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Water footprint of the energy sector in China's two megalopolises

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Abstract: Using a consumption-based Multi-Regional Input-Output (MRIO) model, we investigate the distinctive characteristics, self-efficiency or external dependency, of energy demand’s water footprint in China’s two biggest and fastest developing megalopolises. We find that energy demand water footprint in the Jing-Jin-Ji and the Yangtze Delta amounted to 2.41 and 9.59 billion m^3 of water withdrawal respectively in 2010, of which 848.06 and 973.91 million m^3 was consumed. Among all energy products, electricity contributed the largest share to the energy sector’s water footprint in both regions. The sectoral distribution of water footprint in the upstream supply chain differed by region. Most significantly, the agricultural sector accounted for more than 30% of water consumption footprint. In addition to water used locally, final energy demands in these two regions induced external water footprint beyond their administrative boundaries. The Jing-Jin-Ji region’s energy sector had a smaller water footprint compared to the water-abundant Yangtze Delta region. However, external water footprint occupied a larger proportion in the former. Such divergence can be attributed to the distinctive water endowments and water-using technologies utilized in their respective energy sectors. Bespoke urban governance and policies tailored to local resource and technology portfolios are recommended for different urban agglomeration energy and water flows.

Key words: Water-for-energy nexus; Urban; Jing-Jin-Ji; Yangtze Delta; Water footprint

1. Introduction

Modern energy provision is the cornerstone for development and prosperity of human society. Access to affordable and clean energy is included as one of the 17 Sustainable Development Goals (SDGs) *(United Nations, 2015)*. With economic and population growth, there is historically high and increasing demand for different types of energy supply *(International Energy Agency, 2016)*, especially in rapidly developing countries or regions. Energy provision is closely interlinked with the water sector (*Marsh, 2008*). On the one hand, energy is used to supply water, in processes like desalination and pumping; on the other hand, water is an indispensable input into virtually every stage of energy production, from coal mining and oil refining to, predominantly, cooling water used in electricity generation (*Meldrum et al., 2013*). Such interconnectedness, the so-called 'water-energy nexus', has gained growing appreciation during the last two decades. In this study, we focus on the water use for energy provisions, which is often referred to as the 'water-for-energy nexus'. Water has been recognized as a limiting factor for wide economic and societal development *(World Economic Forum, 2016)*. Decreasing water availability or increasing water temperature has already caused power curtailments in many parts of the world, for example France in 2003, Mississippi River in 2006, and Southeast U.S. in 2007.

Global urbanization has increasingly caused concerns regarding the above mentioned potential for water-energy conflicts *(Wang and Chen, 2016; Fang and Chen, 2017)*. The formation of megalopolises, which are defined as regions of adjacent heavily populated metropolitan cities, facilitates and symbolizes the processes of urbanization *(Briggs, 2015)*. China's two biggest megalopolises, the so-called Jing-Jin-Ji (the Beijing-Tianjin-Hebei national capital region in the north of China), and the Yangtze Delta (which includes Shanghai, Jiangsu and Zhejiang in the east) (Figure 1) are excellent examples.

Looking at direct water use by the energy sector in China from a production perspective, both megalopolises have been recognized as vulnerable to water-related risks or related policy violations (*Qin et al., 2015; Liao et al., 2016*). However, urbanization typically depends on materials from elsewhere as upstream inputs to produce goods for final consumption by their own populations, often referred to as external resource footprints *(Hubacek et al., 2009)*, and this principle also applies to the water-for-energy nexus. Thus, studies from a consumption perspective using the concept of water footprint may better reveal the true dependence, impacts, and vulnerabilities to water supplies on urban populations from both within and beyond geographical boundaries. According to Bai (2016), different urban ecosystems may exhibit different characteristics in terms of their dependence on external resources i.e. self-sufficiency or external dependency, which correspond to the energy sectors' internal and external water footprints. Multi-Regional Input-Output (MRIO) models have been widely utilized to reveal such patterns. For instance, Duan and Chen (2017) investigated water use per unit of international energy trade of China; Liao et al. (2018) analyzed virtual water transfers through China's electric power sector. Also with MRIO models, much scholarly work has been done on the Jing-Jin-Ji region due to their dire water scarcity. For example, Zhao et al. (2017) and Zhang et al. (2016) investigated the region's water footprint and energy flows respectively. Wang and Chen (2016) inventoried the water-related energy and energy-related water in this region. Fang and

Chen (2017) furthered the analysis with a special focus on the capital city Beijing. However, there are more than one urban agglomerations rising fast in China and they embrace different patterns of resource utilizations due to natural endowments and technological differences. Comparative analysis adds new perspectives to the research questions, sheds light on different potential real-world problems and offers alternative pathways for development. For example, Haas and Ban (2014) used satellite data to study urbanization’s impacts on ecosystem in China’s three largest and most important urban agglomerations: Jing-Jin-Ji, the Yangtze Delta and the Pearl River Delta. Due to MRIO data unavailability in the Pearl River Delta, this study focuses on the Jing-Jin-Ji and Yangtze Delta urban agglomerations and quantifies their energy sector’s water footprint. It then discusses the relationship between their water-for-energy nexus patterns i.e. self-sufficiency and external dependency, and their own distinctive growth pathways and resource endowments.

