude up to 40.3% of the total DWW by Chinese industry. Guangdong and Zhejiang are the leading interregional embodied water-import regions, accounting for 14.2% and 11.7% of the total WEII, respectively, followed by Shanghai (8.1%), Jiangsu (6.2%), Shandong (4.9%), Hebei (4.6%), and Henan (4.5%). The aforementioned 7 regions are responsible for

54.1% of the total WEII. The largest interregional embodied water-export region is Jiangsu with 22.3% of the total WEIE, followed by Shanghai (7.6%), Hebei (6.0%), Hunan (5.1%), Hubei (4.9%), Yunnan (4.3%), and Guangdong (4.1%). The aforementioned 7 regions are responsible for 54.3% of the total WEIE.

The 30 regions can be further categorized into two groups according to the WEIB indicator: 15 regions with negative WEIB are deficit receivers of embodied water, while the other 15 regions with positive WEIB are surplus receivers (Also see Fig. 6). In the deficit group, Jiangsu is the largest deficit receiver, receiving  $3,846 \times 10^6 \text{ m}^3$  of net

**Table 2** Distribution of the EWUs in interregional trade by region

Region	WEII		WEIE		WEIB
	( $\times 10^6 \text{ m}^3$ )	Fraction/%	( $\times 10^6 \text{ m}^3$ )	Fraction/%	( $\times 10^6 \text{ m}^3$ )
Heilongjiang	588	2.5	708	3.0	-120
Jilin	713	3.0	556	2.3	157
Liaoning	646	2.7	587	2.5	59
Beijing	881	3.7	116	0.5	765
Tianjin	761	3.2	167	0.7	594
Hebei	1,094	4.6	1,428	6.0	-333
Shandong	1,180	4.9	779	3.3	400
Shanxi	328	1.4	455	1.9	-127
Henan	1,079	4.5	858	3.6	221
Hubei	441	1.8	1,165	4.9	-724
Hunan	570	2.4	1,231	5.1	-661
Jiangxi	778	3.3	587	2.5	191
Anhui	682	2.9	807	3.4	-125
Shanghai	1,937	8.1	1,809	7.6	128
Jiangsu	1,474	6.2	5,321	22.3	-3,846
Zhejiang	2,788	11.7	814	3.4	1,974
Fujian	613	2.6	466	1.9	147
Guangdong	3,384	14.2	972	4.1	2,412
Hainan	40	0.2	43	0.2	-3
Inner Mongolia	313	1.3	461	1.9	-148
Shaanxi	617	2.6	338	1.4	278
Ningxia	130	0.5	131	0.5	-1
Gansu	290	1.2	283	1.2	6
Qinghai	94	0.4	53	0.2	41
Xinjiang	400	1.7	558	2.3	-159
Sichuan	542	2.3	424	1.8	118
Chongqing	429	1.8	577	2.4	-148
Guizhou	282	1.2	459	1.9	-177
Yunnan	426	1.8	1,034	4.3	-608
Guangxi	395	1.7	710	3.0	-315
Total	23,896	100.0	23,896	100.0	0

