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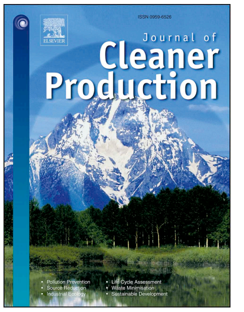


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# Water footprint of Jing-Jin-Ji urban agglomeration in China

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## Abstract

A rapidly expanding economy and increasing water demand for agricultural and industrial production is placing enormous stress on water quantity and the aquatic environment in Northern China, especially the so-called Jing-Jin-Ji (Beijing-Tianjin-Hebei) urban agglomeration, home to over 110 million people producing 10% of China's overall GDP. Several studies have focused on energy consumption, air pollution, $CO_2$ emissions and regional blue water footprint (WF) following release of the Jing-Jin-Ji Integration Strategy by the China government in 2013. However, a comprehensive assessment distinguishing blue, green and grey WF amongst different industrial sectors, ascertaining how WF transfers internally and beyond the region and final demand consumption is not available. We consider this to be crucial in understanding and addressing the deteriorating water situation in the Jing-Jin-Ji. In this study, we quantified the WF and virtual water flow on a sectoral basis for the year 2010 through coupling the multi-regional input-output model (MRIO) with WF assessment. The results showed that Beijing and Tianjin are net importers of green, blue and grey water from Hebei and other China provinces to support their needs. Conversely, Hebei exports all WF colors to Beijing, Tianjin and other provinces in China, and more than 60% of WF is transferred as virtual water. For the overall Jing-Jin-Ji region a small amount of blue water (2,086 million $m^3$) is exported, but huge amounts of green water (15,573 million $m^3$) and grey water (30,620 million $m^3$) are outsourced. A "Virtual Water Strategy" is one measure which could alleviate water stress at the regional scale, with consideration of financial compensation from water receiving regions made to water supplying regions in the context of achieving water management targets. We also found that physical water transfer to Jing-Jin-Ji could not balance virtual blue water exports, not to mention compensating for internal water

consumption. Our research suggests that a continuation of an export-based economic development model will worsen Hebei's water stress. Reducing the dependency of Hebei's sectoral economy on export of water intensive and low value added agricultural products may be one strategy to reduce the pressure on regional water resources. In addition, the Beijing-Tianjin-Hebei Integration Strategy drives industrial transfer from Beijing to Hebei resulting in the transfer of enterprises with low water utilization efficiency and producing heavy pollution. As a result, the government should consider incentivizing corporations to adopt technologies that reduce water consumption and pollution.

**Keywords:** water footprint; urban agglomeration; MRIO model; virtual water; industrial sectors.

# 1 Introduction

Freshwater availability is recognized as a limiting factor in economic and social development. With rapid economic and population growth, global demand for freshwater has increased fourfold in the last 60 years (Uitto and Schneider, 1997). Water consumption has increased twice as fast as population growth during the last century (FAO and UN, 2007), and is predicted to rise by a further 50% in developing countries and 18% in developed countries by 2035 (WWAP, 2006). Some scientists forecast that half of the world's population will suffer the consequences of severe water stress by 2030 (Oki and Kanae, 2006; Vörösmarty et al., 2010). This emerging water crisis is becoming one of the most serious challenges faced by humanity in the 21$^{st}$ Century (World Economic Forum, 2015).

Water consumption has also grown in China. In 2014 China consumed 609.5 billion m$^3$ freshwater resource (National Bureau of Statistics of China, 2015), equivalent to 15% of global water withdrawal (FAO, 2016). A rapidly developing economy and increasing demand from agricultural and industrial production has placed enormous pressure on the water environment. This is particularly true for Northern China and the Beijing-Tianjin-Hebei urban agglomeration (the so-called Jing-Jin-Ji). To address this problem the China government made its top priority in 2011 the implementation of the most stringent water resource management plan, concretized by the "three redlines" concerning total national water use, water use efficiency, and water pollution (Liu et al., 2013). In this policy China's highest water demand area, Jing-Jin-Ji, is required to reduce its total water use to 34 billion m$^3$ (5.2 for Beijing, 4.2 for Tianjin and 24.6 for Hebei), and 95% of all freshwater bodies will need to reach or exceed the required water quality standard by 2030 (The State Council of China, 2013). In response, local governments have produced plans for regional water security ranging from end-of-pipe control, to closing, restructuring and relocating industry.

Economic activity and social provision require freshwater as one type of input element. Water pollution and water consumption have placed huge pressure on the water environment (White et al., 2015). Understanding the structure of the economy in relation to water flow from production to household consumption is essential to solve finite freshwater resource scarcity. In the past few years Jing-Jin-Ji has become one of the most important industrial areas of China producing a wild range of products and services for other regions. For example, in 2014, Jing-Jin-Ji accounted for 27% total steel and 6% total agricultural production in China (National Bureau of Statistics of China, 2014). Products related to metal and agriculture comprised 13% and 4% respectively of Jing-Jin-Ji's total industrial output (National Bureau of Statistics of China, 2015). However, these underpinning industries also incur enormous water consumption and produce significant water pollution. In 2014, Jing-Jin-Ji directly consumed 25.4 billion $m^3$ freshwater (63% to agriculture and 14% to industrial sectors), and discharged nearly 5.5 billion tons wastewater to the environment. Water pollution and other environmental issues have a negative impact on freshwater availability and create a “choke point” in terms of sustainable development. The region faces huge obstacles in achieving the “Beijing-Tianjin-Hebei Integration Strategy”.

Hoekstra and Hung (2002) introduced the concept of the water footprint (WF) as a consumption-based indicator of water use. The WF is the total volume of freshwater used to produce goods and services consumed by people, business, nations or economic regions both directly and indirectly (Klaus Hubacek et al., 2009). In water footprint and virtual water flow studies, water is typically classed as one of three types: blue, green or grey water (Chapagain and Hoekstra, 2004). Allan (1998) introduced the concept of ‘virtual water’ as an alternative strategy to alleviate water scarcity, specifically using virtual water import as a tool to reduce the burden of domestically scarce water resources. Over time, the term ‘virtual water’ has expanded to mean the volume of water that is required to produce any good or service.

Several studies have focused on the Jing-Jin-Ji since the Integration Strategy was announced in 2013, for example ground subsidence (Zhang et al., 2016), energy consumption (Wang and Chen, 2016), carbon emissions (Han et al., 2016), and air pollution (Zhao et al., 2016a). White et al. (2015) estimated the blue WF and water stress in the Haihe River Basin for the year 2007. Wang and Chen (2016) investigated the nexus between water and energy for urban agglomerations, selecting Jing-Jin-Ji as a case study. Zhao et al (2010) calculated the blue WF for the Haihe river basin based on the input-output analysis tool for the years 1997, 2002, 2007. Most studies have focused on blue WF; a comprehensive water footprint assessment distinguishing blue, green and grey water footprint amongst different industrial sectors and ascertaining how WF transfers within and beyond the region and final demand consumption hasn’t been identified. We consider such a study to be important in addressing the water situation in the Jing-Jin-Ji.

