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Evaluating the vulnerability of physical and virtual water resource networks in China's megacities

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Highlights

- Megacity water resource network should include physical and virtual water supply
- Input-output analysis is used to analyze megacity water vulnerability
- Megacities were more vulnerable to external than internal water scarcity
- Virtual water inflow help decrease vulnerability in water stressed megacities

Abstract

The water resource networks that provide water for urban consumption consists not only of physical water supply, but also water embodied in imported goods and services i.e. virtual water supply or external water footprint. However, it remains unknown that if relying on external water footprint will increase or decrease the vulnerability of cities' water resource networks. Here, we evaluate the vulnerability of urban water resource networks for China's six megacities i.e. Beijing, Tianjin, Shanghai, Chongqing, Guangzhou, and Shenzhen. The vulnerability index was developed through combining a refined multi-region input-output table with both water footprint and water scarcity footprint analysis. The results showed that megacities need to import large volumes of virtual water embodied in food related sectors to balance their physical water shortages. The external blue water footprint (BWF) of the six megacities accounted for 80.7% of their total BWF, and was almost twice their physical water supply. The large share of external BWF helped Beijing, Tianjin, and Shanghai, which suffer extreme water stress in their urban areas, to decrease their total vulnerability by 39%, 33%, and 28% respectively, but conversely increase their vulnerability to external water shortages i.e. indirect vulnerability. Establishing megacity physical and virtual water resource networks based on input-output analysis provides an opportunity for urban water planners to internalize the risk of their external water footprint. Avoiding import water-intensive products from regions suffering extreme water stress, or managing indirect vulnerability through cooperation with those regions are suggested as viable water

management approaches.

Keywords:

Input-output analysis, Virtual water, Water footprint, Water Stress Index

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Abbreviations	
MRIO	Multi-region input-output
WSI	Water stress index
DWSI	Direct water stress index
IWSI	Indirect water stress index
WPL	Water productivity leverage
WVL	Water volume leverage
BWF	Blue water footprint
BWSF	Blue water scarcity footprint

1. Introduction

In this urbanizing world, sufficient freshwater supply is a fundamental challenge for many cities due to their increasing populations and rising levels of affluence (Hadjikakou et al. , 2019, McDonald et al. , 2014). Globally, urban freshwater use has quintupled since the 1950s (Padowski and Gorelick, 2014), and urban domestic and industrial water use combined correspond to 31% of global freshwater withdrawals (Larsen et al., 2016). Particular concerns have been raised in cities in rapidly developing economies, such as China and India, in which unprecedented rates of urbanization are occurring, making these nations need to restrict economic development due to inadequate water supplies (Srinivasan et al. , 2013).

While urban water planners seek to secure physical water supplies through water resource networks (Jeong and Park, 2020), the need for large amounts of virtual water supply emanating from beyond the city boundary (the "external water footprint") to support the growing urban consumption demand is often overlooked (Zhang et al., 2019). The virtual water concept, first introduced by Allan (1992), may generally be defined as the water required for the production of goods and services along the associated supply chain (Yang and Zehnder, 2007). Hence, virtual water studies are usually linked to the impact of trade activities on regional or global water stress alleviation or aggregation (Orlowsky et al. , 2014, Zhao et al. , 2018, 2016). The water footprint, subsequently proposed by Hoekstra and Hung (2002), is the water use of goods and services consumed by a defined geographical region (or an industrial sector or population) (Hoekstra, 2017). The water footprint concept is frequently used to evaluate the effects of regional consumption on global water resources (Hoekstra and Mekonnen, 2012, Hoff et al., 2014, Hou et al., 2018). According to Hoekstra and Mekonnen (2016), the "internal water footprint" is thus the water use within a geographical boundary to produce the goods and services that are consumed within that boundary, and the "external water footprint" is the water use in other geographical regions to produce the goods and services which are then imported and consumed within the geographical boundary under consideration.

A city's reliance on external water footprint has been addressed in literature (Zhang et al., 2012, Zhao et al., 2016, Rushforth and Ruddell, 2016, Chini et al., 2017). For example, Rushforth and Ruddell (2016) indicated that the external blue water footprint of Flagstaff, USA amounted to 93.7% of the total blue water footprint of the city. These studies suggest that external water footprint provides a non-negligible virtual water supply to modern cities which, by necessity, must be included in a cities' water resource networks alongside physical water supply for water management and planning purposes.

Relying on external water footprint, as so many cities do, has its risks and benefits in terms of water resource networks. On the one hand, through economic activity, cities can generate a leverage to more external water footprint than its own physical water supply (Rushforth and Ruddell, 2016). Such leverage help cities to shift the burden of their own water stress and use its own limited physical water endowment to produce high value goods and services (Zhao et al., 2015, 2016). On the other hand, the dependence on external water footprint introduces a risk to cities when the water of the exporting region is overexploited (Hoekstra and Mekonnen, 2016, Orlowsky et al., 2014), or is capped for its consumption (Liu et al., 2018). This inverse relationship reveals that cities are not only vulnerable to internal water shortages but also to external water shortages. Hence, it is crucial for urban water planners to understand and balance the trade-offs between the leverage of utilizing external water resources and the vulnerability existing in the external water footprint.

Previous studies have evaluated virtual water flows, as well as direct vulnerability (vulnerable to internal water shortages) and indirect vulnerability (vulnerable to external water shortages) for cities based on bilateral commodity flow data (Rushforth and Ruddell, 2016, Djehdian et al., 2019). However, the bilateral trade data has the limitation of being unable to distinguish between intermediate and final demand products, thus is difficult to trace the life cycle processes of water use along complex supply chains (Hoekstra et al. , 2011, Kastner et al., 2011). In contrast, the accounting framework based on the multi-region input-output (MRIO) table has the advantage of showing whole industry supply chain effects, and provides relatively more detailed sector disaggregation for industrial products (Feng et al., 2011). The MRIO approach, capable of reflecting economic transactions between different regions and economic sectors, has been widely used to quantify the virtual water flows (Feng et al., 2014, Hou et al., 2018, Serrano et al., 2016). However, to best of our knowledge, there is no study applying a MRIO analysis approach to evaluate and compare the direct and indirect vulnerability of physical and virtual water resource networks in different megacities.

