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Abstract

Trade of commodities can lead to virtual water flows between trading partners. When commodities flow from regions of high water productivity to regions of low water productivity, the trade has the potential to generate water saving. However, this accounting of water saving does not account for the water scarcity status in different regions. It could be that the water saving generated from this trade occurs at the expense of the intensified water scarcity in the exporting region, and exerts limited effect on water stress alleviation in importing regions. In this paper, we propose an approach to measure the scarce water saving associated with virtual water trade (measuring in water withdrawal/use). The scarce water is quantified by multiplying the water use in production with the water stress index (WSI). We assessed the scarce water saving/loss through interprovincial trade within China using a multi-region input-output table from 2010. The results show that interprovincial trade resulted in 14.2 km^3 of water loss without considering water stress, but only 0.4 km^3 scarce water loss using the scarce water concept. Among the 435 total connections of virtual water flows, 254 connections contributed to 20.2 km^3 of scarce water saving. Most of these connections are virtual water flows from provinces with lower WSI to that with higher WSI. Conversely, 175 connections contributed to 20.6 km^3 of scarce water loss. The virtual water flow connections between Xinjiang and other provinces stood out as the biggest contributors, accounting for 66% of total scarce water loss. The results show the importance of assessing water savings generated from trade with consideration of both water scarcity status and water productivity across regions. Identifying key connections of scarce water saving is useful in guiding interregional economic restructuring towards water stress alleviation, a major goal of China's sustainable development strategy.

1. Introduction

A significant amount of the world's water consumption arises as a result of economic production for trade (Vörösmarty *et al* 2015). The water embodied in traded commodities entails virtual water flows (Allan 1997, Yang *et al* 2006). The difference in water productivity between importing and exporting regions creates a water saving/loss from an interregional perspective. When commodities are exported from one region with higher water productivity to a region with lower water productivity, a water saving is generated (Chapagain *et al* 2006, Dalin *et al* 2012). Previous studies have shown water savings are achieved in the trade of commodities at global level (Chapagain *et al* 2006, Yang *et al* 2006, Fader *et al* 2011), and such savings have

substantially increased in recent decades alongside increasing volumes of trade (Dalin *et al* 2012, Konar *et al* 2012, Konar *et al* 2013). For example, Dalin *et al* (2012) found that the water savings from international food trade have increased from 18% of the global virtual water trade volume in 1986 to 42% in 2007. In addition, studies related to water saving through virtual water flows can also be found at sub-national or sub-continental level (Konar and Caylor 2013, Dalin *et al* 2014, Dang *et al* 2015, Dalin *et al* 2015). However, the current accounting of water saving induced by virtual water trade has only been described in terms of quantity, and is not linked to regional water stress impact on both exporting and importing regions. As a result, efforts towards water saving might be at the expense of intensified water stress in exporting regions, and may exert limited effect on water stress alleviation in importing regions. This situation could happen when the exporting regions are in extreme water stress and the importing regions have minor water stress.

There is increasing concern of water stress aggravated by the influence of virtual water trade on regional water stress (Vörösmarty *et al* 2010, Hoekstra and Mekonnen 2012, Liu *et al* 2015, Zhao *et al* 2015). To quantify the impact of virtual water flows on regional water stress, Feng *et al* (2014) introduced the index of virtual scarce water. This term was derived from the multiplication of interregional virtual water flows and the water stress index (WSI). They quantified the virtual scarce water flows among China's provinces and argued that what matters in local water management is the flow of virtual scarce water rather than volumetric virtual water because alleviating regional water stress only works when virtual scarce water is taken into account (Feng *et al* 2014). A similar idea can be traced back to the work of Ridoutt and Pfister (2010), who introduced a stress-weighted water footprint through multiplication of the volumetric water footprint with the WSI. However, to the best of our knowledge, no studies have incorporated regional water stress evaluation into the water saving measurement.