# 2 Materials and Methods

**2.1 Study site**

The Jing-Jin-Ji urban agglomeration is one of the key infrastructure development areas for China. It is located on the coast of the Bohai Sea (Figure 1) with a total area of 21.67 million ha, is home to greater than 110 million inhabitants (8% of China’s total population), and a GDP equivalent to ca. 10% of that for China in 2014. Available freshwater volume is about 13.8 billion $m^3$, just 0.5% of China’s total, and the high population density of 500 persons per $km^2$, and low water resource endowment of 125 $m^3$ per person/year make the Jing-Jin-Ji highly water stressed. Each part of the Jing-Jin-Ji plays a different role in regional water utilization. Currently, the imbalance between economic development, administrative systems, and water scarcity severely hinder further integration and cooperation.

**2.2 Multi-regional input-output model (MRIO)**

Multi-regional input-output modelling (MRIO) is a powerful tool for tracing the environmental impact of consumption between sectors amongst different economic regions. The tool was developed by Leontief in the late 1930s (Leontief, 1941, 1970). The MRIO approach was chosen for several reasons: first, MRIO is based on final rather than apparent consumption (production is assigned to the end-product) and, second, MRIO can comprehensively describe supply chain effects which is vital for allocating responsibility to the final consumer. Furthermore, MRIO is well recognized for calculating the WF of industrial sectors. As a result, we used an environmentally extended MRIO model to capture the water flows and their interconnections along the supply chain between industrial sectors within the Jing-Jin-Ji, and externally with other China provinces in 2010. We extracted a three-region input-output table for the Jing-Jin-Ji based on the latest China multi-regional input-output tables for 2010 compiled by Liu et al (Liu et al., 2014). Liu's model has been used in various studies (Feng et al., 2013), (Feng et al., 2014), (Zhao et al., 2015) and (Liang et al., 2014). Here, our three-region model of the Jing-Jin-Ji included detailed information for 30 industrial sectors (see table S1) of inter-provincial trade and export. The model structure is presented in table S2. For clarity we utilized some mathematical symbols, formulas and equations in the following sections. Scalars are denoted by italicized lower case letters (e.g. *x*), matrices are indicated by bold upright capital letters (e.g. **X**), and vectors by bold upright lower case letters (e.g. **x**). The monetary flow balance in each row can thus be written as:

$$\sum_{s=1}^{3}\sum_{j=1}^{30} z_{ij}^{rs} + \sum_{s=1}^{3} y_i^{rs} + \sum_{t=1}^{28} e_i^{rt} = x_i^r \quad (1)$$

Where, $z_{ij}^{rs}$ refers to inter-provincial industrial demand from sector *i* in province *r* to sector *j* in province *s*. $y_i^{rs}$ indicates finished products of sector *i* produced in province *r* and consumed in province *s*. $e_i^{rt}$ refers to exports from sector *i* in province *r* to the other 27 provinces in China and other countries, and $x_i^r$ is the total output of sector *i* in region *r*.

According to the MRIO model, the technical coefficient from sector *i* in province *r* to produce unit output for sector *j* in province *s* can be formulated by:

$$a_{ij}^{rs} = z_{ij}^{rs}/x_j^s \quad (2)$$

Combining Eq (1) with Eq (2) yields Eq (3) as follows:

$$\mathbf{Ax} + \mathbf{y} + \mathbf{e} = \mathbf{x} \quad (3)$$

Where **A** is a technical coefficient matrix, **y** is a vector of total final demand by sector, **e** is a vector of export by sector, and **x** means total output of each sector.

The Leontief inverse matrix $(I\text{-}A)^{-1}$ captures both direct and indirect inputs. Solving for x results can also be expressed in terms of the well-known Leontief inverse equation (4):

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}(\mathbf{y} + \mathbf{e}) \quad (4)$$

Thus, the WF considering the supply chain in Jing-Jin-Ji can be calculated as:

$$\mathbf{wf}^s = \mathbf{d}^s * \mathbf{x}^s \quad (5)$$

Where, $\mathbf{wf}^s$ is the vector of the total water footprint related to the production of goods and services along the whole national supply chain triggered by final consumption in each sector (blue

WF, green WF and grey WF) of province *s;* $\mathbf{d}^s$ is the vector of direct water use intensity, which means the water consumption directly discharged to increase one unit of total economic output in each sector; and $\mathbf{x}^s$ is the vector of total economic output in province *s*.

Equation (5) captures the total direct and indirect water consumption associated with the final demand of a region. However, it isn't able to distinguish between the water for final consumption from domestic water resources (DWF) and virtual water trade. To calculate the Virtual Water Export (VWE) and Virtual Water Import (VWI) from province *s* to other provinces, equation (5) can be rewritten as:

$$\mathbf{vwe^s} = \mathbf{d^s}(\mathbf{I} - \mathbf{A^{ss}})^{-1} \sum_{r \neq s} \mathbf{e^{sr}} \quad (6)$$

$\mathbf{d^s}$, $\mathbf{A^{ss}}$ and $\mathbf{e^{rs}}$ of region s are, respectively, direct water use intensity, technical coefficient of domestic intermediate inputs, and import from province s to province r.

The virtual water import of province *s*, $\mathbf{vwi^s}$, may be treated as the virtual water export from other regions to province *s*. So, $\mathbf{vwi^s}$ is calculated by summing over the virtual water exports of other regions to province *s*, equation (7):

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

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

The Consumption-based water footprint (CWF) in province *s* is the sum of consumed domestic water resources (DWF) to meet the internal final demand of province *s*, and the consumption of external water resources via virtual water import from external provinces in goods and services (VWI). CWF can measure the impact that the final demand of one province has on another province's water resources (equation 8):

$$\text{CWF}=\text{DWF}+\text{VWI} \quad (8)$$

The Production-based water footprint (PWF) in province *s* is the sum of domestic water resources consumed for domestic demand (DWF) and exported to other provinces via embodied virtual water in goods and services (VWE) for external demands. This accounts for the use of the Jing-Jin-Ji's domestic water resources to meet internal and external demands (equation 9):

$$\text{PWF}=\text{DWF}+\text{VWE} \quad (9)$$

**2.3 Data sources**

In this research we used the GEPIC model (GIS-based Environmental Policy Integrated Climate model) (Liu, 2009) to simulate direct blue and green water footprint for the primary agricultural sector, particularly the main agricultural crops. The GEPIC model has been used to calculate water consumption in agriculture at the global, national and regional scales and several studies have shown it to have good performance in China (Liu et al., 2007b; Liu et al., 2007a; Liu and Yang, 2010; Zhao et al., 2014); we have therefore used the same parameters in our simulations. Detailed simulation processes for the GEPIC model may be found in Liu (2009) and Liu and Yang

(2010). Our results showed that blue WF and green WF of crop production in China was about 85,050 million $m^3$ and 580,900 million $m^3$ respectively, however Mekonnen and Hoekstra's (2011) previously calculated these two indicators as 118,600 million $m^3$ and 623,880 million $m^3$ respectively; our simulations are therefore smaller by 28% and 7% of their study. One of the most important reasons for this difference is that our calculations were focused solely on the agricultural growing season, but Mekonnen and Hoeksta's results were calculated for the whole year. Our study was concerned with the actual water consumption by agricultural output, thus the water footprint during the growing season was considered more suitable for this purpose. The AgMERRA climate forcing dataset was obtained from the AgMIP group (Ruane et al., 2015).