In this study, we develop an accounting framework based on a refined MRIO table to investigate the characteristics of physical and virtual blue water flows for six Chinese megacities. The indicators of water volume and water productivity leverage, as well as vulnerability of these megacities to external water resources were derived from previous work (Rushforth and Ruddell, 2016, Zhao et al., 2016), and combined into the MRIO framework. The vulnerability of these megacities water resource networks was further explained through the introduction of the concept of a water scarcity footprint (Ridoutt and Pfister, 2010).

2. Data and Methodology

2.1 Data

The Chinese MRIO table formally contains four Chinese provincial-level megacities: Beijing, Tianjin, Shanghai and Chongqing. Accordingly, existing water footprint studies within China using the MRIO approach tend to have only considered these four megacities (Li and Han, 2018), and have ignored two other recognized megacities; Shenzhen and Guangzhou. In order to give a comprehensive analysis of the water footprint of China's megacities, we have thus extended the existing Chinese MRIO table to include Shenzhen and Guangzhou. We selected the 2010 Chinese MRIO table from Liu et al. (2014), which is the most up to date at the time the work was carried out, to perform the extension. The 2010 Chinese MRIO table contains 30 economic sectors for 30 provincial-level administrative regions (provinces, autonomous regions, and municipalities – here referred to as provinces for simplicity). Because both Shenzhen and Guangzhou form part of Guangdong Province, we disaggregated Guangdong Province into three sub-regions: Guangzhou, Shenzhen, and Rest of Guangdong (ROG). Detailed sector and region information can be found in Appendices (Table A1-A2). The interregional trade of the three sub-regions was estimated using a gravity model, originally developed by Leontief and Strout (1963). According to Miller and Blair (2009), data of three variables is needed to estimate the interregional trade of the three sub-regions using the gravity model. These are the supply of sector i in the exporting sub-region, the demand of sector i in importing sub-region, and the total production of sector i for all sub-regions. These data were obtained through the single region input-output tables of Guangzhou, Shenzhen, and Guangdong Province. Finally, the interregional trade between the three sub-regions and other provinces in China was estimated using similar trade ratios between Guangzhou Province and other provinces in China.

In this study, we only considered blue virtual water (surface water and groundwater) to match with the physical water supply. We didn’t consider green virtual water (soil water) or grey virtual water (polluted water) in quantifying the water footprint and vulnerability of each megacities’ water resource networks. Green water is a value substitute resource to blue water (Hoekstra et al., 2011), and grey water and their effects on water quality are important issues for megacities (Zhao et al., 2016). Both green and grey water will be addressed in our future work. For blue water, we applied consumptive water use rather than water withdrawal/use. The difference between consumptive water use and water withdrawal/use is that consumptive water use excludes the part of a diverted flow that is not consumptively used and returned to its original source or another body of water i.e. return flows (http://water.usgs.gov/edu/dictionary.html). The sectoral water use data for all provinces was obtained according to Zhao et al. (2018). We then multiplied the sectoral water use data by the water consumption coefficient for that sector to acquire sectoral water consumption data. The water consumption coefficient is taken from the Water Resource Bulletin in different provinces. It is worth noting our study of the six Chinese megacities took into consideration all urban districts, including all counties within the cities’ jurisdiction. This means these megacities also rely on their counties to provide physical and virtual water resources to the urban area.

The Water Stress Index (WSI) as a water scarcity indicator was used to evaluate the vulnerability of a megacities' water resource networks. Derived from Pfister et al. (2009), the WSI was developed through the WaterGAP2 global model with a spatial resolution of 0.5º. Pfister et al. (2009) adapted the water withdrawal-to-availability indicator applying a logistic function to acquire continuous values between 0.01 and 1 for WSI. Hence, four levels of water stress were described in WSI i.e. Minor (0.01-0.09); Moderate (0.09-0.5); Severe (0.5-0.91); and Extreme (0.91-1). The WSI in Pfister et al (2009) are presented at the grid level. In order to achieve the provincial and megacity level WSI, we aggregated the WSI values to the provincial and megacity level in China using the arithmetic average of grid WSI within that province or megacity.

2.2 Combining leverage and vulnerability assessment with the multi-region input-output model

We utilise the "Water Embodied in Trade" approach with the MRIO table to quantify both internal and external blue water footprint (BWF) in China's megacities (Feng et al., 2011, Zhao et al., 2016). A detailed illustration of the "Water Embodied in Trade" approach can be found in Zhao et al. (2016). The BWF is the sum of the internal BWF and external BWF. In order to quantify the BWF of city *r*, direct water use intensity is introduced, which is the blue water consumption $\mathbf{w}^r$ of each sector per unit of their total output $\mathbf{x}^r$, i.e. $\mathbf{d}^r = \mathbf{w}^r \cdot (\mathbf{x}^r)^{-1}$. Hence, the internal and external BWF can be expressed as:

$$\mathbf{ibwf}^r = \mathbf{d}^r (\mathbf{I} - \mathbf{A}^{rr})^{-1} \mathbf{y}^{rr} \quad (2)$$

$$\mathbf{ebwf}^{r} = \sum_{s \neq r} \mathbf{d}^{s} (\mathbf{I}\text{-}\mathbf{A}^{ss})^{-1} \mathbf{e}^{sr} \quad (3)$$

Where $\mathbf{ibwf}^{r}$ and $\mathbf{ebwf}^{r}$ are the internal and external BWF of city *r*, respectively, $\mathbf{d}^{r}$ and $\mathbf{d}^{s}$ are direct water use intensity of city *r* and region *s*, $\mathbf{I}$ is the unit matrix, $\mathbf{A}^{rr} = \mathbf{Z}^{rr} \cdot (\mathbf{x}^{r})^{-1}$ is the technical coefficient of city *r*, representing the intermediate inputs $\mathbf{Z}^{rr}$ of each sector per unit of their total output $\mathbf{x}^{r}$ of city *r*. $\mathbf{y}^{rr}$ is the final demand of city *r* derived from local production of city *r*. $\mathbf{A}^{ss}$ is the technical coefficient of regions *s,* and $\mathbf{e}^{sr}$ represents the exports of region *s* to fulfill the final demand of city *r*.

