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- Analysis of virtual water flows for both quantity and quality
- Quantification of burden shifting of water stress from Shanghai
- Discussion of consumer responsibility for megacities

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Burden shifting of water quantity and quality stress from megacity Shanghai

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Abstract Much attention has been paid to burden shifting of CO_2 emissions from developed regions to developing regions through trade. However, less discussed is that trade also acts as a mechanism enabling wealthy consumers to shift water quantity and quality stress to their trading partners. In this study, we investigate how Shanghai, the largest megacity in China, draws water resources from all over China and outsources its pollution through virtual quantity and quality water flows associated with trade. The results show that Shanghai's consumption of goods and services in 2007 led to 11.6 billion m^3 of freshwater consumption, 796 thousand tons of COD, and 16.2 thousand tons of NH_3-N in discharged wastewater. Of this, 79% of freshwater consumption, 82.9% of COD and 82.5% of NH_3-N occurred in other Chinese Provinces which provide goods and services to Shanghai. Thirteen Provinces with severe and extreme water quantity stress accounted for 60% of net virtual water import to Shanghai, while 19 Provinces experiencing water quality stress endured 79% of net COD outsourcing and 75.5% of net NH_3-N outsourcing from Shanghai. In accordance with the three "redlines" recently put forward by the Chinese central government to control water pollution and cap total water use in all provinces, we suggest that Shanghai should share its responsibility for reducing water quantity and quality stress in its trading partners through taking measures at provincial, industrial, and consumer levels. In the meantime, Shanghai needs to enhance demand side management by promoting low water intensity consumption.

1. Introduction

Many studies have linked carbon dioxide (CO_2) emissions, air pollution, and threats to biodiversity with export-intensive industries, and then linked the exports to consuming countries/regions [*Lenzen et al*., 2012; *Lin et al*., 2014; *Peters et al*., 2011]. In studies of carbon dioxide (CO_2) emissions, for example, one of the commonly accepted facts is that developing countries/regions generate large amounts of CO_2 emissions due to exports to developed countries/regions [*Arto and Dietzenbacher*, 2014; *Feng et al*., 2013]. As a result, wealthy countries/regions shift the burden of CO_2 emissions to the economically poorer exporters, which is also known as weak carbon leakage [*Kanemoto et al*., 2014]. Many have argued that the burden shifting of CO_2 emissions has undermined current regulations of territorial carbon emissions [e.g., *Davis and Caldeira*, 2010; *Weber and Peters*, 2009]. Consumption-based accounting has been proposed to address consumer responsibility, which accounts for pollutants or resources embodied in finally demanded commodities, no matter where the resources are used or pollutants are discharged [*Lenzen et al*., 2007; *Wiedmann*, 2009].

It was recently found that trade also acts as a mechanism through which wealthy consumers shift local water quantity stress to the economically poorer exporters of goods and services. This perspective is based upon the following research facts and principles: first, through international trade, regions virtually import or export water used for the production of goods and services, known as virtual water [*Allan*, 1992; *Tamea et al*., 2014]. The net inflow of virtual water helps water scarce regions relieve their water quantity stress [*Oki and Kanae*, 2004]. However, such relief has been shown to have a far more deleterious effect through excessive water consumption in some exporting regions. For example, *Hoekstra and Mekonnen* [2012] found that about 50% of global blue virtual water (ground and surface water) export was derived from a small number of countries which were all under different levels of water stress. A scenario analysis for China's Provinces showed that future water quantity stress in the main virtual water exporting Provinces is likely to increase due to increasing demand from the main virtual water importers [*Zhao et al*., 2015]. Second, recent studies have indicated that virtual water trade is closely correlated with affluence. Using multivariate regression analyses, *Tamea et al*. [2014] showed that affluence (GDP) along with population and geographical distance are the major drivers of virtual water trade. Studies of virtual water trade within China indicated that virtual water flowed from economically poor to economically rich Provinces [*Feng et al*., 2014; *Zhao et al*., 2015].

Although the water quantity stress implications relating to trade have been studied at the global, national, and basin levels [e.g., *Lenzen et al*., 2013; *Lutter et al*., 2016; *Wang and Zimmerman*, 2016], few studies have focused on how a large group of wealthy consumers, typically a megacity, transfers its water stress in terms of both quantity and quality to other regions. A megacity is usually defined as a city or urban agglomeration of greater than 10 million inhabitants [*United Nations*, 2010]. In 2014, one in eight urban dwellers lived in 28 global megacities, whilst conservative projections suggest that there will be an additional 13 megacities by 2030 [*Li et al*., 2015]. Given this rapid increase in urbanization, increasing amounts of virtual water will be required to support growing consumption demand in megacities. Questions which may be raised and discussed at policy level include what consumers in megacities can do to relieve water stress in their trading partners, and how water stressed exporters can reduce the impact of virtual water export on local water resources. In addition, we consider that research on the burden-shifting of water stress through trade from the perspective of the megacity marks the beginning of promotion of a shared responsibility between wealthy consumers and economically poor water-stressed exporters.

With the deteriorating state of freshwater resources due to rising pollution, it becomes important to address water stress in terms of both quantity and quality [*Scanlon et al*., 2007; *Zeng et al*., 2013]. However, impacts of trade on water quality have rarely been investigated. Notable exceptions include the work of *Okadera et al*. [2006] and *Guan and Hubacek* [2007]. To the best of our knowledge, detailed elaboration on how a megacity has shifted the burden of both water quantity and quality stress to its trading partners has not previously been reported. The aim of this study therefore is to investigate the extent to which a large group of consumers in a megacity relies on virtual water import and outsourcing of water pollutants, and to evaluate the impacts of their consumption on external water resources for both water quantity and quality. We choose the megacity of Shanghai, the largest city in China and the third largest city in the world, as a case study. With a population of over 24 million, Shanghai places significant reliance on external import of resources. Thus, Shanghai is an excellent case study of the burden-shift of mega-cities, and addresses the issues relating to consumer responsibility for causing water quantity and quality stress in its trading partners.