Blue water use of the secondary and tertiary sectors was obtained from the China Water Resource Bulletin of different provinces (The Ministry of Water Resources of China, 2011). Water use data in each sector was converted to blue WF by multiplying with the water consumption coefficient, which was taken from the provincial Water Resource Bulletin (The Ministry of Water Resources of China, 2011). Total blue WF at secondary and tertiary sector level was disaggregated into 29 sectors based on water consumption per unit of economic output for 30 provinces in 2007, which was estimated from the China Economic Census Yearbook 2008 (National Bureau of Statistics of China, 2008). For the grey WF for each sector, Hoekstra et al. (2011) introduced a global standard. In China, water quality is categorized into five grades (Ministry of Environmental Protection of China, 2002), with Grade III and above indicating water suitable for fishery, aquaculture, and recreational purposes. Water resources categorized below Grade III indicate poorer quality which is deemed unsuitable for safe use. Grade V indicates water which is so seriously polluted so as to be unfit for any beneficial use. Here, we estimated the grey WF component according to these rules and calculated the volume of water needed to assimilate nutrients so that they could achieve Grade III status. COD, $NH_3$-N, TN and TP discharges were selected as water pollutant indicators to estimate the grey WF for each sector. We then selected the maximum dilution water consumption as the grey WF for that sector; this practice has been successfully applied by Zeng et al. (Zeng and Liu, 2013). Agricultural non-point source discharge pollution data in 2010 was estimated based on agricultural non-point pollution datasets from the China Economic Census Yearbook 2008. Annual water pollutant discharge data (measured in tons) for each sector at national level is recorded in the Environmental Statistics Yearbook (National Bureau of Statistics of China, 2011). We disaggregated this data into provincial scales based on the province's economic outputs on a sector scale by assuming that the technology level and efficiency in each area/province was homogeneous.

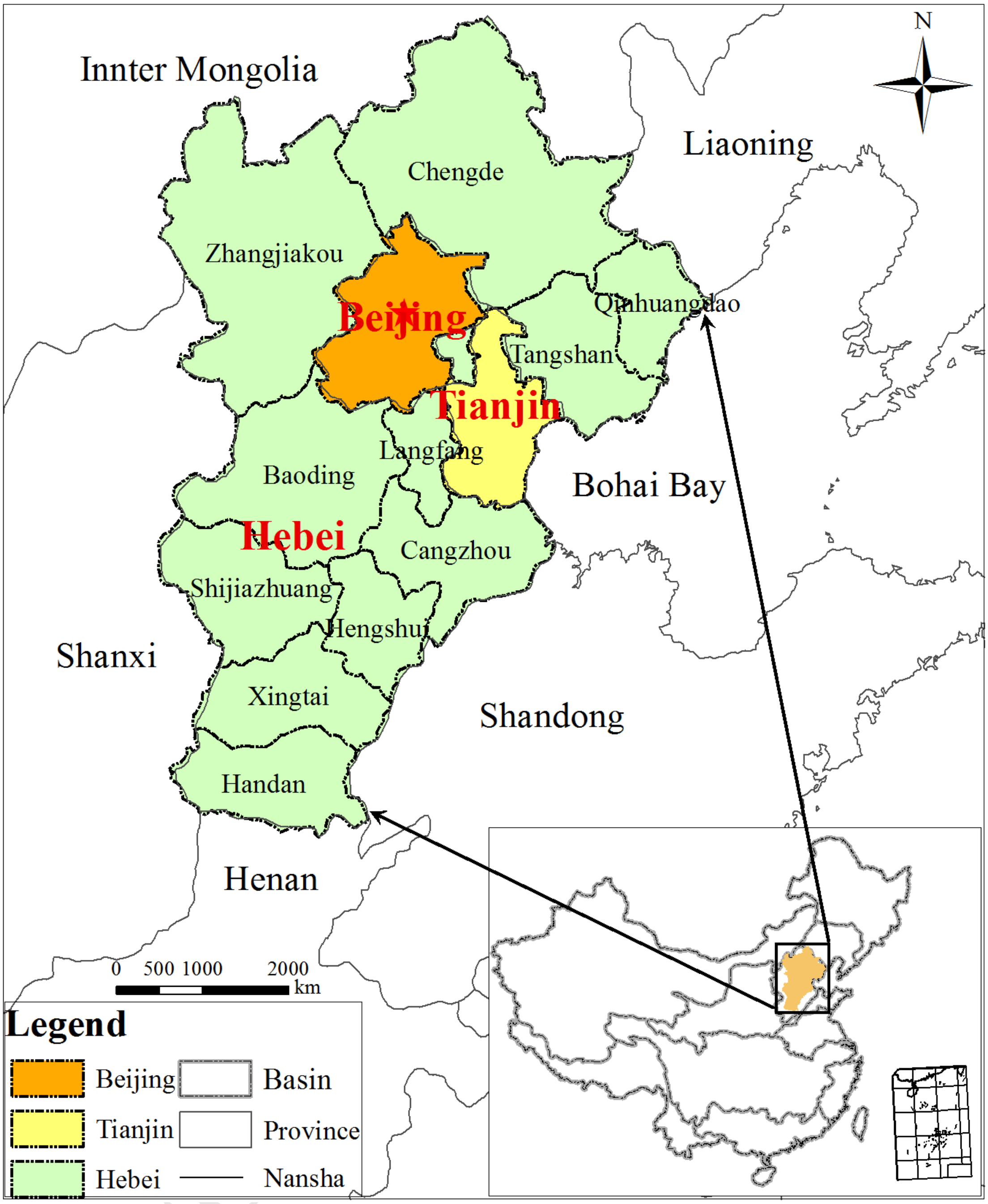


*Figure 1 Geographical location of the Jing-Jin-Ji national capital region.*

# 3 Results

## 3.1 The water footprint of the Jing-Jin-Ji distinguishing between blue water, green water and grey water

In 2010, in terms of the consumption-based water footprint (CWF) for Jing-Jin-Ji, we found there was a total of 15,292 million $m^3$ blue water or 146 $m^3$ per capita, and 36,477 million $m^3$ green water or 349 $m^3$ per capita consumed by domestic homes and businesses. This varied between 2,964 million $m^3$ blue WF in Beijing and 17,987 million $m^3$ green water in Hebei. A further 292,710 million $m^3$ freshwater or 2,800 $m^3$ per capita was used to dilute the resulting water pollution discharged by business and household activities, which is significantly greater than the sum of the blue WF and green WF (See Table 1). In the CWF account, virtual water imports made an important contribution to the water footprint of all categories (55% for blue WF, 78% for green WF, and 63% for grey WF). This was particularly true for Beijing and Tianjin, where more than 80% of the total CWF was restricted to import from other provinces. Hebei mainly relied on its local water resource rather than the import of blue WF and grey WF (See Figure 2).