Megacity leverage to external water resources is two-fold. First, megacities may leverage the import of more virtual water, rather than use their own local physical water supplies to support the production of final consumption. Such leverage may be defined as water volume leverage (WVL). The WVL is used to measure the extent to which a megacity has access to external water resources. The WVL of city *r* can be expressed as the ratio between external BWF (or blue virtual water import) and physical water consumption:

$$WVL^{r} = \frac{\sum EBWF^{r}}{PWC^{r}} \quad (4)$$

Where WVL^{r} is the WVL of city *r*, $EBWF^{r}$ is the external BWF of city *r*, and PWC^{r} is the physical water consumption of city *r,* including water use for production and for domestic use.

Comparing the leverage on water quantity, cities also have the leverage to use water more economic efficiently (Rushforth and Ruddell, 2016; Zhao et al., 2016), i.e.

cities may have larger economic water productivity. For example, Zhao et al. (2016) found that every 1 m^3 of water used in the megacity Shanghai on average produces 1000 Chinese Yuan of products, but only produces 111 Chinese Yuan of products imported from other provinces. Such leverage, termed Water Productivity Leverage (WPL) in this paper, helps the megacities import low value products, and make use their own limited water supply to produce high value products. The WPL is used to evaluate the extent to which a megacity has the leverage to import low value water-intensive products and use its own limited water resources to produce high value products (Rushforth and Ruddell, 2016, Zhao et al., 2016). The WPL of city r (WVL^r) is calculated as the ratio between value intensity of exports (vie^r) and value intensity of imports (vii^r), i.e. $WPL^r = \frac{vie^r}{vii^r}$. The value intensity measures how much goods and services can be produced in terms of value per unit water consumption (direct and indirect). vii^r and vie^r may be obtained as follows:

$$vii^r = \sum_{s \neq r} \mathbf{e}^{sr} / \sum_j \mathbf{vwi}^r \tag{5}$$

$$vie^r = \sum_j \sum_{s \neq r} \mathbf{e}^{rs} / \sum_j \mathbf{vwe}^r \tag{6}$$

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

2.3 Measuring the vulnerability of megacity water resource networks

Megacity water resource networks are more vulnerable when their water demand is sourced in regions with higher water stress (Rushforth and Ruddell, 2016). In order to evaluate this vulnerability, megacity water footprint must be linked to the water scarcity situation where the water is consumed. When the BWF is weighted by the water scarcity indicator of the region where the water consumption is located, this new indicator may be termed the blue water scarcity footprint (BWSF). The BWSF is an appropriate indicator showing the impact of water consumption on water scarcity (Hess et al. , 2015, Ridoutt and Pfister, 2010), and can be used to measure the vulnerability of megacity water resource networks. For example, two megacities may have the same external BWF, but the megacity with the higher external BWSF is more vulnerable to its external water sources.

Both physical water supply and virtual water supply (external BWF) constitute megacities' water resource networks. Hence, physical water consumption and external BWF impact on a megacity's internal and external water availability, respectively. The vulnerability of a megacities' water resources network can therefore be classified into direct vulnerability (vulnerable to internal water shortages) and indirect vulnerability (vulnerable to external water shortages). Direct vulnerability of city *r* (DV^r) is the water stress index (WSI) of city *r* weighted by the ratio of city's physical water consumption to its total physical and virtual water supply:

$$DV^r = DWSI^r \times \left(\frac{PWC^r}{EBWF^r + PWC^r} \right) \quad (7)$$

Where $DWSI^r$ is the WSI of city *r*. PWC^r and $EBWF^r$ are physical water consumption and external BWF of city *r*, respectively.

Indirect vulnerability of city *r* (IV^r) is the indirect water stress index (IWSI) of city *r* weighted by the ratio of city's external BWF to its total physical and virtual water supply:

$$IV^r = IWSI^r \times \left(\frac{EBWF^r}{EBWF^r + PWC^r} \right) \quad (8)$$

Where $IWSI^r$ is the IWSI of city *r*, which can be quantified as the ratio between external BWSF and external BWF of city *r:*

$$IWSI^r = \frac{EBWSF^r}{EBWF^r} = \sum_{s \neq r} \frac{VWE^{s-r} \times DWSI^s}{\sum_{s \neq r} VWE^{s-r}} \quad (9)$$

Where $EBWSF^r$ and $EBWF^r$ are external BWSF and BWF of city *r*, VWE^{s-r} is the virtual water export from region *s* to city *r*, and $DWSI^s$ is the WSI of region *s*.

Thus, the total vulnerability of city *r* (TV^r) is the combination of its direct vulnerability and indirect vulnerability:

$$TV^r = IV^r + DV^r \quad (10)$$

Similar to WSI, total vulnerability may also be classified as four levels, i.e. Minor (0.01-0.09); Moderate (0.09-0.5); Severe (0.5-0.91); and Extreme (0.91-1).

As can be seen from equation (7) and (8), direct vulnerability of city *r* is positively correlated with the city's WSI and physical water consumption, whilst indirect vulnerability of city *r* is positively correlated with the city's IWSI and external BWF.

