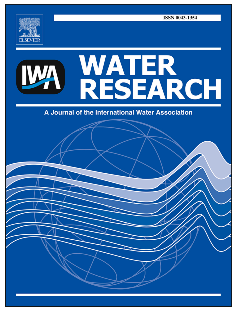

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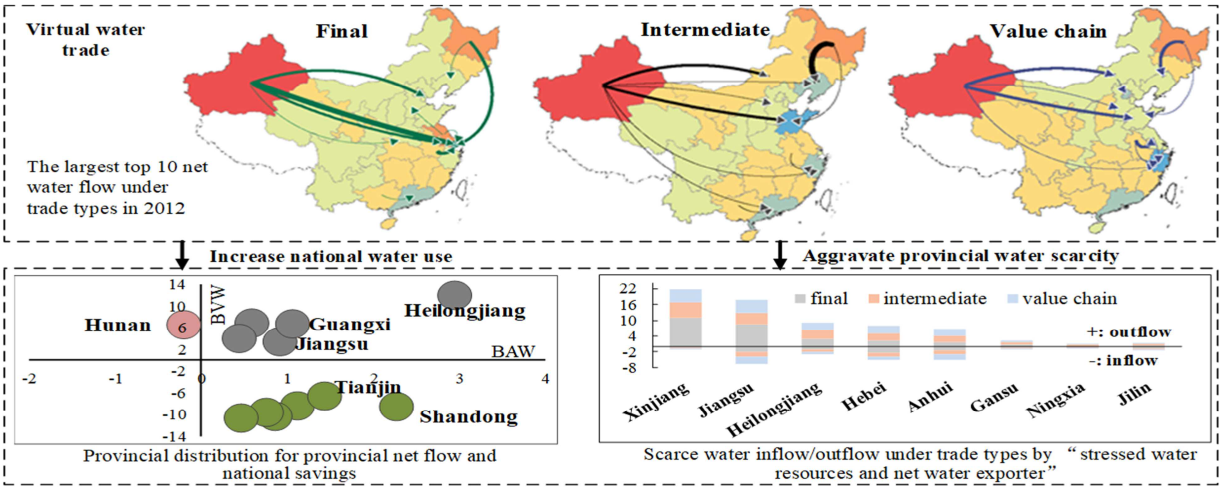

Graphic abstract

Can virtual water trade save water resources?

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Abstract

At times, certain areas of China suffering from water shortages. While China's government is spurring innovation and infrastructure to help head off such problems, it may be that some water conservation could help as well. It is well-known that water is embodied in traded goods—so called "virtual water trade" (VWT). In China, it seems that many water-poor areas are perversely engaged in VWT. Further, China is engaging in the global trend of fragmentation in production, even as an interregional phenomenon. Perhaps something could be learned about conserving or reducing VWT, if we knew where and how it is practiced. Given some proximate causes, perhaps viable policies could be formulated. To this end, we employ China's multiregional input-output tables straddling two periods to trace the trade of a given region's three types of goods: local final goods, local intermediate goods, and goods that shipped to other regions and countries. We find that goods traded interregionally in China in 2012 embodied 30.4% of all water used nationwide. Nationwide, water use increased substantially over 2007-2012 due to greater shipment volumes of water-intensive products. In fact, as suspected, the rise in value chain-related trade became a major contributing factor. Coastal areas tended to be net receivers of VWT from interior provinces, although reasons differed, e.g. Shanghai received more to fulfill final demand (67.8% of net inflow) and Zhejiang for value-chain related trade (40.2% of net inflow). In sum, the variety of our findings reveals an urgent need to consider trade types and water scarcity when developing water resource allocation and conservation policies.

Keywords: multiregional input-output analysis; value chain; virtual water trade; national water savings; embodied water

Nomenclature	
MRIO	multiregional input-output
VWT	virtual water trade
TF	trade of final goods
TI	trade of intermediate goods for the final stage of production
TVC	trade in value chain/value chain-related trade
BVW	balance of virtual water embodied in trade
VW	virtual water embodied in trade
WAI	virtual water uses avoided by imports
BAW	balance of avoided water uses
BVWs	balance of virtual scarce water embodied in trade
BAWs	balance of avoided scarce water use
$\mathbf{T}^{sr}$	total outflows from region s to r
$\mathbf{Y}^{sr}$	final demand of region r for products from region *s*
$\mathbf{Z}^{sr}$	intermediate use of products in region r from region *s*
$\mathbf{A}^{sr}$	input coefficient matrix for region *r*'s intermediate use that are produced in region *s*
$\mathbf{B}^{sr}$	Leontief inverse matrix
$\mathbf{X}^{t}$	exports to foreign countries from region *t*
$\mathbf{T}_{\mathrm{d}}^{sr}$	domestic value chain-related trade in region r from region *s*
$\mathbf{T}_{\mathrm{g}}^{sr}$	global value chain-related trade in region r from region *s*
s, *r*, *t*	region *s, r, t*
m^3/yr	m^3/year

1. Introduction

Due to the nature of watersheds, China's water resources are unevenly distributed; About 66% of water resources are located in South China (Ministry of Water Resources of the People's Republic of China, 2015). It is perhaps no wonder that many parts of China are suffering from severe water shortages as a result since it uses about 14% of the world's fresh water (The World Bank, 2014). Moreover, the nation's demand for water is growing, exacerbating water scarcity issues (Distefano and Kelly, 2017; Sowers et al., 2010). Clearly, better management measures are needed to ensure a more sustainable China.

So, how can China make water resources more sustainable? Technological innovation is one approach toward making more efficient use of water, And infrastructure such as the "South to North Water Diversion" should mitigate some water scarcity (Zhang et al., 2011). An alternative way to generate sustainable water use practices is to consider virtual trade of water. Oki and Kanae (2004) coined the term "virtual water trade" (VWT) to discuss water that is used as an input into the production of goods and services that are traded.

Water resources used in international trade more than doubled from 1986 to 2007 (Dalin et al., 2012). Chapagain et al. (2006) identified global water savings in international agricultural products trade. Chouchane et al. (2018); Duarte et al. (2019) identified some proximate causes of VWT; Lenzen et al. (2013) examine water scarcity. All of the above plus Hoekstra and Hung (2005) addressed effective water management policies. In summary, VWT is influenced by many factors--economy, population size, cultivated area, water endowments, etc. But it does not always benefit water-scarce regions (Kumar and Singh, 2005).

