**Title: Worse than imagined: Unidentified virtual water flows in
China**

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Abstract:

The impact of virtual water flows on regional water scarcity in China had been deeply discussed in previous research. However, these studies only focused on water quantity, the impact of virtual water flows on water quality has been largely neglected. In this study, we incorporate the blue water footprint related with water quantity and grey water footprint related with water quality into virtual water flow analysis based on the multiregional input-output model of 2007. The results find that the interprovincial virtual flows accounts for 23.4% of China's water footprint. The virtual grey water flows are 8.65 times greater than the virtual blue water flows; the virtual blue water and grey water flows are 91.8 and 794.6 Gm³/y, respectively. The use of the indicators related with water quantity to represent virtual water flows in previous studies will underestimate its impact on water resources. In addition, the virtual water flows are mainly derived from agriculture, chemical industry and petroleum processing and the coking industry, which account for 66.8%, 7.1% and 6.2% of the total virtual water flows, respectively. Virtual water flows have intensified both quantity- and quality-induced water scarcity of export regions, where low-value-added but water-intensive and high-pollution goods are produced. Our study on virtual water flows can inform effective water use policy for both water resources and water pollution in China. Our methodology about virtual water flows also can be used in global scale or other countries if data available.

Keywords: Virtual water flows; Water footprint; Water scarcity; Multiregional input-output analysis

1. Introduction

China has been experiencing serious water scarcity problems in the presence of rapid socioeconomic development, climate change, rapid urbanization and industrialization (Liu and Yang, 2012; Piao et al., 2010). A spatial distribution mismatch between available water resources and water demand along with the degraded water quality constitute the main causes of water scarcity in China (Dalin et al., 2014; Zhao et al., 2015). Northern China uses 19.1% of total water resources to satisfy water demand for 45.2% of country's population (Jiang, 2009). Currently, 14.9% of the total rivers and 26.1% of all lakes present water quality that cannot be used for any purpose (Ministry of Water Resources., 2014). Most regions in China face water scarcity issues. Local water problems cannot be only treated locally, as virtual water flows between regions can redistribute water resources and pollution discharge (Hoekstra and Hung, 2002; Marston et al., 2015).

However, the impact of virtual water flows on local water resources has generally been neglected in government policy-making (Hoekstra and Mekonnen, 2012). Moreover, local governments lack a comprehensive understanding of sustainable water use when they focus exclusively on water use in their own territories (Vorosmarty et al., 2015). Many regions outsource their water demand or environmental impacts through trade without considering water consumption or pollution of imported products occurring in producing regions (Hoekstra and Mekonnen, 2012). For example, previous study had pointed out that the developed countries (like USA and EU) had imported lots of product with large volume of water consumption or water pollution discharge to sustain their own consumption from the undeveloped countries (like African countries) (Carr et al., 2015; Lutter et al., 2016; O'Bannon et al., 2014; Suweis et al., 2013; Wang et al., 2016b). Information on virtual water flows is of relevance to local governments, especially in terms of water resources utilization planning and water scarcity mitigation measures (Antonelli and Sartori, 2015).

Previous studies have presented in-depth discussions on virtual water flows and its

1 impact on local water resources in China. Dalin and colleagues (Dalin et al., 2014;
2 Dalin et al., 2015) found that the virtual water flows related to agricultural products
3 trade among China can save blue water. Zhuo and colleagues found that the virtual
4 water had transferred from water-scarce North to water-rich South since 2000 in China
5 (Zhuo et al., 2016). Zhao and colleagues (Zhao et al., 2015) show that physical and
6 virtual water cannot mitigate the regional water stress. Other studies have assessed
7 virtual water flows and their impact on local water scarcity based on multiregional
8 input-output model (Dong et al., 2014; Feng et al., 2014; Zhang and Anadon, 2014).
9 Previous studies have shown that virtual water flows account for more than 30% of all
10 water use in China (Dong et al., 2014; Feng et al., 2014; Zhang and Anadon, 2014;
11 Zhao et al., 2015). Moreover, virtual water flows have not mitigated water scarcities of
12 water-importing regions and have aggravated water shortage problems
13 of water-exporting regions (Zhao et al., 2015). These studies only discussed the impact
14 of trade between regions on water consumption or withdrawal related to water
15 quantity. Trade between regions also leads to the outsourcing of wastewater discharge
16 and affects local water quality (Vorosmarty et al., 2015), but the impact of trade
17 between regions on local water quality had been largely neglected in previous studies.

18 The water footprint (WF) is an indicator that can be used to bridge this gap.
19 Unlike government water use accounts, which primarily focus on water withdrawal or
20 water consumption, the WF measures the appropriation of water resources for human
21 activities and includes three components: blue, green and grey. The blue WF refers to
22 surface and groundwater consumption, the green WF refers to the volume of rainwater
23 consumption, and the grey WF is defined as the volume of freshwater needed to
24 assimilate the load of pollutants based on natural background concentrations and
25 existing ambient water quality standards (Franke et al., 2013). Since Hoekstra et
26 al. (Hoekstra, 2003) first introduced the WF concept, several studies on WF
27 assessments have been conducted in China, at the local level (Zeng et al., 2013), in
28 reference to river basins (Feng et al., 2012) and at the national scale (Zhao et al.,
29 2009). However, these studies seldom consider the grey WF. Even when the grey WF
30 has been considered, it has been determined only in reference to a single pollutant like

chemical oxygen demand(Zeng et al., 2013; Zhi et al., 2015) or nitrogen (Mekonnen and Hoekstra, 2015).

