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Assessing the environmental impact of the water footprint in Beijing, China

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Abstract

Beijing is experiencing a shortage of water resources. Its rapid development and dense population have caused an extreme demand for water. This study quantifies the water footprint of Beijing at the sectoral level using a modified input–output model and estimates the impacts of freshwater use by life cycle impact assessment. The results suggest that the main water source of Beijing industries is groundwater, which is quite different from the main use of surface water in China. By coupling the input–output model with the eco-indicator 99 method, the environmental impact of the water footprint was quantified. The results show those sectors that introduced severe impacts in 2002 and continued to make large impacts in the following 5 years; the major impact of water use is resource depletion. In addition, the inconsistency of the eco-indicator points and the eco-indicator index of sectors leads us to control sectors with large eco-indicator points and develop those with small eco-indicator indexes. Furthermore, a regional comparison was conducted using the eco-scarcity method and verified that Beijing is under severe water pressure, with a value ranked fifth nationally. We conclude that the control of groundwater use and the externalization of local water pressure should be prioritized in water management in Beijing.

Keywords: Beijing; Environmental impact; Life cycle impact assessment; Water footprint; Water resources

1. Introduction

Rapid economic growth, population explosion and need for a better quality of life have driven water demand to increase greatly (Yang *et al.*, 2012). Freshwater is a precious and increasingly scarce resource and related problems, such as water scarcity, water pollution and water waste, are only expected to

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worsen (Dong *et al.*, 2013). Water is essential for humans and ecosystems, whereas human health and ecosystem quality are seriously affected by changes in the global water cycle; these changes are caused primarily by human activities. It is expected that the pressure on freshwater resources will increase significantly, which could cause worldwide social and environmental problems.

Measuring water consumption and assessing its environmental impact, particularly on a life cycle basis, provide important information for attributing responsibility and developing solutions to water shortage. The water footprint, analogous to the ecological footprint (Hoekstra, 2009), is one of the methods for assessing water use on a life cycle basis and is perhaps the most widely used method. It was developed by Hoekstra in 2003 (Hoekstra & Hung, 2003) and has been elaborated upon since then. It is defined as the total volume of freshwater needed to produce the goods and services consumed by individuals, communities or regions (Hoekstra *et al.*, 2009). There have been many studies focused on the micro-scale level of a product's virtual water content (Chapagain & Hoekstra, 2011; Hoekstra, 2012) as well as on the macro-scale level of national or regional water footprints (Hoekstra & Mekonnen, 2012; Dong *et al.*, 2013). While the developer argued the intention of this method was not to be an aggregated index, it does not reflect the potential environmental and social impact of water consumption, an important perspective in life cycle assessment (LCA) (Hoekstra *et al.*, 2009).

LCA evaluates the environmental impact of specific elements throughout the production system; its implementation varies on the adoption pattern and required precision and its core concept is on the assessment at each stage of the life cycle (Udo De Haes & Heijungs, 2007). Currently, water use is not systematically recorded in the life cycle inventory (LCI) database; LCA methodology is lacking a comprehensive approach to evaluate the environmental impacts associated with freshwater use (Koehler, 2008). This approach was developed for industrial systems where emissions and resources are assessed and recorded for their environmental impact; less attention has been paid to water use in life cycle impact assessments (LCIAs) (Jungbluth, 2005). Thus far, LCIAs do not consider impacts related to water use (Koehler, 2008). The type of method chosen to assess the impact of water use has been an essential problem and plays an important role in further exploration of water management.

Beijing, the capital of China, is one of the most water-scarce regions in China due to its rapid economic development and population growth. According to the Beijing Water Authority (BWA), the water resources available per capita of Beijing were approximately 119 m^3 in 2012 (BWA, 2012), which is only equal to one-eighth of that of the nation, which is far below the internationally recognized minimum standard of 1,000 m^3 per year (Sivakumar, 2011). Also, the abstraction of freshwater for production processes has exerted great impacts on the ecological system and humans (Zhang *et al.*, 2012). Thus, how to utilize water resources sustainably and how to assess the impact of water use effectively have become issues of broad concern.

The objective of this study is to assess the environmental impact of the water footprint in Beijing. First, a modified input–output (IO) model was proposed to quantify the gross water footprint (GWF) at the sector level for Beijing. Then, the environmental impact of water use was assessed by applying two LCIA methods. The first is the eco-indicator 99 (EI-99) method; we used Simapro software (version 7.1.8, released by the enterprise named 'PRé Consultants' as a not-for-profit version) to quantify the environmental impacts in terms of the eco-indicator points (EIPs) and environmental impact index of different sources in Beijing. The environmental impact index, expressed by the eco-indicator index (EII) of different sectors, refers to the environmental impacts introduced by an increase of one monetary unit of output. The second is the eco-scarcity method. We used this method to assess the water pressure for 31 regions in China and to compare Beijing to other regions. The results of this study allow the impacts related to freshwater use to become transparent and provide new insights for water management in Beijing.