In this study, we propose an approach to measure scarce water savings associated with virtual water trade by considering both the water stress difference and water productivity difference between trading partners. Scarce water is defined here as the volume of water withdrawn from water bodies and used for the production of commodities, where water stress will be potentially aggravated due to withdrawal (use) of this water. Scarce water use in a region was quantified by multiplying the water use in production with the WSI. The WSI, ranging from 0.01–1 (Pfister *et al* 2009), is introduced as a 'discount factor'. When the WSI is 1, the water use equals to the scarce water use, and this means the water use has full impact to aggravate local water stress. And when the WSI is 0.01, the scarce water use is only 1% of the water use, meaning the water use has the least impact on local water stress. Virtual scarce water refers to the scarce water embodied in traded commodities. We thus propose that scarce water will be saved if one region has imported less virtual scarce water embodied in the imported products than it would hypothetically have used in scarce water withdrawn from local resources to produce the same products. To the best of our knowledge, few studies have evaluated scarce water savings or losses through interregional virtual water trade. Since scarce water savings suggest the water stress situation between the trading partners as a whole is improved, we argue that the relationship between water saving/loss and alleviation/intensification of regional water stress will produce a useful evaluation and guide for regional water stress alleviation.

In this study, we developed a scarce water saving accounting framework based on input-output (IO) analysis. The metric was used to quantify scarce water savings from interprovincial virtual water flows in China. Since China's water resources are known as unevenly distributed, a lot of researchers chose to study virtual water flows within China at provincial level (Dalin *et al* 2014, Dalin *et al* 2015, Guan and Hubacek 2007, Ma *et al* 2006, Zhang and Anadon 2014). We accounted virtual water trade for 30 economic sectors using a top-down approach. As a top-down approach, the IO analysis provides a consumption-based quantification, i.e. it quantifies the virtual water flows for final consumption thereby linking the virtual water embodied in production of the whole supply chain.

In accounting for water saving and scarce water saving, we have only considered blue water (ground- and surface-water). We haven't considered green water (rain water) because it doesn't contribute to water scarcity (Ridoutt and Pfister 2010). We also chose water use (or water withdrawal) instead of water consumption data for our study, i.e. the quantity of water removed from water source and distributed to users, including water lost in transmission. The main reason was that the WSI accounts for water withdrawal rather than water consumption (van Vliet *et al* 2017).
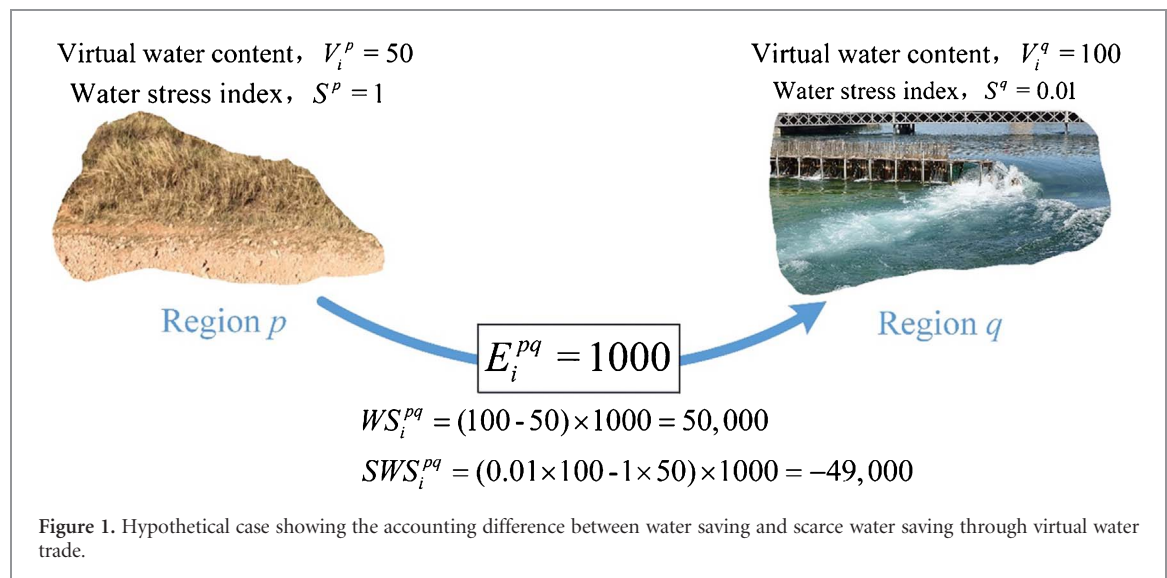
2. Methodology and data