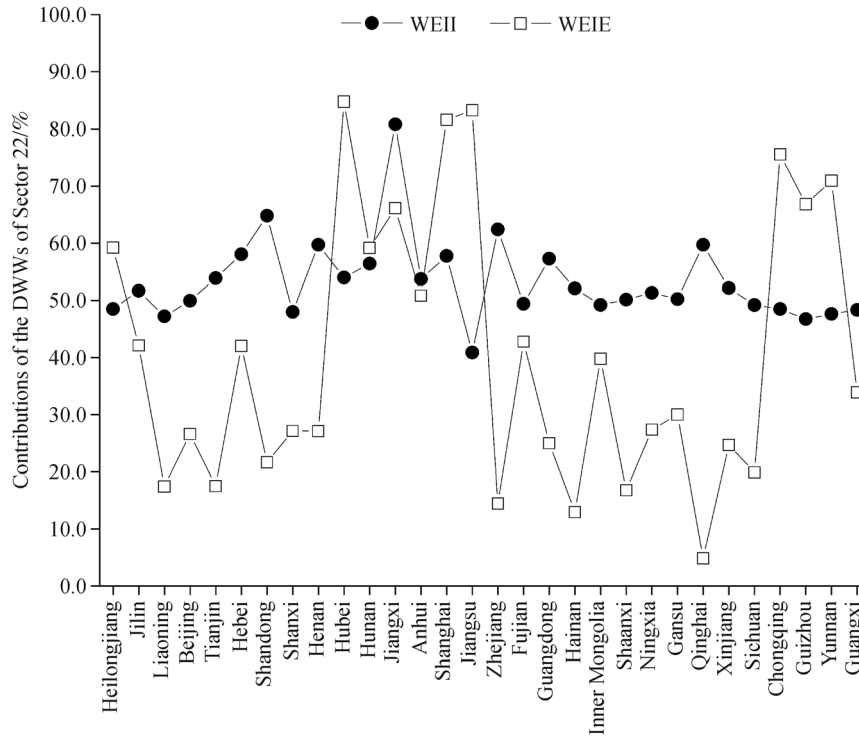


Fig. 5 Contributions of the DWWs of Sector 22 to regional WEIs and WEIEs.

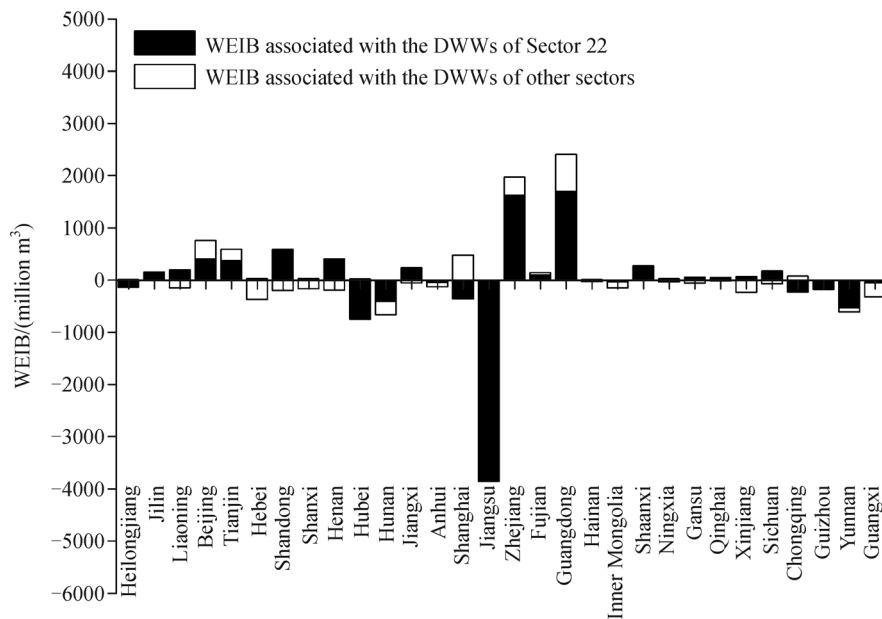


Fig. 6 Distribution of the WEIB by region.

embodied water outflow, followed by Hubei, Hunan, Yunnan, Hebei, and Guangxi. In the surplus group, Guangdong is the leading region with the net embodied water inflow of  $2,412 \times 10^6 \text{ m}^3$ . Zhejiang, Beijing, Tianjin,

and Shandong are the next four largest surplus receivers. The main net interregional importers of embodied water are the developed coastal regions which have an above average GDP per capita and produce the majority of

Chinese exports. For instance, 50.9%, 39.1%, 36.8%, and 35.7% of the WEII in Guangdong, Zhejiang, Jiangsu, and Shanghai can be attributed to the demands of these regions' exports.

