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Unveiling the dynamic of water-electricity conflict within and beyond megacity boundary

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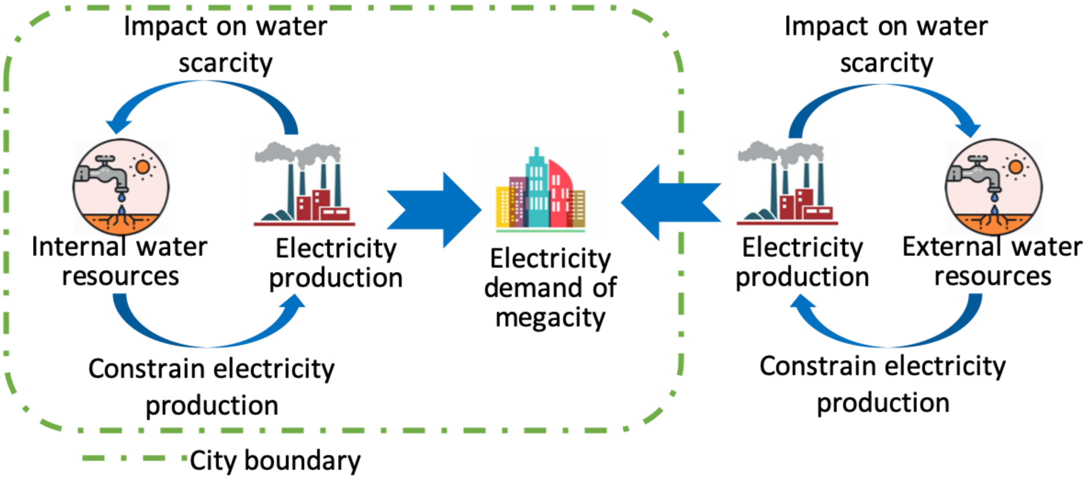
Highlights

- Water related vulnerability of electricity production was dynamic during 2006-2016.
- Water related vulnerability in four Chinese megacities was diverse.
- Tianjin had the highest water related vulnerability and water scarcity footprint.
- The external water scarcity footprint of Beijing was the largest, but decreasing.
- Changes in water related vulnerability may differ to water scarcity footprint.



Abstract

Electricity demand in megacities may exert substantial stress on water resources, which is often expressed through the water scarcity footprint for electricity consumption (WSFE). Conversely, water scarcity may constrain electricity production, leading to increased vulnerability for megacities electricity production. The WSFE and the water related vulnerability of electricity production reflect two aspects of water-electricity conflict. This varies over time by both the amount and location of electricity production. However, no studies have conducted time-series analysis to evaluate the trends of these two indicators, both in terms of severity and spatial characteristics. Our study focused on evaluating trends in water-electricity conflict both within and beyond megacity administrative boundaries. China's four provincial-level megacities, i.e. Beijing, Tianjin, Shanghai and Chongqing, were chosen as case studies. The results show that water related vulnerability of electricity production in Tianjin, Beijing, Shanghai and Chongqing was diverse and can be classified as extreme, severe, moderate and minor, respectively. Between 2006 and 2016, the WSFE of Tianjin experienced an increasing trend, and its water related vulnerability of electricity production remained at the highest level. Beijing's WSFE has decreased, but its water related vulnerability of electricity production has increased. These differing trends highlight the need for joint reductions to both WSFE and water related vulnerability of electricity production in mitigating water-electricity conflict.

Keywords: water footprint, water scarcity footprint, water related vulnerability, electricity production

1. Introduction

The scale and rate of urbanization in China is unprecedented in human history and unparalleled around the world (United Nations Development Program (UNDP), 2013). Between 1950 and 2018, China's urbanization rate increased from 13 % to 59.6 %, and is expected to further increase to 70 % by 2030 (World Bank, 2014). Currently, more than 20 of the world's largest 100 cities are located in China (Satterthwaite, 2020). In parallel to rapid urbanization is increasing amounts and intensity of electricity consumption. Between 2006 and 2016, electricity consumption in China's urban areas almost doubled from 1354.04 TWh to 2657.70 TWh (National Bureau of Statistic).

The production of electricity to meet urban demand requires huge amounts of input water (Liao et al., 2019a). For example, electricity generation is the largest water consumer in the Detroit Metropolitan Area (Liang et al., 2019). Electricity production and the resulting water consumption to support urban electricity demand often happens beyond the city boundary (Feng et al., 2019; Bai, 2016). Comparing electricity production and use in 43 U.S. cities Cohen and Ramaswami (2014) found that 60% of cities import more than half their electricity, and nearly 80% rely on some level of electricity imports. Ramaswami et al. (2017) also showed that Delhi produces just 24% of the electricity it needs, and imports more than 45% from its neighboring states. This aggravates groundwater overexploitation for these states, leading to severe water shortages. According to Liao et al. (2019 b) electricity consumption in China's two megalopolises, defined as adjacent regions of heavily populated metropolitan cities i.e. the "Jing-Jin-Ji" and the Yangtze River Delta, rely heavily on water resources consumed elsewhere for electricity production. Taken together, these studies demonstrate cities are becoming more vulnerable to water scarcity in electricity production regions where is usually beyond the city boundary.