2.1. Measuring scarce water savings from virtual water flows

The accounting for water savings without considering water stress through the trade of product i from an exporting region p to an importing region q, i.e. WS_i^{pq}, can be expressed as follows:

$$WS_i^{pq} = (V_i^q - V_i^p) \times E_i^{pq} = HVW_i^{pq} - VW_i^{pq}. \quad (1)$$

Where E_i^{pq} is the export of product i from region p to region q, V_i^p and V_i^q are the virtual water content (VWC) of product i in region p and q respectively. The VWC of product i represents the amount of water required for the production of a unit of product i. VW_i^{pq} is the virtual water export from region p to

Figure 1. Hypothetical case showing the accounting difference between water saving and scarce water saving through virtual water trade.

q. HVW_i^{pq} represents a hypothetical virtual water use in q, assuming the importing region q would not have virtual water inflows from region p but would withdraw the required water entirely from local water resources to produce product i.

The scarce water saving accounting is shown below:

$$SWS_i^{pq} = (S^q \times V_i^q - S^p \times V_i^p)$$
$$= HVSW_i^{pq} - VSW_i^{pq}. \quad (2)$$

Where SWS_i^{pq} is the scarce water saving, S^p and S^q are the water stress index (WSI) of region p and q respectively. VSW_i^{pq} represents the virtual scarce water exports from region p to q, while $HVSW_i^{pq}$ represents the hypothetical virtual scarce water used in region q to produce product i. A positive value for SWS_i^{pq} means scarce water is saved from the exporting of product i from p to q, whereas a negative or zero value of SWS_i^{pq} means a loss or zero saving. In addition, $S^p \times V_i^p$ can be defined as the virtual scarce water content (VSWC) of region p, meaning the amount of virtual scarce water required for the production of a unit of product i.

Figure 1 is a simple case illustrating the accounting difference between water saving and scarce water saving. To account for water saving and scarce water saving through China's interprovincial virtual water trade with sectoral details, we have applied the top-down approach 'Water Embodied in Trade' (WET) with data from the multi-region input-output table (MRIO) (Feng *et al* 2011, Yang *et al* 2013). And the WSI developed by Pfister *et al* (2009) was used in quantifying the scarce water saving. See the Supplementary available at stacks.iop.org/ERL/13/054012/mmedia for additional illustration of the simple case, as well as the WET and WSI accounting methods.

2.2. Data
We collected blue water use data at Provincial level. The detailed sectors was shown in table 1. The water use data for individual sectors in the Primary, Secondary, and Tertiary industries for each province was generally acquired from the Water Resources Bulletin at provincial level (Provincial Water Resources Bureau 2010). Furthermore, to breakdown water use data in Secondary Industry with detailed sectors, we used the water use percentage of detailed sectors in Secondary Industry from the Chinese Economic Census Yearbook 2008, assuming the economic structure and economic water use efficiency in 2010 were the same as in 2008. Water used in the Tertiary Industry is calculated as the domestic water use from the people working in the sector. For the water use breakdown of the Tertiary Industry, we followed the percentages provided by Zhao *et al* (2015).

According to Pfister *et al* (2009), the WSI is quantified for over 10000 watersheds in the world, and in each watershed the WSI of different grids has the same value, which is the WSI value of that watershed. We used the WSI results from Pfister *et al* (2009) at the grid level and then aggregated the values to the provincial level in China by using arithmetic average of grid WSI within that province. The 2010 Chinese MRIO table used in this study were compiled by Liu *et al* (2014). The table contains 30 industrial sectors within 30 provincial-level administrative regions (provinces, autonomous regions, and municipalities—for simplicity, they are referred to as provinces). The details of provinces and sectors are shown in figure 2 and table 1, respectively. The provinces not included are due to absence of data.

3. Results

3.1 Virtual water and virtual scarce water flows within China
In 2010, China's total water use for the production of goods and services was 537.6 km³, of which 36% (194.2 km³) was scarce water. The volume of virtual

Table 1. Sectoral distribution of water saving from both virtual water and virtual scarce water perspectives (million m^3).