2. Methodology and data

2.1. Method for quantifying the water footprint-modified IO model

IO analysis is a quantitative framework concerning the interdependences among different economic sectors, originated by Leontief (1936), and then extended to relate the environmental pollution and abatement associated with products (Leontief, 1970). On the basis of the Beijing IO table, the modified IO model adds a row for water resources.

The traditional IO model starts with the balance of monetary flows.

$$X_i = \sum_{j=1}^{n} X_{ij} + Y_i \tag{1}$$

$$A = [a_{ij}], \quad a_{ij} = \frac{X_{ij}}{X_j} \tag{2}$$

$$B = [I - A]^{-1} = [b_{ij}] \tag{3}$$

X_i is the gross output of sector i; Y_i is the final demand of sector i; X_{ij} is the input from sector i to sector j. Matrix (2) is the technical coefficient matrix. The a_{ij} shows the intersectoral input from sector i to increase one monetary unit of output in sector j. Matrix (3) is the Leontief inverse matrix. The b_{ij} shows the gross input from sector i for generating one monetary unit of final demand in sector j.

The direct water footprint (DWF) is the direct water input from nature to production. The water footprint intensity was measured using the following: the direct water footprint intensity (DWI) and gross water footprint intensity (GWI) are the amount of direct and gross water input, respectively, for generating one monetary unit of final demand. The GWF is the gross amount of water used throughout life cycle production.

It can be calculated as the following:

$$\mathrm{DWI} = [\mathrm{DWI}_{1,}\mathrm{DWI}_2, \mathrm{DWI}_3, \ldots \mathrm{DWI}_n], \quad \mathrm{DWI}_j = \frac{\mathrm{DWF}_j}{X_j} \tag{4}$$

$$\mathrm{GWI} = \mathrm{DWI} \times B = [\mathrm{GWI}_1, \mathrm{GWI}_2, \mathrm{GWI}_3, \ldots \mathrm{GWI}_n], \quad \mathrm{GWI}_i = \sum \mathrm{DWI}_i \times b_{ij} \tag{5}$$

$$\mathrm{GWF}_i = \mathrm{GWI}_i \times Y_i \tag{6}$$

Y_i is the domestic final demand of sector i.

2.2. Method for assessing the environmental impact of the water footprint – LCIA

2.2.1. The eco-indicator 99 method. The EI-99 method is one of the LCIA methods that rely on the principle of environmental damage. The damage can be categorized as human health damage, ecosystem quality impact and resource consumption, and then further divided into 11 sub-aspects (Goedkoop & Spriensma, 2001). The results derived from this system are quantified as EIPs, which indicate the environmental impact of a material or process based on data from an LCA. A higher indicator means a greater environmental impact. One EIP is equivalent to one thousandth of the yearly environmental impact of an average European inhabitant (Dreyer *et al.*, 2003); the impact index here is expressed in EIPs (Pt) or milli-indicator points (mPt) (Lye *et al.*, 2001). For example, the EIP value for copper is 1,400 mPt, meaning the use of 1 kg copper can quantitatively produce 1,400 mPt of environmental impact (Yu *et al.*, 2012).

Thus, the EII_i refers to the environmental impacts introduced by an increase of one monetary unit of output, which reveals the environmental effects of sectoral interactions. It can be derived in the following way:

$$\mathrm{EII}_i = \frac{\mathrm{EIP}_i}{X_i} \tag{7}$$

where X_i is the gross output of sector i.

2.2.2. The eco-scarcity method. Freshwater is scarce in some regions, while in other regions there is a surplus. This method provides eco-factors (EFs) for various impacts, including water use. Water use, referring to the total input of freshwater for production or consumption, is categorized into six different scarcity situations (low, moderate, medium, high, very high, and extreme) (Frischknecht *et al.*, 2006). This permits – depending upon the LCI available from case to case – a highly differentiated analysis (Frischknecht *et al.*, 2009). Each category is assigned an individual EF based on the average water withdrawal-to-availability (WTA) values to assess the impacts of water scarcity (Jeswani & Azapagic, 2011).

According to the Organisation for Economic Co-operation and Development (OECD, 2004), the scarcity of freshwater resources can be expressed as the share of gross consumption in the available renewable water resource.

$$\begin{aligned} \textit{Eco-factor} &= \frac{1 \times EP}{\textit{Normalisation}} \times \textit{Weighting} \times \textit{Constant}\,t \\ &= K \cdot \frac{1 \cdot EP}{F_n} \cdot \left(\frac{1}{20\%}\right)^2 \cdot (WTA)^2 \cdot c \end{aligned} \tag{8}$$

In this equation, K – characterization (optional) factor of a pollutant or a resource (not considered in freshwater); F_n – normalization factor for water consumption (km^3/yr; Switzerland was used as a reference region; $F_n = 2.57\ \mathrm{km}^3$/yr); WTA – water withdrawal-to-availability (expressed by ratio of water use to available water resources); 20% – a tolerable water stress is 20% of the available water resource, according to OECD (2004); c – constant (10^{12}/yr) for obtaining presentable numerical quantities;

EP – eco-point (the unit of assessed impact). Table 1 shows the eco-scarcity factors (Frischknecht *et al.*, 2006).