Due to the large water requirement of urban electricity generation, researchers and policy makers are increasingly concerned by urban water-electricity conflict (Behrens et al., 2017), which lies in two aspects (Zheng et al., 2016). On the one hand, water consumption from electricity generation may contribute to water scarcity, both within and beyond the city boundary. Such effects have recently been evaluated using the stress-weighted water consumption, i.e. water scarcity footprint (Zhang et al., 2017; Djehdian et al., 2019; Liao et al., 2020). On the other hand, water scarcity in electricity supply regions may constrain electricity demand of cities which, in turn, will limit urban economic development. These effects have resulted in research into the vulnerability of electricity production to water scarcity (Wang et al., 2019). Some studies have investigated the water related vulnerability of electricity production based on water availability from a territorial perspective (van Vliet et al., 2016; Zheng et al., 2016; Behrens et al., 2017). Other studies have established frameworks to quantify both direct and indirect water related vulnerability for electricity production. Wang et al. (2017) used population as an indicator for the water related vulnerability for electricity production in the US. Their study found that 58 million people living in water-abundant areas are vulnerable to the electricity production demands of water-scarce regions, lasting for at least one month per year. Djehdian et al. (2019) constructed a metric, based on a hydro-economic vulnerability indicator and framework developed by Rushforth and Ruddell (2015), to quantify electricity consumption exposure to external water scarcity in 69 metropolitan areas of the US.

Such studies have provided snapshots of water related vulnerability of electricity generation in a specific timeframe. However, the source and amount of electricity production that cities rely on is dynamic, which means both direct and indirect water related vulnerability are changing over time. Additionally, previous studies and their policy recommendations, have typically considered just one aspect of the water-electricity conflict, ignoring the two different aspects may evolve in opposite directions. Temporal analysis thus allows for better understanding of the dynamics of water-electricity conflict. Hence, it is important to conduct time-series analysis to evaluate the changing trends of water related vulnerability of electricity production as well as water scarcity footprint for electricity consumption (WSFE) for cities both in terms of severity and spatial characteristics.

Our study investigated the characteristics and trends in urban water-electricity conflict within and beyond the megacity boundary. China has four municipalities directly under central government administration, i.e. Beijing, Shanghai, Tianjin and Chongqing. These were chosen to evaluate their electricity consumption impacts on internal and external water resources, as well as the vulnerability of electricity production to water scarcity both within their city areas and in other regions, between 2006 and 2016. To answer these questions, a unified framework was constructed to evaluate the trend of the water footprint for electricity consumption, water scarcity footprint for electricity consumption, and water related vulnerability of electricity production. These four municipalities were chosen because: (1) they are among the largest cities in China (top five), each with a population greater than 10 million, classifying them as megacities; (2) they are the only four provincial-equivalent cities in China and therefore have financial and administrative autonomy so that they can adopt policy measures in response to emergent challenges; (3) they are the only four provincial-equivalent cities in China where energy and water statistics are readily available; and (4) the four municipalities represent a wide range of social, economic and environmental characteristics, with Beijing and Tianjin located in the north China plain where freshwater resources are extremely scarce, and Shanghai and Chongqing located along the Yangtze River where water resources are abundant. Beijing, Tianjin and Shanghai are more economically advanced than Chongqing, the only municipality located in inland China.

2. Methodology and data

2.1 Evaluating water footprint for electricity consumption

The water footprint quantifies the volume of freshwater consumed in the production of certain goods or services and consumed by a particular group of people (Hoekstra et al., 2011; Liao et al. 2019). The water footprint for electricity consumption in city *r* is quantified according to equations (1) – (3) below:

$$WFE^{r} = IWFE^{r} + EWFE^{r} \qquad (1)$$

$$IWFE^r = WFF^r \times EP^r \qquad (2)$$

$$EWFE^r = \sum_1^n WFF^s \times ET^{sr} \qquad (3)$$

Where WFE^r represents the total water footprint for electricity consumption in city *r*; $IWFE^r$ and $EWFE^r$ are the Internal Water Footprint for Electricity Consumption (IWFE) and the External Water Footprint for Electricity Consumption (EWFE) for city *r*, respectively; WFF^r and WFF^s represent the water footprint factor for electricity production, i.e. water footprint per unit of electricity generated (m^3/MWh), in city *r* and *s*; EP^r is the electricity produced within the municipal administrative boundary in city *r*, and ET^{sr} is the electricity consumption of city *r* that is transmitted from province *s* to city *r*; there are *n* provinces in total which have transmitted electricity to city *r*.

2.2 Evaluating water scarcity footprint for electricity consumption

A volume of water consumed in different places has a different impact based on the local water resource endowment (Zhao et al., 2018). It is thus important to consider water scarcity in the volumetric accounting of water footprint (Ridoutt and Pfister, 2010; Zhang et al., 2020a). For this purpose, the water stress index (WSI), defined by Pfister et al. (2009), is used to adjust the volumetric water footprint into stress-weighted volumes of water footprint. The WSI has been adapted from the water withdrawal-to-availability indicator by applying an S-curved logistic function to acquire continuous values between 0.01 and 1. Four levels of water stress were classified in the 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 was calculated according to the following equation (4):

$$WSI = \frac{1}{(1 + e^{-6.4WTA^{*}(1/0.01-1)})} \qquad (4)$$

Where *WTA** is a modified water withdrawal-to-availability indicator considering precipitation variability.

The Water Scarcity Footprint for Electricity Consumption (WSFE) can thus be calculated by combining the WFE of different cities/provinces with the corresponding WSI. The WSFE can be further divided into internal and external WSFE, which may be expressed by equations (5) – (7) below:

$$WSFE^{r} = IWSFE^{r} + EWSFE^{r} \tag{5}$$

$$IWSFE^{r} = DWSI^{r} \times IWFE^{r} \tag{6}$$

$$EWSFE^{r} = \sum_{s \neq r} DWSI^{s} \times VWF^{sr} \tag{7}$$

Where $WSFE^{r}$ is the WSFE of city *r*; $IWSFE^{r}$ and $EWSFE^{r}$ represent internal and external WSFE of city *r* respectively; $DWSI^{r}$ and $DWSI^{s}$ represent direct WSI in city *r* and province *s;* and VWF^{sr} is virtual water flow from province *s* to city *r*.