	Sector	Water saving/loss	Scarce water saving/loss
Primary Industry	Agriculture	−16144	−7076
Secondary Industry	Coal Mining and Dressing	529	−290
	Petroleum and Natural Gas Extraction	127	130
	Metals Mining and Dressing	99	61
	Nonmetal Minerals Mining and Dressing	85	200
	Food and Tobacco Processing	995	5082
	Textile Industry	−937	−672
	Garments, Leather, Furs, Down and Related Products	2166	1222
	Timber Processing and Furniture Manufacturing	−350	378
	Papermaking, Cultural, Educational and Sports Articles	−130	259
	Petroleum Processing and Coking	53	−265
	Chemicals	−419	−447
	Nonmetal Mineral Products	538	396
	Smelting and Pressing of Metals	−696	−137
	Metal Products	−134	−213
	General and Specialized Machinery	568	−425
	Transportation Equipment	286	426
	Electric Equipment and Machinery	−331	−141
	Electronic and Telecommunications Equipment	142	84
	Instruments, Meters Cultural and Office Machinery	−12	4
	Other Manufacturing Products	348	131
	Electricity and Heating Power Production and Supply	−858	1144
	Gas and Water Production and Supply	−13	−6
	Construction	−480	−196
Tertiary Industry	Freight Transport and Warehousing	−309	−228
	Wholesale and Retail Trade	64	−31
	Hotels, Food and Beverage Places	−695	−176
	Real Estate and Social Services	71	123
	Scientific Research	279	45
	Other Services	996	250
	Total	−14162	−370
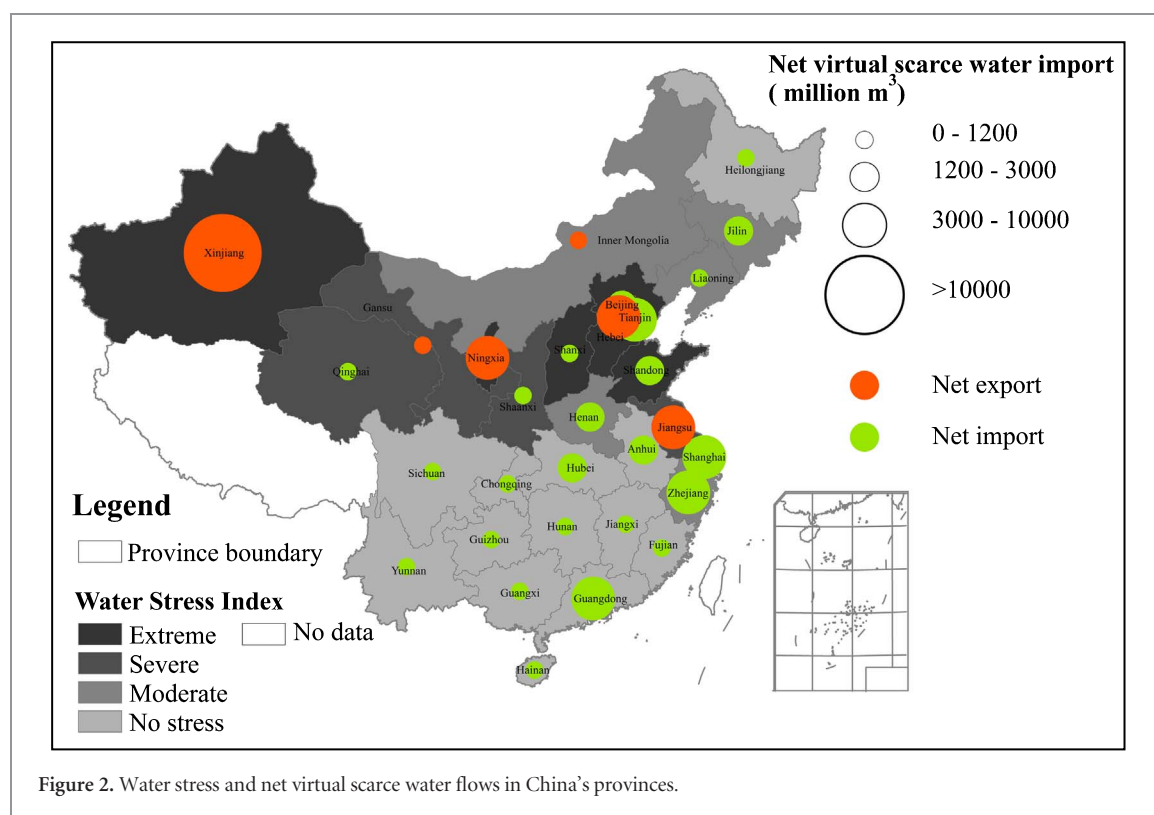
Figure 2. Water stress and net virtual scarce water flows in China's provinces.

water flows amongst China's provinces was 209.5 km^3 in 2010, accounting for 39% of total water use in China. The volume of virtual scarce water flows was 78.5 km^3, accounting for 37.5% of the virtual water flows, and 40.4% of total scarce water use in China.