Two types of water use have been investigated in the existing literature, water withdrawal and water consumption. Water withdrawn from the environment but not discharged back to any water bodies is defined as water consumption, in which water may be either transformed into final products or evaporated during production processes *(AQUASTAT, 1998)*. A large amount of water withdrawal typifies the energy sectors’ heavy dependence on water supplies, while a large amount of water consumption means the energy sector has to compete with other sectors for limited water supply. Here, we consider both water withdrawal and water consumption in our study.

Our article is organized as follows: Section 2 describes the models and data used in this study; Section 3 illustrates our findings from three different aspects: the quantity of final energy demand water footprints in the two megalopolises in 2010, the sectoral distribution of the upstream water footprints, and the geographical origins of the above-quantified water footprints i.e. internally or externally to the megalopolis; finally Section 4 concludes and discusses the social, economic and policy implications of our study.

2. Models and data

2.1 Description of the study areas

These two study regions, Jing-jin-ji and the Yangtze Delta, are home to 111 and 158 million people respectively, of which the urban population represents 62.5% and 69.8% of the total population. In 2016, these two regions generated over 10% and 20% of national GDP *(National Bureau of Statistics, 2016)*. The Jing-Jin-Ji region comprises the capital city Beijing, another municipality direct under the central government, Tianjin, and province Hebei. The Yangtze Delta region is located at the river mouth of the mighty Yangtze River and includes China’s financial center Shanghai and two provinces Jiangsu and Zhejiang. Beijing, Shanghai and Tianjian are all megacities with over 10 million inhabitants. Besides, the capital city of Jiangsu and Zhejiang, Nanjing and Hangzhou respectively, both have over 5 million inhabitants (*China City Development Statistics 2016*).

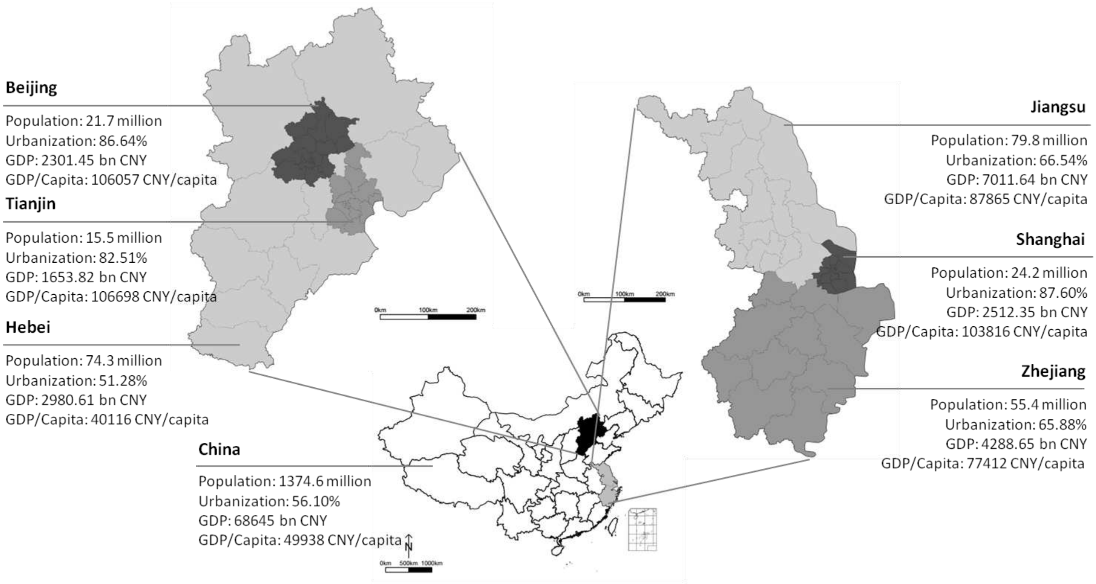

Figure 1. Geographical locations of Jing-Jin-Ji (left) and the Yangtze Delta megalopolises