We use the latest national multiregion input-output (MRIO) table to assess the consumptive water use and pollutants in discharged wastewater (chemical oxygen demand, COD and ammoniacal nitrogen, NH_3-N) in Shanghai and other provincial level administrative regions (hereby Provinces) stemming from the final demand of Shanghai at sectoral detail. Recently, there has been growing interest in using the MRIO table to study consumption-induced environmental issues [e.g., *Ewing et al*., 2012; *Kanemoto et al*., 2014; *Lin et al*., 2014; *Wiedmann*, 2009; *Wiedmann et al*., 2015]. The quantification using the MRIO table has the advantage of distinguishing production structure and technology for each region to carry out consumption-based analysis with sectoral level of detail. For China, given the advantage of MRIO and recent data quality improvements in it is MRIO table, more scholars are choosing to use the MRIO framework to quantify virtual water flows within China [*Feng et al*., 2012; *Zhang and Anadon*, 2014; *Zhang et al*., 2011]. Using the economic data from the MRIO table compiled for China's 30 Provinces, we applied the "Water Embodied in Trade" (WET) method [*Feng et al*., 2011] to account for the virtual water quantity and quality flows between Shanghai and other regions. The water quantity and quality stress index is then introduced to study Shanghai's contribution to internal and other Provinces' water stress.

2. Shanghai's Water Endowment

The Huangpu River, a tributary of the Yangtze River crossing through Shanghai, is traditionally the main water source for the city [*Finlayson et al*., 2013]. Until 2010 up to 72% of Shanghai's freshwater supply came

Figure 1. Shanghai's location, water sources, and reserviors.

from the Taihu Lake via the Huangpu River [*Shanghai Water Resources Bureau*, 2010]. Located in the Yangtze delta (Figure 1), Shanghai's water quality is heavily dependent on upstream flows [*Yin et al*., 2005]. In recent decades, the Taihu Lake has become seriously polluted due to economic development and lack of pollution controls in the upstream Provinces of Jiangsu and Zhejiang [*Jiao et al*., 2015]. In China water quality is categorized into five grades with Grade III and below indicating the water is suitable for fishery, aquaculture, and recreational purposes. A water quality standard above Grade III indicates poor water quality which is unsuitable for safe use. Grade V means the water is so seriously polluted as not to be fit for any beneficial use. In 2007, only 12.5% of length of the Huangpu River met the surface water quality standard (Grade III or better), whereas 56.7% of the length of the river was considered to be worse than the Grade V [*Shanghai Water Resources Bureau*, 2007]. The Huangpu River has effectively become a channel to transport polluted discharge from Shanghai and the upstream regions to the sea. Faced with such severe pollution in its traditional water sources, Shanghai has resorted to the main stream of the Yangtze River for its water supply. Three reservoirs have recently been built to store water (Figure 1), making the Yangtze River the main water resource for Shanghai. Since 2012, the Qingcaosha and Chenhang Reservoirs have been diverting water from the Yangtze River accounting for 77% of Shanghai's water supply.

3. Data

In accounting for virtual water quantity, we only consider blue water and exclude green water (rain water) accounting. We use consumptive water use to quantify virtual water trade between different sectors of different Provinces, rather than water withdrawal or water use. Consumptive water use is defined as the part of water withdrawal that is evaporated, transpired by plants, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment (http://water.usgs.

gov/edu/dictionary.html). Distinct from water withdrawal, consumptive water use in its accounting excludes return flows which are part of a diverted flow that is not consumptively used and returned to its original source or another body of water (http://water.usgs.gov/edu/dictionary.html). The main reason we choose the consumptive water use in our accounting framework is that water conservation efforts are suggested to focus on reducing consumptive water use [*Ward and Pulido-Velazquez*, 2008]. This is because in many cases, attempts at improving water use efficiency only result in a decrease in return flow, but paradoxically increase the consumptive water use in the long-term and lower flow benefits for environmental users [see e.g., *Adamson and Loch*, 2014; *Gomez and Gutierrez*, 2011; *Loch and Adamson*, 2015; *Ward and Pulido-Velazquez*, 2008].

To obtain the consumptive water use data for each sector (in our case 30 sectors, see Figure 2 for detailed list) in each Province, we first collected water use data at Provincial level. Among the sectors shown in Figure 2, the agricultural sector is defined as primary industry; sector of Coal Mining and Dressing to sector of Construction are defined as secondary industry; and sector of Freight Transport and Warehousing to sector of Other Services are defined as tertiary industry or service industry. The water use data of secondary industry in different Provinces is taken from the China Economic Census Yearbook 2008 [*The State Council Leading Group Office of Second China Economic Census*, 2008]. The water use data of primary and tertiary industry are from the Water Resource Bulletin in different Provinces [*Provincial Water Resources Bureau* (*PWRB*), 2007]. Water use data in each sector are then converted to water consumption by multiplying the water consumption coefficient for that sector, which is taken from Water Resource Bulletin in different Provinces [*PWRB*, 2007].