2.3. Data sources

To construct the modified IO model, the 2002 and 2007 Beijing IO tables and the 2007 Chinese IO table were chosen, containing the intersectoral input flows as well as the final demand and gross output of each industrial sector.

The water withdrawal is the total freshwater drawn from water sources to meet the demand for industrial production and is regarded as the DWF of each sector in this study, thus revealing the direct impacts of industries on the environment. It is difficult to determine the DWF values for different sectors, particularly at the provincial level, and the Economic Census Yearbook is the only public source that can directly provide detailed water data. It is not published annually, and only two have been published, in 2004 and 2008. Thus, the DWF of different sectors for China 2007 was obtained from the China Economic Census Yearbook 2008, whereas the DWF for Beijing in 2002 and 2007 was obtained from the Beijing Economic Census Yearbook 2004 and the China Economic Census Yearbook 2008, respectively. The water sources were divided into surface water, groundwater and tap water, and then the 38 economic sectors were aggregated into 23 industrial sectors to be consistent with the IO model as shown in Table 2. Primary and tertiary industries were not included in this study due to the lack of accurate data for water withdrawal from the different sources. In addition, the water production and supply were not included for the industrial uniqueness: water is treated as both a final product and an input. The data sources for the water use and water resources of 31 regions in China were the China Statistical Yearbooks for 2003 and 2008.

3. Results

3.1. Water footprints from different sources at the sectoral level

According to the National Bureau of Statistics of China, the 23 sectors can be classified into three industries: sectors 1–4 are mining, sectors 5–21 are manufacturing, and sectors 22–23 are energy production and supply. By using the modified IO model, the GWF of different sectors and industries for Beijing 2002 and 2007 was calculated. The GWF for China 2007 was also presented to compare the

Table 1. Water withdrawal-to-availability values and eco-factors for evaluating water use impacts.

Water pressure category	WTA range	WTA used for weighting calculation	Weighting factor	*Fn* normalization (km^3/yr)	Eco-factor (EP/m^3)
Low	< 0.1	0.05	0.0625	2.57	24
Moderate	0.1–0.2	0.15	0.563	2.57	220
Medium	0.2–0.4	0.3	2.25	2.57	880
High	0.4–0.6	0.5	6.25	2.57	2,400
Very high	0.6–1.0	0.8	16	2.57	6,200
Extreme	> 1.0	1.5	56.3	2.57	22,000

Table 2. The eco-factors of regional water resources among China in 2002 and 2007.

		Water resources		Water use		WTA		Total water pressure		Surface water pressure		Groundwater pressure	
Code	Region	2002	2007	2002	2007	2002	2007	2002	2007	2002	2007	2002	2007
1	Beijing	16.99	23.81	34.62	34.81	2.04	1.46	●●●	●●●	●●●	●●	●●●	●●●
2	Tianjin	3.67	11.31	19.96	23.37	5.44	2.07	●●●	●●●	●●●	●●●	●●●	●●●
3	Hebei	86.14	119.79	211.38	202.50	2.45	1.69	●●●	●●●	●●●	●●●	●●●	●●●
4	Shanxi	78.73	103.40	57.50	58.74	0.73	0.57	●●	●	●	○○○	●	●
5	Inner Mongolia	314.89	295.86	178.23	180.04	0.57	0.61	●	●●	●	●	○○○	●
6	Liaoning	148.26	261.72	127.13	142.87	0.86	0.55	●●	●	○○○	○○○	●●	●●
7	Heilongjiang	632.62	346.04	252.28	100.78	0.40	0.29	○○○	○○○	○○○	○○○	○○○	●
8	Jilin	368.69	491.85	111.69	291.37	0.30	0.59	○○○	●	○○○	●	○	●
9	Shanghai	46.07	34.50	104.27	120.19	2.26	3.48	●●●	●●●	●●●	●●●	**N.A.**	○
10	Jiangsu	268.02	495.71	478.74	558.34	1.79	1.13	●●●	●●●	●●●	●●●	○○	○
11	Zhejiang	1,230.48	892.15	208.00	210.98	0.17	0.24	○○	○○○	○○	○○○	○	○
12	Anhui	824.68	712.46	199.83	232.05	0.24	0.33	○○○	○○○	○○○	○○○	○	○○
13	Fujian	1,201.43	1,072.90	182.86	196.28	0.15	0.18	○○	○○	○○	○○	○	○
14	Jiangxi	1,983.26	1,112.96	202.06	234.87	0.10	0.21	○	○○○	○	○○○	○	○
15	Shandong	98.11	387.11	252.37	219.55	2.57	0.57	●●●	●	●●●	●	●●●	○
16	Henan	313.58	465.18	218.81	209.28	0.70	0.45	●●	●	●	○○○	●●	●●
17	Hubei	1,155.46	1,015.06	240.86	258.73	0.21	0.25	○○○	○○○	○○○	○○○	○	○
18	Hunan	2,566.63	1,426.55	306.91	324.26	0.12	0.23	○○	○○○	○○	○○○	○	○
19	Guangdong	1,884.63	1,581.15	447.03	462.51	0.24	0.29	○○○	○○○	○○○	○○○	○	○
20	Guangxi	2,372.59	1,386.26	297.47	310.41	0.13	0.22	○○	○○○	○○	○○○	○	○
21	Hainan	333.12	283.53	44.09	46.69	0.13	0.16	○○	○○	○○	○○	○	○
22	Chongqing	545.84	662.96	60.30	77.43	0.11	0.12	○○	○○	○○	○○	○	○
23	Sichuan	2,066.16	2,299.84	208.61	213.98	0.10	0.09	○	○	○	○	○	○
24	Guizhou	1,117.57	1,054.62	89.94	98.03	0.08	0.09	○	○	○	○	○	○
25	Yunnan	2,308.87	2,255.52	148.50	150.03	0.06	0.07	○	○	○	○	○	○
26	Tibet	4,243.49	4,321.38	30.08	36.70	0.01	0.01	○	○	○	○	○	○
27	Shaanxi	255.43	377.03	78.01	81.55	0.31	0.22	○○○	○○○	○○	○○	○○○	○○○
28	Gansu	150.32	228.73	122.64	122.50	0.82	0.54	●●	●	●●	●	○○○	○○○
29	Qinghai	558.23	661.62	27.02	31.11	0.05	0.05	○	○	○	○	○	○
30	Ningxia	12.76	10.39	81.52	71.00	6.39	6.83	●●●	●●●	●●●	●●●	○○○	○○○
31	Xinjiang	1,068.20	863.77	474.56	517.74	0.44	0.60	●	●	●	●	○	○○
32	Nation	28,254.92	25,255.16	5497.27	5,818.69	0.19	0.23	○○	○○○	○○	○○	○○	○○