From 2006 to 2015, the total energy consumption of these regions increased markedly by 162 and 253 million tons of Standard Coal Equivalent (SCE) respectively, reaching 535 and 760 million tons SCE against a total national demand of 8598 million tons SCE. Such huge energy demand requires significant amounts of water input throughout the energy provision life cycle. However, the water endowment for these regions varies significantly. For the Jing-Jin-Ji megalopolis, low precipitation and dense population results in freshwater availability being as low as 125 m^3 per capita (*National Bureau of Statistics, 2016*). It is thus facing extreme water scarcity (<500 m^3) according to the Falkenmark Indicator (Falkenmark et al., 1989). The highly unbalanced energy demand and water availability therefore places the region at high risk from a power supply security perspective *(Sadoff et al., 2015)*. For the Yangtze Delta megalopolis, Jiangsu withdraws the largest amount of water for power production amongst all of China's 30 provinces *(Liao et al., 2016),* and the regions' power industry relies heavily on its fresh water supplies. Here, increase in water temperature in the Yangtze River under future climate change scenarios has been identified as carrying potential risk to security of power supply *(Sun et al., 2014)*.

2.2 Models

Multi-Regional Input-Output (MRIO) model

To study the material flows between different economic regions and sectors we first introduce a Multi-Regional Input-Output (MRIO) model (Feng et al. 2011; Zhao et al., 2015). In an MRIO model, the total output $\boldsymbol{Y}^{r}$ for region ***r*** (in vector form) is given by summing over its intermediate and final consumption, as in Eq. (1) below:

$$\boldsymbol{Y}^{r}=\boldsymbol{X}^{rr}+\sum_{s\neq r}\boldsymbol{X}^{rs}+\boldsymbol{f}^{rr}+\sum_{s\neq r}\boldsymbol{f}^{rs} \tag{1}$$

where $\boldsymbol{X}^{rr}$ is the domestic intermediate consumption and $\sum_{s\neq r}\boldsymbol{X}^{rs}$ is the sum of external intermediate consumption from different regions, taking region ***s*** for example here (export from region ***r*** to ***s***). $\boldsymbol{f}^{rr}$ is the domestic final consumption, and $\sum_{s\neq r}\boldsymbol{f}^{rs}$ is the sum of external final consumption from region ***s***.

We assume that all bilateral trades between regions are directed towards final consumption (*Peters and Hertwich*, 2008). In doing so, we combine $\sum_{s\neq r}\boldsymbol{f}^{rs}$ and $\sum_{s\neq r}\boldsymbol{X}^{rs}$ in Eq. (1) as $\sum_{s\neq r}\boldsymbol{e}^{rs}$, which represents the external final consumption. Eq. (1) can thus be expressed as below:

$$\boldsymbol{Y}^{r}=\boldsymbol{X}^{rr}+\boldsymbol{f}^{rr}+\sum_{s\neq r}\boldsymbol{e}^{rs} \tag{2}$$

Then, according to the input-output model, we introduce the technical coefficient ***A***, which equals to ***X/Y*** to represent the intermediate inputs of each sector per unit of their output. Therefore, Eq. (2) can be solved as follows:

$$\boldsymbol{Y}^{r} = (\boldsymbol{I} - \boldsymbol{A}^{rr})^{-1}(\boldsymbol{f}^{rr} + \textstyle\sum_{r \neq s} \boldsymbol{e}^{rs}) \tag{3}$$

where $(\boldsymbol{I}\text{-}\boldsymbol{A}^{rr})^{-1}$ is a Leontief inverse matrix and $\boldsymbol{I}$ is the unit matrix. Eq. (3) can be expanded to show the economic interrelationship among multiple regions, $\boldsymbol{p}$ for example here, and the matrix form of the MRIO for $\boldsymbol{p}$ regions is shown below:

$$\begin{bmatrix} \boldsymbol{Y}^{1} \\ \vdots \\ \boldsymbol{Y}^{r} \\ \vdots \\ \boldsymbol{Y}^{p} \end{bmatrix} = \begin{bmatrix} \boldsymbol{A}^{11} & \dots & \mathbf{0} & \dots & \mathbf{0} \\ \vdots & \ddots & \vdots & & \vdots \\ \mathbf{0} & \dots & \boldsymbol{A}^{rr} & \dots & \mathbf{0} \\ \vdots & & \vdots & \ddots & \vdots \\ \mathbf{0} & \dots & \mathbf{0} & \dots & \boldsymbol{A}^{pp} \end{bmatrix} \begin{bmatrix} \boldsymbol{Y}^{1} \\ \vdots \\ \boldsymbol{Y}^{r} \\ \vdots \\ \boldsymbol{Y}^{p} \end{bmatrix} + \begin{bmatrix} \boldsymbol{f}^{11} + \sum_{s \neq 1} \boldsymbol{e}^{1s} \\ \vdots \\ \boldsymbol{f}^{rr} + \sum_{s \neq r} \boldsymbol{e}^{rs} \\ \vdots \\ \boldsymbol{f}^{pp} + \sum_{s \neq p} \boldsymbol{e}^{ps} \end{bmatrix} \tag{4}$$