In China, water pollution data are generally lacking and the existing official statistics are often of poor quality. Statistics on agricultural nonpoint source pollution and water pollution data for individual sectors at the

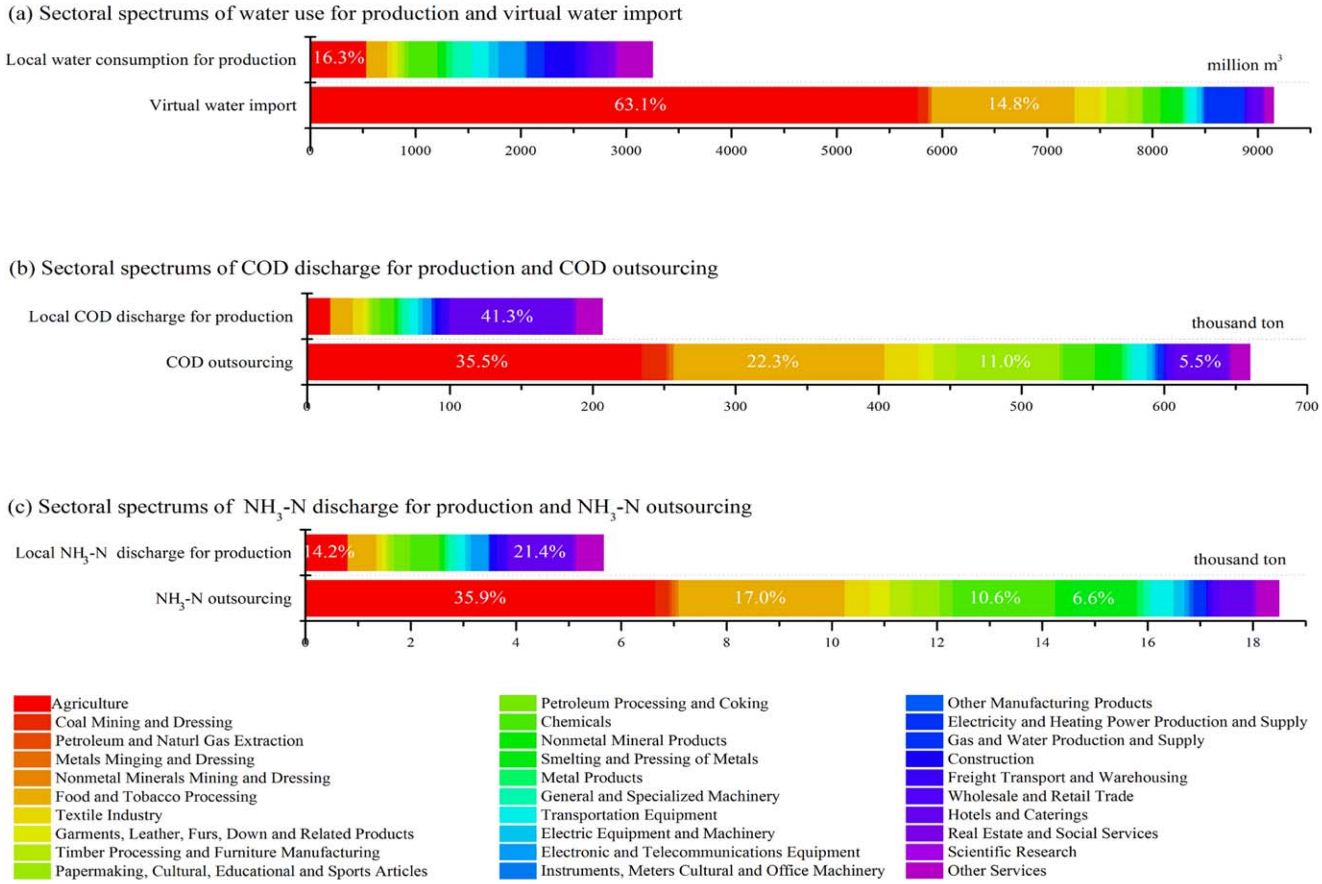


Figure 2. (a) Sectoral spectrums of water consumption for production and virtual water import. Percentages indicate the shares of the sectors in total water consumption; (b) Sectoral spectrums of COD for production and virtual COD outsourcing. Percentages indicate the shares of the sectors; and (c) Sectoral spectrums of NH$_3$-N for production and virtual COD outsourcing. Percentages indicate the shares of the sectors.

Provincial level are usually absent. This makes it difficult to study embodied water pollution for individual sectors in their inter-Provincial trade. In this study, we use data from the "First National Census on Pollution Source" (Hereby the Census) [*Editorial Board of First Pollution Census Data*, 2011]. The census took two years (2007–2009) and involved 5,925,600 enterprises/factories nationwide to investigate water pollution from agriculture and all types of sectors for the year 2007. The census assessed the basic situation of enterprises, main pollutants generated, and those discharged after end-of-pipe treatment for different kinds of pollution sources. Data on emission levels, main pollutants, and operating conditions of pollution control facilities were comprehensively investigated [*Yao et al*., 2016]. In this study, we choose the chemical oxygen demand (COD) and ammoniacal nitrogen (NH_3-N) as proxies of water quality. Both indictors are extensively used in China and throughout the world to measure water quality in surface water.

This study uses China's latest multiregion input-output table developed by *Feng et al*. [2013] as the database. The MRIO table is aggregated to 30 industrial sectors within the 30 Provinces of mainland China. For subsequent analysis, we highlight Agriculture; Food and Tobacco Processing; and Hotel and Catering i.e., "food related sectors." The latter two sectors are highly dependent on raw materials produced by the former. In this study, we focus on the impact of Shanghai's consumption on water quantity and quality to other Provinces within China. The virtual water, COD, and NH_3-N flows embedded in Shanghai's international trade are ignored. By setting the system boundary within China, virtual water export from Shanghai to other countries and COD and NH_3-N retained within Shanghai are assumed to be within the consumer responsibility of Shanghai.