3. Results

3.1. The characteristics of physical and virtual water resource networks in China's megacities

The characteristics of physical and virtual blue water flows in China's six megacity water resource networks are shown in Fig. 1. The physical water consumption within the boundary of each megacity is partly consumed for domestic water demand, and partly for production of goods and services. Once consumed in the production process, water is turned from its “physical form” to its “virtual form” and flows through the supply chain. This virtual water embodiment may then be further disaggregated to blue virtual water export and internal BWF (Fig. 1). The other source of virtual water is external BWF (i.e. blue virtual water imports), flowing from exporting regions outside the megacity boundary. Hence, the total BWF is the sum of the internal BWF and external BWF.

Quantitatively, the total BWF of the six Chinese megacities amounted to 30.4 km^3. These megacities, having 8.1% of the national population, consumed 11.1% of national BWF. The total external BWF of the six megacities was 24.5 km^3, which was almost twice their physical water consumption, and accounted for 80.7% of the total BWF. The total physical water consumption within the boundaries of these megacities was 12.5 km^3, comprising 3.3 km^3 for domestic use and 9.2 km^3 of virtual water used for production. This virtual water embodiment derived from local physical water supply can be further divided to 3.3 km^3 of blue virtual water export and 5.9 km^3 of internal BWF.

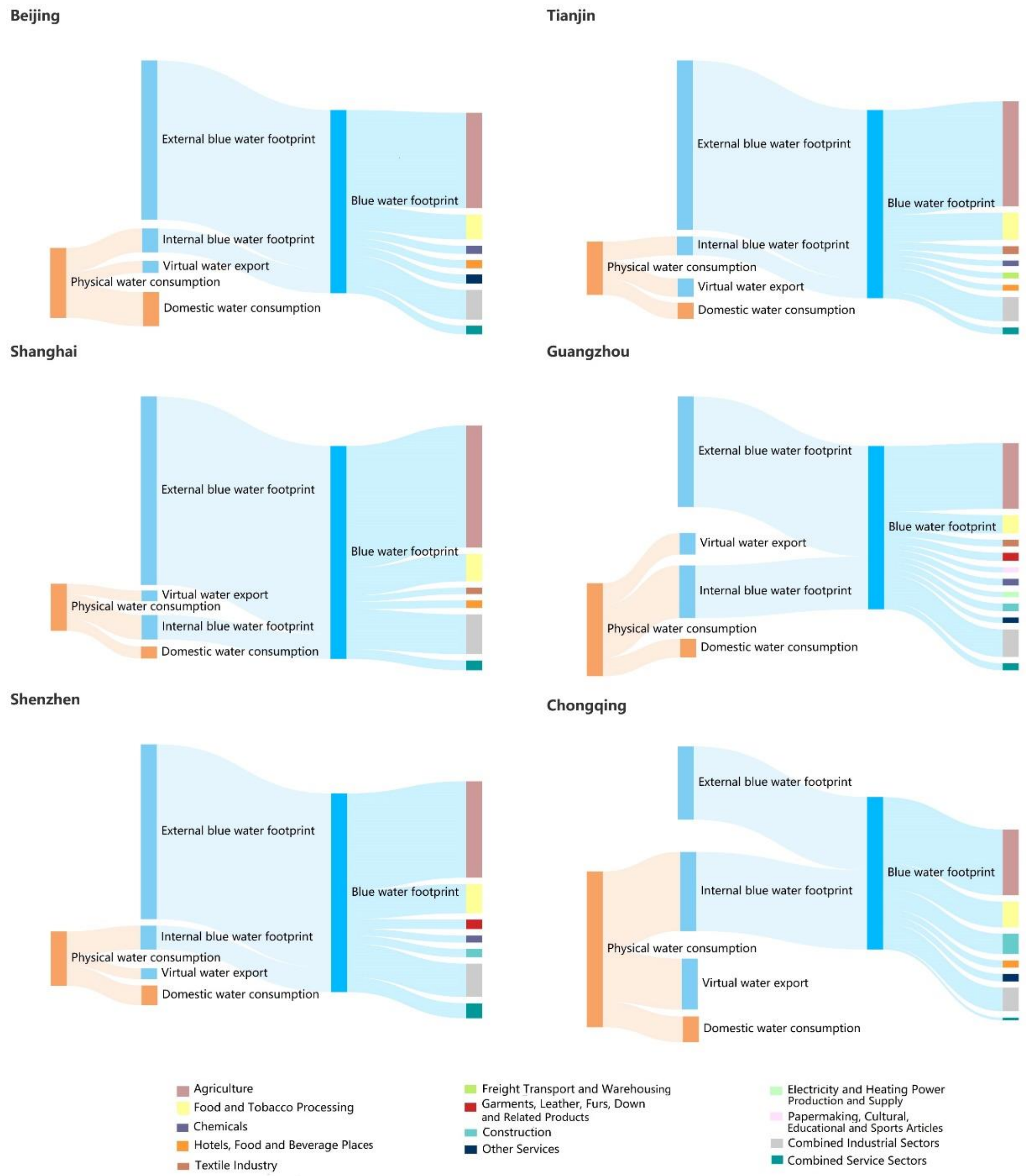

Fig. 1. Physical and virtual blue water flows in China's megacity water resource networks

The physical and virtual water flows in the water resource networks of the six megacities are different in volume and distribution. Fig. 1 shows the numerical relationships between BWF, external BWF, internal BWF, and physical water consumption for each megacity. Shanghai had the largest BWF (10.3 km^3), followed by Beijing (5.4 km^3), Tianjin (5.3 km^3), Chongqing (4.0 km^3), Guangzhou (3.5 km^3), and

Shenzhen (1.8 km^3). For most of the studied megacities, the BWF consists of a larger proportion of external BWF and smaller proportion of internal BWF. Chongqing was the exception, having a slightly larger share of internal BWF accounting for 51.9% of its BWF. Chongqing also had the largest physical water consumption (4.1 km^3), followed by Shanghai (2.3 km^3), Beijing (2.1 km^3), Guangzhou (2.0 km^3), Tianjin (1.5 km^3), and Shenzhen (0.5 km^3). For all megacities, most of their physical water consumption is transformed into virtual water flow, and these virtual water flows were mostly consumed as internal BWF. In addition, all megacity blue virtual water exports were lower than their virtual water imports.