For the production-based water footprint (PWF), 17,348 million $m^3$ blue water or 166 $m^3$ per capita, and 20,903 million $m^3$ green water or 200 $m^3$ per capita, was used to produce goods and services. This ranged from 750 million $m^3$ blue WF in Beijing to 19,047 million $m^3$ green WF in Hebei. Dealing with water pollution consumed 262,089 million $m^3$ freshwater or 2,507 $m^3$ per capita to achieve the Grade III water quality standard, which is greater than the total available water resource in this area (National Bureau of Statistics of China, 2011). In the production-based approach account, virtual water export also played a major role for all types of water footprint (60% for blue WF, 64% for green WF, and 58% for grey WF). This was particularly the case for Hebei, which accounted for almost 90% of total virtual water export. Overall, about 60% of water was traded virtually and areas such as Beijing and Hebei imported and exported substantial proportions of their water. The CWF approach to accounting for the Jing-Jin-Ji's green WF and grey WF led to a higher estimate than the PWF approach because of the significant net import of virtual water, however the region is a modest net exporter of virtual water in terms of blue WF.

*Table 1: Jing-Jin-Ji's regional water consumption. Domestic consumption refers to the consumption of local water resources to meet the internal final demand of one zone; virtual water import is the consumption of external water resource from other provinces to meet local final demand; virtual water exports shows the consumption of local water resources to meet the final demand of another province.*

| | | Blue WF [$10^6$ $m^3$] | | | | Green WF [$10^6$ $m^3$] | | | | Grey WF [$10^6$ $m^3$] | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Beijing | Tianjin | Hebei | Total | Beijing | Tianjin | Hebei | Total | Beijing | Tianjin | Hebei | Total |
| **Domestic Consumption water footprint (DWF)** | Absolute | 502 | 488 | 5,898 | 6,888 | 544 | 528 | 6,928 | 8,001 | 15,306 | 13,215 | 80,322 | 108,843 |
| | Per capita ($m^3$) | 26 | 38 | 82 | 66 | 28 | 41 | 96 | 77 | 780 | 1,017 | 1,117 | 1,041 |
| **Virtual Water Import (VWI)** | Absolute | 2,462 | 2,865 | 3,078 | 8,404 | 9,776 | 7,641 | 11,059 | 28,476 | 63,173 | 51,561 | 69,134 | 183,867 |
| | Per capita ($m^3$) | 125 | 221 | 43 | 80 | 498 | 588 | 154 | 272 | 3,220 | 3,969 | 961 | 1,759 |
| **Virtual Water Export (VWE)** | Absolute | 248 | 471 | 9,741 | 10,460 | 270 | 514 | 12,119 | 12,902 | 7,484 | 12,451 | 133,312 | 153,246 |
| | Per capita ($m^3$) | 13 | 36 | 135 | 100 | 14 | 40 | 168 | 123 | 381 | 958 | 1,853 | 1,466 |
| **Production-based water footprint (PWF)** | Absolute | 750 | 959 | 15,639 | 17,348 | 814 | 1,042 | 19,047 | 20,903 | 22,790 | 25,666 | 213,634 | 262,089 |
| | Per capita ($m^3$) | 38 | 74 | 217 | 166 | 41 | 80 | 265 | 200 | 1,162 | 1,976 | 2,970 | 2,507 |
| **Consumption-based water footprint (PWF)** | Absolute | 2,964 | 3,353 | 8,976 | 15,292 | 10,320 | 8,169 | 17,987 | 36,477 | 78,478 | 64,776 | 149,456 | 292,710 |
| | Per capita ($m^3$) | 151 | 258 | 125 | 146 | 526 | 629 | 250 | 349 | 4,000 | 4,987 | 2,078 | 2,800 |

### 3.2 The water footprint distribution among different industrial sectors

The WF component of different industrial sectors in the CWF account is summarized in Figure 2. The ratios of VWI to total CWF in Beijing and Tianjin exceeded 80%, and for green WF the proportion reached 95%. A further decomposition to VWI showed that Beijing and Tianjin dependence on VWI from other provinces was mainly from food related sectors i.e Agriculture, and Food and Tobacco Processing. Beijing's agricultural VWI was 1,329 million $m^3$ (54% of the blue VWI), 5,866 million $m^3$ (60% of the green VWI), and 32,850 million $m^3$ (52% of the grey VWI). This value was 1,518 million $m^3$ (53% of blue VWI), 3,897 million $m^3$ (51% of green VWI), and 23,202 million $m^3$ (45% of the grey VWI) for Tianjin. Considering local and supply chain water consumption, Food and Tobacco Processing was the second largest virtual water importer for these two cities. These results suggest that Beijing and Tianjin were supporting their populations through the importation of huge amounts of virtual water. In other words, Beijing and Tianjin were largely supported by other external provinces. As for the third Jing-Jin-Ji region, Hebei, we found that domestic water footprint played a major role in the blue CWF and grey CWF categories, but only a minor role in the green CWF. In detail, Agriculture was the biggest water consumption sector in all water lists, ranging from 44,177 million $m^3$ (55% of domestic grey CWF) to 1,231 million $m^3$ (40 % of blue VWI), and Food and Tobacco Processing was the second largest water consumption sector.