The scale and structure of VWT has received some attention at the municipal level in China, e.g. Beijing (Han et al., 2015; Zhang et al., 2011); provincial and multi-provincial level, e.g., Hebei (Liu et al., 2018; Liu et al., 2017b), Liaoning (Dong et al., 2013) and 30 provinces (Chen et al., 2017; Dong et al., 2014; Zhang and Anadon, 2014; Zhao et al., 2015); watershed, e.g., Haihe River Basin (White et al., 2015; Zhao et al., 2010); and eight hydro-economic regions (Guan and Hubacek, 2007). Zhao et al. (2019) note that VWT runs from China's water-scarce north to its south (from less-developed to more-developed areas); so VWT runs against water availability. So Feng et al. (2014) suggest incorporating a measure of water scarcity into subnational VWT analysis. Nonetheless, Zhao et al. (2019) note that the relative productivity of land between agriculture and non-agriculture uses is a better indicator than is water availability.

We note from a multi-provincial table of China for 2007 that 31% of interregional trade is due to the exchange of final goods and 69% is due to intermediate inputs, where the latter relates to value chains. This suggests that the fragmentation of production is strong within China. That is, there is an abundance of industrial activity in China that focuses on producing goods across multiple borders, from the production of individual unfinished parts to assemblage of final products (Athukorala and Yamashita, 2007). The fragmentation of production is increasing interregionally in China as well as internationally (Meng et al., 2014).

Due to the global financial crisis (2008-2009), international trade's share of total global production declined by three percentage points from 2007 to 2010 according to the 30 multi-provincial table of China. Meanwhile, the value of final goods and intermediate input trade increased substantially, by 67% and 22%, respectively. And trade increased further through 2012, by another 28%. This implies that trade in intermediate inputs is accelerating and that provinces are intensifying their specialization of production. Meanwhile this means that firms are getting more specific in targeting locations from which they buy intermediate products to support their domestic supply chains. These trade trends in intermediate inputs affect the locations in which water is used. In this vein, it is necessary for us to analyze how production fragmentation shapes trade types and, thereby, water use across provinces and nations. The effects of production fragmentation on VWT have been largely ignored.

We decompose interregional trade to learn how the fragmentation of domestic production is affecting the apparent availability of provincial and national water resources. To date, literature on the effects of production fragmentation have mostly focused on the virtual trade of carbon and particularly at an international scale, testing the pollution haven hypothesis (Zhang et al., 2017). A few studies point out that China's west incurs higher environmental costs but provides lower value-added gains via its position in the domestic supply chains as well as industry mix compared to other regions (Liu et al., 2015; Meng et al., 2013).

Herein we evaluate VWT from 2007 to 2012. This enables an examination into how the economic crisis of 2008−2009 has altered interregional trade and its impact on the environment. Moreover, our distinction between the trade for goods in final versus intermediate uses is useful in testing the importance of VWT, e.g., environmental policy concentrating on the responsibility of water usage. Our approach helps identify the responsibility for virtual water use by incorporating multiple stakeholders. Another policy is related to alleviating water scarcity, Zhao et al. (2015) and Feng et al. (2014) discuss the necessity of improving the supply-side perspective of efficiency and considering water scarcity into policy framework. Instead, our analysis yields insight into the full supply-chain context. Further, for national water use, the effects (savings or losses) of existing VWT and production fragmentation is unclear. The broader vision of VWT impacts on water resources in China, which our approach yields, can be important in this vein.

To depict the production fragmentation, we distinguish different purposes of the inflows of virtual water based on production stages: final consumption, processing for final consumption, and processing for re-export. Accordingly, three different trade types emerge. The first two focus upon the trade of final goods and of intermediate goods in a final stage of production. The goods traded interregionally are "used" by receivers of inflows. The third trade type is associated with the production of intermediate goods that are shipped to be used as inputs for further production in another region or nation. We call this "value chain-related trade". This type of trade determines whether a region or a nation receives intermediate products for processing and ships the intermediates for processing or final consumption to a different region or country (Borin and Mancini, 2015; Dean and Lovely, 2010; Wang et al., 2017b).

In prior studies, various methods have been employed. Some use a bottom-up, crop-by-crop accounting framework to trace VWT in agriculture products (Dalin et al., 2014; Ma et al., 2006; Zeng et al., 2012). Others use environmental extended input-output (IO) analysis of various spatial resolutions, e.g. single region or multiregional (Deng et al., 2016; Duarte et al., 2002; Lenzen, 2009; Liu et al., 2018; Llop, 2013). The IO method expands the scope beyond agriculture products by involving industrial products and services. This enables a study of VWT by considering water-intensive products, like electric power, chemical manufacturing, paper products and food processing.

We employ a multiregional input-output (MRIO) approach to evaluate VWT along with water savings in interprovincial trade over two periods, 2007-2010 and 2010-2012. We focus on the role of three different trade types: (i) the trade of final goods (TF), (ii) the trade of intermediate goods for the final stage of production (TI) and (iii) trade in value chain (TVC) (*Appendix S1 Equation (*2)). Our analyses focuses on freshwater *use* (quantify of water distributed to users, part of which returns to the environment) instead of freshwater *consumption* (includes only water lost via evaporation, absorption by products, and/or any other losses). The former seems to better represent the broader impact of humans on local water resources and ecosystems and data accuracy, so we employed freshwater use to assess the resource losses in the goods production in specific provinces.

Researchers have considered how changes in the balance of VWT affects provincial water use given provincial water scarcity (Feng et al., 2014; White et al., 2015). The water stress index is a key indicator of water scarcity and is defined as the ratio of water demanded to total local water resources available (Liu et al., 2017a; Pfister et al., 2009). Such studies enable an understanding of the causes of water scarcity and of the region suffering from them. Instead, we distinguish how water scarcity varies across provinces to reveal its influence on VWT under different trade types. Thus, our study identifies the impacts of both trade types and water scarcity and suggests how to improve water management policies.