The objective of this study is to estimate the WF of China at the provincial level and the impact of virtual water flows on local water scarcity. As the blue WF and grey WF show different implications(Aldaya et al., 2012), we calculated the blue and grey WF separately and discussed the impact of virtual blue and grey water flows on regional quantity and quality induced water scarcity separately. The green WF is not considered here because it is not directly accessible for alternative human uses and without contribution to blue water scarcity(Zhao and Chen, 2014). First, the WF of each province in 2007 was estimated which included agriculture, industry, services sectors and direct household WF from the water used and related pollutant discharge for cooking, washing clothes, bathing and other activities in home. Second, virtual water flows within China were assessed through the incorporation of blue and grey WF for 30 economic sectors of each province into an extended environmental multiregional input–output model (MRIO). Finally, the effects of virtual water flows on regional water scarcity were measured in terms of both quantity and quality by identifying the water scarcity regions and then determining whether the virtual water flows had intensified or mitigated the regional water scarcity.

Compared to previous research, our calculations of WF and virtual water flows are more comprehensive and precise. First, unlike previous studies on grey WF calculations, which have primarily focused on one area(Zeng et al., 2013) or one sector (e.g., agriculture(O'Bannon et al., 2014)), the grey WF for 30 sectors and the households of each province were calculated, as well as its effects on local water quality. Second, our grey WF calculations account for 8 pollutants (see Materials and Methods) rather than that previous studies considered only one pollutant (e.g., nitrogen or chemical oxygen demand)(Mekonnen and Hoekstra, 2015; Zeng et al., 2013; Zhi et al., 2015). The grey WF is an indicator that is based on the assimilation capacity of a water body, and assimilation capacity values vary when different pollutants are considered(Wang et al., 2013). When more pollutants are considered, a more precise grey WF value is obtained. Third, the grey WF was incorporated into an analysis of

virtual water flows to estimate its impact on local water quality which had not been done in most previous studies about virtual water flows in China.

2. Materials and Method

2.1 Blue Water Footprint

The blue water footprint for different sectors is primarily derived from the Water Resources Bulletin (WRB) for each province and from the Environmental Statistics Database 2007(ESD)(State Environmental Protection Administration., 2007). The WRB and ESD data were for the same year 2007. The WRB and ESD are the official statistics in China, these two had been widely used in previous study, such as (Feng et al., 2014; Guan et al., 2014; Wang et al., 2016a; Zhang and Anadon, 2014) which discussed about the embodied water consumption or water pollution in interregional trade:

For the blue water footprint calculation, it is generally accepted that the volume of water consumption equated to blue water footprint(Aldaya et al., 2012; Feng et al., 2014) and blue water footprint is defined as surface or ground water consumption in this study. The WRB included the water consumption data for agriculture, industry, services sector and household. The blue water footprint for agriculture, services sectors and households for each province in 2007 derived from the WRB for each province (see Table S2 for data). Water consumption data for services sectors are aggregated at the provincial level, and we assume that water consumption intensity for each service sector are the same in a province based on other research studies(Feng et al., 2014; Guan et al., 2014). The blue water footprint for industrial sectors was calculated through using the volume of water withdrawal and wastewater discharge(Zhang and Anadon, 2014), with data both derived from the ESD. The ESD included the water withdrawal and wastewater discharge for industrial enterprise. The calculation of blue water footprint for industry sectors is based on three processes.

First, we calculated the water consumption (WC) of each industrial enterprise.

We use the volume of water withdrawal minus wastewater discharge to get the waterconsumption for each enterprise for sector i in province j .

$$WC_{ij} = WW_{ij} - WD_{ij} \quad [1]$$

where WC_{ij} is the water consumption for each industrial enterprise of sector i in province j . The WW_{ij} and WD_{ij} are the volume of water withdrawal and wastewater discharge for each industrial enterprise respectively.

Second, we summed the water consumption data for each enterprisebased on different industrial sectors in a province.

$$BWF_{ij}^* = \sum_{i=n} WC_{ij} \quad [2]$$

where BWF_{ij}^* is the blue water footprint for industry sector i in province j based on the data from ESD. However, the ESD have not included all industrial enterprises for each province, we have to adjust the blue water footprint for each industrial sectors in a province.

$$BWF_{ij} = BWF_{ij}^* \times I_{bj} \quad [3]$$

where BWF_{ij} is the final blue water footprint for sector i in province j used in this study, the I_{bj} is the adjustment coefficient (calculated by equation 4)for province j . We have multiplied the blue water footprint for each industry sectors derived from ESD by the I_{bi} to get the final blue water footprint for each industry sectors in a province.