4. Methods

4.1. The Water Embodied in Trade Method to Estimate Transactions Between Regions

To study the virtual quantity and quality of water flows between Shanghai and its trade partners, we applied the "Water Embodied in Trade" (WET) method [*Feng et al*., 2011], an equivalent method to that of "Emissions Embodied in Trade" (EET) [*Peters et al*., 2011]. We chose the WET model because it is more appropriate to study the environmental issues under bilateral trade [*Peters and Hertwich*, 2008].

For an economy of region r, the total output $\mathbf{x}^r$ (in vector form) is produced for intermediate consumption and final consumption. The intermediate consumption includes domestic purchase $\mathbf{Z}^{rr}$ and the sum of international purchase from different regions s (export from region r to s)$\sum_{s\neq r}\mathbf{Z}^{rs}$. Likewise, there are domestic purchases $\mathbf{y}^{rr}$and international purchases $\sum_{s\neq r}\mathbf{y}^{rs}$ for final consumption. Hence, the total output $\mathbf{x}^r$ is given by summing over intermediate and final consumption.

$$\mathbf{x}^r=\mathbf{Z}^{rr}+\sum_{s\neq r}\mathbf{Z}^{rs}+\mathbf{y}^{rr}+\sum_{s\neq r}\mathbf{y}^{rs} \tag{1}$$

In a WET/EET framework, the assumption is that bilateral trade between regions are all directed toward final consumption [*Peters and Hertwich*, 2008]. This means in equation (1) there is no international purchase of intermediate consumption, and the international purchase of intermediate consumption is assigned to the international purchase of final consumption. This means $\sum_{s\neq r}\mathbf{y}^{rs}$ is replaced by$\sum_{s\neq r}\mathbf{e}^{rs}=\sum_{s\neq r}\mathbf{Z}^{rs}+\mathbf{y}^{rs}$, where $\sum_{s\neq r}\mathbf{e}^{rs}$ represents the international purchase of final consumption under the WET/EET framework. We then have the formulation of "WET/EET."

$$\mathbf{x}^r=\mathbf{Z}^{rr}+\mathbf{y}^{rr}+\sum_{s\neq r}\mathbf{e}^{rs} \tag{2}$$

To solve $\mathbf{x}^r$ for any arbitrary final consumption, the technical coefficient $\mathbf{A}=Z/x$ was introduced which represents the intermediate inputs of each sector per unit of their output. In equation (2), let $\mathbf{Z}^{rr}=\mathbf{A}^{rr}\mathbf{x}^r$ where $\mathbf{A}^{rr}$ represents technical coefficients of domestic intermediate inputs:

$$\mathbf{x}^r=\mathbf{A}^{rr}\mathbf{x}^r+\mathbf{y}^{rr}+\sum_{s\neq r}\mathbf{e}^{rs} \tag{3}$$

Equation (3) can be solved as follows:

$$\mathbf{x}^r=(\mathbf{I}-\mathbf{A}^{rr})^{-1}\left(\mathbf{y}^{rr}+\sum_{s\neq r}\mathbf{e}^{rs}\right) \tag{4}$$

Equation (4) may be expanded to show the economic interrelationship among *p* regions, and the matrix form of WET/EET for *p* regions is shown below:

$$\begin{bmatrix} \mathbf{x}^1 \\ \vdots \\ \mathbf{x}^r \\ \vdots \\ \mathbf{x}^p \end{bmatrix} = \begin{bmatrix} \mathbf{A}^{11} & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & & \vdots \\ 0 & \cdots & \mathbf{A}^{rr} & \cdots & 0 \\ \vdots & & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & \mathbf{A}^{pp} \end{bmatrix} \begin{bmatrix} \mathbf{x}^1 \\ \vdots \\ \mathbf{x}^r \\ \vdots \\ \mathbf{x}^p \end{bmatrix} + \begin{bmatrix} \mathbf{y}^{11} + \sum_{s \neq 1} \mathbf{e}^{1s} \\ \vdots \\ \mathbf{y}^{rr} + \sum_{s \neq r} \mathbf{e}^{rs} \\ \vdots \\ \mathbf{y}^{pp} + \sum_{s \neq p} \mathbf{e}^{ps} \end{bmatrix} \quad (5)$$

4.2. Quantifying Virtual Water Trade Between Regions

To calculate the total direct and indirect virtual water trade between region *r* and other regions, Leontief multipliers of regional water consumption $\mathbf{m}^r$ are introduced as follows:

$$\mathbf{m}^r = \mathbf{d}^r (\mathbf{I} - \mathbf{A}^{rr})^{-1} \quad (6)$$

Where $\mathbf{m}^r$represents the vector of total direct and indirect consumptive water use to produce a unit of final consumption using water supply from region *r*. $\mathbf{d}^r = {}^{\mathbf{w}^r}/_{\mathbf{x}^r}$ is the vector of direct water use intensity of region *r* that represents the direct consumptive water use per unit of output in each sector. $\mathbf{w}^r$ is the vector of consumptive water use in each sector of region r.

The virtual water export from region *r* to other regions $\mathbf{vwe}^r$ can be calculated as follows:

$$\mathbf{vwe}^r = \mathbf{d}^r (\mathbf{I} - \mathbf{A}^{rr})^{-1} \sum_{s \neq r} \mathbf{e}^{rs} \quad (7)$$

The virtual water import of region *r*, $\mathbf{vwi}^r$, can be looked upon as the virtual water export from other regions to region *r*. So $\mathbf{vwi}^r$is calculated by summing over the virtual water export of other regions to region *r*:

$$\mathbf{vwi}^r = \sum_{s \neq r} \mathbf{d}^s (\mathbf{I} - \mathbf{A}^{ss})^{-1} \mathbf{e}^{sr} \quad (8)$$

where $\mathbf{d}^s$, $\mathbf{A}^{ss}$, and $\mathbf{e}^{sr}$ of region *s* are, respectively, direct water use intensity, technical coefficients of domestic intermediate inputs, and export from region *s* to region *r*.