For the WEIB compositions of Jiangsu (the biggest deficit receiver of embodied water), the main water-trade regions are Zhejiang (26.7% of Jiangsu's net embodied water outflow), Shanghai (11.1%), Guangdong (4.0%), Henan (5.4%), Hebei (5.0%), Jiangxi (4.8%), Beijing (4.3%), and Tianjin (3.8%), which concentrate in short-distance regions, economically developed regions, and regions with both short distance and developed economy. For instance, Zhejiang and Shanghai are adjacent to Jiangsu, which also are economically developed regions. As to the WEIB composition of Guangdong (the biggest surplus receiver), the main water-saving helpers are Yunnan (19.4% of Guangdong's net embodied water inflow), Jiangsu (16.7%), Hunan (11.0%), Shanghai (7.9%), Chongqing (6.8%), Guangxi (6.7%), Hubei (4.0%), and Guizhou (4.0%). Yunnan, Hunan, Guangxi, Chongqing, and Guizhou located in the southern part of China are the short-distance regions for Guangdong.

The eight-area classification can reflect the similarity of economic structure and spatial location of different regions in China (Feng et al., 2013; Meng et al., 2013), with corresponding regional information listed in Appendix Table A2. As such, a regional aggregation is made to present the embodied water transfers among eight areas through interregional trade. Table 3 shows the results of the EWU in interregional trade among eight areas.

The Central Coast and Central areas are the leading embodied water-exporters, accounting for 33.2% and 21.4% of the national total WEIE, respectively. Meanwhile, the Central Coast, South Coast and Central areas are the main water importers, accounting for 25.9%, 16.9% and 16.2% of the national total WEII, respectively. Furthermore, the Central Coast, Central and Southwest areas as the main net exporters of embodied water have the water deficits of  $(1,744, 1,224$  and  $1,129) \times 10^6$  m<sup>3</sup>,

respectively. The South Coast and Beijing-Tianjin area are the top two net importers, with the water surpluses of  $(2,556$  and  $1,360) \times 10^6$  m<sup>3</sup>, respectively. The Southwest, Central Coast, and Central areas respectively contribute to 37.6%, 28.7%, and 25.0% of the total net embodied water inflows in the South Coast area, which implicates that the water-abundant South Coast area imports a large number of water-intensive industrial products from other areas through domestic trade.

#### 4.3 Embodied water transfers associated with the DWWs of Sector 22

Energy production such as electricity often requires a large amount of water (Varbanov, 2014). In China, more than half of the direct DWWs can be attributed to Sector 22 (*Electric Power, Steam and Hot Water Production and Supply*). Meanwhile, the DWWs of this sector embodied in interregional trade contribute to 55.5% of the national total WEII/WEIE. Figure 5 shows the contributions of the DWWs of Sector 22 embodied in interregional trade to regional WEIIs and WEIEs. By considering the intra-regional and interregional electricity consumption for industrial production, large amounts of embodied water inflows and outflows can be identified in interregional trade associated with the DWWs of Sector 22. The embodied water inflows associated with the DWWs of Sector 22 contribute to about 50%–70% of the regional WEIIs and particularly 80.9% in Jiangxi. By contrast, embodied water outflows associated with the DWWs of Sector 22 contribute 84.8%, 83.4%, 81.7%, 75.6%, 71.0%, 66.9%, and 66.2% to the total WEIEs in Hubei, Shanghai, Jiangsu, Chongqing, Yunnan, Guizhou, and Jiangxi, respectively. Figure 6 further presents the distribution of regional WEIB associated with the DWWs of Sector 22 and the other 29 sectors. The top 5 deficit receivers for the WEIB associated with the DWWs of Sector 22 are Jiangsu ( $3,831 \times 10^6$  m<sup>3</sup>, 99.6% of the regional total WEIB), Hubei ( $750 \times 10^6$  m<sup>3</sup>), Yunnan ( $531 \times 10^6$  m<sup>3</sup>),