The I_{bj} is calculated by dividing the water consumption data of industry from WRB (see SI, Table S2 for data) by data of industry from ESD for province j .

$$I_{bj} = \frac{WC_{icj}}{BWF_{icj}^*} \quad [4]$$

where WC_{icj} is the water consumption for industry of province j which derived from WRB for each provinces; the BWF_{icj}^* is the water consumption for industry of province j which was calculated by the sum of BWF_{ij}^* based on the data from ESD.

2.2 Grey Water Footprint

The grey water footprint refers to the volume of water needed to assimilate pollutant loads based on water quality standards(Aldaya et al., 2012). The grey water footprint (GWF)is calculated by dividing the pollutant load ()by the difference between the ambient water quality standard for that pollutant and its natural concentration in the receiving water body(Aldaya et al., 2012).

$$GWF = \max_{r-i} \left(\frac{L_r}{C_{rm} - C_{rn}} \right) \quad [5]$$

where the L_r is the pollutant load of pollutant r , C_{rm} is the maximum acceptable concentration of pollutant r which is decided by the water quality standard. The C_{rn} is the natural concentration of pollutant r in the receiving water body with no human disturbance in the catchment and usually has been assumed as 0(Franke et al., 2013). In this study, the C_{rm} has been defined as the concentration of pollutants of Grade III according to the Environmental Quality Standards for Surface Water in China(State Administration of Quality Supervision and Environmental Protection., 2002)(see SI, Table S7 for data). The Grade III indicates the water is suitable for fish, aquaculture and swimming and it is also usually used as an indicator to show the water quality in China, such as the proportion of the river length or the proportion of the fracture surface with water quality standard below Grade III and so on. If there are different kinds of pollutants, the GWF_r of each pollutant were calculated and the final GWF should be the maximum between different GWF_r of pollutants.

2.2.1 Grey water footprint for agriculture

For agriculture, we considered main pollutant emissions (COD, nitrogen, phosphorus and $\text{NH}_3\text{-N}$) from fertilizer application for crop production, livestock and poultry industry as well as aquaculture industry. The L_r in equation 5 for agricultural sector equated to the volume of four pollutant emissions from agriculture at the provincial level and the data came from the First Pollution Sources Census(FPSC)(First Pollution Sources Census Data Editorial Board., 2010)(see SI,

1 Table S4).

2 2.2.2 Grey water footprint for industry sectors

3 The L_r in equation 5 for industrial sectors equated to the volume of COD, NH₃-N,
4 petroleum pollutant, volatile phenol, plumbum and mercury discharge which derived
5 from the ESD. The L_r is the pollution load in wastewater discharge. The L_r for industry
6 sector is calculated by the following processes.

7 First, the ESD included the 6 pollutants load data for each industrial enterprise.
8 We summed the 6 pollutant load data for each enterprise based on different sectors
9 and then we got the volume of 6 pollutant discharge for each sectors of industry in a
10 province.

$$11 \quad L_{rij}^* = \sum_{i=n} D_{rij} \quad [6]$$

12 where L_{rij}^* is the pollution load of pollutants r for industry sector i in province j
13 based on the data from ESD, D_{rij} is the discharge of pollutant r for each enterprise
14 in province j . The volume of emission from the industrial enterprises in ESD only
15 contains 85% of the whole nation rather than the total. We need to adjust the L_{rij}^* for
16 each sectors of industry based on the data from ESD.

$$17 \quad L_{rij} = L_{rij}^* \times I_{rj} \quad [7]$$

18 where L_{rij} is the pollution load used for the calculation of grey water footprint
19 of industry sectors, I_{rj} is the adjustment coefficient (calculated by equation 8) of
20 pollutants r for province j . We multiplied the 6 pollutants discharge data for each
21 industry sectors based on the data from ESD by the I_{rj} and then we got the final 6
22 pollutants load for industry sectors in a province. Finally, we calculated the grey
23 water footprint for each sectors of industry at province level based on the equation 5.

24 The I_{rj} is calculated by dividing the 6 total industry pollutants discharge data
25 derived from Environment Statistical Yearbook 2008 (State Statistics Bureau., 2008b)
26 (see Table S6 for data) by data derived from ESD for each province.

$$I_{rj} = \frac{L_{rjdj}}{L_{rjdj}^*} \quad [8]$$

where L_{rjdj} is the volume of r pollutants load for the second industry of province j based on the data from Environmental Statistical Yearbook 2008¹, L_{rjdj}^* is the r pollutants discharge for industry of province j which was calculated by the sum of L_{rjdj}^* based on the data from ESD.

2.2.3 Grey water footprint for services sectors and household

For the services sectors and household, we considered COD and NH₃-N discharge. In China, the COD and NH₃-N discharge for services sectors and household have been aggregated as domestic pollution discharge by the Environment Statistical Yearbook(State Statistics Bureau., 2008b). We first derive the ratio of theregional water pollutant emissions (COD and NH₃-N) of service sectors to total domestic pollution discharge according to FPSC.Secondly, we allocated the water pollutant emissions from domestic pollution discharged in Environmental Statistics Yearbook 2007 to services sectors based on the respective ratio derived(Wang et al., 2016a). Thirdly, sectoralemissions for service sectors of each regioncan be averaged based on the respective sectoral output in MRIO for eachregion like previous researchesdid (Guan et al., 2014) and then we got the COD and NH₃-N discharge data for services sectors in a province. Finally, we calculated the grey water footprint of services sectors and household in a province based on the equation 5.