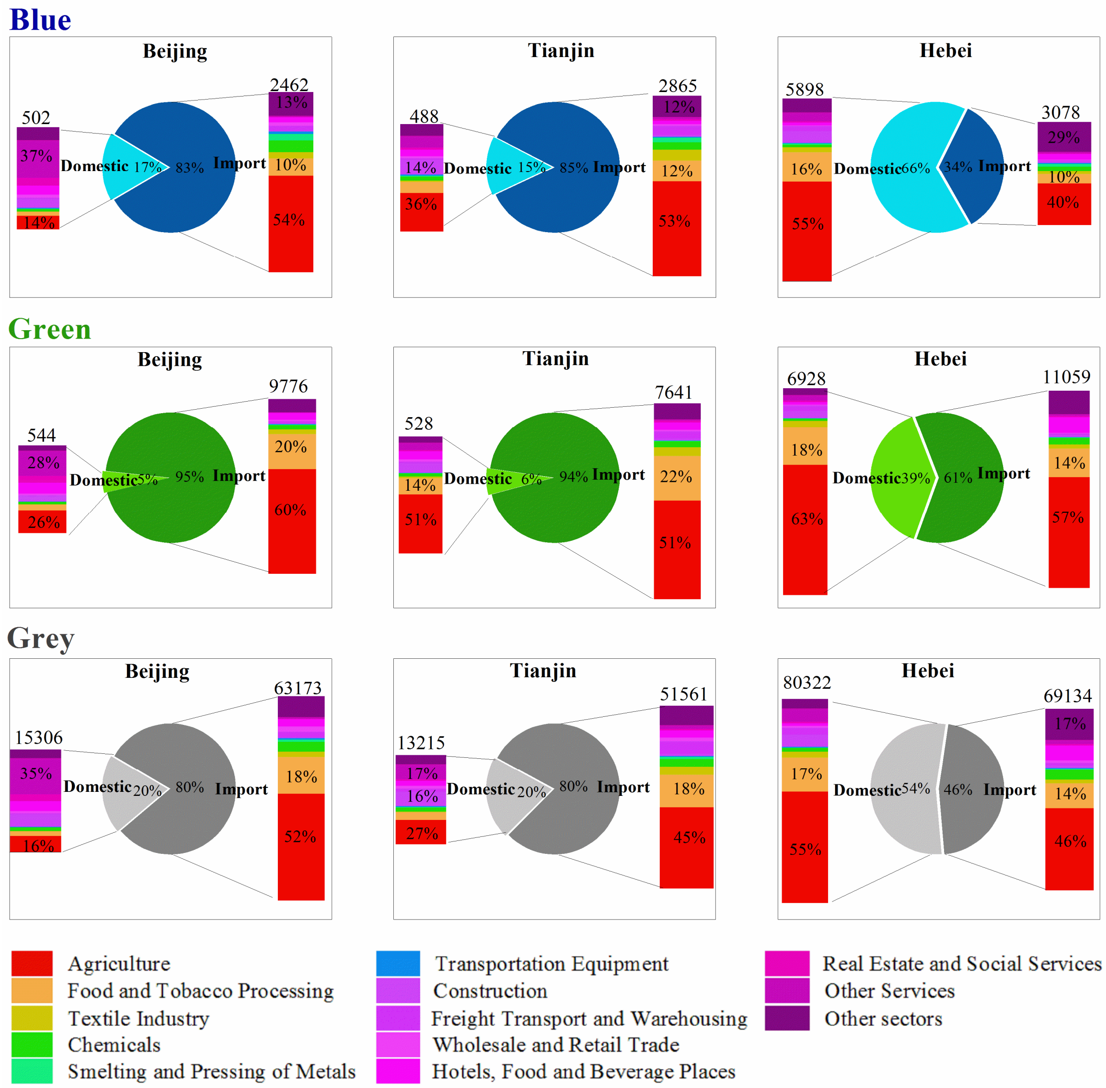


*Figure 2 Consumption-based water footprint (CWF) [$10^6 m^3$]*

Figure 3 shows the water footprint components for different industrial sectors contained in the PWF account. In Beijing, an interesting observation was that about two-thirds of the total PWF was consumed internally for all water footprint colors, which indicated mostly local water resource being used to meet local demand. A further analysis of the domestic PWF showed that nearly 35% was consumed in the Other Services sector: 170.68 million $m^3$ for blue PWF, 152.3 million $m^3$ for green PWF and 5,357 million $m^3$ for grey. The Agriculture, and Hotels, Food and Beverage Places sectors made an important contribution to domestic PWF. In Tianjin, half of the PWF was consumed by domestic demand, the other half being used for export in virtual water trade. In detail, the food related sectors accounted for 55% of the blue PWF, 70% of the green PWF and nearly 20% of the grey PWF. Water use and water pollution in the Construction sector could not be ignored: for the biggest area, Hebei, more than 60% of total PWF was used for export through virtual water flow. Furthermore, Hebei was the region that exported major water resource to other provinces. In particular, food related commodities contributed nearly 80% of PWF (70% for Agriculture, and 10% for Food and Tobacco Processing).