2. Materials and Methods

2.1 Multiregional input-output analysis (MRIO)

Provincial virtual water trade under different trade types is calculated by using a MRIO analysis. In this framework, the total commodity outflows from region *s* to *r* (*s*, *r*=1,…, *G*), can be written as, $\mathbf{T}^{sr}=\mathbf{Y}^{sr}+\mathbf{Z}^{sr}$, where $\mathbf{Y}^{sr}$ is region *r*'s final demand for products from region *s*, $\mathbf{Z}^{sr}$ is region *r*'s intermediate use of products from region *s*. Like Zhang et al. (2017), we classify trade between each pair of provinces *s* and *r*, $\mathbf{T}^{sr}$, into three types as follows:

$$\mathbf{T}^{sr}=\underbrace{\mathbf{Y}^{sr}}_{TF^{sr}}+\underbrace{\mathbf{A}^{sr}\mathbf{B}^{rr}\mathbf{Y}^{rr}}_{TI^{sr}}+\underbrace{\underbrace{\mathbf{A}^{sr}\mathbf{B}^{rr}\sum_{t\neq r}^{G}\mathbf{A}^{rt}\mathbf{B}^{tr}\mathbf{Y}^{rr}+\mathbf{A}^{sr}\sum_{t\neq r}^{G}\mathbf{B}^{rt}\mathbf{Y}^{tr}+\mathbf{A}^{sr}\sum_{t}^{G}\mathbf{B}^{rt}\sum_{u\neq r}^{G}\mathbf{Y}^{tu}}_{T_d^{sr}}+\underbrace{\mathbf{A}^{sr}\sum_{t}^{G}\mathbf{B}^{rt}\mathbf{X}^{t}}_{T_g^{sr}}}_{TVC^{sr}} \quad (1)$$

where $\mathbf{B}^{rr}=(\mathbf{I}\text{-}\mathbf{A}^{rr})^{-1}$, $\mathbf{A}^{sr}$ is the input coefficient matrix for region *r*'s intermediate uses that are produced in region *s*. $\mathbf{B}^{tr}$ is the Leontief inverse matrix, representing the gross output of region *t* required to produce a unit increase in the final demand of region *r*. $\mathbf{X}^{t}$ is the array of exports to foreign countries from region *t*. TF^{sr} defines the trade in final products, in which the trade partner region directly uses the shipped products located in the shipping region. TI^{sr} defines the trade in intermediate products for the final stage of production, in which those products are further processed by a trade partner before that trade partner uses them as a final good. TVC^{sr} defines value-chain-related trade, both domestic value chain-related trade (T_d^{sr}) and global value chain-related trade (T_g^{sr}). For TVC^{sr}, traded products cross provincial borders more than once. The products may be finally absorbed by a province (T_d^{sr}) or further processed to become exported (T_g^{sr}). Then, based on the balance of gross output of a province, total outputs can be decomposed into five parts: use in local economic activities, export to foreign countries, and outflow to other regions as a final product, outflow for use in the final stage of production, and outflow as value chain-related trade. Similarly, each province's water uses as embodied in these five output components can be derived. This is done my pre-multiplying output by a multiregional vector of sectoral water-use intensities (*Appendix S1*).

A province's net virtual inflow of water (or *balance of virtual water use* embodied in trade between regions, BVW) is the difference between its total virtual water inflows and outflows from and to all other provinces. The virtual water inflows or outflows can be further disaggregated into virtual water embodied in trade in final products, trade in intermediate products for the final stage of production and the value chain-related trade as follows:

$$BVW^{sr}=VW^{sr}-VW^{rs}=(\boldsymbol{F}^{s}\boldsymbol{B}^{ss}TF^{sr}-\boldsymbol{F}^{r}\boldsymbol{B}^{rr}TF^{rs})+(\boldsymbol{F}^{s}\boldsymbol{B}^{ss}TI^{sr}-\boldsymbol{F}^{r}\boldsymbol{B}^{rr}TI^{rs})+(\boldsymbol{F}^{s}\boldsymbol{B}^{ss}TVC^{sr}-\boldsymbol{F}^{r}\boldsymbol{B}^{rr}TVC^{rs}) \quad (2)$$

where, the BVW^{sr} represents the net virtual water inflow into region *r* from region *s* and VW^{sr} (VW^{rs}) indicates the virtual water outflows from region *s* (*r*) to region *r* (*s*). A positive net virtual water outflow (*VWT* exporter) indicates that interprovincial trade causes a province's water use to be higher than might otherwise be thought.

We also evaluated effects of interprovincial trade on national water savings via *balance of avoided water uses, BAW*. The BAW induced by the trade between two provinces is obtained as the difference between virtual water uses embodied in commodity outflows (VW) and virtual water uses avoided by the inflow of commodities (WAI):

$$\begin{aligned} BAW^{sr} &= (VW^{sr} - WAI^{sr}) + (VW^{rs} - WAI^{rs}) \\ &= (\boldsymbol{F}^s\boldsymbol{B}^{ss} - \boldsymbol{F}^r\boldsymbol{B}^{rr})TF^{sr} + (\boldsymbol{F}^s\boldsymbol{B}^{ss} - \boldsymbol{F}^r\boldsymbol{B}^{rr})TI^{sr} + (\boldsymbol{F}^s\boldsymbol{B}^{ss} - \boldsymbol{F}^r\boldsymbol{B}^{rr})TVC^{sr} \\ &\quad + (\boldsymbol{F}^r\boldsymbol{B}^{rr} - \boldsymbol{F}^s\boldsymbol{B}^{ss})TF^{rs} + (\boldsymbol{F}^r\boldsymbol{B}^{rr} - \boldsymbol{F}^s\boldsymbol{B}^{ss})TI^{rs} + (\boldsymbol{F}^r\boldsymbol{B}^{rr} - \boldsymbol{F}^s\boldsymbol{B}^{ss})TVC^{rs} \end{aligned}$$

(3)

The first three terms in Equation (3) identify national water savings from the perspective of the production structure and amount of water saved via outflows of commodities from region *s* to *r*. These can be further divided into the three trade types. The last three terms explain national water savings associated with the inflows of commodities to region *s* from *r*. We calculated each province's national water savings as the average of its water savings via commodity inflows and outflows, $BAW^s = (\sum_{r \neq s}^{G} BAW^{sr})/2$. Subsequently we obtained a new measure of national water savings by summing across provincial average national water savings, $BAW = \sum_s^G BAW^s$. A positive value of this quantity indicates that interprovincial trade induces higher-than-expected national water use (when no interprovincial trade). The same goes for its components for the three trade types. Clearly, national water uses are "saved" when virtual water is shipped from a relatively more water-efficient province to one that is less water-efficient (Dalin et al., 2014).