Looking at the interprovincial virtual water flows in sectors, about 43% of virtual water flows (90 km^3) was embodied in the traded final products of Agriculture. Other sectors with high virtual water flows included Food and Tobacco Processing (33 km^3), Electricity and

Heating Power Production and Supply (13.6 km³), and Chemicals (11 km³). Regarding virtual scarce water flows, 52% was found to be embodied in Agriculture. The high percentage of virtual scarce water flows in Agriculture implies that more products from Agriculture were produced in water scarce regions compared to other sectors, leading to a larger 'discount factor' in Agriculture than for other sectors.

Provincial WSI was used to study scarce water use and virtual scarce water flows amongst provinces. The results showed that 17 provinces were in different levels of water stress, amongst which 14 provinces are located in north China (figure 2). All 7 provinces in extreme water stress are also located in north China. According to figure 2, most provinces studied were net virtual scarce water importers. Only 6 water stressed provinces, i.e. Xinjiang, Hebei, Ningxia, Jiangsu, Gansu, and Inner Mongolia were net virtual scarce water exporters.

3.2. Water saving from both virtual water and virtual scarce water perspectives

Without considering water stress in the accounting, the flows of virtual water within China resulted in 14.2 km³ of water loss, accounting for 6.8% of virtual water flows within China, and 2.6% of total water use in China. The results of total water loss associated with virtual water flows implies that more virtual water flowed from less water use efficient provinces to more water use efficient provinces. There were a total of 435 connections of virtual water flows (one connection represents the net virtual water flow between any two provinces) for the 30 studied provinces. Amongst these connections, we found 211 generating a water saving, and the volumetric sum was 20.3 km³. A further 224 connections generated about 34.4 km³ of water loss.

Using the scarce water saving concept, the flows of virtual scarce water resulted in only 0.4 km³ of scarce water loss, which was much less than the water loss quantified without considering water stress status of individual provinces. Most connections were found to save scarce water. The number of virtual water trade connections that contributed to scarce water savings increased to 254, which saved a total of 20.2 km³ virtual scarce water. At the same time, 175 connections contributed to 20.6 km³ of virtual scarce water loss.

The breakdown of water saving by sector revealed a varied scale of water saving/loss (table 1). Without considering water stress, the virtual water trade from Agriculture generated the largest water loss (16.1 km³). For the Garments, Leather, Furs, Down and Related Products; Other Services; and Food and Tobacco Processing sectors, virtual water trade contributed most to water saving and slightly offset total water loss. Using the scarce water saving concept, the largest scarce water loss arose from Agriculture trade (7.1 km³). However, such loss was largely offset by trade from the Food and Tobacco Processing; Garments, Leather, Furs, Down and Related Products; and Electricity and Heating

Power Production and Supply sectors, which contributed about 5.1 km³, 1.2 km³, and 1.1 km³ of scarce water saving respectively.

3.3. Shift of water saving/loss status from virtual water and virtual scarce water perspectives

We identified 103 connections which generated a water loss without considering water stress, but produced a scarce water saving with consideration of water stress. Conversely, 59 connections were identified as generating a water saving but having a scarce water loss. An example of changes from water saving to scarce water loss was virtual water trade between Hebei and Zhejiang. There were 0.7 km³ of net virtual water flowed from the former to the latter. Without considering water stress, we found about 0.2 km³ of water was saved, which indicated the portfolio of goods and services produced in Hebei have higher economic water productivity or economic water use efficiency. However, about 0.56 km³ of scarce water loss was generated using the scarce water saving concept. This was because the net exporting province of Hebei was in extreme water stress (WSI = 0.961), whilst the net importer Zhejiang was only in moderate water stress (WSI = 0.192). As a result, more virtual scarce water was embodied in goods and services exported from Hebei to Zhejiang than the hypothetical virtual scarce water used to produce the same products using local resources. The reverse situation can be shown through virtual water trade between Shanghai and Anhui. In this case, there was 1.3 km³ of net virtual water flow from Anhui to Shanghai. Excluding the effects of water stress, trade generated 0.44 km³ of water loss, but with consideration of water stress it generated 0.58 km³ of water saving. In this example, the net importer Shanghai was in extreme water stress (WSI = 1) and the net exporter Anhui had minor water stress (WSI = 0.03).