3.2 Blue water footprint in sectorial detail

Based on our accounting framework, the total BWF may be disaggregated to sectoral level BWF (Table A1). For each megacity, the agricultural BWF formed the largest component of their total BWF (Fig. 1); the share ranging from 40.25% (Guangzhou) to 57.37% (Shanghai). The second largest sectoral BWF for each megacity was “Food and tobacco processing”, ranging from 11.12%（Guangzhou） to 16.82% (Chongqing) of the total BWF of the respective cities. The large BWF of this sector is due to overwhelmingly water input from agricultural sector as intermediate demand. Indeed, the processing of this sector only generated 4% of the BWF, and the production of the intermediate agricultural products generated 94% of the BWF. Beijing, Tianjin and Shanghai had relatively smaller shares of BWF for their industrial sectors, ranging from 34.03% to 34.47%. In comparison, Guangzhou, Chongqing, and

Shenzhen had larger share of industrial BWF, ranging from 43.91% (Shenzhen) to 52.14% (Guangzhou). Summing up sectoral BWF for all the megacities, the sectors with the largest share of BWF were “Agriculture” (51.75%), “Food and tobacco processing” (13.69%), “Construction”(3.68%), “Hotels, food and beverage places”(3.55%), “Chemicals”(3.27%), “Other services”(3.13%), and “Textile industry” (2.98%).

3.3. External blue water footprint in regional and sectorial detail

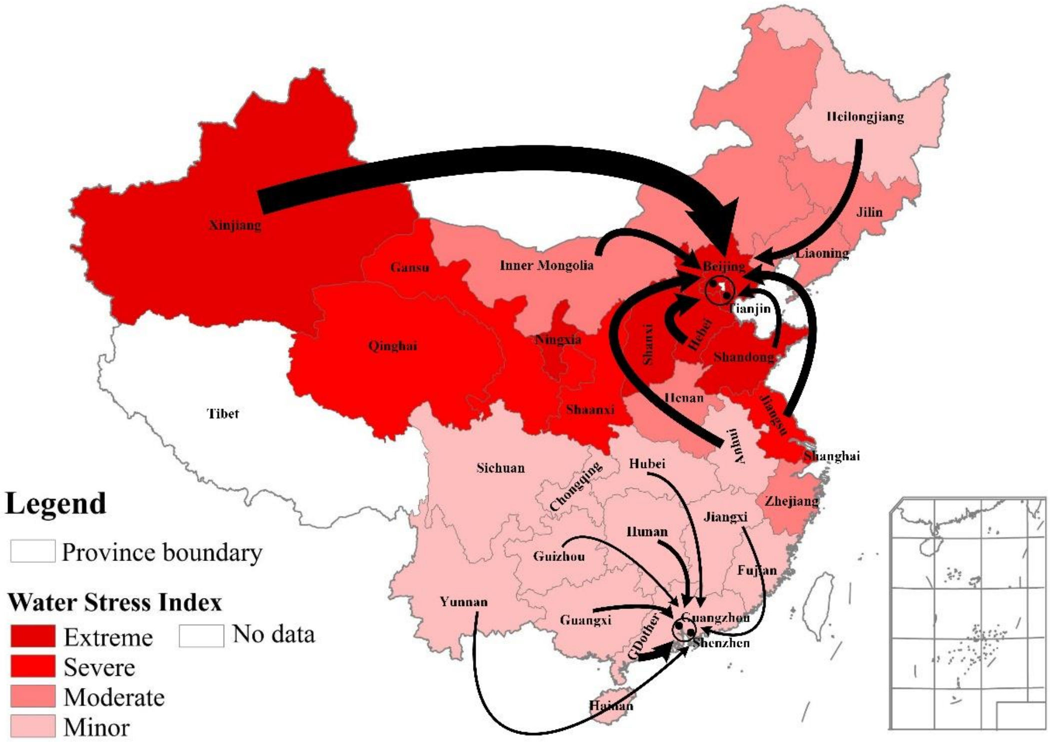

Fig. 2. Top blue virtual water flows to selected megacities: Beijing and Tianjin versus Guangzhou and Shenzhen. The black arrows show the virtual water flows from virtual water exporting provinces to the megacities, and the width of the arrows show the magnitude of virtual water flow.

The provinces from which the six studied megacities imported the largest volumes of blue virtual water were Xinjiang, Hebei, Anhui, Jiangsu, Heilongjiang, Inner Mongolia, Shandong, Guangxi, Guangdong other, and Hunan respectively (Table A2).

These top 10 provinces cumulatively accounted for 68.0% of the external BWF of the six megacities. Amongst these 10 provinces, the top 7 provinces are located in northern China, or the border area between northern and southern China (Anhui and Jiangsu). Megacities in different geographical locations in China imported large volumes of blue virtual water from different provinces. Taking two northern cities (Beijing and Tianjin) and southern cities (Shenzhen and Guangzhou) as examples (Fig. 2), Beijing and Tianjin imported their largest amounts of blue virtual water from northern China or the north-south border areas, i.e. Xinjiang, Hebei, Anhui, Jiangsu, Inner Mongolia, Heilongjiang, and Shandong, accounting for 65.6% of their external BWF. In contrast, Guangzhou and Shenzhen imported their largest blue virtual water from areas of southern China i.e. Guangdong other, Hunan, Guangxi, Hubei, Yunnan, Jiangxi, and Guizhou, amounting to 59.0% of external BWF for these two megacities.