○ Low, ○○ Moderate, ○○○ Medium, ● High, ●● Very high, ●●● Extreme, **N.A**. Data not available.

level of Beijing with the national average. Figure 1 shows the proportion of the GWFs from different sources of mining, manufacturing, energy and total sectors.

The surface water and groundwater for total sectors decreased greatly from 2002 to 2007 in Beijing: surface water decreased from 29,900 to 12,461 10^4 m^3, groundwater decreased from 59,712 to 35,375 10^4 m^3 and a slight decrease for tap water was observed; this decrease in tap water can be attributed to all three industries. The ratio of tap water for each industry rose significantly, and its ratio for all sectors increased from 15 to 25%. The total surface water ratio decreased, particularly for the energy industry, from 60 to 31%. The total groundwater ratio showed little change, although there was an obvious decrease for mining and an adversely large increase for energy production and supply.

Nationally, the surface water was the overriding source, accounting for 68%, 67% and 92% for the three industries, respectively. The groundwater and tap water were relatively small and only accounted for 13 and 18% in total, respectively. In Beijing, the groundwater was the major source, accounting for 56% of the total water, whereas the surface water and tap water contributed 20 and 25%, respectively.

3.2. Environmental impact of the water footprint

3.2.1. EIPs of Beijing in 2002 and 2007. Figure 2 shows the environmental impacts, which were expressed in terms of the EIP (Pt) for the total water use for the 23 sectors of Beijing in 2002 and 2007 (see the Note below Figure 2 for the sector numbers). In 2002, the EIP of sectors 13 and 15 ranked the top two among all, reaching 3.59 and 3.45 million Pt, respectively, followed by sectors 11, 18, 16, 5 and 17, all with EIP values larger than 1 million Pt. At the industry scale, the EIP of manufacturing was the most prominent of all sectors, accounting for approximately 19.4 million Pt, whereas those of mining and energy production and supply were only 0.31 and 0.96 million Pt, respectively. In 2007, the largest EIPs were in sectors 18 and 13, and the EIP of sectors 16, 15, 11 and 5 were more than 1 million Pt. The EIP of mining, manufacturing, and energy production and supply were 0.14, 11.3 and 0.29 million Pt, respectively; manufacturing still represented the largest value of all three industries.