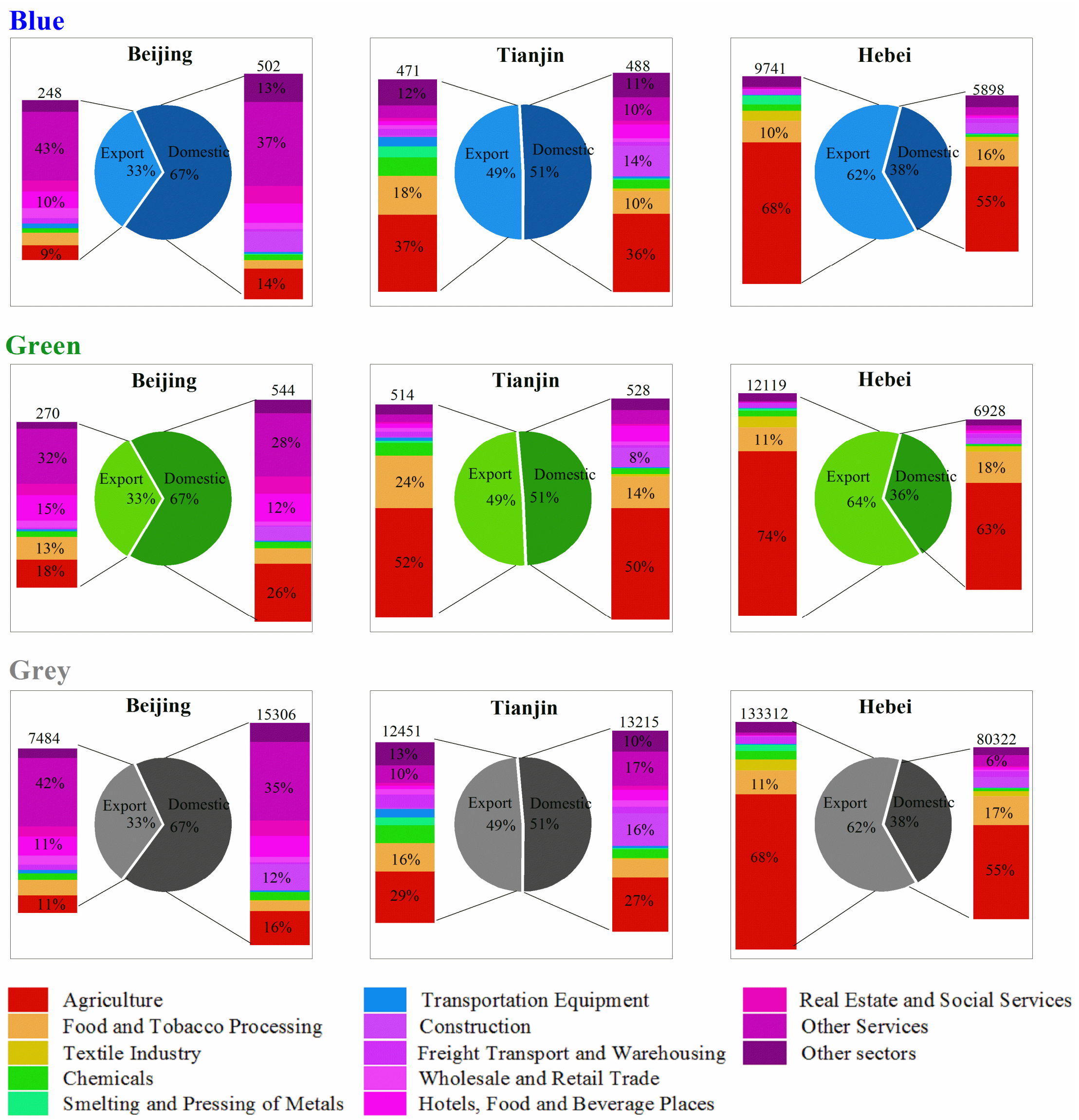


*Figure 3 Production-based water footprint (PWF) [$10^6 m^3$]*

### 3.3 Net virtual water flow

The Jing-Jin-Ji exported a total of 2,056 million $m^3$ blue virtual water, but imported 15,574 million $m^3$ green virtual water, and 30,621 million $m^3$ grey virtual water (Figure 4). In particular, Hebei played a vital role in Jing-Jin-Ji virtual water flow, being the biggest exporter of water resource and also the biggest importer, accounting for more than 50% of virtual water trade within the area. In fact, Hebei was a net virtual water exporter of 6,663 million $m^3$ blue, 1,060 million $m^3$ green, and 64,178 million $m^3$ grey virtual water. Conversely, Beijing and Tianjin were net virtual water importers of all colors. In other words, Hebei appeared to be a "Producer", whilst Beijing and Tianjin were "Consumers". Water intensive products from the Agriculture, and Food and Tobacco Processing sectors transferred about two-thirds of virtual water to other provinces from Hebei. Figure 4 also illustrates the predicament faced by Beijing and Tianjin, which imported a large amount of virtual water from other provinces compared to their exports, and are clearly out-of-balance.

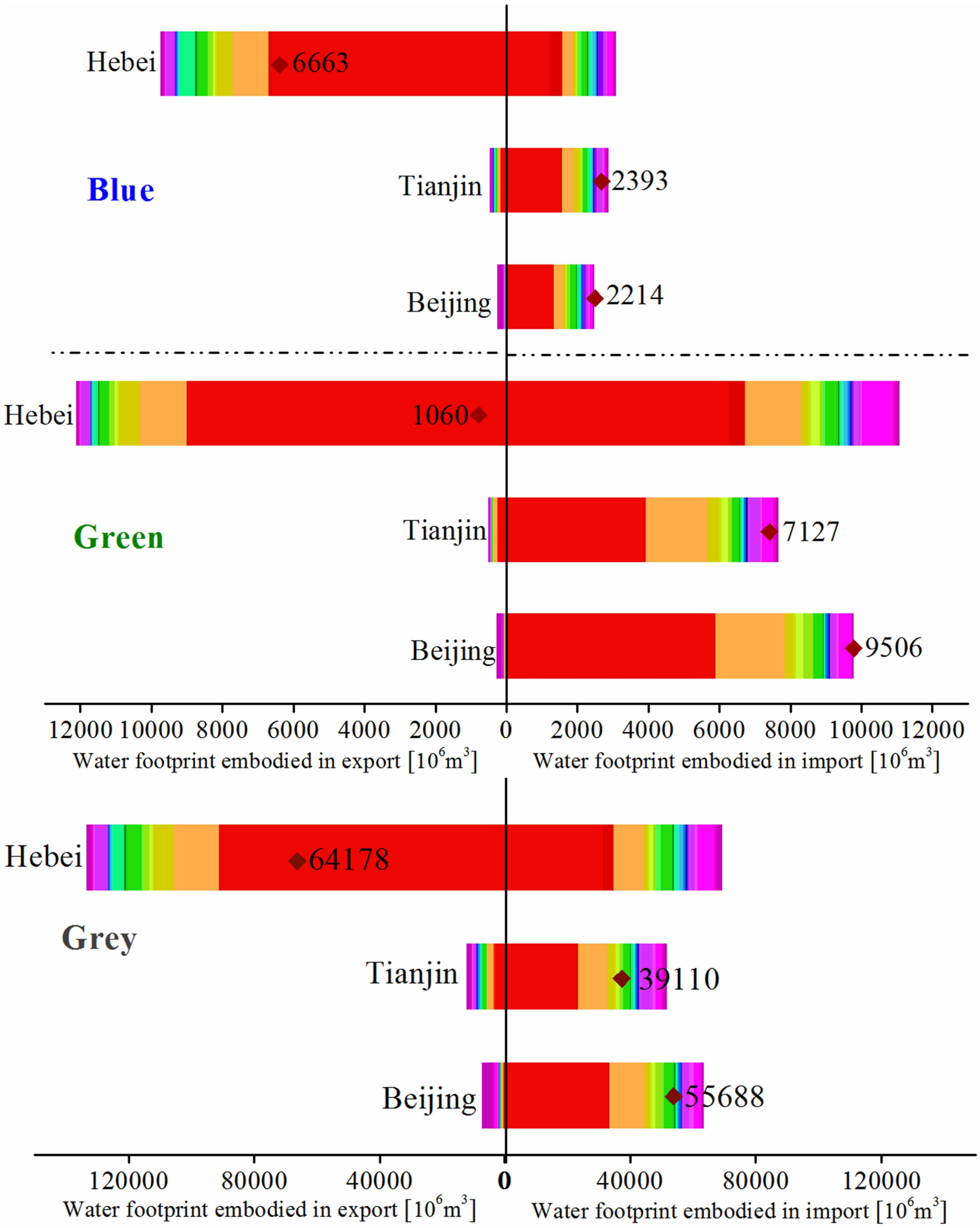


*Figure 4: net virtual water flows in the Jing-Jin-Ji by sector. The bar color indicates sector as in TableS1; the dot in the diagram shows the amount of net virtual water import or export.*

**3.4 The inter-region net virtual water flow by region and sector**

Virtual water transfers within the Jing-Jin-Ji and external regions for the main classes of industrial account (primary, secondary and tertiary) are summarized in Figure 5. Overall, Hebei transferred all virtual water colors to Beijing and Tianjin for all industrial sectors. For primary and secondary industries, Beijing imported virtual water from Tianjin, but in terms of tertiary industry it exported water to Tianjin. In detail, we found that virtual water flowed from the economically poor and less populated region (Hebei) to the more affluent and densely populated regions (Beijing and Tianjin).