2.3 Water Scarcity Assessment

2.3.1 Water Quantity Scarcity Index(WQSI)

WQSI refers to the water scarcity arising from water consumption from local water resources in this study. It can be expressed as the ratio of the blue water

¹ This is the official statistics which included the monitored industrial enterprises, while the unmonitored pollution would be missing. As a result, the data was conservative.

footprint to the blue water available. The blue water availability was calculated as natural runoff which is equal to the total annual amount of surface and groundwater flows (data see Table S3) minus environmental flow requirement. We did not use the water withdrawal as an indicator to show the water quantity scarcity, for the water withdrawal partly returns to the catchment and this returned water made no contribution to the water scarcity (Hoekstra and Mekonnen, 2011). The environmental flow requirements are defined as the ‘quantity, timing and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihood and well-being that depend on these ecosystems’ (Poff et al., 2010). In order to establish the environmental flow requirement we have adopted the “presumptive environmental flow standard” as proposed by Richter et al. (Richter et al., 2012) and Aldaya et al. (Aldaya et al., 2012; Richter et al., 2012) based on the sustainability boundary approach of Richter which involves restricting hydrological alterations to within a percentage-based range around natural or historic flow variability (Richter, 2010). According to Richter et al. (Richter et al., 2012) 20 percent of the natural runoff can be considered as the blue water available for human use without affecting the integrity of the water-dependent ecosystems. As a result, if the $WQSI > 0.2$, the regions would face quantity-induced water scarcity.

2.3.2 Water Quality Scarcity Index (WQASI)

WQASI refers to the water scarcity arising from the pollutants discharge; in this study it was defined as the ratio of grey water footprint to the amount of local water resources availability. If the $WQASI > 1$, it means the local available water resources are not enough for the assimilation of the pollutants discharge and a given region faces quality-induced water scarcity problems (Zeng et al., 2013).

2.4 Using the MRIO to Calculate Interprovincial Virtual Water Flows

The multiregional input–output model (MRIO) has been widely used for the assessment of virtual water flows between regions (Feng et al., 2014; Lenzen et al.,

2013; Zhao et al., 2015). In a MRIO framework, different regions are connected through inter-regional trade. The technical coefficient submatrix A^{rs} is composed of a_{ij}^{rs} elements, which are derived from $a_{ij}^{rs} = z_{ij}^{rs} / x_j^s$, where z_{ij}^{rs} is the intersector monetary flow from sector i in region r to sector j in region s and where x_j^s is the total output of sector j in region s . The final demand matrix Y includes $[y_i^{rs}]$ elements, where y_i^{rs} denotes the final demand in region s for goods produced in region r . Therefore, the MRIO analysis can be written as:

$$\begin{bmatrix} x_1 \\ \vdots \\ x_r \\ \vdots \\ x_n \end{bmatrix} = \begin{bmatrix} A_{11} & \cdots & A_{1r} & \cdots & A_{1p} \\ \vdots & \ddots & \vdots & & \vdots \\ A_{r1} & \cdots & A_{rr} & \cdots & A_{rp} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ A_{n1} & \cdots & A_{nr} & \cdots & A_{nn} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_r \\ \vdots \\ x_n \end{bmatrix} + \sum_n \begin{bmatrix} y_{1r} + \sum_{s \neq 1} y_{1s} \\ \vdots \\ y_{rr} + \sum_{s \neq r} y_{rs} \\ \vdots \\ y_{nr} + \sum_{s \neq n} y_{ns} \end{bmatrix} \quad [9]$$

Using familiar matrix notation and dropping the subscripts, equation 9 can be written as $x = Ax + y$ or $x = (I - A)^{-1}y$, where $(I - A)^{-1}$ is the Leontief inverse matrix that captures both direct and indirect inputs required to satisfy one unit of final demand in monetary value and where I is the identity matrix. The MRIO used in this study included 30 sectors in 30 Chinese provinces at the year of 2007 (Liu WD, 2012).

To calculate virtual water flows between regions, the MRIO table was extended with the sector-specific water footprint:

$$WF_i = f_i x_i = f_i (I - A_i)^{-1} y_i \quad [10]$$

where WF_i is the vector of water footprint (sum of blue and grey water footprint) for each sector of region i , x_i is the total economic output of region i , f_i is the vector of direct water footprint intensity which shows the direct water footprint per unit of output in each sector, y_i is the vector of final demand, A_i is the matrix of technical coefficients and I is the unit matrix. As the methods show that the direct and indirect WF had been calculated through the MRIO.