2.2 Incorporating water scarcity into MRIO

We also consider water scarcity. For this, we weight *provincial water use* by a *water stress index* (the ratio of water demanded to total local water resources available) and obtain an indicator that we call *scarce water use*. Higher values of scarce water use indicate that a province consumes more water than it "should", given its resource base. Subsequently, we also derived a measure scarcity-weighted VWT (virtual scarce water trade). A "*scarce water exporter*" is a province with little available water that, in net, outwardly ships water-intensive products. Further, scarcity-weighted national water savings ("*national scarce water savings*") identifies the impact of VWT on the scarce water use nationwide. When water resources flow from a less water-stressed, more water-efficient province to a province that is more water-stressed, but less-efficient water user, national scarce water resources are "saved" through trade. (*Appendix S1*).

2.3 Data sources

MRIO tables allows us to trace water embodied in goods so that the water uses can allocated to ultimate consumers. MRIO tables of China quantify economic transactions amongst 30 sectors across 30 provinces for 2007, 2010 and 2012. They all were retrieved from School of International Development, University of East Anglia.

Our analysis focuses on the blue water impacts of the interprovincial trade on provincial and national water uses, aligning with Zhao et al. (2015); Zhao et al. (2010). We linked the MRIO table of China to data on freshwater use. For this, first, we extracted the volume of water used by primary, secondary and tertiary industries from the *Chinese Statistical Yearbook 2008, 2011 and 2013* (China National Bureau of Statistics, 2011) and the *China Urban-Rural Construction Statistical Yearbook*

2007, 2010 and 2012 (Ministry of Housing and Urban-Rural Development, 2011). Water used by primary industry is mostly agricultural—crops, grassland, forestry, orchards and fishing. Secondary industry's water use is concentrated in mining, manufacturing, electricity and construction. Tertiary industries used water to produce services, e.g. commerce, restaurants, posts, cargo transportation and telecommunications (China National Bureau of Statistics, 2011).

Second, more details on water use data by secondary industries is available from the *Chinese Economic Census Yearbook 2008* (The State Council 's second national economic census leading group office, 2010); so we used them to estimate water-use shares (see Zhao et al. (2015)), which we applied to 2007, 2010 and 2012. Third, we base subsectoral tertiary water use on each subsector's share of intermediate inputs from the "water production as suggested by (Zhang and Anadon, 2014) (see *Appendix S2*).

3. Results

3.1 Water uses by trade type. National water use increased continuously from 580.4 billion m^3/yr in 2007 to 613.8 billion m^3/yr in 2012, in which 30.4% (186.9 billion m^3/yr) was embodied in interprovincial trade within China. For 2012, we show that of this traded aspect, TI, TF and TVC composed relatively equal shares (*Appendix Table S1*). Water embodied in international exports showed up as a negative impact brought by the financial crisis since it decreased by 13% over 2007-2010 and by 9% further over 2010-2012. Of course, global value chain-related trade decreased too, by 23% over 2007-2010 and by 19% more over 2010-2012. Structural changes in interregional trade arose too. As a result, they shifted from an orientation toward TVC (2007) toward TF (2010), then toward TI (2012). This suggests that the VWT has gained more of an interregional trade tilt over time.

In 2012, the share of total provincial water use embodied in interregional trade ranged widely across China's 30 provinces—from 8.1% in Guangdong to 56.5% in Anhui. The main provinces involved in upstream processes were generally less-developed central, west and northeast parts of China, e.g. Anhui, Heilongjiang, Xinjiang, Inner Mongolia. These provinces have a dominant TI trade type that ranges from 14.3% to 20.1%; this indicates that they ship intermediate goods for further processing elsewhere domestically. Provinces with large amounts of water embodied in trade in the 2007-2010 period tended to display a similar tendency in 2012, but with a slight difference in the dominant trade type (TVC in 2007, TF in 2010). The dominant trade type was particular to provinces. For example, Heilongjiang (TVC in 2007, TI in 2012) shifted its mix of commodity outflows after the financial crisis, reducing international exports while increasing the domestically destined outflows of intermediate goods (*Appendix Fig. S1*, *Table S2-S4*).

3.2 Interprovincial water flows by trade type. We identify critical virtual importers and exporters of water for the three trade types (see Fig. 1, *Tables S5-S8*). Results show that the developed coastal provinces tend to rely on virtual imports of water from less-developed agricultural provinces. Major sectors and regions that virtually export or import water remain largely unchanged over the study period. Nonetheless, water flows strengthen among the central provinces by 2012. Provinces located in the northwest, southwest, northeast, and Yangtze River regions, which feature agriculture as a major industry, were top virtual exporters of water. The virtual outflows of water declined in the west and northeast regions between 2007 and 2012. For example, Xinjiang's total water outflows ranked it first among all flows for each trade type over the three years. But the outflows from Xinjiang declined by 1.2 billion m^3/yr from 2007 to 2012. In contrast, the Yangtze River regions intensified their virtual outflows of water. For example, Anhui's water outflows rose by 2.1 billion m^3/yr between 2007 and 2012, and its total virtual outflows of water ranked it among the top four flows in 2012. Top importers provinces consist were either populous, coastal, or both. Virtual inflows of water into coastal provinces declined from 2007 to 2012. For example, the east coast, particularly Shanghai, decreased its virtual imports of water via final goods by 3.1 billion m^3/yr from 2007 to 2012, although the inflows to Shanghai have always been among the largest TF flows. In contrast, the Yellow River region increased it virtual imports of water, e.g. Inner Mongolia shifted from being a virtual water exporter via value chain-related goods to one for final goods.

Further, our results highlight the disparities among Chinese provinces via the different trade types of net virtual inflows/outflows of water. For example, as a virtual water importer, Shanghai mainly receives an inflow of goods for final consumption, indicating its downstream position in domestic production chains. Shandong and Guangdong, meanwhile, mainly receive virtual inflows of water via goods they further process before consuming the goods themselves as a final use; Zhejiang also obtains virtual inflows of water for further processing but it mostly re-exports those processed goods. As a virtual exporter of water, for example, Xinjiang mainly ships goods elsewhere for final consumption; Heilongjiang, Guangxi and Anhui ship such goods, which are processed and eventually consumed as final goods by the regions that receive them. Hubei, Guizhou, and Gansu virtually ship water for value chain-related trade. Water-intensive goods are largely agriculture commodities and electricity; the difference is that a province either directly consumes them as an imported good (direct trade) or as a good for further processing (indirect trade) and does so differently given its position within the domestic supply chain. (for analysis about regional VWT, refer to *Appendix S3*).