**Table 3** The EWUs in interregional trade among eight areas

		Water inflows/( $\times 10^6$ m <sup>3</sup> )								Total WEIE
		Northeast	Beijing- Tianjin	North	Central	Central Coast	South Coast	Northwest	Southwest	(million m <sup>3</sup> )
Water outflows	Northeast	596	162	313	203	277	113	108	79	1,851
	Beijing-Tianjin	39	17	33	42	70	26	32	24	283
	North	251	261	142	310	681	215	198	149	2,207
	Central	208	266	550	807	1,605	941	318	407	5,102
	Central Coast	558	525	787	1,467	2,204	1,132	699	572	7,943
	South Coast	62	83	76	303	399	191	114	253	1,481
	Northwest	161	181	197	243	487	206	205	145	1,824
	Southwest	72	148	176	503	477	1,214	168	445	3,203
Total WEII	1,947	1,643	2,274	3,879	6,199	4,037	1,843	2,074	23,896	

Hunan ( $407 \times 10^6 \text{ m}^3$ ), and Shanghai ( $357 \times 10^6 \text{ m}^3$ ), and the top 5 net surplus receivers are Guangdong ( $1,698 \times 10^6 \text{ m}^3$ , 70.4% of the regional total WEIB), Zhejiang ( $1,624 \times 10^6 \text{ m}^3$ , 82.3% of the regional total), Shandong ( $596 \times 10^6 \text{ m}^3$ ), Henan ( $412 \times 10^6 \text{ m}^3$ ), and Beijing ( $410 \times 10^6 \text{ m}^3$ ).

Considering the significant embodied water transfers in interregional trade of industrial products and the dominant role of coal in the electricity mix of China, the interregional trade coordination associated with the water issues are becoming increasingly important for the regional distribution of the power industry. China's energy resources are mainly located in the central and western regions which provide coal and other energy resources to support the economic development of eastern coast regions (Lindner et al., 2013). For instance, the geographical inverse distribution of coal production and consumption leads to the large-scale, long-distance coal transportation from north to south and west to east in recent decades. Currently, thermal power in the central and western regions has been planned and constructed to realize energy local conversion, and to transmit power directly instead of coal transportation (Meng et al., 2011). However, in North and West China, water is scarcer and ecological systems are more vulnerable than in other regions. Along with the industrialization processes in northern and western regions, the imbalance between water availability and industrial water demands tends to intensify in these regions characterized by their water-deficit endowments. Therefore, water resources condition should be the necessary prerequisite to the layout of Chinese power industry considering the water impact of interregional trade of industrial products.

## 5 Concluding remarks

China is struggling to harmonize its industrial development and water supply, given that its water resources on which the industrial production relies have been heavily exploited or even over-exploited. By using multi-regional input-output modeling, the results of industrial water uses at the regional and sectoral levels in this study reveal the causal relationship between the direct water withdrawals by Chinese industry and demand-driven embodied industrial water uses for final demand and interregional trade.

The main conclusions are as follows,

1) The estimated total water withdrawals (DWW) by Chinese industry amount to  $59.3 \times 10^9 \text{ m}^3$  in 2007, of which surface water, ground water, tap water, and others account for 70.1%, 12.4%, 15.7%, and 1.8%, respectively. Eight regions among all of the 30 regions contribute to 61.9% of the national total DWW. Six sectors out of all the 22 industrial sub-sectors are responsible for 83.2% of the total DWW, among which *Electric Power, Steam, and Hot Water Production and Supply* contributes the largest share

of 55.8%.