The variable x_i can be calculated as:

$$x_i = A_{ii} x_i + y_{ii} + \sum_{r \neq i} e_{ir} \quad [11]$$

where A_{ii} represents the domestic technical coefficients, and y_{ii} shows the

domestically produced products to fulfill final demand. The export from region i to region r ($e_i = \sum_{r \neq i} e_{ir}$) is the total bilateral trade (Weber and Matthews, 2007). Thus, the equation 10 can be shown as

$$WF_i = f_i x_i = f_i (I - A_{ii})^{-1} (y_{ii} + \sum_{r \neq i} e_{ir}) \quad [12]$$

Then, the total water footprint in region i can be decomposed as:

$$WF_i = f_i x_i = f_i (I - A_{ii})^{-1} y_{ii} + f_i (I - A_{ii})^{-1} \sum_{r \neq i} e_{ir} = WF_i + vwe_{ir} \quad [13]$$

where WF_i represents the water footprint to satisfy the domestic and final demand, and the vwe_{ir} is the total virtual water export from region i to region r . Besides the total virtual water flows between regions, we also calculated the virtual blue and grey water flows through the same methods.

3. Results

3.1 China's Water Footprint

The total WF for China was 3778.1 Gm³/y in 2007, with agriculture, the household and chemical industry being the major contributors to the total WF in China (see Fig. 1). These three sectors accounted for 81.8% of the total WF in China. Agriculture presents the largest WF among the various sectors examined, representing 49.9% of the total WF which is 1885.3 Gm³/y. Agriculture accounted for 76.1% of all water consumption at 225.0 Gm³/y in 2007. Moreover, the grey WF of the agricultural sector accounted for 47.7% of the total grey WF at 1660.87 Gm³/y. In addition to agriculture, households represent the second largest WF among the various sectors examined which accounts for 26.1% of the total WF. Households were one of the most significant water pollution emitters; chemical oxygen demand (COD) and ammonia nitrogen (NH₃-N) from households represented 27.3% and 62.2% of all these two pollutants' emission for the entire country respectively. In turn, the grey WF for household is also one of the largest, accounting for 27.5% of the total grey WF. As a result, the major agricultural and populous regions like Henan, Shandong and

1 Guangdong provinces show larger WF than other provinces. The chemical industry
2 generated the third largest WF among the various sectors examined, accounting for 5.1%
3 of the total WF. The grey WF of chemical industry holds about 5.5% of the total grey
4 WF.

5 The grey WF was the most significant WF value in 2007, representing 91.3% of
6 the total. At the provincial scale, the grey WF was also the largest contributor to the
7 local WF. The average blue WF share of the WF was only 9.2% for the various
8 provinces studied and ranged from 1.66 Gm³/y for Tianjin to 33.55 Gm³/y for
9 Xinjiang. The average share of the grey WF relative to the WF was 90.8 % for each
10 province and ranged from 13.58 Gm³/y for Qinghai to 351.63 Gm³/y for Shandong in
11 2007 (see Fig 2). More water resources were appropriated to water pollutant
12 emissions resulting from production and daily living than to direct water consumption
13 at the provincial level. More water resources were appropriated in order to meet water
14 quality objectives caused by water pollutant emissions resulting from production and
15 daily living than to direct water consumption at the provincial level.

Figure 1. Composition of total water footprint for each province (Unit: Gm³/y)
(the whole picture for 30 sectors can be found in SI, Figure S1)

Regions that have experienced higher levels of economic development present higher degrees of water use efficiency (the ratio of the volume of blue water footprint to regional GDP) and lower grey WF intensity. Developed coastal areas such as Beijing,

Guangdong and Shanghai present lower blue and grey WF intensity than undeveloped inland regions such as Xinjiang, Heilongjiang and Henan (see Fig.2). Undeveloped regions such as Xinjiang were the most significant water consumers, representing 12.4% of all water consumption in China, whereas the GDP accounted for only 1.3% of the GDP of country. Compared to Xinjiang, developed regions such as Beijing represented 3.4% of the total GDP but only 0.8% of total water consumption. Undeveloped regions also present higher water pollutant emissions intensity; for example, COD and NH₃-N emissions originating from Heilongjiang accounted for 3.7% and 3.9% of the total, respectively, whereas GDP accounted for only 2.5% of that for the entire country. However, economically developed regions such as Guangdong accounted for 11.3% of China's GDP, whereas COD and NH₃-N emissions represented only 7.6% and 8.9% of the total in 2007, respectively.

Figure 2. Water footprint and water footprint intensity for each province. *Left:* water footprint at provincial level (Gm³/y) *Right:* water footprint intensity at provincial level (m³/¥1000 GDP)

3.2 Water Scarcity Assessment

Based on the calculation of WQSI and WQASI for each province, our results

show most regions in China face either quantity- or quality-induced water scarcity issues. According to our assessment of water scarcity, only 8 provinces did not face water scarcity problems in 2007, as Fig. 3 shows. Eight provinces presented quality-induced water scarcity issues, denoting that available water resources in these provinces are not sufficient for the assimilation of water pollutant discharge. Xinjiang presented only quantity-induced water scarcity issues. Meanwhile, 13 other provinces faced both quantity- and quality-induced water scarcity issues.