When examining the external BWF for all the megacities at sectoral level, we found that the external BWF of “Agriculture” and “Food and tobacco processing” had an even larger share, accounting for 56.63% and 15.54% of the total external BWF of all the megacities. This result indicates that blue virtual water was imported mainly to satisfy the food demands of the six megacities. The sectors having the largest share of BWF also had the largest share of external BWF except for “Construction”, which accounted for only 0.36% of total external BWF.

3.4. Megacity leverage to external water resources

Megacity quantitative leverage to external water resources is expressed through the ratio between external BWF and physical water consumption. According to Table 1, five of the studied megacities had a WVL larger than 1 meaning these cities have consumed more external virtual water resources than their own physical water supplies in order to satisfy final consumption. For example, Shanghai with the largest WVL (4.01) of the six megacities, gained greater leverage to import virtual water, but was also more susceptible to changes to the external water resources on which it also depends.

The WPL shows megacity leverage towards greater economic efficient use of water. The results of WPL analysis varied significantly, ranging from 1.76 (Chongqing) to 77.97 (Shenzhen) (Table 1), mainly due to the large differences in value intensity of exports between the six megacities. As shown in Table 1, the value intensity of imports ranged relatively narrowly between 26 USD/m^3 (USD: US dollar) and 35 USD/m^3, whereas the value intensity of exports ranged much more significantly between 49 USD/m^3 to 2,224 USD/m^3. These two indicators, calculated according to equation (5) and (6), signify the average value created by the imported or exported products from consumption of 1 m^3 of water. Taking Shenzhen as an example, 1 m^3 of imported virtual water produced just 29 USD of products, whereas the same amount of exported virtual water created 2,224 USD of products. This means Shenzhen enjoys great leverage over its importation of products with low value intensity, and uses its physical water supply to produce products with high value intensity.

Table 1 Water Volume Leverage and Water Productivity Leverage of the studied megacities

	Water Volume Leverage (WVL)	Value Intensity of Imports (VII) Unit: USD/m^3	Value Intensity of Exports (VIE) Unit: USD/m^3	Water Productivity Leverage (WPL=VIE/VII)
Beijing	2.28	28	334	12.09
Tianjin	3.17	26	233	8.92
Shanghai	4.01	24	324	13.30
Guangzhou	1.19	35	219	6.35
Shenzhen	3.22	29	2224	77.97
Chongqing	0.47	28	49	1.76

3.5. The vulnerability of megacity water resource networks

The total vulnerability of a megacity's water footprint is determined by its physical water consumption, internal and external BWF, and BWSF (Eq. 7-10). Comparing the BWF and BWSF of the six megacities (Fig. 3), we found that Tianjin and Beijing (located in northern China), and Shanghai (located in the border region between northern and southern China) had larger BWF and BWF per capita than the other three megacities located in southern China, namely Guangzhou, Shenzhen, and Chongqing. However, this difference is not significant: for example, Chongqing had the largest internal BWF among all the studied megacities, and the per capita BWF of Guangzhou was close to that of Beijing. In contrast, the BWSF and per capita BWSF of Shanghai, Beijing, and Tianjin were significantly larger than those of the southern megacities. Such large discrepencies may be explained by both the large DWSI and IWSI of Shanghai, Beijing, and Tianjin (Table 2). As for DWSI, the megacities located in northern China i.e. Beijing and Tianjin have the highest DWSI, followed by Shanghai (0.795). In contrast, the megacities located in southern China i.e. Guangzhou, Shenzhen, and Chongqing all had DWSI lower than 0.1 (minor water stress). The differences on the spatial pattern of virtual water import have substantial impact on the indirect water stress index (IWSI) of these megacities. The cities with higher DWSI also had higher IWSI. This is mainly because the blue virtual water imports of Beijing, Tianjin, and Shanghai imported more of their BWF from the water scarce regions of northern China (Fig. 2).

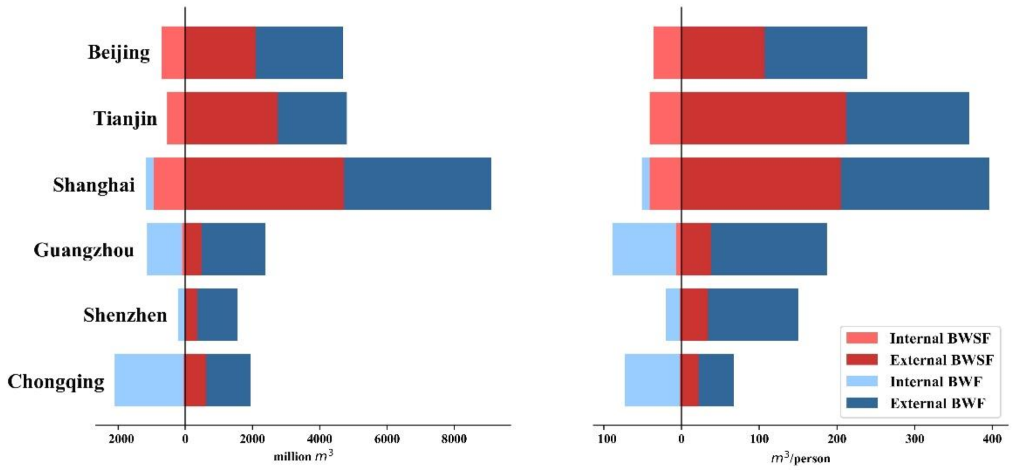

Fig. 3. Comparison of blue water footprint (BWF) and blue scarcity water footprint (BWSF) in both volumetic and per capita terms. (The m^3/per capita of each megacity was calculated through dividing BWF or BWSF by population of that city.)