In analogy to the carbon intensity of trade proposed by *Davis and Caldeira* [2010], we hereby introduce water intensity of trade which is the direct and indirect water consumption per unit of trade (in water volume per imports and exports). The water intensity of export (wie^r) and import (wii^r) for each region *r* can be expressed as follows:

$$wie^r = \sum_j \mathbf{vwe}^r / \sum_j \sum_{s \neq r} \mathbf{e}^{rs} \quad (9)$$

$$wii^r = \sum_j \mathbf{vwi}^r / \sum_{s \neq r} \mathbf{e}^{sr} \quad (10)$$

where $\sum_j \mathbf{vwe}^r$ and $\sum_j \mathbf{vwi}^r$ are the sum of virtual water export and import of region *r* for *j* sectors.

Finally, the above equations can also be used to study COD and NH_3-N outsourcing by replacing $\mathbf{w}^r$ with $\mathbf{o}^r$ or $\mathbf{n}^r$, which are the load of COD and NH_3-N, respectively.

4.3. Water Quantity and Quality Stress Index

In this study, the water quantity stress index I_q is calculated as the ratio of water withdrawal (W, m^3/yr) to annual renewable freshwater (Q, m^3/yr):

$$I_q = \frac{W}{Q} \quad (11)$$

We classify $I_q$into four levels: Extreme ($1 < I_q$); Severe ($0.4 < I_q < 1$); Moderate ($0.2 < I_q < 0.4$); and No stress ($0.2 < I_q < 0.4$).

Water bodies can be too polluted to provide any beneficial use, which may be termed "pollutant induced water scarcity" [*Liu et al.*, 2016]. Our water quality stress index (I_p) is designed to quantify the extent of pollutant induced water scarcity. Here we use the concept of the "grey water footprint" (G, m^3/yr), which means the volume of freshwater required to assimilate the pollutant load based on its ambient water quality standard and natural background concentration [*Hoekstra et al.*, 2011]:

$$G = \max\left(\frac{L}{C_{\max} - C_{nat}}\right) \tag{12}$$

where L (ton/yr) is the load of pollutants, $C_{\max}$ (mg/L) is the ambient water quality standard, and C_{nat}(mg/L) is the natural background concentration. $C_{\max}$ is derived from the Environmental Quality Standards for Surface Water [*Ministry of Environment Protection of China*, 2002]. Since Grade III of China's water quality grades represents the minimum quality of water that is suitable for fishery, aquaculture, and recreational use, it has been selected as $C_{\max}$. According to this standard, the maximum concentration ($C_{\max}$) of COD and NH_3-N are 20 and 1mg/L, respectively. C_{nat} is usually set as zero due to data limitations [*Zeng et al*., 2013]. $G$is calculated with the largest volume among the load of pollutants.

Thus, I_p may be calculated by the ratio of G to Q:

$$I_p = \frac{G}{Q} \tag{13}$$

According to criteria suggested by *Hoekstra et al*. [2011] and *Zeng et al*. [2013], if I_p is less than 1, this implies Q can assimilate the existing load of pollutants based on the local water quality standard. Hence, $I_p < 1$ is defined as no stress. In contrast, if I_p is greater than 1, then freshwater availability is insufficient to dilute the polluted water. We then subdivide water stress into three classes according to the proximity of the results cluster: Extreme ($5 < I_p$); Severe ($2 < I_p < 5$); and Moderate ($1 < I_p < 2$).

5. Results

5.1. Impact on Water Quantity From Shanghai's Consumption

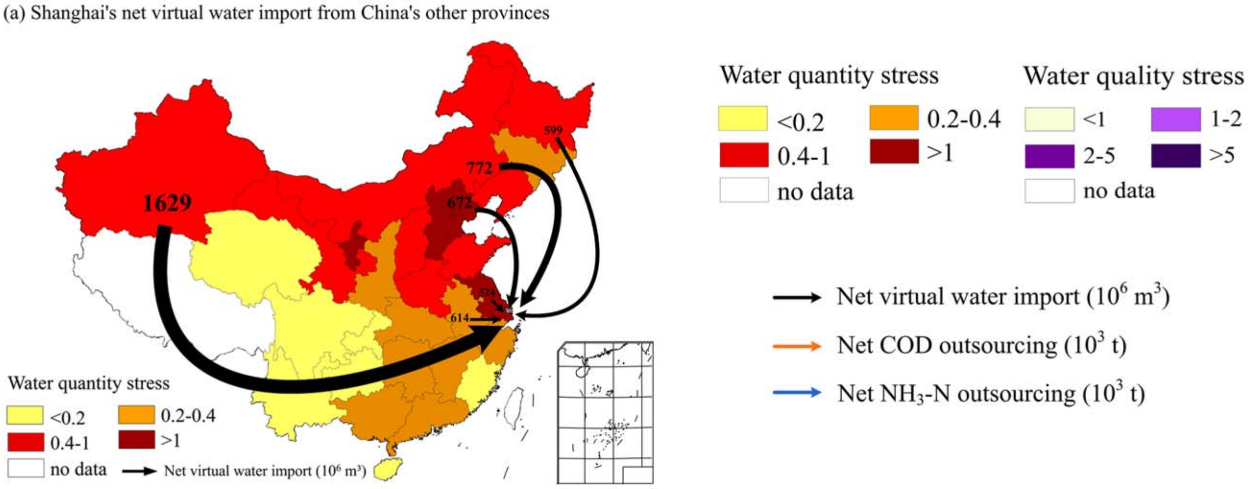
In 2007, 11.6 billion m^3 of water was consumed to support Shanghai's consumption of goods and services, of which 79% of virtual water (9.2 billion m^3) was imported from other Provinces. Shanghai's local water consumption for producing goods and services, drawing on local water supply, was 3.3 billion m^3 (Figure 2a).