8

9 **Figure 3. Water scarcity levels for different provinces.** WQSI and WQASI are
10 indicators for quantity and quality-induced water scarcity, respectively: a. regions
11 facing both quantity and quality-induced water scarcity ($WQSI > 0.2$ and $WQASI > 1$),
12 b. regions facing quality-induced water scarcity ($WQSI < 0.2$ and $WQASI > 1$), c.
13 regions without water scarcity ($WQSI < 0.2$ and $WQASI < 1$), d. regions facing
14 quantity-induced water scarcity ($WQSI > 0.2$ and $WQASI < 1$).

15 3.3 Virtual Water Flows Between Provinces

16 Virtual grey water flows account for a much larger proportion of total virtual
17 water flows than virtual blue water flows. Virtual water flows between the provinces

1 were recorded at 886.6 Gm³/y, accounting for 23.4% of the total WF for China.
2 Virtual blue water flows amounted to only 91.8 Gm³/y and represented 30.5% of the
3 total blue WF. Meanwhile, virtual grey water flows were 8.65 times larger than virtual
4 blue water flows, which reached 794.6 Gm³/y and accounted for 22.9% of the total grey
5 WF.

6 At the provincial level, virtual blue water and grey water flows intensified
7 quantity- and quality-induced water scarcity of the exporting regions. The major net
8 blue water exporters were identified: Xinjiang, Heilongjiang and Inner Mongolia (see
9 Fig. 4a). Virtual blue water export volumes for these regions accounted for 44.1%, 56.3%
10 and 47.4% of local blue WF, respectively. Meanwhile, these regions also faced
11 quantity-induced water scarcity issues. Virtual blue water flows intensified water
12 scarcity issues for 6 provinces besides the major blue water exporters, which already
13 faced quantity-induced water scarcity issues. Seven provinces that faced
14 quantity-induced water scarcity problems had got a benefit from virtual blue water
15 imports. Developed regions such as Beijing, Tianjin and Shanghai especially
16 benefitted, accounting for 21.4% of all virtual blue water imports (see SI, Fig. S8).
17 Important net exporters of virtual grey water included Hebei, Heilongjiang and
18 Henan, which presented quality-induced water scarcity issues (see Fig. 4b); virtual grey
19 water export volumes accounted for 41.4%, 36.9% and 27.7% of local grey WF in
20 these areas, respectively. Virtual grey water flows intensified water scarcity conditions
21 in 10 provinces besides the major virtual grey water exporters. Developed regions
22 like Guangdong, Shanghai and Beijing were the main net virtual grey water importers,
23 accounting for 23.0% of all virtual grey water imports, 6 provinces with
24 quality-induced water scarcity issues benefited from virtual grey water flows in
25 addition to the main importers (see SI, Fig. S8). The main net virtual water exporters
26 included Hebei, Heilongjiang and Henan when combining virtual blue and grey water
27 flows (see Fig. 4c); virtual water export volumes accounted for 42.1%, 37.7% and
28 27.7% of local WF in these provinces, respectively. However, these net virtual water
29 export regions face both quantity and quality induced water scarcity. Moreover,
30 Shanghai, Guangdong and Beijing were the main virtual water importers, accounting

1 for 23.1% of the total virtual water imports.

Figure 4. Virtual water flows in China. The regions with no measure are primary importers, and the others are primary exporters. The regions listed in bold font face quantity-induced water scarcity issues, the underlined regions faced quality-induced water scarcity issues, underlined regions listed in bold font face quantity and quality-induced water scarcity issues. a. Net virtual blue water exports in China (only net blue water flows of $>0.5 \text{ Gm}^3/\text{y}$ were labeled), only primary importers and exporters are shown, the whole picture can be found in SI, Fig. S2. b. Net virtual grey water exports in China (only net grey water flows of $>1.5 \text{ Gm}^3/\text{y}$ were labeled), only primary importers and exporters are shown, the whole picture can be found in SI, Fig. S3. c. Net total virtual water exports in China (only virtual water flows of $>2.0 \text{ Gm}^3/\text{y}$ were labeled), only primary importers and exporters are shown, the whole picture can be found in SI, Fig S4. These three figures were created by using the D3.js software program (Bostock, 2012)

3.4 Virtual Water Flows for Different Sectors

Agricultural sector made the largest contribution to virtual blue water flows. Agriculture accounted for 86.2% of the total virtual blue water flows, followed by the electricity and heating and chemical sectors, which accounted for 8.7% and 1.3%, respectively (see SI, Fig. S5). At the same time, the agricultural sector represents 64.6% of the total virtual grey water flows. The chemical and petroleum processing and coking sectors were ranked second and third in terms of their contributions to total virtual grey water flows, accounting for 7.9% and 6.8% of the total, respectively (see SI, Fig. S6). When combining virtual blue and grey water flows, the agricultural, chemical industry and petroleum processing and coking industry sectors are the three main contributors to virtual water flows. Virtual water flows from these three sectors accounted for 66.8%, 7.1% and 6.2% of the total virtual water flows, respectively.