Environmental Extended MRIO model

To study the water footprint of the final consumption for all sectors in region r, we incorporate water inputs to different economic sectors in different regions in the MRIO model and construct an Environmental Extended MRIO model. First we need to calculate the Leontief multipliers of regional water use $\boldsymbol{L}^{r}$, which are calculated as follows:

$$\boldsymbol{L}^{r} = \boldsymbol{d}^{r}(\boldsymbol{I} - \boldsymbol{A}^{rr})^{-1} \tag{5}$$

where $\boldsymbol{L}^{r}$ represents the vector of total water footprint, including direct water inputs to the energy sector as well as indirect water inputs throughout the upstream supply chain, to produce a unit of final consumption in region $\boldsymbol{r}$. $\boldsymbol{d}^{r} = \boldsymbol{w}^{r}/\boldsymbol{Y}^{r}$ is the vector of direct water use intensity of region $\boldsymbol{r}$ that represents the direct water inputs, either withdrawal or consumption, per unit of output in each sector. $\boldsymbol{w}^{r}$ is the vector of water inputs in each sector of region $\boldsymbol{r}$.

The total water inputs in region $\boldsymbol{r}$, $\boldsymbol{wi}^{r}$, can be expressed with the Leontief multipliers of regional water use $\boldsymbol{L^r}$:

$$\boldsymbol{wi^r} = \boldsymbol{L^r}(\boldsymbol{f^{rr}} + \textstyle\sum_{r\neq s} \boldsymbol{e^{rs}}) \tag{6}$$

$\boldsymbol{wi^r}$ can be divided into water inputs to support local consumption, $\boldsymbol{L^r f^{rr}}$, and water inputs to support final consumption in other regions.

A region ***r***'s total water footprint $\boldsymbol{wf^r}$ can be expressed as:

$$\boldsymbol{wf^r} = \boldsymbol{iwf^r} + \boldsymbol{ewf^r} \tag{7}$$

$$\boldsymbol{iwf^r} = \boldsymbol{L^r f^{rr}} \tag{8}$$

$$\boldsymbol{ewf^r} = \textstyle\sum_{r\neq s} \boldsymbol{L^s e^{sr}} \tag{9}$$

where $\boldsymbol{iwf^r}$and $\boldsymbol{ewf^r}$ are region ***r***'s internal water footprint and external water footprint respectively, each representing region ***r***'s self-sufficiency and external-dependency of water inputs.

Finally, internal and external water footprints of sector ***j*** in region ***r*** can be calculated by Eq. (10) and (11):

$$\boldsymbol{iwf_j^r} = \boldsymbol{L^r}(\boldsymbol{f_{jj}^{rr}} + \textstyle\sum_{j\neq k} \boldsymbol{i_{kj}^{rr}}) \tag{10}$$

$$\boldsymbol{ewf_j^r} = \textstyle\sum_{r\neq s} \boldsymbol{L^s e_j^{sr}} \tag{11}$$

where $\boldsymbol{iwf_j^r}$ and $\boldsymbol{ewf_j^r}$ represent region ***r***'s sector ***j***'s internal and external water footprints respectively; $\boldsymbol{i_{kj}^{rr}}$ is sector ***k***'s intermediate inputs for final demand in sector ***j*** $(\boldsymbol{k} \neq \boldsymbol{j})$ in region ***r,*** and $\boldsymbol{e_j^{sr}}$ is all sectors in other regions' inputs to fulfill final demands in region ***r***'s sector ***j***.

2.3 Data and treatment

The MRIO table and corresponding sectoral water use data were needed to carry out this analysis. China's MRIO table for 2010 was obtained from Liu et al. (2014). The MRIO table contains 30 industrial sectors, among which five are energy-related i.e. coal mining, oil and gas extraction, oil refining and coking, power and heat provision, and gas and water provision. We did not disaggregate gas and water provision for two reasons: (1) water use in this sector is relatively small compared to other energy related sectors, and (2) data at a higher resolution was not available.

Water withdrawal data of other primary and tertiary sectors were taken from the Water Resource Bulletin in different Provinces *(Provincial Water Resources Bureau (PWRB), 2007)*. It should be noted that in the Chinese Water Resources Bulletin, water withdrawal in service sectors is represented as an aggregate together with domestic water use. About 50% of national urban domestic water use was for water use in service sectors. Except the power sector, the water withdrawal data of secondary industry in different Provinces was taken from the China Economic Census Yearbook 2008 *(The State Council Leading Group Office of Second China Economic Census, 2008)* and then extrapolated to 2010. Water withdrawal data in each sector was then converted to water consumption by multiplying the corresponding sectoral water consumption coefficient, the share water consumption occupies in the water withdrawn, which was taken from different provincial Water Resource Bulletins *(PWRB, 2007)*.