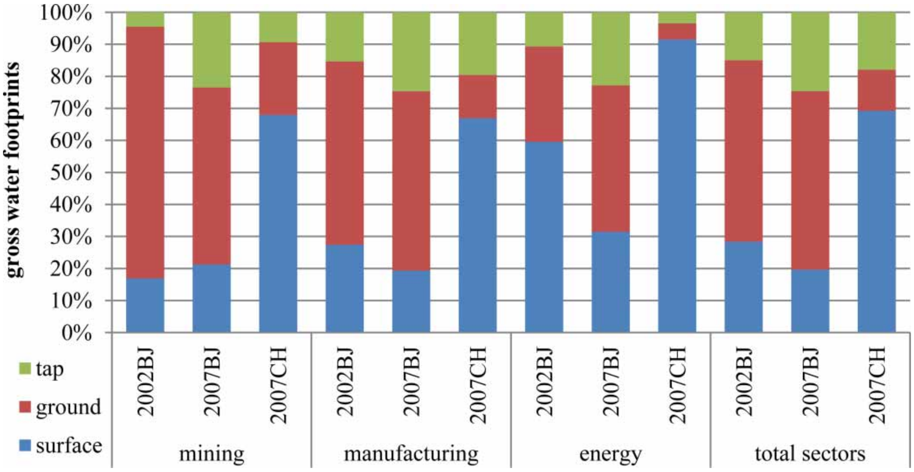

Fig. 1. The proportion of GWFs from different sources of sectors in Beijing 2002, 2007 and China 2007.

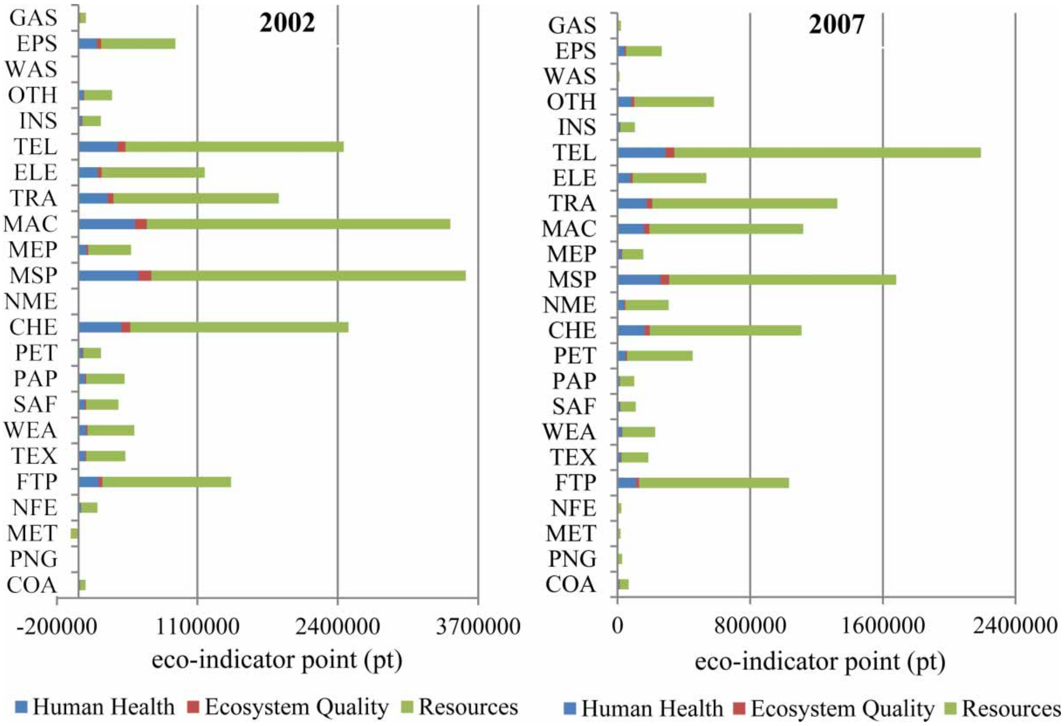

Fig. 2. The environmental impact (EIP) of total water use at the sectoral level in Beijing in 2002 and 2007. 1. COA: coal mining and processing; 2. PNG: petroleum and natural gas; 3. MET: metal ore mining; 4. NFE: non-ferrous mineral mining; 5. FTP: food and tobacco processing; 6. TEX: textile goods; 7. WEA: wearing; 8. SAF: sawmills and furniture; 9. PAP: paper and products; 10. PET: petroleum processing; 11. CHE: chemicals; 12. NME: non-metal mineral products; 13. MSP: metal smelting and products; 14. MEP: metal products; 15. MAC: machinery and equipment; 16. TRA: transport equipment; 17. ELE: electric equipment; 18. TEL: telecommunication equipment; 19. INS: instrument manufacturing; 20. OTH: other manufacturing; 21. WAS: waste recycling; 22. EPS: electricity production and supply; 23. GAS: gas production and supply.

The impact was divided into three categories: human health, ecosystem quality, and resources. The average ratio of the resources impacts among the total impacts for all sectors were 0.811 and 0.837 for the 2 years; the values for the three sources individually were 0.730 for surface water, 0.898 for groundwater, and 0.897 for tap water. We further examined each source and discovered that the surface water represents 0.0329 Pt per m^3, whereas groundwater and tap water represent 0.0132 and 0.0186 Pt per m^3, respectively.