2) The geographic distribution of embodied industrial water uses (EWUs) has significant regional differences, and the picture of regional EWU distribution is quite different from that of regional DWW distribution. Prominently, the EWUs in Beijing and Tianjin are 3.5 and 3.0 times the value of their DWWs, respectively. China's industrial water uses embodied in investment, consumption, and exports are 34.6%, 33.3%, and 30.6% of the national total, respectively. As to the regional EWU composition, investment is the leading final demand category in 12 regions, and consumption in 13 regions. Also, shares of water uses embodied in exports are especially high in five eastern coastal regions (i.e., Guangdong, Shanghai, Zhejiang, Jiangsu, and Fujian). The *Construction* sector has the largest EWU in final demand, accounting for 19.0% of the national total, of which investment contributes the share of 96.6%.

3) The total WEII or WEIE is equivalent to 40.3% of the total water withdrawals by Chinese industry. Water surpluses are obtained by 15 regions when deficits are obtained by the other 15 regions. Jiangsu is shown as the biggest interregional exporter and deficit receiver of embodied water, in contrast to Guangdong as the biggest interregional importer and surplus receiver. The Central Coast, Central, and Southwest areas are the main net exporters of embodied water, and the South Coast and Beijing-Tianjin area are the top two net importers. In particular, 55.5% of the national total WEII/WEIE can be attributed to the DWWs of *Electric Power, Steam, and Hot Water Production and Supply* embodied in interregional trade.

Investment-driven economic development in China has generated huge water withdrawals, especially in the industrial sector. Water requirements for industrial production compete with those for other purposes such as domestic consumption, agriculture, and the ecosystem. Meanwhile, the water shortage can be exacerbated by serious industrial pollution. Without implementing effective water-saving measures and regulations, the water demands in China could dramatically increase along with the industrial development and probably exceed regional water supply capacities, which will bring substantial risk to the sustainable development of China's energy, economy, and environment (Pan et al., 2012).

Technological development can decrease industrial water demands directly through improving water use efficiency and increasing the recycle and reuse amount of wastewater since industrial water use in China is still far from efficient (Cheng and Hu, 2011). Meanwhile, the adjustments to industrial structure to limit the proportion of water-intensive industries are important solutions to reduce water demands from the industrial sector in water-deficient regions. Water stress can also be relieved via the influx of virtual water through interregional trade by importing

industrial products that use a large amount of water to produce and exporting those with low water demands due to the spatial mismatch between the distribution of water resources and those of population and industrial activities. For instance, Northern and Western regions of China can relieve water scarcity and alleviate pressure on local water resources by importing virtual water from Eastern and Southern regions with comparatively abundant water resources; conversely the water resource shortages in Northern and Western regions will be more challenging and the situation can be aggravated. Subsequently, international and interregional trade policies and regulations as the promising strategies play a significant role in the coordination of regional water issues. As water is and will continue to be one of the most critical natural

resources for the development of Chinese industry, considering both direct and embodied water uses therefore can help form effective water management policies, especially for an integration of energy issues in water planning in China.

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## Appendix

See Tables A1 and A2.

**Table A1** Sector information for input-output embodiment analysis

Code	Sector category
S1	<i>Farming, Forestry, Animal Husbandry, and Fishery (Agriculture)</i>
S2	<i>Coal Mining and Dressing</i>
S3	<i>Petroleum and Natural Gas Extraction</i>
S4	<i>Ferrous and Nonferrous Metals Mining and Dressing</i>
S5	<i>Nonmetal and Other Minerals Mining and Dressing</i>
S6	<i>Food Production, Food Processing and Tobacco Processing</i>
S7	<i>Textile</i>
S8	<i>Garments and Other Fiber Products, Leather, Furs, Down and Related Products</i>
S9	<i>Timber Processing, Bamboo, Cane, Palm &amp; Straw Products, Furniture Manufacturing</i>
S10	<i>Papermaking and Paper Products, Printing and Record Medium Reproduction, Cultural, Educational and Sports Articles</i>
S11	<i>Petroleum Processing, Coking, and Nuclear Fuel Processing</i>
S12	<i>Chemical Industry</i>
S13	<i>Nonmetal Mineral Products</i>
S14	<i>Smelting and Pressing of Ferrous and Nonferrous Metals</i>
S15	<i>Metal Products</i>
S16	<i>Ordinary Machinery and Equipment for Special Purposes</i>
S17	<i>Transportation Equipment</i>
S18	<i>Electric Equipment and Machinery</i>
S19	<i>Electronic and Telecommunications Equipment</i>
S20	<i>Instruments, Meters Cultural and Office Machinery</i>
S21	<i>Other Industrial Activities</i>
S22	<i>Electric Power, Steam and Hot Water Production and Supply</i>
S23	<i>Water and Gas Production and Supply</i>
S24	<i>Construction</i>
S25	<i>Transport and Storage Services</i>
S26	<i>Wholesale and Retail Trade</i>
S27	<i>Hotels and Catering Service</i>
S28	<i>Leasing and Business Services</i>
S29	<i>Research and Experimental Development</i>
S30	<i>Other Service Activities</i>