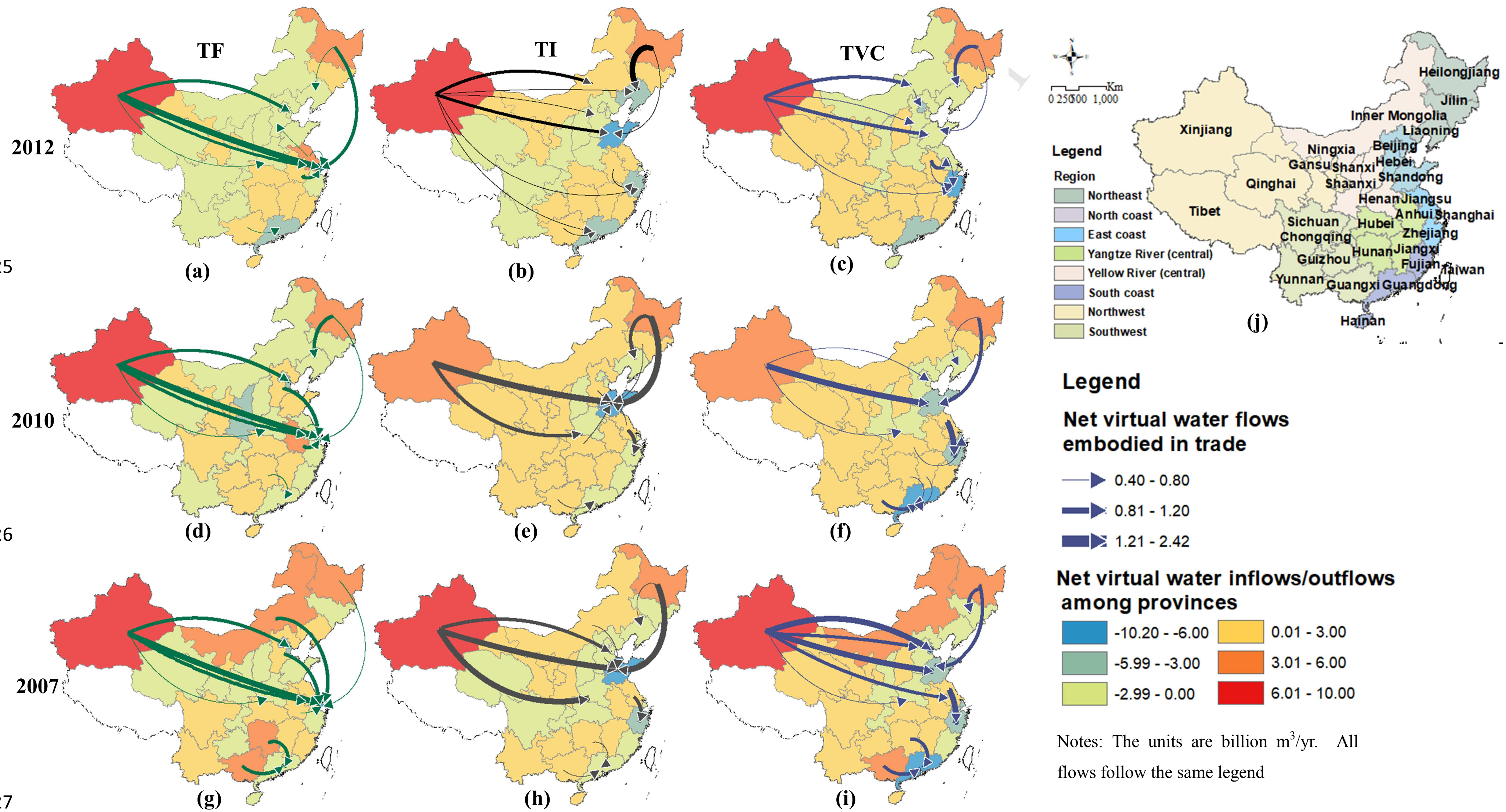

Fig. 1. The 10 largest net water flows in interprovincial trade for three trade types in 2007-2012.

3.3 Water savings. We find interprovincial trade activities consistently lead to a rise in national water use—by 28.0, 13.6 and 20.3 billion m^3/yr for 2007, 2010 and 2012, respectively. We find the proximate cause to be the rising fragmentation of production, with value chain-related trade being the biggest contributor (*Appendix Table S5*). Over the study period, TVC dominates the rise of national water use with more than 37% of the total increase. Although TI also generates a modest increase.

Trade activities enhanced apparent national water use in about two thirds of the provinces. Further, provinces performed differently in terms of BAW and BVW, which we classify into four categories (Fig. 2, *Appendix Table S5*). The most desirable scenario for a province is to be located in the third quadrant. There both water is saved from provincial and national perspective. Shanxi, Chongqing and Shaanxi, are located here with provincial and national water savings of 8.2 and 1.2 billion m^3/yr, respectively.

Provinces identified within the first quadrant experienced higher-than-expected provincial and national water use. Spending an extra 62.6 and 13.2 billion m^3/yr in provincial and national water, respectively. Provinces in this quadrant are natural targets for water conservation efforts. Key trade type and sectors varied by province. For example, Xinjiang should pay attention to TF and TI outflows, since they are major contributors its provincial and national water uses increase (37.9% of BVW, 30.5% of BAW; 33.5% of BVW, 36.7% of BAW). For Heilongjiang and Guangxi, TI outflows should be scrutinized (38.3% of BVW, 42.6% of BAW; 36.0% of BVW, 35.1% of BAW). As might be expected, agriculture sector is an apt target for water savings since it accounts for more than 50% of virtually traded water in most provinces, and is especially key in Guangxi (89.0% in TF), Heilongjiang (89.4% in TI) and Xinjiang (95.9% in TF). Still, electric power producers account for about 20% of the water embodied in trade for several provinces (e.g. Jiangsu, Anhui, Fujian). Similarly, attention to water conservation efforts should be paid to chemical processing in Sichuan and textile production in Fujian (*Appendix Fig. S2*). Note that Xinjiang, Heilongjiang and Guangxi appear to be especially ripe for efforts aimed at reducing national and provincial water use.