There was a large difference in the amount of virtual water flow between Hebei and Beijing-Tianjin. The biggest value was 5,183 million $m^3$ grey WF from Hebei to Beijing for primary industry, and the minimum was just 13 million $m^3$ green WF for tertiary industry. In addition, Beijing plunders its water resources from Tianjin (24 million $m^3$ blue WF, 28 million $m^3$ green WF, and 538 million $m^3$ grey WF) for the development of primary and secondary industries, only compensating in small part to Tianjin in tertiary industries (4 million $m^3$ blue WF, 4 million $m^3$ green WF, and 74 million $m^3$ grey WF). In terms of water resources, we found that 971 million $m^3$ blue WF in total was transferred from Hebei to Beijing-Tianjin through goods and services, which is about 7% of available water resource in Hebei.

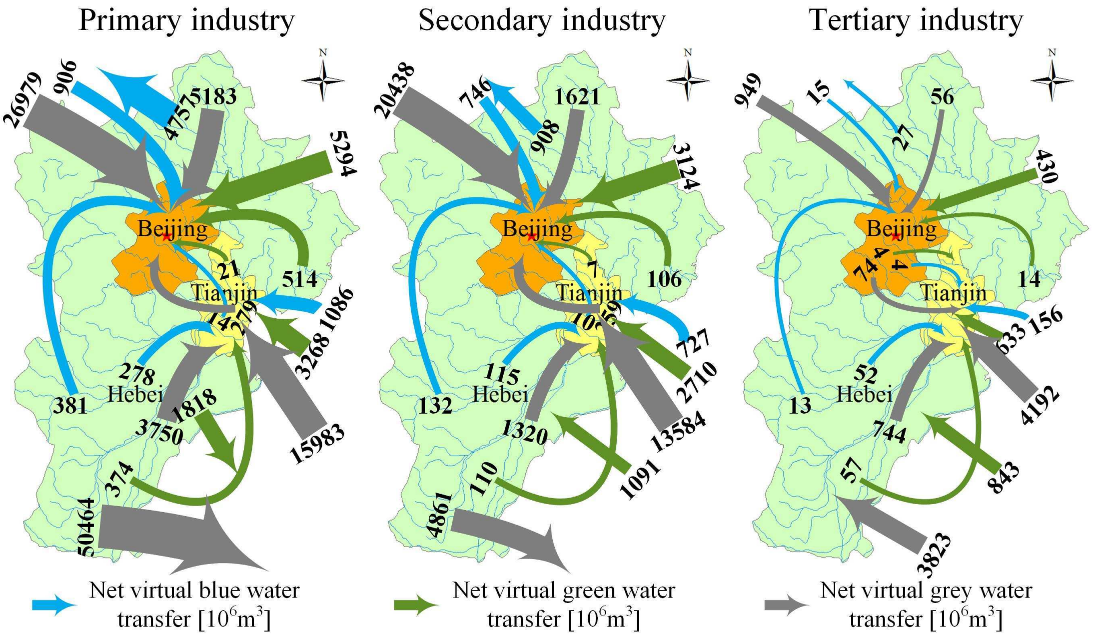


*Figure 5: Net virtual water flows within the Jing-Jin-Ji. The Agricultural sector was defined as primary industry; Coal Mining and Dressing through to the Construction sector was defined as secondary industry; and Freight Transport and Warehousing through to Other Services was defined as tertiary industry; as per Table S1.*

## 4 Limitations of this study

This study conducted a comprehensive water footprint analysis in production-based and consumption-based accounting among different industrial sectors within the Jing-Jin-Ji and between other provinces. We also addressed the importance of offset mechanisms in terms of virtual water trade. However, we would like to recognize some limitations of the study. First, because of data availability, we assumed that the technology level and efficiency in each area/province was homogeneous in order that we could decompose the water pollutant discharge into each province, and for each sector based on the province's economic outputs on a sector scale. This assumption can also be found in Hollanda et al. (2015) for the impacts of energy demand on global freshwater resources. Second, the boundary of our study was restricted to the Jing-Jin-Ji. We placed our emphasis on the internal impact induced by trade within the three areas, and less so on trade with other provinces; this gap should be taken into consideration in future studies. Due to data limitations we were also unable to calculate Jing-Jin-Ji's virtual water transfer to other countries; such boundary setting is commonplace, and can be seen in other work (Guan and

Hubacek, 2007; Zhang and Anadon, 2014; Zhang et al., 2011). Finally, our analysis framework attributes bilateral trade only into final consumption without considering the impact of intermediate imports. This phenomenon, whereby exporters import intermediate products (e.g., raw materials) from upstream industries and produce final products for re-export to final consumers, cannot be traced clearly. The relevant discussion about these problems and their possible solutions can be found in other papers (Lenzen et al., 2007; Zhao et al., 2016b; Zhao et al., 2010).

## 5 Discussion and Conclusions

This study investigated the water footprint in the Jing-Jin-Ji region of China by distinguishing blue, green and grey water. For the first time we have quantified virtual water transfer in terms of water consumption and water pollution with four pollutant indicators in a physically water scarce region. The results showed that the Jing-Jin-Ji exports only small amounts of blue water but outsources huge amounts of green water and grey water (Figure 4). A considerable amount of water footprint was transferred as virtual water. Our study demonstrated that the quantitative targets of “the most stringent water resources management policy” for Jing-Jin-Ji can only be met at the expense of exporting provinces which provide virtual water to it and receive outsourced pollution in return. A “Virtual Water Strategy” is one measure which could alleviate water stress at the provincial scale. On the one hand it will relieve the water crisis in the receiving provinces, on the other hand it will impose pressure on the providing provinces through their supply chains, especially for water stressed areas. As a result, financial compensation from net water receiving provinces to water supplying regions could be considered in the context of achieving water management targets.

Serrano et al. (2016) assessed water footprint based on the consumption-based approach for the EU27 showing that the average blue WF is 398 $m^3$ per capita, which is about 2.5 times bigger than our result for China (143 $m^3$ per capita in the Jing-Jin-Ji region). It is known that European citizens consume large amounts of water-intensive food products in their diets, such as cheese, butter and beef. Conversely, Chinese citizens are more likely to have food with a lower water footprint, such as rice, vegetables and pork. Thus, a domestic diet distinction between these two regions resulted in a large difference in demand for water resource. Zhao et al. (2015) analyzed the virtual blue water transfer and internal domestic consumption for China’s 30 provinces for 2007. He found that Beijing and Tianjin were net virtual blue water importers, and Hebei was a net virtual blue water exporter; our findings for the blue WF account are consistent with this. However, Zhao’s absolute blue water values for the Jing-Jin-Ji were about 52% higher than our results. One reason for this is that Zhao selected water use as his basic blue water element; we also know that water use refers to the quantity of water distributed to users, including water lost in transmission. The blue water footprint used in our study was the volume of freshwater consumed to produce goods or services. Distinct from water use, water footprint in its accounting treatment excludes return flows which are a portion of a diverted water that is not used consumptively or returned to its original source or another region (U.S. Geological Survey, 2016). This comparison indicates that water footprint among supply chains could replace water use to obtain a more accurate picture of overall water consumption.