Virtual water imports from the agricultural and chemical sectors of the major importers which included Guangdong, Shanghai and Beijing represented more than 75% of their total virtual water imports (see Fig. 5). These two sectors are the first and third largest contributors to the WF, as our previous results show. This indicates that the virtual water importers consumed a large number of water-intensive and heavily-polluting products produced by exporters.

Figure 5. Virtual water flows of each sector for 30 provinces. Different colors represent trade in domestic final goods by sector.

4. Discussion

4.1 Calculation of Grey Water Footprint

The grey WF was calculated by dividing the pollutant load by the difference between the ambient water quality standard for that pollutant and its natural concentration in the receiving water body (Aldaya et al., 2012). Our calculation for the point source pollution had taken the pollutant discharge as the pollution load without considering the pollutants which are already in the water body. However, the withdrawal of water from the water body may have already been polluted which would lead to the overestimation of the grey WF. We recalculated the grey WF based on the average concentrations of 6 pollutants for each province derived from the China Environmental Quality Report 2007 (Ministry of Environmental Protection., 2008). Pollutant loads used to calculate the grey WF were reassessed using the pollutant discharge from the point source to subtract pollutants in the water body and other calculation processes were kept the same (details methods see SI). After calculation, we found that the consideration of pollutants in water body for the calculation of grey WF had little impact on our results. When examining pollutant concentrations in withdrawal water bodies, the total grey WF of China was found to be $3223.3 \text{ Gm}^3/\text{y}$ (approximately 7.3% less than the grey WF derived from our previous results for 2007). This does not change the regional quality-induced water scarcity results (the same 21 provinces were found to have faced quality-induced water scarcity issues (see Fig.3)), even when considering the pollution status of withdrawal water. Moreover, the total virtual grey water flows were also found to be 5.8% lower than those of our previous results (748.2 compared to $794.6 \text{ Gm}^3/\text{y}$). Virtual water flows between regions were also less when considering original pollutants in the water body (see SI, Fig. S7).

With or without the consideration of the pollution status of withdrawal water, our results about grey WF (the volume of water needed to assimilate the pollutants) are

much larger than the blue WF (the volume of water consumption). The gap between grey and blue WF is more than 10 times. This was mainly because of the large amount of water pollution discharge in China. Compared with other studies, our results about grey WF were reasonable. For example, according to the study by Guan et al (2014), which use the similar indicator like grey WF to calculate the impacts of water pollution on water resources, there are 3.2–8.5 trillion m³ freshwater would be needed to assimilate the COD discharge during 1992-2007 in China. During the same period, the volume of water consumption for China was only about 0.3 trillion m³ which was also at least 10 times smaller than the volume of water needed to assimilate the COD discharge (Guan et al., 2014).

4.2 Policy Implications

Based on the virtual water flows analysis, previous researches pointed out that the major virtual water exporter which faces water scarcity could decrease the export of products with water-intensive and high pollution products and import these products to mitigate its local water scarcity (Feng et al., 2012; Zhang and Anadon, 2014). This is quite hard to promote in practice without consideration of other social and economic factors besides water resources (Antonelli and Sartori, 2015). The virtual water flows analysis could provide new perspectives on water resources use for policy makers and support the urgency to implement the new governance approach which considering the water use in a wider dimension rather than its own territory (Antonelli and Sartori, 2015). The goal of virtual water flows analysis is to uncover the connection of local water use with distant consumers rather than provide solutions from the analysis itself. Here we provide possible solutions to mitigate the impact of virtual water flows on local water resources in China.

The agriculture shows the largest blue water footprint and made the largest contribution to the virtual blue water flows. The water resources use for agricultural production has been greatly devalued which leads to the lack of incentive for farmers to save water (Jiang, 2009). As a result, the water use efficiency of agriculture was

quite low, especially for the major virtual blue water exporters. The blue water intensity for agriculture sector of major virtual blue water exporters, Xinjiang, Heilongjiang and Inner Mongolia were 300.9, 67.1 and 69.1 m³/1000 RMB, higher than the national average which was 46.9 m³/1000 RMB. The virtual blue water export from agriculture hold 43.6%, 41.2% and 53.1% of blue water footprint for the major three exporters. Our results indicate the urgency to implement the water-saving measures in agriculture production and the major virtual blue water exporters should be the targets for agricultural policies that would improve the water-use efficiency. The economic incentives such as increasing the water price for water use of agricultural production can be taken as the potential means to improve the water use efficiency. As many previous studies had pointed out that the rise in water price would result in reduction of water use for agricultural production in China(Kang et al., 2017; Shi et al., 2014; Yang et al., 2003).

Besides as the largest water consumer, agriculture also has surpassed industry to become the dominant source of water pollution since 2005 in China(Norse and Ju, 2015) and agriculture accounts for 64.6% of the total virtual grey water flows. The excessive fertilizer use was the main cause for the agricultural pollution(Ti et al., 2012).The fertilizer usage has expanded rapidly since the 1970s and China has become the largest consumer of synthetic N fertilizers in the world which hold 30% of the total global(Gu et al., 2013).In China, fertilizer manufacturers have been provided with various subsidies and have been given tax rebates to keep fertilizer prices low, causing farmers to use excessive fertilizers(Li et al., 2013).The government should remove the price distortions on fertilizers to control excessive fertilizer use as this would reduce the grey WF of the agricultural sector and virtual grey water flows resulting from crop products trade between regions.