The results of direct, indirect and total vulnerability of the six megacities are shown in Table 2. The megacities located in southern China all had smaller direct, indirect and total vulnerability. Whilst the total vulnerability of Beijing, Tianjin, and Shanghai were classified as severe, for the other three southern megacities it was classified as moderate. All megacities had larger indirect vulnerability than their direct vulnerability. Interestingly, Beijing, Tianjin, and Shanghai all had larger DWSI than IWSI, but these three megacities still had lower direct than indirect vulnerability. This may be explained by the larger share of external BWF or higher WVL of these megacities, which indicates that higher WVL will raise the indirect vulnerability of megacities. From another point of view, a higher WVL helps to decrease the total vulnerability of water scarce megacities. For example, according to equation (7-10), and assuming that Beijing, Shanghai, and Tianjin had no imports from other provinces, their indirect vulnerability would be zero, and their total vulnerability would then be equal to their direct vulnerability. This means the total vulnerability of these three cities based on a no trade assumption would be 1, 1, and 0.795 respectively (Table 2). Comparing the existing total vulnerability, we can deduce that virtual blue water imports have helped these cities decrease their total vulnerability by 39%, 33%, and 28% respectively.

Table 2 Water stress index and vulnerability of the six megacities

	Direct Water Stress Index (DWSI)	**Indirect Water Stress Index (IWSI)**	**Direct Vulnerability (DV)**	**Indirect Vulnerability (IV)**	**Total Vulnerability (TV)**
Beijing	1	0.45	0.30	0.31	0.61
Tianjin	1	0.57	0.24	0.43	0.67
Shanghai	0.795	0.52	0.16	0.41	0.57
Guangzhou	0.078	0.20	0.04	0.11	0.15
Shenzhen	0.078	0.23	0.02	0.17	0.19
Chongqing	0.021	0.32	0.01	0.10	0.12

We may further analyze the contribution of provinces and sectors to the indirect vulnerability of each megacity. Contributions of different provinces to indirect vulnerability were shown in Table A3. Xinjiang, Hebei, Jiangsu, Shandong, and Ningxia contributed the most to indirect vulnerability. For example, 54.3 % of Tianjin's indirect vulnerability came from Xinjiang, and 17% of Guangzhou's indirect vulnerability came from Jiangsu. Contribution from "Agriculture" to indirect vulnerability was the largest for each city, ranging from 46.2% (Guangzhou) to 70.7% (Shanghai) (Table A4). Other sectors contributing great to indirect vulnerability of the six megacities were "Food and Tobacco Processing", "Textile Industry", and "Chemicals".

4. Discussion

4.1 Understanding the water demand of megacities through their water resource networks

The water resource networks proposed in this study include both physical and virtual water supplies. Understanding such networks help to comprehensively identify the path of water flow in megacities from supply side to end users, and with sectoral levels of detail. The end-use water demand of megacities may be categorised as domestic water consumption, BWF, and virtual water export (Fig. 1). We found that BWF was the largest driver of megacity water supply, accounting for 82.1% of total physical and virtual water inflows to the studied megacity water resource networks. For the six megacities, almost half of their physical water was transformed to virtual water in support of their BWF, but that this transformed virtual water only made up 19.3% of the total BWF. Hence, megacities need to import large volumes of virtual water to balance physical water shortages.

The water resource networks were built based on a MRIO approach. One of the advantages of input-output analysis is to provide a comprehensive coverage of all relevant goods and services and their interrelationships for water footprint accounting (Daniels et al. , 2011). Looking in sectoral detail, we found the “food related sectors” i.e. “Agriculture”, “Food and tobacco processing”, and “Hotels, food and beverage” (Zhao et al., 2016), contributed most to the BWF, together accounting for 69% of total BWF. The large BWF of the latter two sectors is because they used a large amount of agricultural products as their intermediate input. Overall, this illustrates the overwhelming demand of megacities for food related products dominates their total water demand.

It worth noting that the megacities’ BWF of “Electricity and heating power production and supply” only accounted for 1.5% of total BWF. This results are consistent with previous finding that consumptive water use in electricity supply generates a small amount of water consumption but large amount of water withdrawal (Zhang et al., 2016, Zhang and Anadon, 2013). The difference is mainly because the popular once-through cooling technology used in thermal power plants need huge amount of water withdrawal but later return most of the water to the sources.

4.2 Urban agriculture are key determinants in the vulnerability of megacity water resource networks

Historically, a city’s food supply is mainly provided through agricultural activity located in its urban district (Zezza and Tasciotti, 2010). Such a pattern remains evident for Chongqing, which has the largest urban farmland amongst the studied megacities enabling it to meet large proportion of its food consumption demands, with a correspondingly large physical water consumption. Chongqing's urban area is 5,475 km^2, but its urban district area (mostly comprising counties with agricultural land) is 82,135 km^2. The second largest urban district area in our study belongs to Beijing, which has only 16,411 km^3. Relying more on urban agriculture can explain why Chongqing had the lowest WVL and WPL, since the agricultural sector uses the largest amount of water and contributes least to urban GDP growth. However, it is difficult for megacities such as Chongqing to maintain their urban agriculture since the main priority for megacities is economic development. For example, an index decomposition analysis found that recent economic development in Suzhou, a large city located to the west of Shanghai, compressed the agricultural crop area, decreased its internal BWF, and hence increased its external BWF (Zhao et al., 2017).

In addition, we found that megacities externalise their BWF mainly to nearby provinces, which may be viewed as an extension of the megacities' farmland. This might be because nearby provinces have similar climatic conditions and dietary habits. Such a finding suggests that megacities in water scarcity status are more vulnerable than previously thought since their surrounding regions might also be in scarcity status. For example, Beijing and Tianjin both imported large amounts of blue virtual water from their neighboring province i.e. Hebei Province, which is in extreme water stress, but exported the second largest amount of blue virtual water among all provinces to the six megacities. Hence, it is important for water scarce megacities not only to manage their internal agriculture, but also to pay attention to their nearby agriculture in other provinces. China's strategy of "coordinated development for the Beijing-Tianjin-Hebei region", initiated in 2015, provides an opportunity to manage the agriculture and water supply for the whole region. The strategy aims to achieve balanced development between Beijing, Tianjin, and Hebei through a series of actions, given that the development of Hebei is far behind Beijing and Tianjin. Since one of the goals of the strategy is to solve the region's resource and environmental problems together through integrated planning and cooperation, we suggest here to develop a framework under the strategy to compensate for the water loss suffered by Hebei Province due to virtual water exports to Beijing and Tianjin. Such framework could act as a pilot example for water scarce megacities around the world.