3.2.2. EII of Beijing and China. Figure 3 shows the EII of the 23 industrial sectors for Beijing in 2007 and China in 2007. For Beijing, the index of other manufacturing (sector 20) was obviously larger than the other sectors, reaching 1.12 Pt/Chinese Yuan (CNY) 10^4; those of sectors 4, 21 and 13 were 0.65, 0.35 and 0.32 Pt/CNY 10^4, respectively. These four sectors are characterized with high pollution throughout their life cycle production that exceeds that of other sectors, with the rest of the EIIs smaller than 0.3. For China in 2007, the EIIs were statistically approximate and nine of the manufacturing sectors were in the interval from 0.3–0.5. The index of all four mining sectors of Beijing was larger than

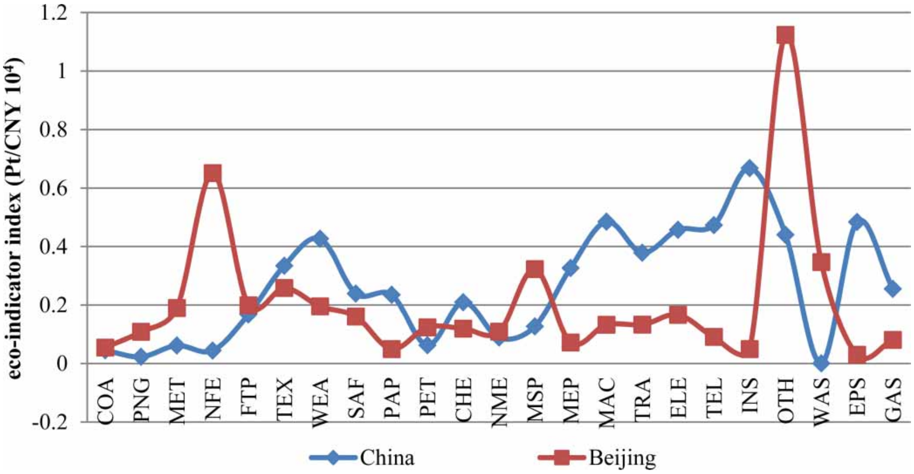

Fig. 3. The environmental impact intensity (EII) for different sectors of Beijing and China in 2007.

that of China. While most manufacturing sectors had a huge water consumption, the impact index of Beijing was comparatively smaller.

3.2.3. Regional comparison of EFs. Table 2 gives the WTA, EF and water pressure concerning regional total water resources, surface water and groundwater of the 31 regions along with national levels in China for 2002 and 2007 based on the eco-scarcity method. In addition, Figure 4 shows the map of the water stress of the 31 regions in the 2 years (excluding national value).

There were seven regions characterized with extreme water pressure in 2002, whereas this value dropped to six in 2007 (except Shandong). Ningxia had the largest WTA among all of the regions in 2002 and 2007; it reached 6.39 and 6.84, respectively. The WTAs of North China were all extremely high and those of Tianjin, Hebei, and Beijing ranked second, fourth and sixth in 2002 and third, fourth and fifth in 2007 at a national scale, respectively. Shanghai and Jiangsu, located in the Yangtze River Basin, were also characterized with extreme water pressure and ranked fifth and seventh in 2002 and second and sixth in 2007, respectively. Shandong exhibited a large decrease in the WTA during these years, decreasing from 2.57 to 0.57; this caused the water ratings to improve considerably.

4. Discussion

4.1. Changes in the environmental impacts of Beijing industry water footprints

Comparing the results of the GWF for the different sectors in Beijing during 2 years, the large decrease in surface water and groundwater is explained by the decrease in direct freshwater withdrawal during these years. Beijing is facing a shortage of water resources, along with rapid urbanization and population density increases, and must minimize water use by industries to guarantee domestic water availability, a stable part of water consumption (Wang *et al.*, 2013).