The industrial sectors also made great contribution for virtual grey water flows besides the agriculture, which held 37.3% of the total virtual grey water flows. The industrial enterprises in different regions face different environmental regulation intensity levels in China. Generally speaking, economically developed regions such as Beijing, Shanghai and Guangdong face to stricter environmental regulations, whereas

undeveloped regions such as, Inner Mongolia, Heilongjiang and Henan experience the opposite. For example, during the 11th Five Year Plan, the Chinese government set different COD reduction targets for each province. The COD reduction targets for Beijing, Shanghai and Guangdong were 14.7%, 14.8% and 15.0%, when comparing values for 2010 with those for 2005, whereas for the inland undeveloped regions like Inner Mongolia, Heilongjiang and Henan, the targets were 6.7%, 10.8% and 10.8% (State Council of China., 2006) (see SI, Table S9 for data). Such distinct environmental regulation intensity levels are mainly due to unbalanced economic development between different provinces in China. To mitigate discrepancies in economic development between regions, the Chinese government introduced the “Development of the West”, “Revitalization of the Northeast” and “Rise of Central China” strategies. Lower environmental regulation intensity levels in turn led local governments to pay more attention to economic development than environmental protection. Wastewater treatment plants constructed in the northeast, west and central regions lag behind those of the eastern coastal regions (Jin et al., 2014). Therefore, COD emissions concentrations from industrial sectors for the major virtual grey importer which included Beijing, Shanghai and Guangdong were less than 112 mg/L. For the Inner Mongolia, Heilongjiang and Henan which were the virtual grey water exporters and located in west, northeast and central of China respectively, this number increased to more than 227 mg/L in 2007 (State Statistics Bureau., 2008b). As a result, weaker environmental regulations result in more industry water pollution discharge. The major virtual grey water export regions with quality-induced water scarcity issues should strengthen environmental regulations to achieve smaller grey WF and reduction in virtual grey water export of industrial sectors (Li et al., 2016).

Consumer behaviors also play an important role in water consumption and pollution discharge. For example, with increasing income people may choose more animal-based food which includes poultry, pork and ruminant for their diet (Tilman and Clark, 2014). The animal-based food leads to much more water consumption and pollution discharge than plant-based food such as grains, vegetables and fruits (Liu

and Savenije, 2008; Westhoek et al., 2014). The major virtual water importers namely Beijing, Shanghai and Guangdong also are the richest regions in China, the consumption of animal-based food for these three regions were 40.5, 42.6 and 48.0 kg per capita respectively in 2007, higher than the national average which was 35.4 kg per capita². The government could raise the price of water-intensive and high-pollution products like animal-based food by water resources tax based on WF to control the consumption of these products and lead to the reduction in importation of virtual water for the major importers.

4.3 Limitations

The analysis had been made in this study were subject to two major limitations. First, the assessment about virtual water flows was based on aggregated sectors rather than the specific product. However, the aggregation is a problem in particular when sectors with high and low water footprint intensity are combined in one aggregated sector (Wiedmann, 2009). For example, the livestock and crop production had been combined in agriculture sector in this study, while the differences of water consumption and water pollution per unit between these two may be large. This aggregation would lead to inevitable error for the calculation of virtual water flows between regions. Future study should improve the accuracy of MRIO to get more precise results about the virtual water flows in China. Second, water scarcity due to virtual water flows between countries which accompanied by international trade had not been included. The scale of virtual water flows due to international export is much smaller (less than half) than that of domestic trade as previous researches show (Zhang and Anadon, 2014). In this study, the analysis was focused on the redistribution of water resources and outsourcing water pollutants within China through virtual blue and grey water flows. The whole picture about virtual water flows under the consideration of both domestic and international trade could be assessed through links of China MRIO and global MRIO models in future studies.

² The number was the average of food consumption for urban and rural resident. Data came from China Statistic Yearbook 2008.

5.Conclusion

The virtual water flow assessment results of this study show that virtual water flows intensified not only quantity-induced water scarcity but also quality-induced water scarcity experienced in the export regions, which had not been explored in previous studies. The use of the indicators related with water quantity like water withdrawal(Zhang and Anadon, 2014; Zhao et al., 2015) or water consumption(Feng et al., 2014) in previous studies to represent virtual water will underestimate its impact on water resources.The virtual water flows analysis should combine both the water quantity and quality into consideration.

Our results show that the developed regions facing water scarcity issues such as Beijing, Shanghai and Guangdong have already served as virtual water importers and outsourcing their water consumption and pollution discharge to undeveloped provinces such as Henan, Hebei and Heilongjiang. If the government neglects these effects of virtual water flows on local water resources, exporting regions will struggle to address water scarcity issues, and importing regions may mitigate water scarcity issues by further outsourcing water use to exporting regions. In turn, water scarcity problems may be merely transferred from importing regions to exporting regions rather than being solved.

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