2.2 Measuring the water related vulnerability of electricity production

Total water related vulnerability of electricity production in city j can thus be quantified using equations (8) – (11) below:

$$DV^{r} = DWSI^{r} \times \left(\frac{IWFE^{r}}{EWFE^{r} + IWFE^{r}} \right) = \frac{IWSFE^{r}}{WFE^{r}} \tag{8}$$

$$NV^{r} = NWSI^{r} \times \left(\frac{EWFE^{r}}{EWFE^{r} + IWFE^{r}} \right) = \frac{EWSFE^{r}}{WFE^{r}} \tag{9}$$

$$NWSI^{r} = \frac{EWSFE^{r}}{EWFE^{r}} = \sum_{s \neq r} \frac{VWF^{sr} \times DWSI^{s}}{\sum_{s \neq r} VWF^{sr}} \tag{10}$$

$$TV^{r} = DV^{r} + NV^{r} \tag{11}$$

Where TV^{r} represents Total Water Related Vulnerability of Electricity Production in city *r*, which consists of Direct Water Related Vulnerability of Electricity Production (DV^{r}) and Indirect Water Related Vulnerability of Electricity Production (NV^{r}). In a similar way to WSI, total water related vulnerability of electricity production in a specific locality may also be classified by four levels, i.e. Minor (0.01-0.09), Moderate (0.09-0.5), Severe (0.5-

0.91) and Extreme (0.91-1).

2.3 Data

China's electricity transmission matrices between 2000 and 2016 were obtained from Zhang et al. (2020a). Zhang et al. (2020a) constructed China's electricity transmission matrices among 30 mainland Chinese provinces, excluding Tibet due to data limitations. These were based on provincial electricity production and consumption data extracted from the China Electricity Yearbooks, and inter-provincial electricity transmission data from the Annual Compilation of Power Industry Statistics. Water consumption data for thermoelectric power production by province and by fuel type are from Zhang et al. (2018), who developed a bottom-up time series water use inventory for China's thermoelectric power plants which cover 99% of national capacity. It should be note that the total electricity generation was not from coal-fired plants only, it also includes natural gas power and nuclear power. Since water consumption in coal-fired plant dominate the water consumption, we assume that all water consumption comes from coal-fired power following Zhang et al. (2020a).

Zhang et al. (2020a) calculated the WSI of 1,120 catchments in China based on an approach proposed by Pfister et al. (2009). They defined a catchment as the minimum spatial area needed to quantify the WSI of provinces. Hence, the provincial WSI is the result of the sum of the WSFE of all catchments located in the province divided by the sum of catchment WFE in the province. This may be expressed as follows:

$$WSI^s = \frac{WSFE^s}{WFE^s} = \frac{\sum WFE^c \times WSI^c}{\sum WFE^c} \tag{12}$$

Where WFE^c and WSI^c are the WFE and WSI of catchment *c* belonging to province *s*. WFE^s, $WSFE^s$ and WSI^s are the WFE, WSFE and WSI of province *s*, respectively. The WSI of the catchments was set constant during the 2006-2016 period, assuming that the WSI represents the average catchment water stress situation. However, the WSI of the provinces was observed to change slightly due to changes in WFE of catchments (see

Table A1).

It should be noted there are other water scarcity indicators also in use, such as the AWARE indicator which was developed by the UNEP/SETAC Life Cycle Initiative (UNEP/SETAC, 2016). A comparison between the WSI and AWARE indicators is presented and discussed later on. The provincial AWARE values of non-irrigation sectors were obtained from Boulay and Lenoir (2020).

3. Results

3.1 Trends in water footprint and water scarcity footprint of electricity in the four megacities

Between 2006 and 2016, the WFE in the four megacities contained in the study increased from 357.2 to 388.1 million m^3, but comprised a decreasing share of national total WFE, from 7.94% in 2006 to 6.57% in 2016 (Table A2). Meanwhile, the WSFE of the four megacities experienced a slight decrease, moving from 224.9 million m^3 in 2006 to 217.9 million m^3 in 2016. This decadal change in the WFE for each megacity is illustrated in Fig.1. The WFE of Chongqing almost doubled from 52.1 million m^3 in 2006 to 96.1 million m^3 in 2016. It is noteworthy that the WFE for Chongqing plummeted in 2012, which is seen as a result of government implementing blocked tariffs aimed at electricity demand management (National Energy Administration of China, 2012). The WFE of Tianjin experienced an upward trend, increasing from 83 million m^3 to 104 million m^3 during the study period. The WFE of Shanghai and Beijing experienced an overall decreasing trend. The WFE for Beijing experienced the largest decrease among the four megacities, decreasing from 118.9 million m^3 in 2006 to 94.9 million m^3 in 2016. Shanghai's WFE decreased from 103 million m^3 in 2006 to 78 million m^3 in 2012, and subsequently increased to 93 million m^3 by 2016.

The lower curves in Fig.1 demonstrate the WSFE of the four megacities. It can be seen that the WSFE occupied the largest share of the WFE in Tianjin, followed by Beijing, Shanghai and Chongqing. In Shanghai, approximately half of the WFE was scarce, while in Chongqing the WSFE was only 1.93 million m^3/year on average during the 10-year study period. The WSFE of Beijing, Tianjin, and Shanghai had similar trends to their WFE's. The exception was Chongqing which, although the WFE displayed an increasing trend exceeding that of Beijing and Shanghai in 2016, had a negligible WSFE. This means the large WFE observed for Chongqing only had a minor impact on water stress.