4.3 Internalizing the risk of virtual water supply beyond the city boundary

An important question for urban water planners is that will relying on external water resources increase or decrease the total vulnerability of cities' water resource networks? To answer this question, we established an accounting framework using a MRIO table to better understand the role of external BWF on the vulnerability of megacity physical and virtual water resource networks. The results showed that for those megacities with extreme water stress i.e. Beijing, Tianjin and Shanghai, relying on external water resources helped to decrease direct and total vulnerability, but at the price of increasing their indirect vulnerability. Hence, the vulnerability index provides an opportunity for urban water planners to internalize the risk of virtual water supply beyond the city boundary i.e. 'managing' the indirect vulnerability.

Beijing and Tianjin, in extreme water stress, have made great efforts to reduce the risk to their physical water supplies following the "limit city scale with water constraints" initiative, which was first proposed by General Secretary Xi Jinping in 2014 (Zhang et al., 2018). This initiative requires the city to monitor its population based on domestic water demand and its corresponding capacity of providing physical water. Such action may help control limited physical water demand, and in the meanwhile contribute indirectly to BWF reduction. However, population control in itself will not decrease per capita water demand from consumption of goods and services, thus can only partially decrease the BWF and vulnerability. Hence, it is recommended that megacities in extreme water stress take action to decrease their indirect vulnerability to their water resource networks. This requires megacities to pinpoint hotspots of large virtual water exporters in extreme water stress within their supply chain, and choose alternative exporting regions with less water stress. Megacities may thus act to internalize, and manage their indirect vulnerability through integrated cooperation with water stressed exporting regions. Zhao et al. (2016) suggested that megacities could provide fiscal aids to support water saving actions in large water stressed exporting regions first through pilot project and then roll out nationally. Since Xinjiang contributed the largest proportion to indirect vulnerability of water stressed megacities (about 54%, 36%, and 24% of indirect vulnerability in Tianjin, Shanghai, and Beijing were due to importing goods and services from Xinjiang),

Xinjiang may be chosen as the first target for fiscal aids. Our work provides a first step i.e. it provides an evaluation framework for both direct and indirect vulnerability of megacity water resource networks.

4.4 Limitations

We recognized several limitations in this study. First, different water scarcity indicators could be used to calculate the BWSF, which may result in different vulnerability results. For example, AWARE method was recently developed by the UNEP/SETAC Life Cycle Initiative (UNEP/SETAC, 2016). The method derived water scarcity indicator through evaluating the relative water remaining in a region by subtracting human consumption and water ecosystem requirement from local renewable water availability (Boulay et al., 2017). Ridoutt et al. (2018) have used both the WSI and AWARE indicator to quantify the BWSF of Australian agricultural products with a MRIO approach. They found that AWARE and WSI are not directly comparable in absolute values, since the range of AWARE is between 0.1-100, and WSI is 0.01-1.However, they found that the BWSF using different indicators were highly correlated at sectoral level; i.e. the top sectors with the highest and lowest water scarcity footprint are consistent for the two indicators. Such finding suggest that exchanging the two indicators has no significant impact to the BWSF results. Based on the above finding, we only used the WSI indicator from Pfister et al. (2009) in this study, which has been widely applied to quantify the BWSF (Feng et al., 2014, Zhao et al., 2018). Comparing the BWSF results of different water scarcity indicator is beyond the scope of this study.

Second, although widely used, the MRIO modelling may result in uncertainties and errors from the approach itself, such as linear production functions, assumptions of homogeneity, sectoral aggregation, and the MRIO table compilation (Lenzen et al., 2010). For example, agriculture is aggregated into only one sector in the Chinese MRIO table due to lack of data. As a result, we were unable to carry out a detailed analysis for different agricultural products, such as crops and livestock. The link of agriculture management practices, such as improving irrigation efficiency, with megacity water vulnerability will be investigated in our future study, through using a hybrid input-output analysis (Ewing et al., 2012).

Last but not least, uncertainties are inevitable for consumptive water use accounting. Sectoral water consumption coefficient and water use data are multiplied to derive consumptive water use at sectoral level, which is considered as a relatively crude method (Lin et al., 2019). In addition, both water consumption coefficient and water use data were acquired from official statistics, which are sensible to the accuracy of data quality. It was estimated that statistical data in China usually has uncertainties between 5%–10% (Du et al., 2018). Overcoming such uncertainties are beyond the scope of this study.

5. Conclusions

We evaluated and compared the direct and indirect vulnerability of water resource networks for six megacities in China, based on a refined MRIO table. Our work highlights the importance of incorporating virtual water flows and "physical to virtual water transformations" in urban water resource management, so as to identify the trade-offs between the leverage and vulnerability to external water resources. We found that all megacities had larger indirect vulnerability than their direct vulnerability, indicating megacities' non-negligible risk to external water shortages. Xinjiang, Hebei, Jiangsu, Shandong, and Ningxia were provinces contributing most to these megacities' indirect vulnerability. Whilst "Agriculture", "Food and Tobacco Processing", "Textile Industry", and "Chemicals" were sectors contributing most to indirect vulnerability. Megacities with extreme water stress, i.e. Beijing, Tianjin, and Shanghai, decreased their direct vulnerability at the price of increasing indirect vulnerability, mostly due to importing large amounts of virtual blue water from nearby provinces. We thus conclude that megacities may act to first internalize, and then manage their indirect vulnerability through integrated planning and cooperation with water stressed provinces that providing goods and services to megacities. It should be noted that water quality problems also represent huge challenges for megacities and their trading partners. Our future work will focus on water quality stress and the resulting vulnerability of megacities.

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