Regarding the power sector in the MRIO tables, it includes Thermoelectric Power, Hydropower, Renewables, and Heat production. According to Zhang and Anadon (2013), water use for heat production was negligible compared to that of power production; hence we did not attempt to disaggregate Power and Heat Production. In terms of direct physical water input to China's power production, and in-keeping with Zhang and Anadon (2013), we only used data for thermoelectric power generation's direct physical water use to represent the whole sector for the following reasons: (1) Thermoelectric power contributes about 80% of China's power generation *(National Bureau of Statistics of China, 2016)*, and only its water use is reported in the abovementioned sources; (2) whilst Hydropower contributes less than 20% of China's power production *(National Bureau of Statistics of China, 2016)*, there are methodological debates concerning attribution of multi-purpose reservoir water consumption, usually evaporation, to different purposes e.g. power production *(Bakken et al., 2016)*; (3) on-site water use of other renewable energy sources e.g. solar PV and wind is negligible *(Meldrum et al., 2013)*. Last but not least, we only include freshwater use in this study. To calculate the power sector's water withdrawal and consumption in the two megalopolises, we recap on the data and methods used in Liao et al. (2016) and multiply the regions' electricity production (MWh) and water use intensity (m^3 /MWh), measured as water use per unit of electricity produced, for both water withdrawal and consumption.

3. Results

3.1 Final energy demand water footprint in the Jing-Jin-Ji and Yangtze Delta

megalopolises

We calculated that the Jing-Jin-Ji and Yangtze Delta megalopolises final energy demand had water withdrawal footprints of 2.41 and 9.59 billion m^3 respectively. It is worth noting that due to the particularly high water withdrawal intensity, final demand of electricity contributed the largest component of the energy sector's water withdrawal footprint. The water withdrawal footprint of final electricity demand in the Jing-Jin-Ji and Yangtze Delta region accounted for 59.9% and 83.9% of the energy sector's total water withdrawal footprint, respectively, in 2010.

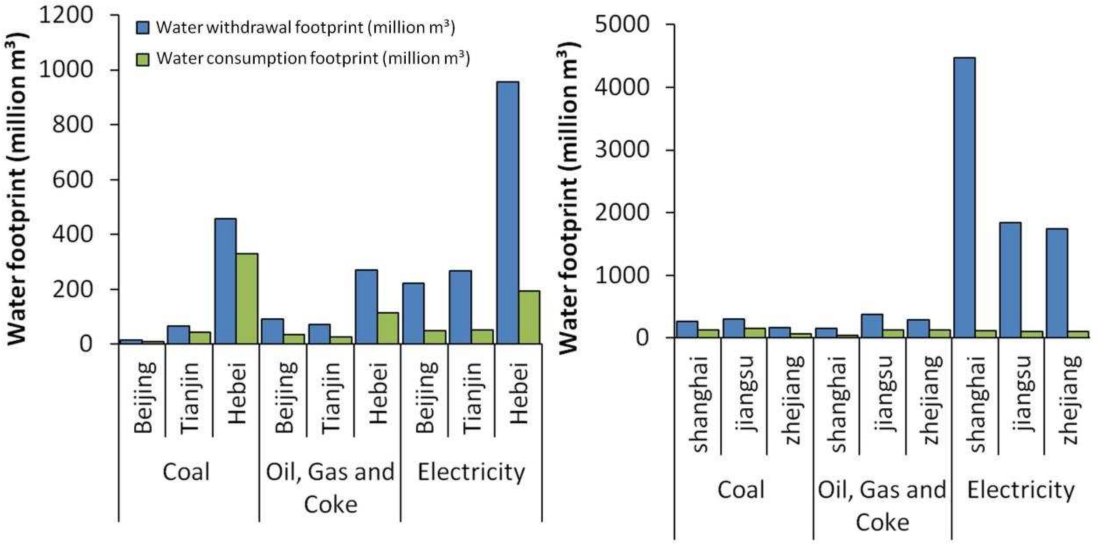

Figure 2. Final energy demand water footprints in Jing-Jin-Ji (left) and the Yangtze Delta megalopolises

Water consumption footprint was 848.06 and 973.91 million m^3 in Jing-Jin-Ji and Yangtze Delta region respectively. The huge discrepancy between water withdrawal and consumption is mainly attributed to the electricity power generation sector. Take the Jing-Jin-Ji region for example, only 4% of water withdrawn by its power sector was consumed, while the figure for Coal Mining and Dressing reached 47.1%. Water withdrawal and consumption for electricity production are primarily determined by power generation infrastructure cooling technology configurations. The water-stressed Jing-Jin-Ji megalopolis predominantly deploys closed-loop cooling systems (Liao et al., 2016) which use recirculated water for cooling and thus have high water consumption due to evaporative loss but low water withdrawals. In contrast, open-loop cooling systems that require significantly larger water withdrawals are mostly used in the water-abundant east, home to the Yangtze Delta megalopolis.