Overall, the total internal WFE of the four megacities was higher than the total external WFE, and the share of internal WFE also increased during the study period. The city with the largest share of external WFE was Beijing, comprising more than half of its WFE. External WFE made up smaller shares in the other three megacities, i.e. less than 50% in Shanghai, about 20% in Tianjin and just over 10% in Chongqing. Compared to WFE, external WSFE occupied much smaller proportions in Shanghai (Fig. A1). This findings indicate Shanghai was suffering from more severe water scarcity than its imported electricity sources. In general, Beijing's electricity consumption required the largest external WSFE, albeit with a decreasing trend from 53.35 million m^3 in 2006 to 38.81 million m^3 in 2016. This was followed by Tianjin, which required between 11 and 17 million m^3 WSFE for its electricity consumption.

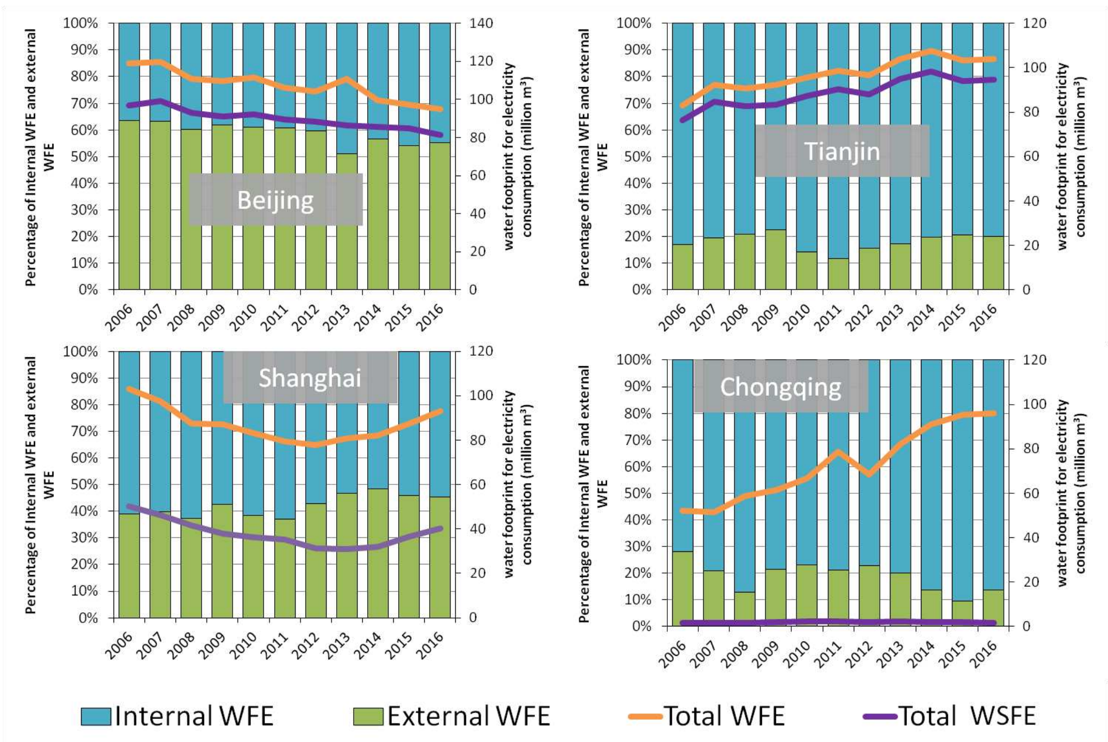


Fig. 1. Trends of water footprint for electricity consumption (WFE) and water scarcity footprint for electricity consumption (WSFE) in the four megacities. Bar charts show the percentage of internal WFE versus external WFE.

It can be seen from Fig. 2 that all four megacities experienced declines in their water footprint and water scarcity footprint factor, i.e. WFE and WSFE per unit of electricity consumed (m^3/MWh). Beijing experienced the steepest decline: in 2006, every MWh of electricity consumed required 1.95 m^3 of water footprint, of which 1.58 m^3 was defined as scarce. These numbers decreased markedly to 0.93 m^3/ MWh for and 0.80 m^3 MWh for water scarcity footprint factor by 2016. Chongqing and Shanghai experienced relatively shallow decreases in their water footprint factors for electricity consumption. Although the water footprint factor has decreased in all four megacities, the WFE has shown different trends. Whilst the WFE declined significantly in Beijing, it increased in both Tianjin and Chongqing and experienced a U-turn in Shanghai, i.e. decreased until 2013 before increasing. These trends show that electricity consumption increases in Tianjin and Chongqing outpaced the water footprint factor decreases. In Shanghai, although electricity consumption had been increasing throughout the study period, the decrease in water footprint factor outpaced its electricity consumption increases between 2006 and 2013, with the trend then reversing. In terms of per capita values, WFE per capita decreased substantially in Beijing, Tianjin and Shanghai from 7.43, 7.72 and 5.26 m^3 per person in 2006, to 4.37, 6.66 and 3.85 m^3 per person in 2016, respectively (Fig. A2). The WSFE per capita in these three megacities also reduced accordingly. In contrast, the WFE per capita in Chongqing increased throughout the decadal study period, rising from 1.85 to 3.15 m^3, albeit with negligible amounts of WSFE.