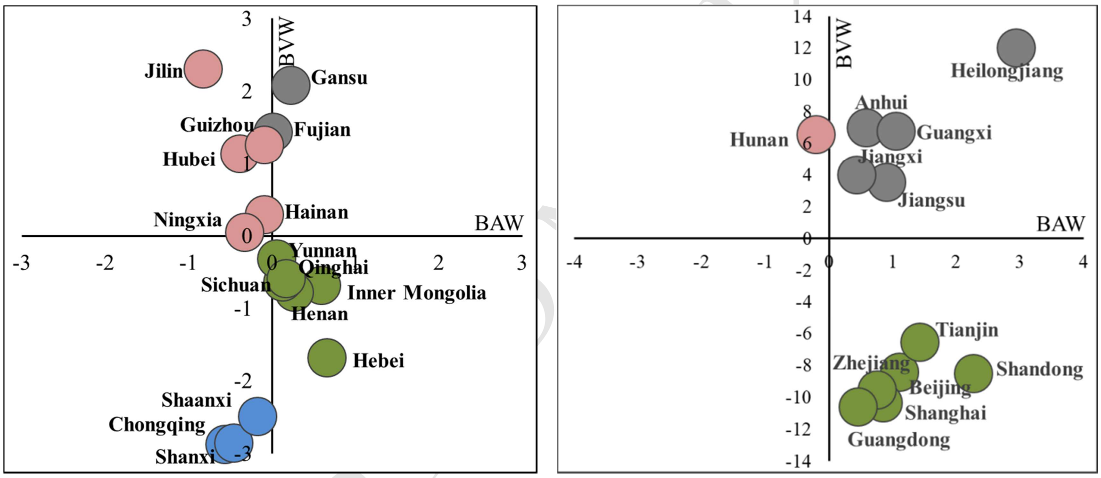

Fig. 2. The distribution of total BVW and BAW in 30 provinces in China in 2012

Note: The units are billion m^3/yr. The left figure identifies provinces with BVW and BAW less than 3 m^3/yr. That on the right contains provinces with BVW and BAW more than 3 m^3/yr. Xinjiang is omitted for high value (7, 26).

3.4 Re-mapping VWT with consideration of water scarcity. We find there was 281.5 billion m^3/yr scarce water in 2012—45.9% of the nationwide water use. Provinces with higher water–stress and, hence, major users of scarce water, are mainly in northern regions (*Appendix Table S12*). For example, Hebei, Shandong and Henan rank 3rd, 5th and 6th in terms total scarce water use, but rank 15th, 12th, and 11th in total water use. Jiangsu, Xinjiang and Heilongjiang have high scarce water use.

In 2012, 92.0 billion m^3/yr of scarce water was associated with interprovincial trade, and were fairly evenly distributed across trade types. Provinces of greatest concern are those that have stressed water resources and net water outflow—Xinjiang, Jiangsu, Heilongjiang, Hebei, Anhui, Gansu, Ningxia, and Jilin. (See Fig. 3, *Appendix Table S13*.)

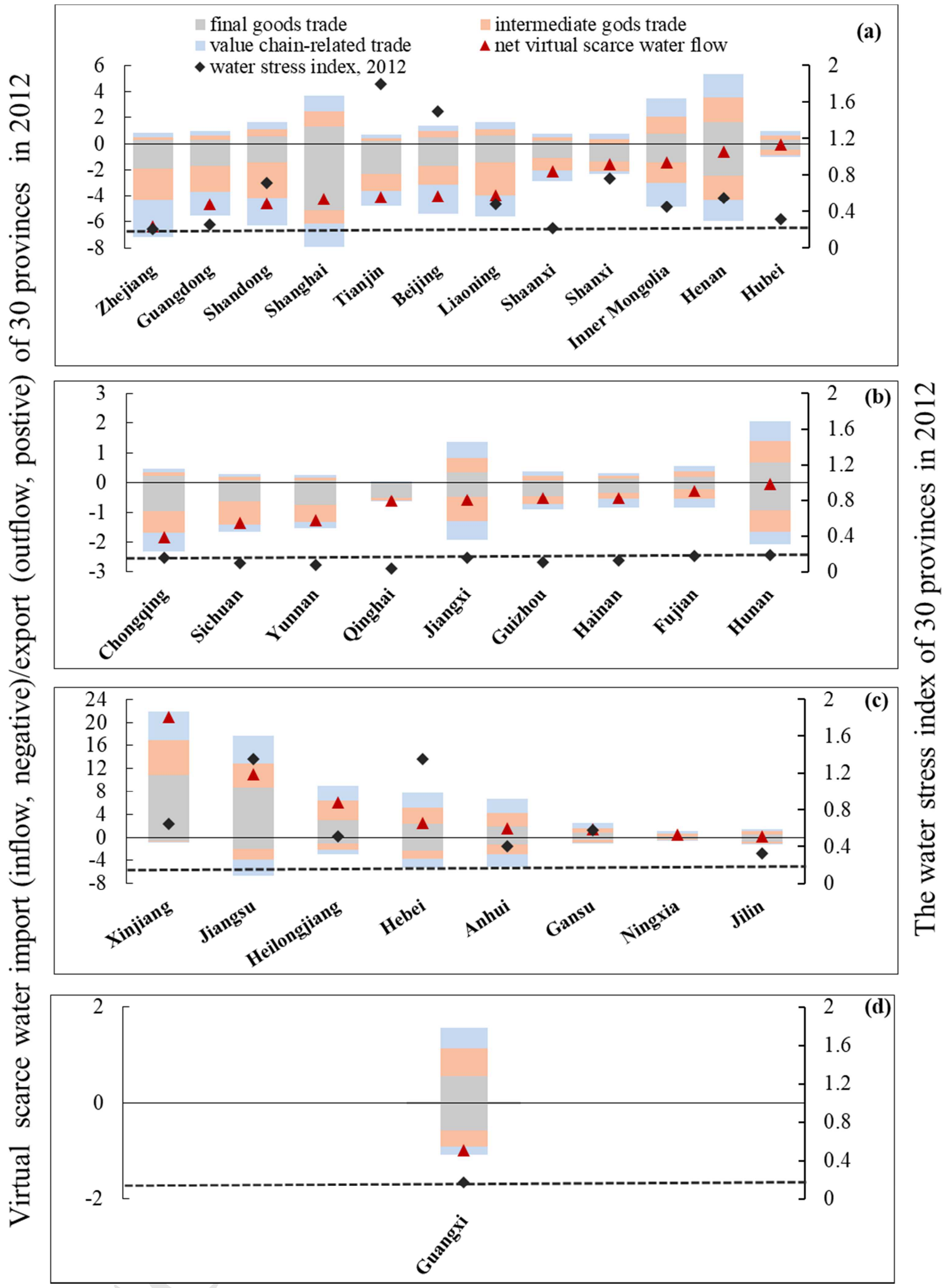

Fig. 3: China's provinces by net scarce water transfer and water scarcity, i.e. (a) stressed water resources and net water importer, (b) abundant water resources and net water importer, (c) stressed water resources and net water exporter, and (d) abundant water resources and net water exporter.