3.2 Sectoral distribution of final energy demand life-cycle water uses

In order to produce the energy products for final demand, water is required in the upstream supply chain of the energy sector throughout the whole economy. As shown in Table 1, direct water withdrawal by the energy sector made up 78.6% for the Jing-Jin-Ji region's energy demand water withdrawal footprint, lower than the national average of 87.3% *(Zhang and Anadon, 2013)*, meaning that energy consumption in the Jing-Jin-Ji region requires bigger proportions of water input from upstream supply chains. In contrast, the figure of 92.5% for the Yangtze Delta region was slightly above the national standard indicating less reliance on the upstream supply chain. Regarding water consumption, energy sector's direct water consumption occupied much smaller proportions in the energy sector's total water consumption footprints, 57.3% in Jing-Jin-Ji and 55.4% in the Yangtze Delta.

Table 1. Sectoral distribution of life-cycle water uses for final energy consumption in the Jing-Jin-Ji and Yangtze Delta megalopolises (million m^3)

Sector	Water Withdrawal			Water Consumption		
	Beijing	Tianjin	Hebei	Beijing	Tianjin	Hebei
Energy Sectors	275.13	338.12	1282.20	60.41	76.65	348.71
Agriculture	32.00	46.86	302.61	21.67	33.93	231.71
Metal and Nonmetal Mining	1.20	1.25	8.57	0.51	0.74	5.72
Manufacturing	8.79	10.75	55.32	3.60	5.22	32.20
Construction	0.20	0.25	1.83	0.08	0.14	1.21
Services	9.04	6.44	30.35	4.26	3.70	17.57
Total water footprint	326.36	403.67	1680.88	90.53	120.38	637.12

Sector	Water Withdrawal			Water Consumption		
	Shanghai	Jiangsu	Zhejiang	Shanghai	Jiangsu	Zhejiang
Energy Sectors	4664.10	2232.48	1979.28	154.07	208.00	177.08
Agriculture	144.90	194.35	136.87	97.98	141.08	96.13
Metal and Nonmetal Mining	3.14	4.52	2.99	1.40	2.20	1.32
Manufacturing	49.88	52.91	43.77	16.59	18.59	14.42
Construction	1.83	1.15	0.75	0.54	0.48	0.27
Services	31.91	26.07	21.28	18.34	14.13	11.28
Total water footprint	4895.76	2511.48	2184.94	288.92	384.48	300.50

Among the non-energy upstream sectors, Agriculture accounted for the biggest proportions of water withdrawal footprints, 15.8% in the Jing-Jin-Ji and 5.0% in the Yangtze Delta, and was followed by Manufacturing, Services, Mining and Construction. . In terms of water consumption, the Agriculture sector played an even more significant role making up more than 30% of the energy sector's water consumption footprint in all six provinces, which is in line with the national situation and can be explained by the high water intensity of agricultural products *(Zhang and Anadon, 2013)*.

3.3 External water footprint of energy demand in the megalopolises

In order to support energy demand in the megalopolises water beyond the regional boundaries is needed to produce either the energy products or their upstream supply chains, which is often referred to as the external water footprint. If a region's water footprint of its energy sector is largely induced externally, it is able to meet its final energy demand while conserving local water resources, however its energy demand depends and impacts negatively on water resources elsewhere.

As shown in Fig 3, both study regions depend heavily on the rest of China (RoC) for water supplies, particularly water withdrawal, to produce energy products for their own consumption. The external water withdrawal footprint of final energy demand in the Jing-Jin-Ji and Yangtze Delta regions amounted to 1.81 and 2.61 billion m^3 respectively in 2010. Within the Jing-Jin-Ji region, energy demand in Beijing required 6.71 (2.89) and 4.24 (2.49) million m^3 of water withdrawal (consumption) footprint in Hebei and Tianjin, respectively.