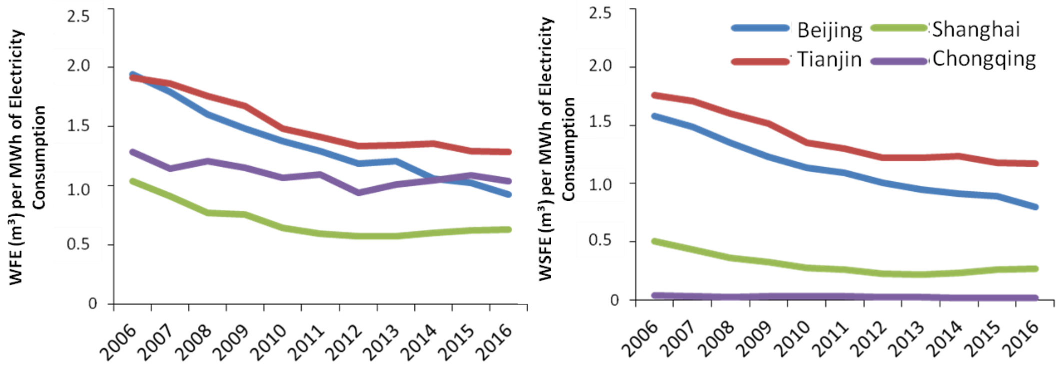


Fig. 2. Water footprint and water scarcity footprint (m³) per unit of electricity consumption (MWh) in the four megacities.

3.2 Origins of external water scarcity footprints for electricity in the four megacities

The northern megacities, i.e. Beijing and Tianjin, showed a range of patterns of external WSFE (locations and volumes) compared to their southern counterparts (Fig. 3). Specifically, the northern megacities required larger amounts of external WSFE compared to the southern megacities. Southern megacities imported their external WSFE from more diversified sources, while megacities in the north tended to import their external WSFE from neighboring provinces. West Inner Mongolia is the primary external WFSE provider to both Beijing and Tianjin's final electricity consumption (Fig. A3). For Beijing, over 74% of its external WSFE (28.99 million m³) was imported from the West Inner Mongolian grid, and 24% (9.49 million m³) was from Shanxi. Tianjin has been importing external WSFE about 9 to 16 million m³ from West Inner Mongolia. Since 2013, this megacity has also imported electricity from Hebei province and this has resulted in more than 2 million m³ of scarce water consumption in Hebei every year. It should be noted that both Shanxi and Hebei provinces are facing extreme water scarcity.

Located in southern China, Shanghai and Chongqing required less external WSFE. Shanghai's external WSFE decreased from about 16.00 million m³ in 2006 to 6.40 million m³ in 2013, before returning to 9.14 million m³ by 2016. Chongqing required the least external WSFE, ranging from 0.49 million m³ (2015) to 1.21 million m³ (2010). Overall, Shanghai and Chongqing had a more diversified portfolio of external WSFE sources for their electricity consumption. Whilst the majority of Shanghai's external WSFE came from Zhejiang and Jiangsu, accounting for 36.38% and 42.06% respectively, it also imported some WSFE from provinces in central China, such as Sichuan and Chongqing, and from the northwest, such as Xinjiang, Ningxia, Gansu and Shaanxi. Chongqing's largest external WSFE was sourced from its neighboring province, Sichuan. It should be noted that, between 2010 and 2013, Chongqing imported some 0.21 million m³ to 0.29 million m³ WSFE from Shaanxi province where water scarcity is classed as severe.

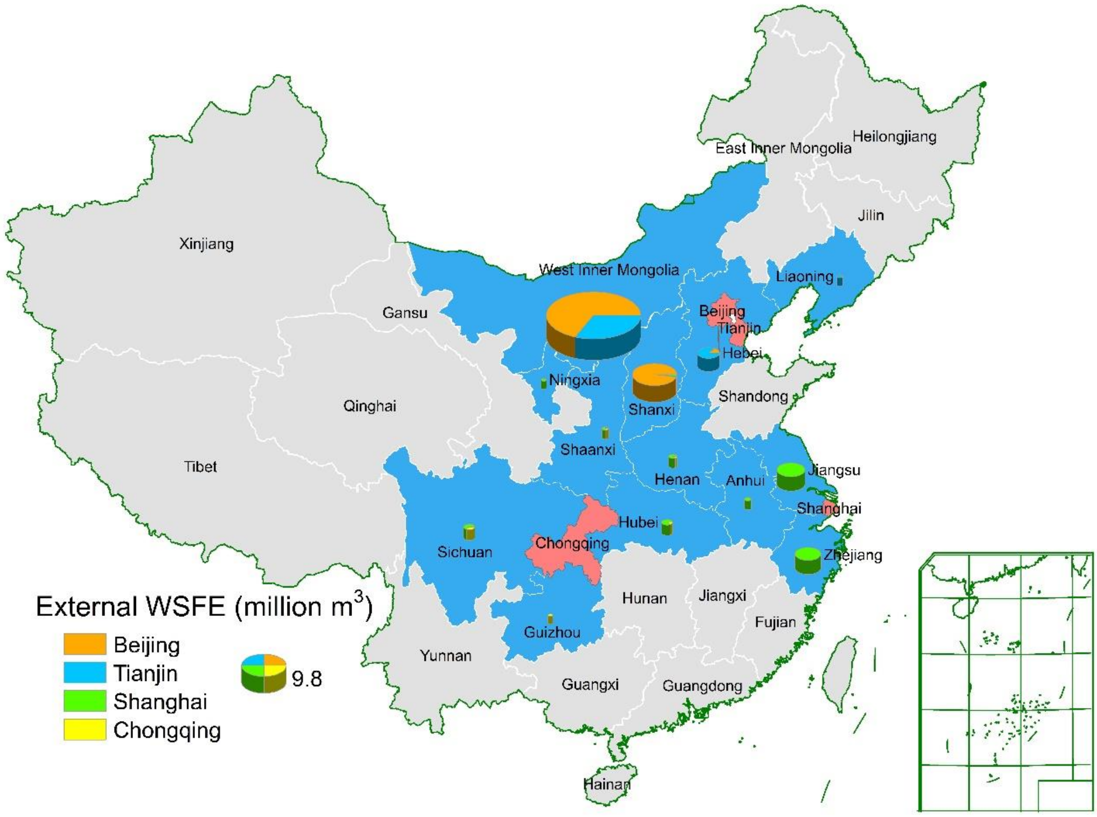


Fig. 3. External water scarcity footprint for electricity consumption (WSFE) in 2016: only volumes greater than 0.1 million m³ are shown