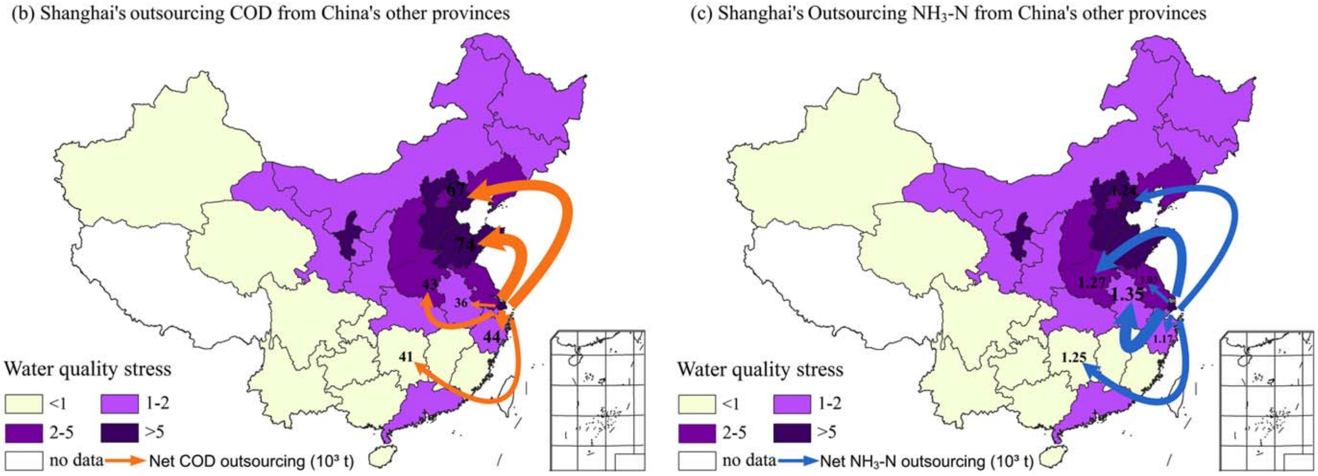
A further breakdown to production sectors showed that Shanghai's dependence on virtual water import from other Provinces is mainly from the "food related sectors" i.e., Agriculture, Food and Tobacco Processing, and Hotel and Catering. Shanghai's agricultural virtual water import was 5.8 billion m^3, accounting for 63% of total net virtual water import. Considering local and supply chain water consumption, Food and Tobacco Processing was the second largest virtual water importer, accounting for 15% of total virtual water import (1.35 billion m^3). The combined "food related sectors" accounted for 79% of virtual water import in Shanghai. These results suggest that Shanghai is supporting its citizens' lifestyles through importation of huge amounts of virtual water. In other words, from a water resource perspective, Shanghai is largely supported by other Provinces.

Twenty-five Provinces were net exporters of some 8357 million m^3 virtual water to Shanghai, while the remaining four Provinces were net importers of 15.6 million m^3 of virtual water from Shanghai. The top net virtual water exporting Provinces to Shanghai were Xinjiang, Inner-Mongolia, Hebei, Anhui, Heilongjiang, and Jiangsu (Figure 3a). These six Provinces together net exported 4811 million m^3 of water, sharing 56% of Shanghai's net virtual water imports.

Figure 3a shows the water quantity stress of the 30 studied Provinces. A surprising outcome is that Shanghai has the largest quantity-related water stress index amongst the 30 Provinces ($I_q = 3.8$). Such a large water stress suggests a severe overexploitation of local water resources. Apart from Shanghai, there are 13 Provinces showing extreme and severe water stress ($I_q > 0.4$). Northern China, owing to its poor water endowment and large water demand, suffers severe water stress. In contrast, southern Provinces in general do not endure quantity water stress (Figure 3a).

Combining the water quantity stress evaluation with Provincial net virtual water export to Shanghai, we found 60% of net virtual water import of Shanghai was from the 13 Provinces with extreme and severe water quantity stress ($I_q > 0.4$). The top net virtual water exporting provinces to Shanghai are all from northern China, and all experience different levels of water quantity stress. Hebei, for example, is among the most water scarce Provinces; however, it virtually exports 6.2% of its annual renewable water resources to Shanghai. A common feature of the major virtual water exporting Provinces is that they are major producers


(a) Shanghai's net virtual water import from China's other provinces


(b) Shanghai's outsourcing COD from China's other provinces

(c) Shanghai's Outsourcing NH_3-N from China's other provinces

Figure 3. (a) Shanghai's net virtual water import from other Provinces. The colors of the provinces indicate their water quantity stress status. The flows with arrows show the top net virtual water exporters to Shanghai. Only a net flow larger than 500 million m^3 is shown; (b) COD in other provinces due to the consumption of Shanghai. The direction of arrows from Shanghai to other provinces means that Shanghai outsources its COD to other Provinces. Only volumes larger than 35 × 10^3 tons are shown; (c) NH_3-N in other provinces due to the consumption of Shanghai. Only volumes larger than 1 × 10^3 tons are shown.

of agricultural products. In the top six net virtual water-exporting provinces, 78–98% of virtual water export to Shanghai is embedded in "food related sectors."

5.2. Water Quality Impact From Shanghai's Consumption

Shanghai's consumption of goods and services resulted in 796 thousand tons of COD and 16.2 thousand tons of NH_3-N in 2007. A large amount of this pollution was in the discharged wastewater of other Provinces due to Shanghai's consumption of goods and services. In 2007, the pollution outsourcing of Shanghai to other Provinces amounted to 660 thousand tons of COD and 18 thousand tons of NH_3-N, accounting for about 82.9% of the total COD and 82.5% of the total NH_3-N. In contrast, 207 thousand tons of COD and 5.7 thousand tons of NH_3-N were in the discharged wastewater for producing goods and services for Shanghai within its geographical boundary (Figures 2b and 2c).