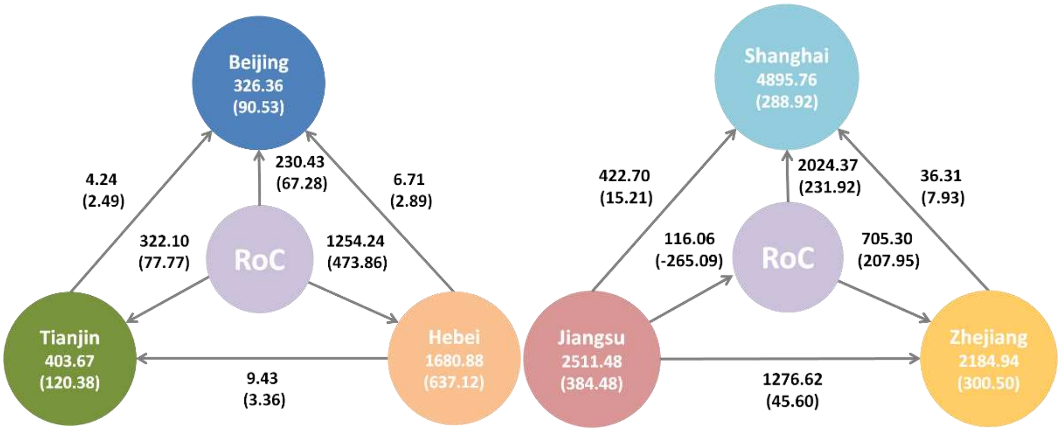

Figure 3. Energy demand life-cycle water withdrawal (water consumption values are in the parenthesis) in the Jing-Jin-Ji and Yangtze Delta megalopolises, and corresponding virtual water transfers (along the arrows) (million m^3)

Note: the amount and geographical origins of the external water footprints are indicated by the arrows

In terms of the Yangtze Delta region, 1.28, 0.42 and 0.12 billion m^3 of water was withdrawn in Jiangsu to meet the energy consumption of Zhejiang, Shanghai and the RoC, respectively. Final energy demand in Shanghai depended heavily on external water supplies by requiring 2.38 billion m^3 of water withdrawal and 255 million m^3

of water consumption from outside the city.

With the exception of Jiangsu, whose energy demand was almost satisfied by water from internal sources, the other five provinces in the two megalopolises relied heavily on external water supplies to meet their final energy demands. For example, almost 90% of Zhejiang's energy demand water footprint was induced elsewhere, amongst which 36% was from outside the Yangtze Delta region and 64% was from within, i.e. Jiangsu. Although Shanghai's energy demands required a large amount of water footprint, its dependence on external water resources was lower at 50.7%. In contrast, although the Jing-Jin-Ji's energy demands have a smaller overall water footprint, a significantly larger proportion (around 80%) was induced from outside of the region.

A summary of the Jing-Jin-Ji and the Yangtze Delta megalopolises energy sector and water footprint characteristics, including their sectoral distributions and geographical origins, is shown in Table 2.

Table 2: Summary of the Jing-Jin-Ji and Yangtze Delta megalopolses water-for-energy nexus and dependence on external water resources

	Jing-Jin-Ji	Yangtze Delta
Population (million)	111	158
Percentage of urban population (%)	62.5	69.8
Energy consumption, 2015 (SCE, million tons)	535	760
Water availability per person (m^3)	156.78	1288.95
Water withdrawal footprint of final energy demands		
Total water footprint (billion m^3)	2.41	9.59
External water footprint (billion m^3)	1.81	2.61
Dependence on external water resources (%)	75.1	27.2
Percentage of energy sector's direct water use	79.03	92.53
Water consumption footprint of final energy demands		
Total water footprint (million m^3)	848.06	973.91

External water footprint (million m^3)	618.91	174.80
Dependence on external water resources (%)	73.0	17.9
Percentage of energy sector's direct water use	57.28	55.36

Taking the water withdrawal footprint as an example, figure 4 further illustrates the top 5 geographical origins of the Jing-Jin-Ji and Yangtze Delta megalopolises energy sector external water footprints. Both megalopolises outsourced their water footprint, primarily from neighboring provinces.

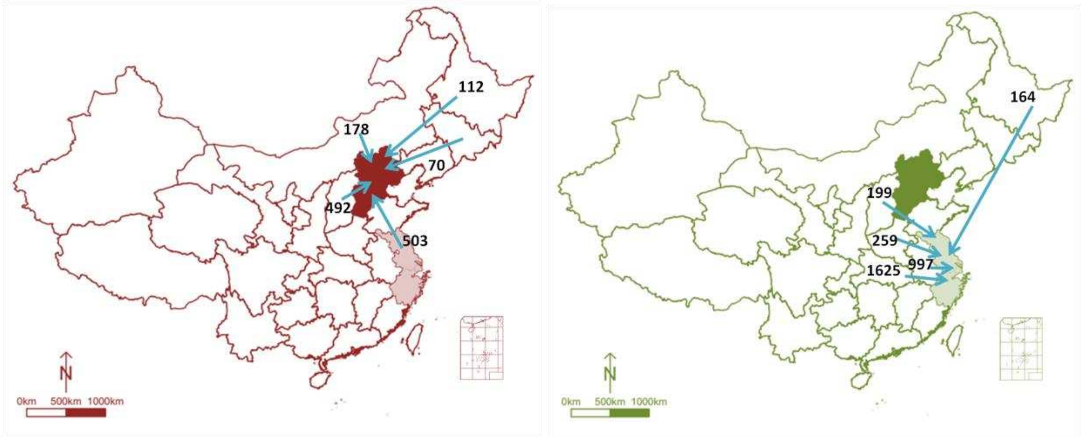

Figure 4. Top 5 geographical origins and amounts of the Jing-Jin-Ji (left) and Yangtze Delta megalopolises energy demand external water withdrawal footprints (million m^3)

Shanxi and Heilongjiang were primary origins for both megalopolises energy sector external water footprints, which can be attributed to their substantial coal exports (Shanxi) and crude oil exports (Heilongjiang). Shanxi is China's largest coal base and Heilongjiang is home to China's largest oilfield, Daqing.