Note: The left vertical axis is scarce water inflow (negative)/outflow (positive) under trade types. The right vertical axis is the water stress index. Water scarcity is classified into four categories: a value below 20% is regarded as "no or low stress", a value between 20% and 40% is "moderate stress", a value between 40% and 100% is "serve stress", and a value above 100% is regarded as "extreme stress". The dotted line indicates a water stress index of 20% in (a), (b), (c) and (d). The water stress index values for Shanghai (3.7) and Ningxia (7.1) are omitted.

Limiting VWT could be a more efficient way to save scarce water than might saving national water use. The VWT led to the heightened national scarce water by 11.9 billion m^3/yr, substantially lower than its enhancements to national water use (20.2 billion m^3/yr) in 2012. About half of the provinces reduced national water scarcity through VWT (Fig. 4). As a result, some national scarce water use was saved (3.9 billion m^3/yr); just a bit more than was saved when ignoring water scarcity (3.5 billion m^3/yr) (*Appendix Table S14*). Provinces in third quadrant are doing quite well, resulting in both provincial and national scarce water savings (9.9 and 2.4 billion m^3/yr). Provinces in the first quadrant pose a problem, since their economies increase scarce water uses at both provincial and national levels (41.9 and 9.5 billion m^3/yr). On the other hand, these same provinces (Xinjiang, Heilongjiang, Jiangsu, Gansu and Hebei) may have the greatest potential to improve scarce water savings. In particular, Xinjiang and Heilongjiang should be targets of enhanced scrutiny in this regard since critical trade types remain whether water scarcity is considered or not.

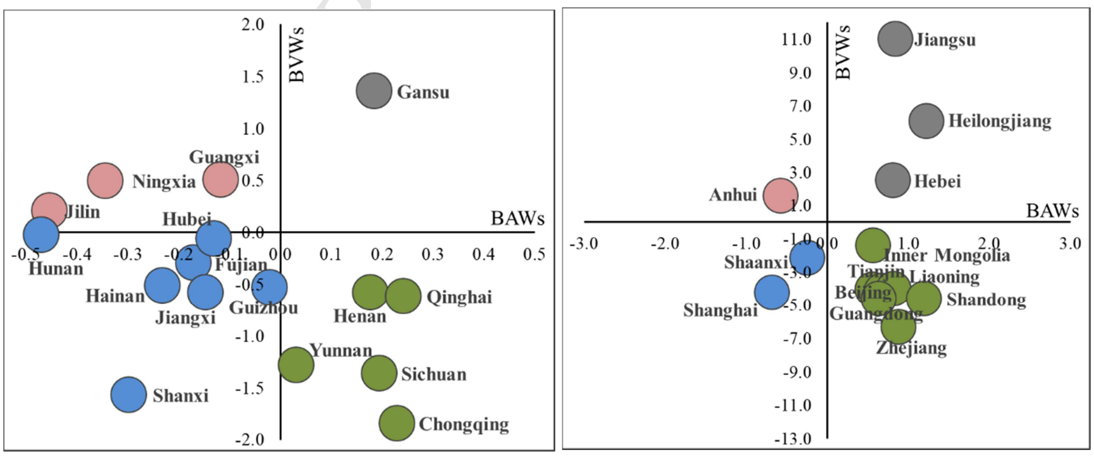

Fig. 4. The distribution of total BVWs and BAWs by Chinese province in 2012 considering water scarcity

Note: The units are billion m^3/yr. The left figure shows provinces with BVWs and BAWs less than 0.5 and 2.0 m^3/yr, respectively; that to the right shows provinces with values that larger than 0.5 and 2.0 m^3/yr, respectively;

for the sake of display, Xinjiang is omitted for high value (6, 21).

4. Discussion

4.1 Virtually trade of water shaped by production fragmentation

Our results suggest that China's present domestic production network results in virtual water flows from western to coastal regions, from less developed to more developed economies via different trade types. Thus, the environmental externalities of virtual water transfer should be considered when designing water conservation policies. A virtual water compensation scheme may be a practical solution to distributing the ecological burdens equally among provinces. Wang et al. (2017a) propose a compensation mechanism for virtual water trade in crops that follows the "whoever benefits will compensate" principle. Their proposal only considered direct bilateral trade partners.

Our study revealed that VWT is related to economic structure, production technology, trade policies and the position in domestic supply chain (Wichelns, 2004; Zhang and Anadon, 2014). We distinguish trade types, i.e. direct and indirect trade to see how it affects VWT, and observe provincial disparity. Results show that the value chain-related trade accounts for 32.7% of VWT. For example, Zhejiang is heavily involved value chain-related trade with other provinces (e.g. Jiangsu, Anhui), which accounts for 40.2% of the total water inflows, followed by final goods trade (24.4%) and intermediate goods trade for final stages of production (35.5%). Insofar as water use responsibility is concerned then, 40.2% of Zhejiang's virtual water inflows should not be fully assigned to Zhejiang. Rather, Zhejiang's third-party receivers are responsible for that aspect of water usage. Following prior research advocating for consumption-based allocation for water-use responsibility, we propose that those provinces involved in interprovincial trade indirect trade (value chain-related trade)—exporters, importers, and a third player, the final consumer—should compensate for their indirect use of water. Specifically, the percentage of indirect trade of water for each province could be used to inform policymakers about the amount of water that should be involved in such a multi-stakeholder compensation framework. This parallels a popular, but somewhat less elaborate, theory of responsibility principle applied in the field of climate change. Here the value gains in the domestic supply chain, the environmental impacts, **and** *water resource utilization* are considered.

4.2 Alleviating water scarcity under the rising fragmentation of production

Although VWT helps coastal provinces meet their total water demand, it has negative impacts: it is potentially increasing the scarcity of water in provinces in which water is already especially scarce. For example, Heilongjiang, had virtual outflows of water to Liaoning, Shandong and other provinces, mainly via intermediate goods trade. While such a strategy relieves water shortages in Shandong, it aggravates water stress in Heilongjiang. Our analysis further informs results in Zhao et al. (2015) by identifying the effects of different trade types.