In 2015, the middle route of the South-North-Water-Transfer-Project (SNWTP) transferred 1,320 million $m^3$ physical water (822 million $m^3$ for Beijing, 373 million $m^3$ for Tianjin, and 125 million $m^3$ for Hebei) (The State Council of China, 2015); just one-fifth of its targeted volume. However, our results showed that the Jing-Jin-Ji exported 2,056 million $m^3$ virtual blue water which was nearly twice that of physical water flow and 12% of available water resource in the region. For the Jing-Jin-Ji physical water transfers cannot balance virtual blue water export, not to mention compensating for provincial water consumption. It is well known that over exploitation of groundwater has been a serious problem in the region, and there is no doubt water scarcity will be aggravated by huge virtual water export. In addition, as the biggest net virtual blue water exporter, Hebei transferred 6,663 million $m^3$, but only 14.5% of this was to the Beijing-Tianjin megacities (526 million $m^3$ for Beijing, and 445 million $m^3$ for Tianjin). From our point of view, improving the ratio of internalization of Hebei's virtual water flow will have positive impacts on water management.

Blue water presents high opportunity costs due to its potential as an input element in the value chain for high value added products and services, rather than its frequent use in intensive primary industry irrigation. As a result, blue water is addressed through water resource policies in China such as reservoir construction, water transfer projects, and flood management etc. However, green water is often ignored due to its exclusive use in agricultural production and "invisibility" in sustaining local ecosystems. Over exploitation of green water may lead to degradation of the local environment, therefore careful planning for agricultural production is crucial to sustainable local water management.

In 2010, Hebei exported huge amounts of water intensive and low value added products to other provinces. Amongst its exports, the two most water-intensive sectors (Agriculture, and Food and Tobacco Processing) accounted for 78% - 85% of Hebei's export-related water consumption, but only contributed 7% to total economic output for the area. A continuation of an export-based economic development model may further worsen Hebei's water stress, impair hydro-ecosystems, and potentially crowd out internal production. Therefore, to reduce these unbalanced water losses, reducing the dependency of this economy on export of water intensive and low value added agricultural products may lead to a more sustainable virtual water balance and reduce the pressure on internal water resources.

In 2010, 30,621 million $m^3$ grey water was imported to the Jing-Jin-Ji. If there isn't virtual water trade-off, water pollution in Jing-Jin-Ji will deteriorate, and about twice the amount of Jing-Jin-Ji's annual watershed will be needed to dilute pollutants to the minimum Grade III reuse standard. Food related sectors were the largest contributor to water pollution. In particular, Agriculture sector non-point source pollution was the main polluting sector; products from this sector were supplied internally for household consumption; Food and Tobacco Processing is second with these products mainly consumed by urban households.

The central government's "Beijing-Tianjin-Hebei Integration Strategy" will lead to a reduction of industrial intensity in Beijing by 2030. Some businesses are likely to retain their headquarters in Beijing, but relocate production facilities to Hebei and/or Tianjin. This will decrease total water consumption in Beijing, and contribute large indirect water flows from Beijing to Tianjin and Hebei. This helps to balance water flows among these areas, however the strategy has also created some problems: the core benefit of the Jing-Jin-Ji is that the three areas are integrated, thereby facilitating flow and potentially increasing efficiency. However, because Beijing is the national capital it enjoys certain bureaucratic advantages over Tianjin and Hebei, and industrial transfer from Beijing to Hebei also results in transfer of some businesses with low water utilization efficiency and heavy pollution, without requiring these businesses to adopt new technologies that improve utilization efficiency and decrease water pollution in their new location. Therefore, the government must pay greater attention to encouraging businesses to adopt technologies that reduce water consumption and pollution.

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## Appendix

*Table S1. Sector categories*

| ID | Sectors | Legend |
|---|---|---|
| ***Primary Sectors*** | | |
| 1 | Agriculture | |
| ***Secondary Sectors*** | | |
| 2 | Coal Mining and Dressing | |
| 3 | Petroleum and Naturl Gas Extraction | |
| 4 | Metals Mining and Dressing | |
| 5 | Nonmetal Minerals Mining and Dressing | |
| 6 | Food and Tobacco Processing | |
| 7 | Textile Industry | |
| 8 | Garments, Leather, Furs, Down and Related Products | |
| 9 | Timber Processing and Furniture Manufacturing | |
| 10 | Papermaking, Cultural, Educational and Sports Articles | |
| 11 | Petroleum Processing and Coking | |
| 12 | Chemicals | |
| 13 | Nonmetal Mineral Products | |
| 14 | Smelting and Pressing of Metals | |
| 15 | Metal Products | |
| 16 | General and Specialized Machinery | |
| 17 | Transportation Equipment | |
| 18 | Electric Equipment and Machinery | |
| 19 | Electronic and Telecommunications Equipment | |
| 20 | Instruments, Meters Cultural and Office Machinery | |
| 21 | Other Manufacturing Products | |

| | |
|---|---|
| 22 | Electricity and Heating Power Production and Supply |
| 23 | Gas and Water Production and Supply |
| 24 | Construction |
| ***Tertiary Sectors*** | |
| 25 | Freight Transport and Warehousing |
| 26 | Wholesale and Retail Trade |
| 27 | Hotels, Food and Beverage Places |
| 28 | Real Estate and Social Services |
| 29 | Scientific Research |
| 30 | Other Services |

*Table S2. Three region input-output table for the Jing-Jin-Ji (modified from Guan et al (2014)*

| | Intermediate Demand | | | Final Demand | | | | Total output | Water account | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Beijing | Tianjin | Hebei | Final consumption | Captial formation | Interprovincial export | International exports | | Direct blue water footprint | Direct green water footprint | Direct Grey water footprint |
| Beijing | z | | | y | | e | | x | D | | |
| Tianjin | | | | | | | | | | | |
| Hebei | | | | | | | | | | | |
| Imports | | | | | | | | | | | |
| Total Inputs | | | | | | | | | | | |

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## Highlights

- Assessing water footprint (WF) is crucial in understanding water deterioration
- WF and virtual water flows are assessed with a multi-regional input-output model
- Jing-Jin-Ji region exported little blue water, but outsourced much green and grey water
- Joint efforts between water receiving and supplying regions are a key for management
- Corporations need to adopt technologies to reduce water consumption and pollution