In terms of sector distribution, secondary industry accounted for the largest share in pollutant outsourcing, accounting for 55.3% of COD outsourcing and 56.5% of NH_3-N outsourcing (Figured 2b and 2c) in 2007. Among these sectors, high COD outsourcing sectors included Food and Tobacco Processing (23.2% of COD outsourcing among all sectors); Papermaking, Cultural, Educational and Sports Articles (10%); Textile Industry (4.1%); and Chemicals (3.7%). While high NH_3-N outsourcing sectors were Food and Tobacco Processing (17% of NH_3-N outsourcing among all sectors); Chemicals (10%); and Smelting and Pressing of Metals (6.6%). Thirty five and a half percent of COD and 35.9% of NH_3-N were from primary industry.

In 2007, 19 Provinces experienced different levels of water quality stress ($I_p > 1$). Geographically, most Provinces suffering from water quality stress were located in northern China (Figures 3b and 3c). As a result, the poor water endowment in northern China was compounded by high water quality stress. Shanghai itself had an extreme water quality stress ($I_p > 5$), despite being to some extent able to relieve this stress through outsourcing of COD and NH_3-N to other Provinces.

Combining the Provincial water quality stress evaluation with Provincial net pollutant outsourcing, we found that 19 Provinces in water quality stress accounted for 79% of net COD outsourcing and 75.5% of net NH_3-N outsourcing from Shanghai. The top Provinces with different levels of water quality stress enduring Shanghai's net COD outsourcing were Shandong, Hebei, Zhejiang, and Henan. While the top Provinces enduring Shanghai's net NH_3-N outsourcing were Anhui, Henan, Hebei, Zhejiang, and Jiangsu. Hebei was found to endure the highest negative impact due to virtual water import and pollutant outsourcing from Shanghai, while also suffering from extreme water stress in terms of both quality and quantity.

5.3. Water Intensity of Trade

For any region, high water intensity of exports represents both the prevalence of highly water intensive products and low value of water intensive exports [*Davis and Caldeira*, 2010]. Our results show that Shanghai's consumption is supported by imports of water intensive goods and services.

In contrast, Shanghai exports low water intensive goods and services to other Provinces. In 2007, the water intensity of imports (9 m^3/thousand CNY) was 9 times higher than its water intensity of exports (1 m^3/thousand CNY). This means every 1 m^3 of water used in Shanghai on average produces 1000 CNY of goods and services exported to other Provinces which, in turn, can only produce 111 CNY of goods and services imported from other provinces. Most Provinces had a larger water intensity of export than Shanghai, with the exception of Beijing (0.5 m^3/thousand CNY) (Figure 4). Xinjiang, the largest virtual water exporter to Shanghai, also had the largest water intensity of export among all Provinces (77.6 m^3/thousand CNY).

Similarly, water intensity can be expressed in terms of water quality. The water pollutant intensity of trade is the direct and indirect water pollutant discharge per unit of trade (in this case in COD and NH_3-N volume per unit of import and export). In 2007 in Shanghai, the COD and NH_3-N intensity of imports (649 ton/billion CNY and 17.8 ton/billion CNY) were more than 7 times larger than the COD and NH_3-N intensity of exports (89 ton/billion CNY and 2.3 ton/billion CNY). Shanghai had both the lowest COD and NH_3-N intensity of