3.4. The relationship between water stress and water saving from the virtual scarce water perspective

Since the WSIs were added as discount factors in the scarce water saving calculation, we can infer from the increased scarce water saving connections that most virtual water connections were flows from provinces with lower WSI to provinces with higher WSI. This can also be seen in figure 3, which shows that 10 out of 13 provinces with minor water stress were net virtual water exporters, and 11 out of 17 provinces under moderate to extreme water stress were net virtual water importers.

Figure 4 shows large net virtual water flow connections which generate scarce water savings and losses. These can further manifest the role of regional water stress status and virtual water trade on scarce water savings. It is clearly shown that most scarce water saving is between net virtual water flows from provinces with lower WSI to provinces with higher WSI (figure 4(a)). However, no clear pattern that scarce water loss was related to WSI difference between trade
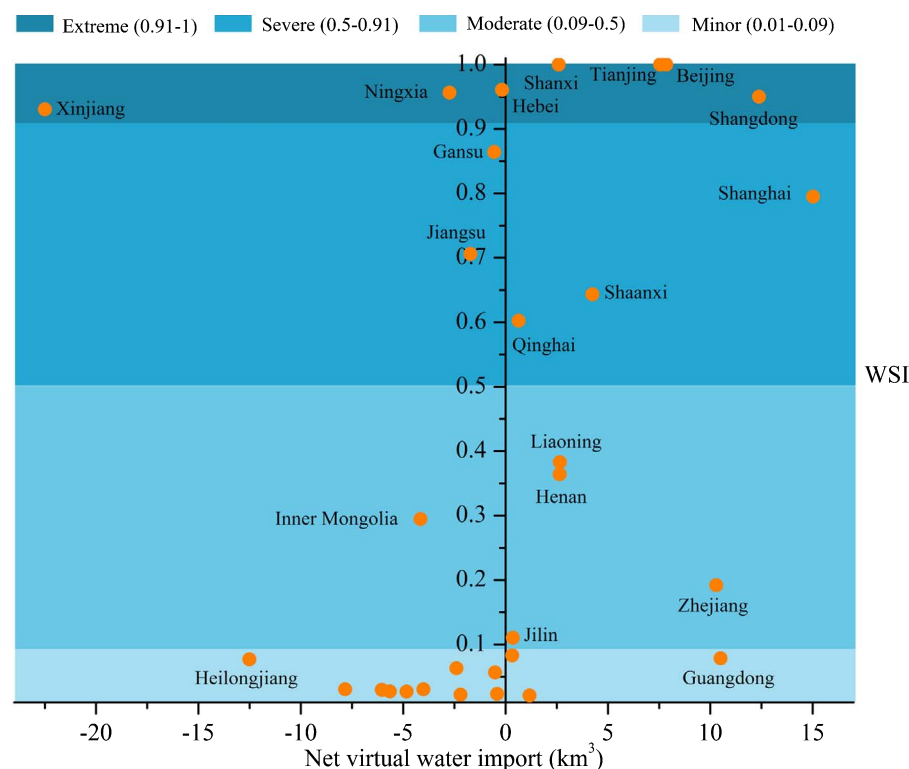
Figure 3. Relationship between net virtual water import and water stress index for China's provinces.

partners is apparent (figure 4(*b*)). According to figure 4(*b*), we can see that virtual water flow connections between Xinjiang and other provinces stand out as the biggest contributors to total scarce water loss. Looking at virtual water flow connections linking Xinjiang with the other 29 provinces, we found 25 connections contributing to scarce water losses, which accounted for 66% of total scarce water loss amongst all 175 connections that contributed to scarce water loss. This is mainly because Xinjiang was the largest net virtual water exporter in 2010 ($22.5 \, km^3$), and in the meanwhile was in extreme water stress (WSI = 0.931). This made Xinjiang the largest net virtual scarce water exporter ($22 \, km^3$, also see figure 2).