4. Discussion and conclusion

Discussion

The final energy demand and corresponding water footprint from a consumption perspective can be understood in two ways. First, these demands rely on local energy production and local water use. Both megalopolises have significantly higher energy consumption per capita than the national average. To meet their energy demands, energy production processes in both regions exacerbate local water scarcity issues, especially in the Jing-Jin-Ji. Since China issued its ‘strategic integration and coordinated development plan’ for the Jing-Jin-Ji region in 2015 *(Politburo of the Communist Party of China, 2015)* and its ‘Yangtze Delta agglomeration development plan’ in 2016 *(National Development and Reform Commission, 2016)*, local energy production will be increased in the future. Energy demand is therefore expected to continue growing in both regions, and their water scarcity is projected to worsen due to climate change, especially in Jing-Jin-Ji. In order to reduce the energy sectors reliance on water supplies and thus avoid potential future water-induced energy outages, other than outsourcing water use by enlarging external water footprints, diversifying the energy mix can also be effective. For example, due to higher conversion efficiency, Combined Cycle Gas Turbines (CCGT) requires less cooling water to dissipate residual heat compared to coal-fired power plants *(Byers et al., 2015)*. Solar power and wind power also require negligible on-site water.

Moreover, apart from the energy sectors’ direct water use occupying the dominant share, the agricultural sector is the largest when it comes to upstream water use. This underlines the importance of cross-sectoral planning in terms of sustainable development. Due to the intermittence issues of renewable energy supplies such as solar and wind, bio-energy and hydropower are often regarded as viable alternatives to conventional fossil fuels *(Liu et al., 2016)*. However, water use in the bioenergy upstream supply chain needs accounting for, and this requires the greatest input in terms of water footprint *(Meldrum et al., 2013)*. Although hydropower is not included in this study, its water consumption in terms of evaporation from dammed water bodies is significant and needs closer examination.

With respect to the biggest water user among the five energy production sectors, the electric power sector, the Yangtze Delta mostly utilises open-loop cooling systems and is prone to capacity decreases brought about by potential climate change-induced water temperature increases *(van Vliet et al., 2016b)*. Changing power plant cooling systems to closed-loop alternatives may help reduce such risks. In the Jing-Jin-Ji megalopolis, changing wet cooling systems to air cooling systems may significantly cut the sector's water use. However, trade-offs need to be made as power plants equipped with air cooling systems normally occupy more land and have lower efficiencies, hence higher coal consumption and greenhouse gas emission intensities *(Department of Energy, 2006)*.

In addition to local water resources, energy consumption in the two megalopolises depend on, and also induce, water use in other regions as external water footprint. For example, about 75% of the Jing-Jin-Ji megalopolis water-for-energy nexus is sourced from beyond the region's boundary. While the Yangtze Delta region requires much more water for its final energy demand, a larger proportion is induced within the region, primarily from Jiangsu province. Utilizing external water and importing water-intensive products is an effective way to alleviate water stress in water-scarce regions without compromising the final demand of various products, e.g. energy. However, it should be noted that as the exporting regions are often water-abundant and tend to adopt less water efficient technologies, trading activities of water-intensive products may increase water footprints on a national scale *(Feng and Chen, 2016)*. Overall, the findings in this research highlight that urbanization in different regions with different natural resource endowments and production technologies generate different impacts on the environment, both internally and externally. We recommend urban planning and development takes these geographical and technological differences as well as inter-sectoral and inter-regional relationships into account.

Conclusion

Urbanization drives and is driven by energy consumption that relies on water supplies from within and outside the urban boundary. Using an Environmental Extended MRIO model, this study sheds light on the distinctive features of the energy sector water footprint in two of China's major urban megalopolises, the Jing-Jin-Ji and Yangtze Delta. The high population density and rapid urbanization typified by these regions drive large energy consumption, hence corresponding water footprint with either self-sufficiency or external-dependency. Our findings are of significance in terms of helping policy and decision makers to better harness policy instruments such as demand side management, cross-sectoral concerted efforts, and outsourcing resource burdens, while taking regional social, economic and environmental characteristics into account.

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