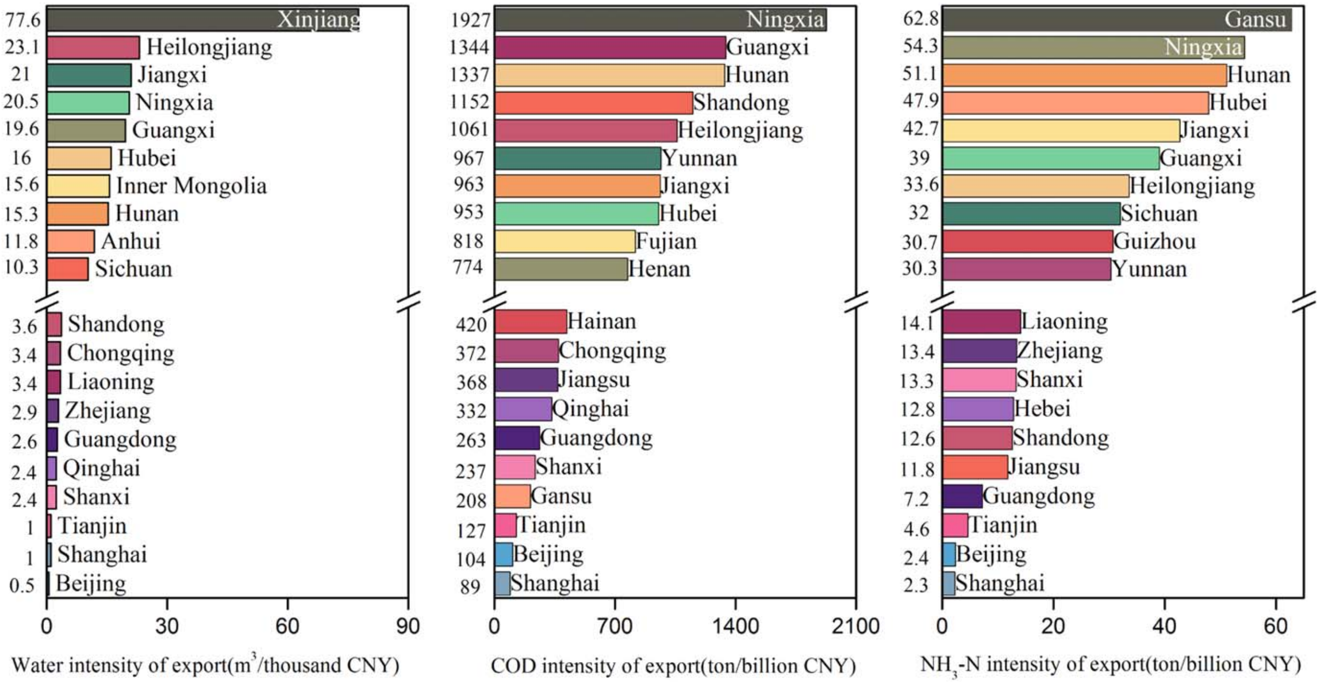


Figure 4. Water intensity of export of top 10 largest and lowest Provinces in China.

exports among all Provinces. Ningxia had the largest COD intensity of exports (1927.3 ton/billion CNY), which was about 21 times larger than Shanghai. Gansu had the largest NH_3-N intensity of exports (62.3 ton/billion CNY), about 27 times larger than Shanghai.

6. Discussion and Conclusions

This study investigated the extent to which a megacity in China can shift the burden of both water quantity and quality stress to regions outside its territory from a consumption-based perspective. For the first time, we have quantified the virtual water transfer in terms of water quality and evaluated its impact on Provincial water quality stress in China. The results show that Shanghai as a megacity not only imported a large amount of virtual water, but also outsourced a large fraction of COD and NH_3-N, which further aggravated the water stress in some exporting Provinces. We thus suggest the construction of mechanisms, regulations, and decision-making systems to tackle the problem of burden shifting of both water quantity and quality stress within China.

It should be noted that in recognizing increasing water quantity and quality stress, in 2011 the Chinese government implemented "the most stringent water resources management policy." An important act of the policy is to set quantitative targets for water use, water use efficiency, and water pollution at both national and Provincial levels for 2020 and 2030, i.e., the so-called "three redlines" [*Liu et al.*, 2013]. Our study demonstrates that Shanghai can meet these targets at the cost of exporting Provinces which provide virtual water to it and at the same time receive its outsourced pollution. We believe that the implementation of the "three redlines" will stimulate a wider discussion of equality in fulfilling targets in different Provinces. Therefore it is important to discuss this shared responsibility. Against this background, we propose two possible solutions to tackle the burden-shifting problem of the megacity.

First, shared responsibility between megacities and water intensive exporters need to be considered in the context of the "three redlines" to achieve water management targets. Shared responsibility can be implemented at different levels. At Provincial level, given the initial market mechanism introduced for China's environmental management, fiscal transfer may be more suitable under the current political system. A pilot project can first be established with fiscal aids from national support and Shanghai's self-raising funds to build on the mechanisms of fiscal transfers from Shanghai to the affected provinces. At company level, the Extended Producer Responsibility, i.e., producers take responsibility for their upstream activities inherent in the selection of materials and in the design of products [*Lenzen et al.*, 2007], can be promoted. The development of both environmental penalty and certification mechanisms will accelerate the process of the Extended Producer Responsibility. At consumer level, more and more consumers in China are willing to pay for environmental protection [*Ding et al.*, 2016*; Li et al.*, 2016*, Shen*, 2012]. Successful design from environmental protection organizations and NGOs can develop the channels which allow consumers to pay to offset their impact on water resources in the exporting areas, for example through incorporation into water stewardship activities (http://allianceforwaterstewardship.org/about-aws.html#what-is-water-stewardship).

Second, conducting demand side management from a consumption-based perspective. Governmental strategies on sustainable water management usually focus on local water consumption through supply side management and efficiency measures, but largely ignore the potential for demand side management [*Feng et al.*, 2012]. However, as shown in our study, Shanghai's impact from its consumption of goods and services on water resources outside of its administrative boundary, or in other words the indirect impact, can be much larger than the direct impact on local water resources. A demand side management from the consumption-based perspective is to control such indirect impact. There are two ways of reducing the indirect impact: one is to change the consumption pattern, such as reducing the consumption of products with high water quantity and quality impact, for example meat products, which has the largest share of water consumption among food related sectors. Relying mainly on external input of food-related products, Shanghai has increased its consumption of meat products by 262% from 1980 to 2010 [*Shanghai Municipal Bureau of Statistics*, 1981−2011]. Propagating such information to consumers is the first step toward encouraging less meat consumption. The other way is to allow consumers to make informed choices about goods and services with reduced water impact. This will require information which shows the water impact of goods and services at sector and product level. Our analysis is helpful in highlighting the key sectors in which consumers have large impact, and could help consumers in making informed choices.

This study conducted a novel analysis of Shanghai's burden shifting of water quantity and quality stress to its trade partners, and addressed aspects of sharing responsibility for improving water resources management with its trade partners. However, we would like to recognize some limitations of this study. First, the boundary of our study is limited to China. Due to data limitations, we were unable to calculate Shanghai's COD and NH_3-N outsourcing to other countries. Such boundary setting is commonplace, and can be seen in similar studies [e.g., *Guan and Hubacek*, 2007; *Zhang and Anadon*, 2014; *Zhang et al*., 2011]. Second, a WET framework assigns the bilateral trade only into final consumption without considering the impact from intermediate import. The situation whereby exporters import intermediate products (e.g., raw materials) from upstream industries and produce the final products with those raw materials and reexport the products to final consumers cannot be accounted for. The relevant discussions on the problems and possible solutions can be found in other works [e.g., *Zhao et al*., 2010, *Lenzen et al*., 2007].

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