4. Discussion

4.1. Implications of incorporating water stress into water saving accounting

In this paper, we proposed an approach to account for scarce water saving/loss associated with trade of commodities between China's provinces. Based on IO analysis, this approach demonstrated the role of interregional virtual water trade through the whole supply chain to regional water stress alleviation or intensification. Although several previous studies have linked virtual water trade with regional water stress (e.g. Zhao *et al* 2015, Feng *et al* 2014, Zhao *et al* 2016, Zhang *et al* 2017), none has assessed regional water stress alleviation/intensification through interregional

virtual water trade. Since the amount of scarce water saved represents the extent of water stress alleviation through trade, scarce water saving accounting can be useful as a guide for interregional economic restructuring towards water stress alleviation. In addition, incorporating water stress into water saving accounting is essential in linking interregional trade to water stress, since water stress is largely a regional concern (Ridoutt and Pfister 2010).

We have indicated that scarce water savings can be determined by the difference between water stress and water productivity. From the perspective of scarce water saving, we recommend the relocation of production to regions and sectors with both low water stress and high water productivity. The Agricultural sector contributed the most to virtual water trade and scarce water saving/loss. The provinces with high economic water productivity in Agriculture and low water stress were Chongqing, Sichuan, Hainan, Fujian, and Guizhou. These provinces could be incentivized towards greater agricultural production from the perspective of saving national scarce water. In contrast Xinjiang, in extreme water stress, had the largest VWC for Agriculture among all provinces and was also the largest virtual water exporter in China. Decreasing VWC and limiting virtual water export from the Agriculture sector in Xinjiang will help to reduce scarce water loss.

We found that most virtual water flows within China were directed to provinces with different levels of water stress, which helped to alleviate water
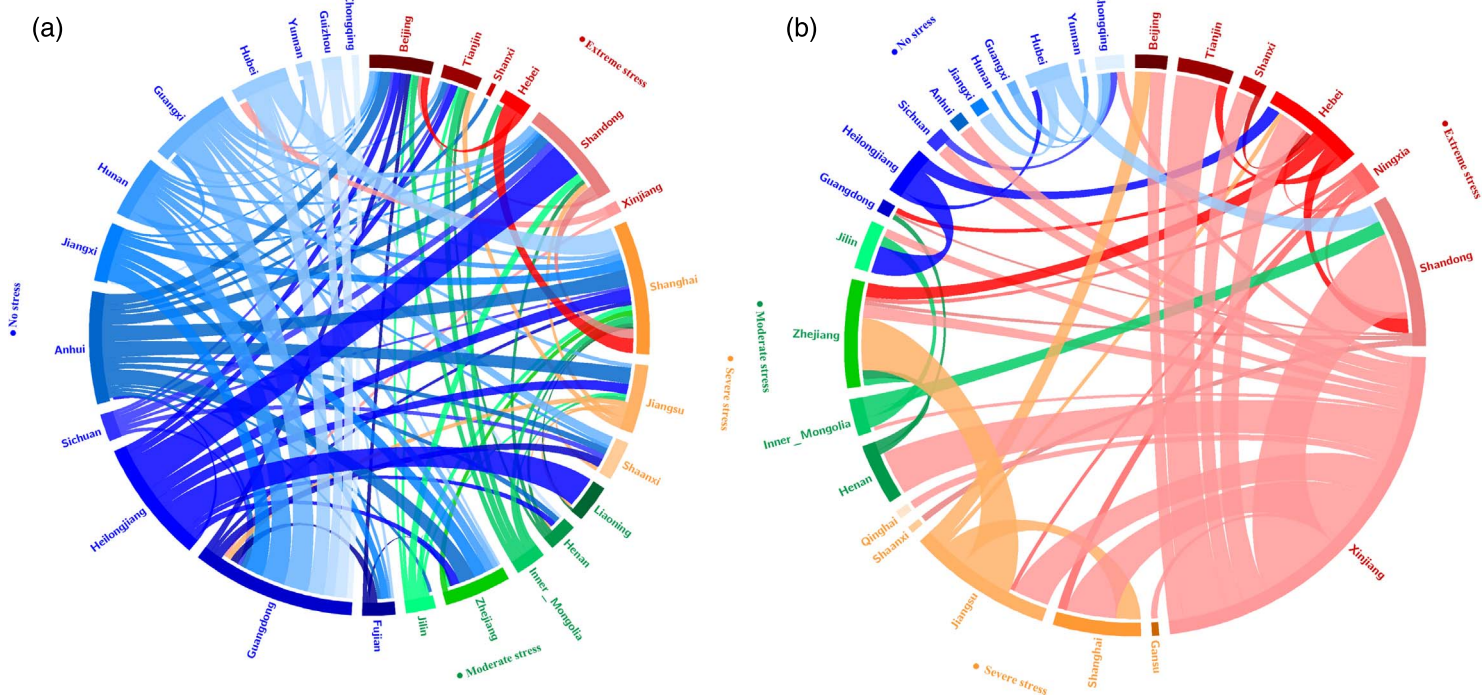
Figure 4. Major net virtual water flows with (a) scarce water saving and (b) scarce water loss.