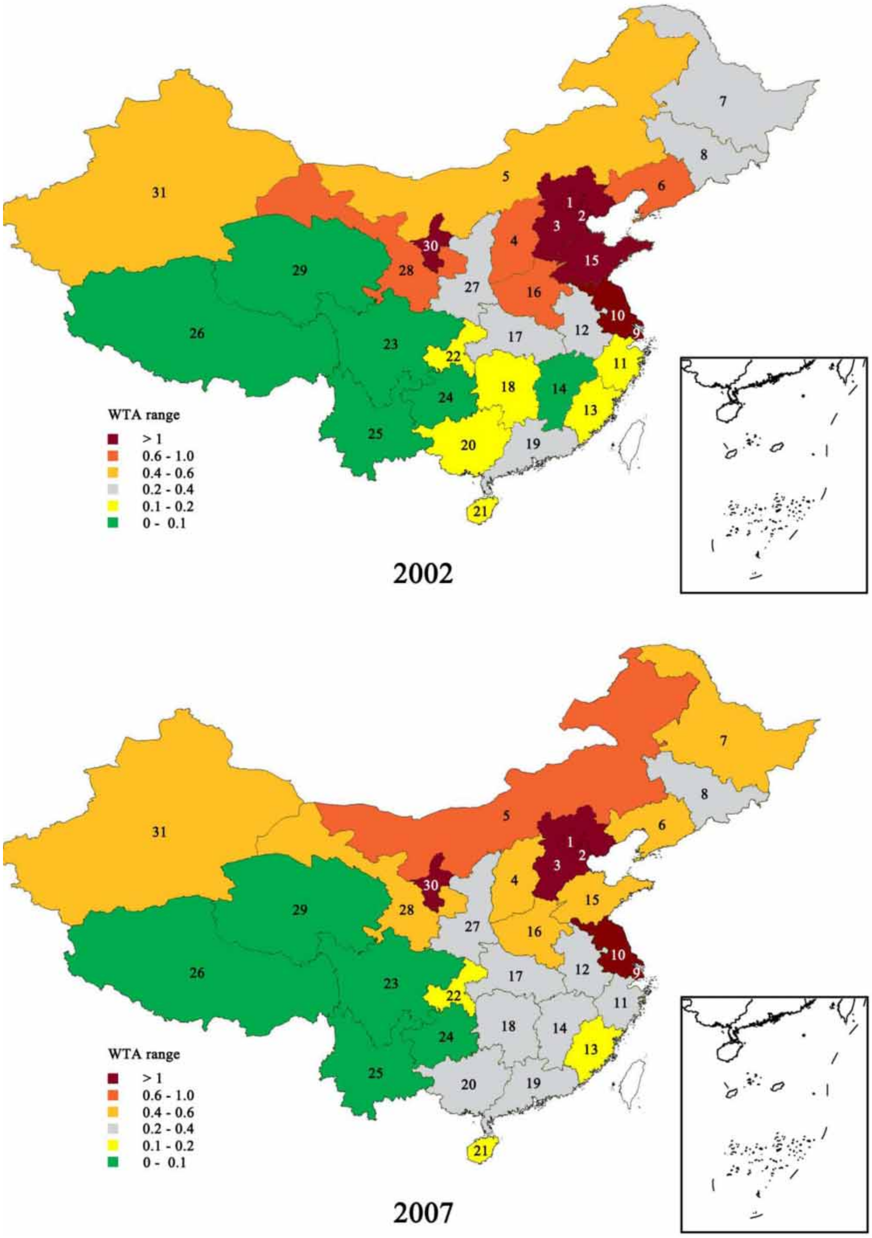

Fig. 4. A map of water pressure for 31 regions in China in 2002 and 2007. *Note:* The regional codes are the same as those in Table 2.

There was a significant difference between Beijing and China in the water withdrawal proportion, revealing their differences in water use characteristics. Nationally, the surface water was the overriding source for industries, as most industries were located in regions with abundant water resources. For Beijing, the extreme shortage of surface water only accounted for 34.2% of the total water resources in 2011

(BWA, 2012), along with their main supply for domestic living; both drove the local industries to dig deeply into the ground to obtain water to sustain their production, thus making groundwater the major industrial water source. However, their over-exploration has led to groundwater depletion, water table decreases and land subsidence (BWA, 2012).

By embodying the IO model with the EI-99 method, we used the GWFs (results of the IO model, divided into three sources) as the inputs for the Simapro calculation. On the one hand, based on the EIP of Beijing in 2002 and 2007, these two values had certain similarities, revealing the characteristics of environmental impacts for each sector were consistent in this period; particularly, the top six sectors were the same (some changes in internal rankings). Thus, these brought severe impacts and kept producing large impacts 5 years later; these impacts need emphatic attention and imposed regulations. On the other hand, for most sectors, the EIP in 2007 was smaller than that in 2002, mainly resulting from the decrease in the GWF mentioned above. Furthermore, the results clearly showed that the most severe environmental impact was in the resources, whereas the impact on human health was comparatively much smaller and that on the ecosystem quality was negligible. By comparing the GWF and EIP values, we found that surface water use introduces more environmental impacts in the EI-99 system. Although the quantity of surface water used did not account for a large amount when combined, it still needs further regulation.

The EII showed that the emphasis on industries brought higher pollution per unit output and when comparing the EII and EIP, we found that these two values were not relevant. There were significant differences between Beijing and China in the EII for each sector. On the one hand, for most sectors with huge water input, the production in Beijing produced smaller EIIs than that in China. On the other hand, the sectors with a large EII in Beijing, particularly sectors 4 and 20, consumed relatively little water inputs. The average EII of all 23 industries was 0.127 for Beijing and 0.283 Pt/CNY 10^4 for China, clearly verifying that the water use during Beijing's industry production was more efficient and environmentally friendly. Furthermore, the inconsistency of the EIPs and EII of sectors highlighted the need to strengthen the management of sectors with large EIPs as well as encourage the development of those with small EIIs.

For the study of EFs, the values of total water and surface water exhibited great similarity and consistency. For most regions, the two WTA numbers were very close to each other. According to the China Statistical Year Book 2008, the surface water was definitely the major source of national available water, and its consumption still accounts for a major proportion in freshwater use (more than half in most regions). Thus, these similarities reveal that the characterization of water use is decided by its current surface water consumption. Furthermore, the environmental impact relating to local water use is mainly from the surface water abstraction.