3.3 The water related vulnerability of electricity production in the four megacities

Between 2006 and 2016, the water related vulnerability of electricity production in Tianjin, Beijing, Shanghai and Chongqing was diverse, and may be classified as extreme, severe, moderate and minor, respectively (Fig. 4). Different patterns were found for the two northern cities, i.e. Beijing and Tianjin, in terms of their direct and indirect water related vulnerability. Indirect water related vulnerability comprised the largest share in Beijing, accounting for 47.6%-55.2% of Beijing's total water related vulnerability of electricity production. In contrast, the indirect water related vulnerability of Tianjin comprised the smallest share, accounting for just 10.1%-19.2% of total water related vulnerability of electricity production. These findings indicate Beijing's electricity consumption was more vulnerable to water scarcity beyond its administrative boundaries, while Tianjin's vulnerability is mainly through exposure to water scarcity within its territory. Both Beijing and Tianjin had a direct WSI classified as extreme, which means relying on their own water supplies will bring extreme water related vulnerability of electricity production to both megacities. However, the reliance of Beijing on external WFE has helped to reduce its total water vulnerability classification to a lower level, i.e. severe. Less than that of Beijing and Tianjin, Shanghai's total water related vulnerability is, on average, greater than 0.4 which is considered moderate. Compared with the other three megacities, Chongqing's electricity consumption faces the least water related vulnerability - less than 0.04 (minor). This is attributed to Chongqing and its surrounding provinces abundant water endowments, and Chongqing's relatively slower pace of economic development requiring less electricity supply. Hence, Chongqing's electricity consumption is unlikely to be disrupted by water shortage related problems in the foreseeable future.

The changes of direct and indirect water related vulnerability of electricity production over time were also different for the four megacities. The water related vulnerability of Beijing has seen an increasing trend, with an increasing direct vulnerability but decreasing indirect vulnerability. In contrast, the water related vulnerability of Shanghai has experienced a decreasing trend, mainly owning to the decrease in its indirect water related vulnerability. Meanwhile, the direct and indirect vulnerabilities of Tianjin and Chongqing showed only a slight change.

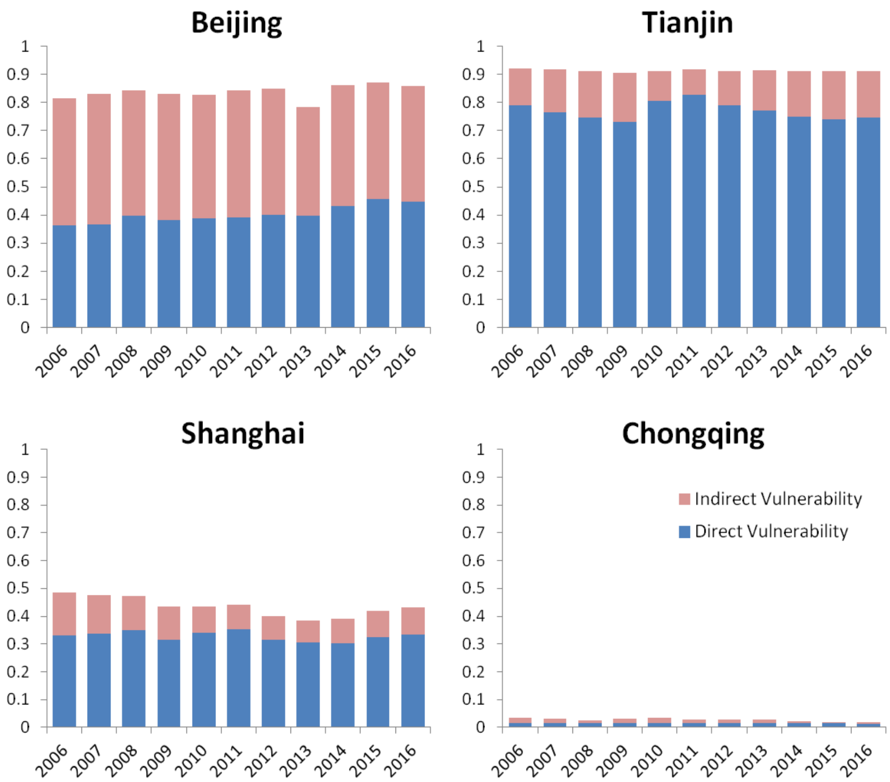


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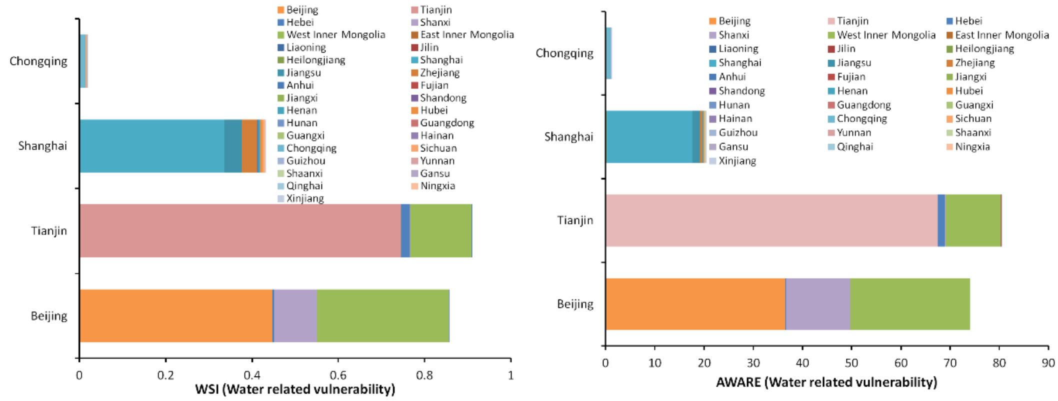
Fig. 4. Changes of direct and indirect water related vulnerability of electricity production in the four megacities; where 0.01-0.09 (Minor), 0.09-0.5 (Moderate), 0.5-0.91 (Severe) and 0.91-1 (Extreme).