stress of these provinces. However, the exporting regions will have a higher risk of intensifying their water stress due to continuing virtual water exports, regardless of whether the exporting regions are water scarce or water abundant. Meanwhile, when virtual water flows from water abundant to water scarce regions, scarce water savings will be offset when the exporting regions have larger VWC compared with the importing regions. Hence, decreasing the VWC in water abundant exporting regions can help to achieve greater scarce water savings. Attention should also be paid to the risk of increasing VWC in exporting regions due to climate change (Orlowsky *et al* 2014). These effects will reduce scarce water savings in the long term. One suggestion would be to cap regional water use based on regional water stress reduction targets for all trade partners. Although China has set a 'water use redline' for each province (Liu *et al* 2013), a scenario analysis has shown that the current redline will intensify water stress for some provinces in 2030 (Zhao *et al* 2015). This is partly because these caps were not based on targets of reducing provincial water stress or in consideration of virtual water trade. Our results thus provide a basis for setting more feasible water use caps within China.

4.2. Rationality of scarce water accounting

It should be noted that debate about the rationality of scarce water or stress-weighted water footprint is still ongoing. The debate was between two sides: one side is the researchers of the Water Footprint Network (Hoekstra *et al* 2009, Hoekstra 2016), who has developed the metric to quantify volumetric water footprint and virtual water. The other is the researchers who have developed the stress-weighted water footprint (Pfister and Hellweg 2009, Pfister *et al* 2017). In our opinion, we believe both volumetric virtual water and scarce water are useful in addressing human impact on water. And we agree with Pfister *et al* (2017) that stress-weighted water footprint/scarce water is an index representing potential impact of human production on water resources, and can be used to compare the human impact on water across different regions. However, we also agree with Hoekstra (2016) that water is a global resource. And based on global perspective, one suggestion from Hoekstra (2016) to mitigate water stress in water scare regions is to use water resources in water rich region more productively. It suggests the relocation of production to regions and sectors with both low water stress and high water productivity, which is one of the main suggestions from this study. Since the Water Footprint Network acknowledges the idea of water saving, and the original idea of scarce water is from Ridoutt and Pfister (2010), we believe scarce water saving can serve as a case to show the compatibilities of both volumetric water footprint/virtual water accounting and scarce water/stress-weighted water footprint accounting.

4.3. Limitations of this study

Like other water saving studies, the water saving metric in this study has a non-negligible assumption that the imported goods and services can be produced in the importing regions. But this is not always the case in real world. For example the inland province, say Xinjiang province, can import sea food from the province along the coast, say Fujian province, but it is impossible for Xinjiang to produce the sea food. Hence, the above assumption will leave part of the water/scarce water saving results meaningless.

In scarce water accounting, changes in WSI is linked to changes in water use. This is because water use is one of the determining factors of the WSI. One of the steps to quantify the water/scarce water saving is to assume that the importing region would produce the imported goods and services by themselves, and the underlying change is that water use would increase due to that production. As a result, the WSI of the importing region would change accordingly. But like other water saving studies, we assume the WSI to be an independent and unchanged index due to the complexity and data constraints in quantifying such changes.

In addition, the WSI in this study was based on a global hydrological model, and the data used for the WSI accounting such as water use and water availability was not refined for the specific research area of China. For example, the WSI results showed minor stress in Heilongjiang province, but domestic data shows that Heilongjiang was at least in moderate water stress. Notwithstanding this, we argue that the main purpose of this study was to develop a new approach to address water stress issues associated with virtual water trade. In practice, data can be further refined at the stage of policy formulation.

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