**Table A2** Direct water withdrawals of the industrial sector by region in 2007 ( $\times 10^6$  m<sup>3</sup>)

Regional information	Surface water	Ground water	Tap water	Others	Total	Fraction/%
<b>1. Northeast</b>	1,771	917	604	135	3,427	5.7
Heilongjiang (R1)	844	254	206	31	1,335	2.2
Jilin (R2)	586	137	58	7	788	1.3
Liaoning (R3)	340	526	341	98	1,304	2.2
<b>2. Beijing-Tianjin</b>	121	226	204	59	610	1.0
Beijing (R4)	53	134	74	49	310	0.5
Tianjin (R5)	69	92	130	10	300	0.5
<b>3. North</b>	1,748	2,442	828	178	5,196	8.8
Hebei (R6)	1,132	971	168	85	2,355	4.0
Shandong (R7)	616	1,471	660	93	2,840	4.8
<b>4. Central</b>	9,205	1,632	1,337	121	12,296	20.8
Shanxi (R8)	192	478	176	21	868	1.5
Henan (R9)	517	714	177	63	1,471	2.5
Hubei (R10)	2,390	60	367	11	2,828	4.8
Hunan (R11)	2,944	139	242	4	3,329	5.6
Jiangxi (R12)	1,941	82	162	6	2,191	3.7
Anhui (R13)	1,221	158	213	17	1,609	2.7
<b>5. Central Coast</b>	18,251	317	2,811	186	21,565	36.4
Shanghai (R14)	5,488	5	474	132	6,100	10.3
Jiangsu (R15)	11,111	227	1,278	27	12,644	21.3
Zhejiang (R16)	1,652	85	1,059	26	2,822	4.8
<b>6. South Coast</b>	3,048	249	2,488	153	5,938	10.0
Fujian (R17)	1,498	115	397	73	2,082	3.5
Guangdong (R18)	1,487	122	2,071	40	3,719	6.3
Hainan (R19)	64	12	21	41	137	0.2
<b>7. Northwest</b>	1,384	1,201	496	99	3,179	5.3
Inner Mongolia (R20)	171	317	129	23	639	1.1
Shaanxi (R21)	156	246	83	15	500	0.8
Ningxia (R22)	82	118	22	14	235	0.4
Gansu (R23)	344	104	125	46	619	1.0
Qinghai (R24)	25	68	11	0	104	0.2
Xinjiang (R25)	606	349	127	0	1,082	1.8
<b>8. Southwest</b>	6,090	385	545	118	7,139	11.9
Sichuan (R26)	1,058	175	178	15	1,426	2.4
Chongqing (R27)	1,305	12	126	61	1,503	2.5
Guizhou (R28)	700	28	51	11	789	1.3
Yunnan (R29)	1,744	96	55	26	1,920	3.2
Guangxi (R30)	1,283	75	136	6	1,501	2.5
<b>Total</b>	41,618	7,369	9,312	1,050	59,349	100.0

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