4. Discussion

4.1 Comparison of water related vulnerability for electricity consumption based on WSI and AWARE models

In this study, the WSI was used as a water scarcity indicator to derive water related vulnerability in electricity consumption. However, different water scarcity indicators have been developed based on different conceptual frameworks and model structures and which may yield different water related vulnerability results (Ridoutt et al., 2018). We therefore compared the results of water related vulnerability derived from two water scarcity indicators, namely the WSI applied in this study and the AWARE model. The AWARE model derives water scarcity indicators through evaluation of the relative water remaining in a region once human consumption and water ecosystem requirements have been subtracted from local renewable water availability (Boulay et al., 2017). As can be seen in Fig.5 using the AWARE indicator, water related vulnerability ranges from 0.1 to 100 with its absolute numbers much larger than the results derived from the WSI indictor. However, the general patterns of the four megacities' water related vulnerabilities for electricity consumption based on the AWARE indicator broadly agree with the results based on WSI, with Tianjin's electricity consumption being exposed to the highest water related vulnerability, followed by Beijing, Shanghai and Chongqing.

The largest difference between the two indicators was seen in Shanghai's results. Using the AWARE indicator, Shanghai's water related vulnerability became relatively smaller compared to that of Beijing and Tianjin. Conversely, using WSI, Beijing's and Tianjin's water related vulnerability for electricity consumption was 1.98 and 2.11 times that of Shanghai's, respectively. However, these differences increase to 3.62 and 3.94 times using the AWARE indicator. The reason for this is because Shanghai's indirect water related vulnerability has become smaller compared to that of Beijing and Tianjin. Generally speaking, applying the two different indicators does not change the overall trend or pattern of water related vulnerabilities faced by electricity consumption, especially for those cities experiencing extreme and severe water stress.



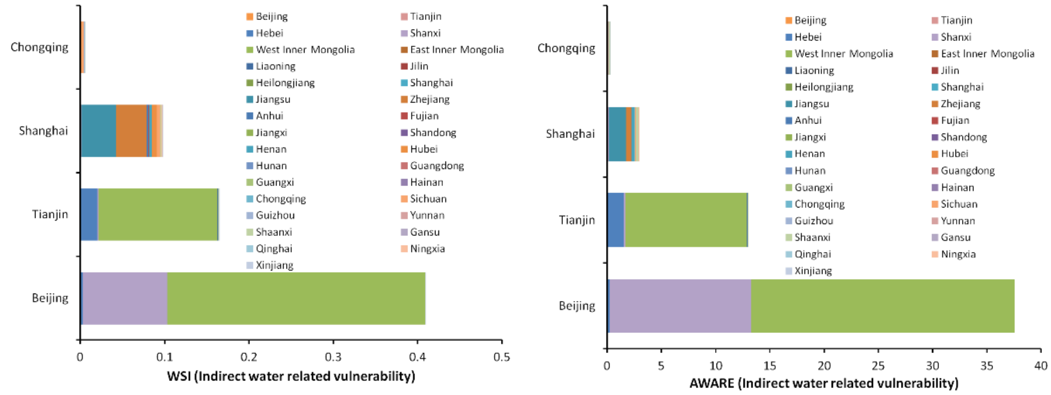


Fig.5. Water related vulnerability (upper panel) and indirect water related vulnerability (lower panel) of electricity production in 2016, based on WSI and AWARE models.

4.2 Varied trend between water scarcity footprint and water related vulnerability of electricity production

Existing research and recommendations usually focus on one aspect of the water-electricity conflict, implying that the other aspect of this conflict will be solved simultaneously. Our study has emphasized the importance of jointly investigating the temporal changes of these two aspects. Two indicators, i.e. the WSFE and the water related vulnerability for electricity consumption were used to reflect the two aspects of water-electricity conflict. Whilst the WSFE indicates the impacts of electricity consumption on water resources, water vulnerability indicates the extent that electricity consumption is vulnerable to water shortages. Our results show differing trends between these two indicators for Beijing and Tianjin, which have suffered both water scarcity and water related vulnerability for electricity consumption. For Beijing, a decreasing trend was found for its WSFE, but an increasing trend for its water related vulnerability. Tianjin's water related vulnerability only shows a slight change, but its WSFE has experienced an increasing trend. Such differences indicate that the sole effort of reducing one aspect of water-electricity conflict cannot simultaneously guarantee the reduction of the other aspect. Hence, policies should be oriented towards joint reduction in the impact of electricity consumption on water scarcity as well as the water related vulnerability for megacity electricity consumption.

Effective policy measures may include decreasing water use intensity (Liang et al., 2019; Zhang et al., 2020b), setting a cap for urban electricity demand (Zhang et al., 2017), and shifting electricity sourcing from water scarce to more water abundant regions (Behrens et al., 2017; Liao et al., 2020). Policy makers should also consider combined measures and set priorities based not only on the water-electricity conflict in the considered megacity, but also the external source regions.

4.3 Policy implications in mitigating water-electricity conflict for the studied megacities

Our results showed different trends and characteristics of the two aspects of water-electricity conflict in the four megacities. Comparing these differences amongst the megacities provides implications for urban policy makers worldwide to mitigating the water-electricity conflict for their own cities. Among the four megacities, Beijing and Tianjin, located in China's arid and semi-arid northern regions, had a higher WSFE and higher levels of water related vulnerability for their electricity consumption between 2006 and 2016. This situation may be further explored, both within and beyond their megacity boundaries. Within the megacity boundaries, Beijing and Tianjin faced extreme water scarcity with their WSI ranging from 0.93-1 (Table A1). One of the major differences between the two megacities was that Tianjin relied more on electricity generation within its boundary. Consequently, over 81% and 82% of Tianjin's WSFE and water related vulnerability, respectively, were due to internal consumption of water for electricity generation (Fig. 4 and Fig. A1). For Beijing, internal water consumption contributed to less than 53% of total WSFE and water related vulnerability. For Tianjin, the reliance on extremely scarce water resources within the city boundary was the major cause for its highest level of water related vulnerability and the largest WSFE among the four megacities, hence requires urgent action in reducing its internal WSFE. In 2004, Beijing adopted a policy requiring all new coal-fired power plants to install air-cooling systems which have lower water requirements. This had the effect of reducing Beijing's water scarcity footprint factor. Examining and comparing and the results of Beijing and Tianjin, we suggest a similar approach be an immediate priority for Tianjin in reducing its water scarcity footprint factor. In 2016, if Tianjin had the same water scarcity footprint factor as Beijing, the internal WSFE would be reduced by 23%, and the direct water related vulnerability of energy consumption would also decrease accordingly.

Externally, these two cities have imported almost all electricity from water-scarce regions, i.e. Shanxi, Hebei and West Inner Mongolia. Since the 1970's, China has built large-scale inter-regional electricity transmission infrastructure systems, such as the "West-to-East" electricity transmission project, to transmit electricity from either the coal-abundant northwest regions or the water-abundant southwest regions of the country to the electricity load centers of the east coast (Zhou, 2003). The northern corridor of the West-to-East transmission project conveys electricity from coal-abundant Shanxi and Inner Mongolia to the load centers of Beijing and Tianjin. Consequently, water availability for coal-fired generation is rarely considered in China's energy planning and development. For example, while Shanxi and Ningxia are already facing severe water scarcity constraints, China's National Energy Administration initiated the construction of a new long-distance electricity transmission line to transfer electricity generated from coal-firing in these provinces (National Energy Administration of China (NEA, 2014). Our findings of large indirect water related vulnerability for Beijing and Tianjin raise alarms for such policy decisions, as coal resources should not be the sole concern. Water endowments in electricity-exporting regions must also be considered in future policy formulations.

Shanghai imports large amounts of electricity from its two neighboring provinces, Jiangsu and Zhejiang. Although these provinces are all located on the Yangtze Delta and are therefore endowed with large amounts of available water, they are ranked among the most developed and populated provinces in China whose large populations and economic activities have resulted in moderate water related vulnerability for Shanghai's electricity consumption. Furthermore, water shortages such as drought events in the three Yangtze Delta provinces could lead to electricity supply disruption in Shanghai, further highlighting the importance of maintaining sufficient flows in the river. While China's south-western provinces such as Sichuan and Yunnan are endowed with rich hydropower potential, they face annual hydropower abandonment primarily caused by institutional limits in which other provinces are unwilling to sacrifice their own local coal-fired plants and accept externally transmitted electricity. China could therefore place greater emphasis in developing both its infrastructure and institutional capabilities to utilize hydroelectricity generated in water-abundant provinces in the south, to satisfy demand in water-scarce provinces in the north, and in demand-driven water scarcity provinces in the east.

4.4 Limitations of this study and future directions

There are a number of limitations with this study, and which offer future directions for research. First, we focused on water use by coal-fired power plants. Although coal-fired power production occupies more than 70% of China's electricity profile, hydropower makes up a further 15-20% of China's electricity production. Whilst we have recommended further exploitation of hydropower resources in China's southwestern regions, hydropower clearly has much higher dependence on water resources. Further work should be conducted to evaluate the risks of hydropower in the southwest and to develop a national strategy which also reduces reliance on electricity systems which currently incorporate water availability as a constraining factor. Furthermore, whilst we analyzed empirical data, climate change is expected to fundamentally alter watershed regimes, which may either alleviate or aggravate water scarcity. For example, a number of hydrological studies have projected that, under future climate change, China's dry north may experience increased precipitation which may alleviate local water scarcity. On the other hand, rivers in China's water-abundant south may experience flow reduction which may hinder hydropower utilization. Since constructed electricity transmission infrastructure are locked in for several decades, it is also important for future studies to incorporate the impacts of climate change into their evaluations.

5. Conclusions

This study examined and compared the dynamics of water-electricity conflict for China's four provincial-level megacities through a time-series analysis. Two indicators, i.e. the WSFE and the water related vulnerability for electricity consumption, were chosen to represent two aspects of water-electricity conflict. Both indicators were evaluated within and beyond the megacity boundaries. The results show that northern megacities, i.e. Tianjin and Beijing, had larger WSFE and higher levels of water related vulnerability. These two cities also required larger amounts of external WSFE than their southern megacity counterparts, and mainly imported their external WSFE from neighboring provinces that are also located in the water scarce north. Temporally, our study, for the first time, shows that the indicators of the WSFE and the water related vulnerability may evolve in opposite directions. These different levels, origins and trends of the WSFE and water related vulnerability provide important policy implications in mitigating megacity water-electricity conflict. Combined measures aimed at jointly reducing the WSFE and water related vulnerability indicators are thus needed by policy makers considering both the megacities themselves, and their external electricity source regions.

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