4.2. Exploration into Beijing EFs at a national scale

The regions facing severe water pressure remained stable in these years; however, Shandong resolved its local problem by increasing its water resources from 9.81 to 38.71 billion (referring to 10^9 in this paper) m^3. This is mainly because 2002 was a dry year, whereas 2007 was a wet year. The precipitation, surface water and groundwater in 2007 were 35.6%, 155.7% and 39.3% larger than in 2002, respectively. These 2 years represent two extreme conditions, thus making the water sources extremely different in comparison. In addition, the efforts from Shandong province, such as protecting reservoirs and increasing water storage, made additional contributions (WRDSP, 2007). By exploring the remaining six regions suffering from extreme water pressure, we encounter different problems. Ningxia is the most severe water-shortage province; it only had 1.27 and 1.04 billion tons of total water resources, whereas it consumed 8.15 and 7.10 billion tons of water in 2002 and 2007, respectively. The amount of water resources is impossible to improve and is only expected to worsen over time, thus the extremely high pressure on the local water resources is considered difficult to ameliorate (Ge *et al.*, 2011). Although Shanghai and Jiangsu are located in the Yangtze River Delta, which is rich in water resources, they are both known for their advanced manufacturing systems and dense populations. These factors required great freshwater investments to ensure their development and even exceeded the local water limits significantly.

North China has long been one of the most water-deprived areas in the world. Beijing, the capital of China, is densely populated, highly developed and the most water-deficient city in China. According to the BWA, in 2011 it was equipped with 2.68 billion tons of water resources and consumed 3.60 billion tons (BWA, 2012). Fortunately, the water demand in Beijing remained stable, whereas the water resources increased; this was mainly attributed to the deep exploration into groundwater sources. From 2002 to 2007 the groundwater resources increased from 1.45 to 1.87 billion tons, whereas surface water only added 0.14 billion tons.

In comparison, the local water scarcity is not severe in South Central China and Southwest China. The map shows that except for Chongqing, the remaining four provinces in Southwest China were all under low water pressure during the 2 years; for five of the six regions in South Central China, the water pressure was rated as medium or moderate. As a whole, their WTAs were relatively small. Equipped with abundant water resources while sharing comparatively small water consumption, they are suffering little pressure on freshwater use, which introduces limited impacts on the local ecosystem and humans.

4.3. Policy implication

The water supply is stretched to the limit in Beijing, thus the water use in industry should be minimized to guarantee domestic water availability in the future (Wang *et al.*, 2013). As Beijing is facing a water shortage and great water demand simultaneously, it should limit the water withdrawal for secondary industries. In the future, water regulation and environmental management in Beijing should place greater emphasis on the industries that introduced large environmental impacts (usually indicated by a large GWF); these industries should be given priority in the assessments and be either compressed or phased out in industry reconstruction.

Furthermore, Beijing and several other North China regions have externalized their water consumption by importing from other regions in both real and virtual forms (Zhao *et al.*, 2010; Huang *et al.*, 2011; Zhang *et al.*, 2011). It is estimated that Beijing will benefit from the south–north water transfer project and import 12,000 million tons of freshwater in a real form annually by 2020 (Kim, 2003). Considering both more effective and environmentally friendly water use in Beijing and more abundant water resources and smaller water pressure in South China, Beijing's industries can rely on imports of virtual and real water and externalize local water pressure (Lin *et al.*, 2012). Furthermore, importing products with high water inputs can help reduce the demand for local water resources and ease local water pressure.

In addition, although the exploration into groundwater has eased local water pressure to some extent, the issue of environmental damage cannot be neglected. We need to decrease the groundwater withdrawal, converting to surface water and tap water as a supplement.

5. Conclusions

Studies for assessing the impacts of freshwater use can demonstrate how the production process interacts with the natural environment and humans. The water footprint is treated as an important step, although it does not include the issue of water availability or scarcity, which is of great concern in impact assessment. Thus, this study coupled the water footprint concept with the LCIA to better evaluate the impacts of water consumption.

This study quantifies the EIPs and EII of 24 industries of Beijing in 2007 by joining the GWF with the EI-99 method. The results show the EIP and EII in terms of different sources and different impact categories. They show that the sectors exerted severe environmental impacts, which is consistent with those in prior years. The impact of water use lies primarily in the depletion of resources, and the impact on ecosystem quality and human health is much smaller. Furthermore, when considering the inconsistency in the EIP and EII of each sector, the focus of water-saving and impact minimization should be placed on the industries with a high EIP rather than on those with a high EII.

Finally, the water pressure of 31 regions in China was evaluated and allocated among sources by the eco-scarcity method. Beijing is under severe water pressure and its EF ranked sixth in 2002 and fifth in 2007 nationally. In comparison with other regions under severe pressure, Beijing is facing a dilemma of both shortage of water resources and great demand of water input. The regulation on surface water uses and externalization of water use by importing both real and virtual water should be the primary water management strategy for Beijing. This could effectively ease the local water pressure and reduce environmental impacts of freshwater use.

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