By focusing on trade types, we may be able to devise other ways to reduce water scarcity, e.g. by conserving water related to the trade in intermediate goods. It could be critical to monitor and attempt to control water use within each supply chain. Key initiatives might be to prefer adoption of processes that display greater water efficiency, the more efficient use of inputs, or a higher recycling rate of intermediate products. *A good example* is green supply chains, those that aims to minimize lifecycle environmental impacts of a product via greener design, resource savings, production recycling, etc. (Ahi and Searcy, 2015). It is still at the initial stage in China. With rising fragment production, it is more necessary for all participants in supply chains to make commitment to doing business with environmentally responsible suppliers who produce with less natural resource and pollution. Including the water resource use in the metrics when evaluating the relative green supply-chain performance would focus on water savings as embodied in direct and indirect trades.

Another option, a market-based instrument, would be to let water prices vary to reflect water scarcity. This could be especially valid in arid regions, where it gives an incentive to reduce water scarcity. The distinction between final and intermediate goods may help the proper identification of commodity exporter, importer, third player who would be more affected by the resulting price increases. The affected agents would share the costs of the price increase with production fragmentation in trade. It has been argued that water prices are too low for major water uses like irrigation; raising them substantially would give farmers more reason to conserve water (Yang et al., 2003). In essence, a major reform to China's system of water prices, at least in certain regions, could stiffly alter water use by agriculture, industry and household. To better address water conservation, reform of water pricing seems appropriate but with it is equally clear that the allocation of water rights will be essential (Webber et al., 2008).

4.3 Saving national and provincial water under production fragmentation

The existing VWT network did not benefit national water use since it enabled water-intensive products to be produced in regions that are less water efficient. Due to VWT, national water use was effectively 20.3 billion m^3/yr higher in 2012. An example is Xinjiang's virtual outflows of water to Shandong and Inner Mongolia. Further, as we stated before, the virtual water embodied in the trade of intermediate goods (value chain-related trade) is a main contributor. That is, production fragmentation exacerbates national water use via national water stress. This should be a major concern for China, as blue water resources are becoming increasingly polluted or scarce (Liu et al., 2013). But if production fragmentation continues its rise within China without accompanying efficiency improvements and shifts in interregional trade network, national water resources will become more constrained. So new measures should be considered. The first is to reorganize trade (especially for crops) so that water is used more effectively and efficiently, i.e. trade flows from more water-efficient to less water-efficient provinces (Dalin et al., 2014). A second is to promote better water conservation and industry productivity locally by all parties. This should help decrease national water use and enhance local commodity supplies (e.g. food).

Ideally, targets for water conservation policy would develop at a provincial scale since our results show some particularly large interregional and intersectoral flows.

We identify provinces (i.e. Xinjiang and Heilongjiang) that have *net* virtual outflows of water due to *gross* outflows of relatively large volumes of water-intensive products. We also identify different trade flows types to be targeted to reduce water use. For example, attention should be paid to the intermediate goods shipped from Heilongjiang and used by other regions in a final stage of production. Further, the awareness of water conservation need should focus on both final goods and intermediate goods traded from Xinjiang in preparation for a final stage of production.

Sectorally, our findings support those found elsewhere: agriculture is a main water user, followed by the electric power and chemical industries (*Appendix Fig. S3).* For improving the agricultural water use efficiency, direct potential measures include technological innovation, enhanced awareness of water-saving practices, and the production of crop hybrids that demand less water. Of course, simply improving crop yields alone would prove useful (Foley et al., 2011). In the electric power sector, shifts toward air cooling systems for steam and the use of renewables, especially wind and solar generation, would help (Zhang and Anadon, 2013). Still, production processes may lack the incentive to improve water use efficiency due, for example, to its cost increment. So demand-side management could lead to the water savings. The employment of an eco-labelling scheme that provides final consumers and the industries with new information regarding environmental responsibility (Banerjee and Solomon, 2003). This could be particularly helpful in populated coastal regions.

4.4 Limitations

As with other studies using the MRIO approach, this study has potential limitations, resulting in uncertainties in the analysis: First, our results are aggregated sectorally, so some variation in processes across regions are neglected. Second, we ignore heterogeneity of industrial processes within regions as well, but we heterogeneity exists and can influence estimates of VWT embodied in various trade sectors. Adding product differentiation of industrial processes should is a future research goal.

While unavoidable, water use data also results in analytical uncertainty, especially that for secondary industrial sectoral water uses. Use of a 2008 water use ratio is unable to represent the efficiency improvement in each sector properly. Incorporating technological change by sector would be a challenge too, and this is a future research direction.

Apart from the water use, water consumption is also used by others to evaluate the impacts of virtual water transfers (Hollanda et al., 2015). The latter represents evaporation and water loss. Future research could be conducted to consider both indicators to gain a better understanding of the virtual water transfers under various trade types.

5. Conclusions

When it comes to water resources, China is at a crossroads of sorts. Water shortages are on the horizon, and both vertical specialization and the fragmentation of production appear to be making the situation worse through the virtual trade of water. This is so since China's developed coastal region is demanding virtual water from its less developed inland regions. In this paper, we apply a framework that traces the water embodied in different trade types across 30 provinces. It tracks how production and trade shape water use. Through it we find different provinces gain or lose water resources via production fragmentation by dominate trade type. For example, the largest source of water inflows into Shanghai and Zhejiang are those for final goods (67.8%) and value chain-related (40.2%). We further find that national water use was more than believed due to interprovincial trade activities; which flow from less water-efficient provinces to more efficient ones. Value chain-related trade was the main contributor.

To address China's large, untapped water saving potential, some provinces (e.g. Xinjiang, Heilongjiang), trade types (e.g. intermediate goods trade for the final stage of production), and sectors (e.g. agriculture, electricity) should be a priority when water saving actions are undertaken. Accounting for relative water scarcity in a virtual water trade network can highlight risks of aggravating water stress regions. Still we find that interregional trade would not increase national water scarcity as much as it would national water use. Our findings underline the need to consider trade types and water scarcity when it comes to developing water resource allocation policies.

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Supporting Information. Additional details on approaches, data sources, additional results analysis, figures and tables.

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Highlights:

(1) Effects of production fragmentation on virtual water trade was examined.

(2) Provincial disparity was observed for net virtual water trade in trade types.

(3) Value chain-related trade contributes to national water use increase the most.

(4) High water saving potential was revealed in provinces, trade type and sectors.

(5) We re-map the virtual water trade considering provincial water scarcity.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: