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Embodied water for urban economy: A three-scale input–output analysis for Beijing 2010

M.Y. Han[a], G.Q. Chen[a,b,*], M.T. Mustafa[c], T. Hayat[b,d], Ling Shao[e], J.S. Li[a], X.H. Xia[f], Xi Ji[g]

[a] College of Engineering, Peking University, Beijing 100871, PR China
[b] NAAM Group, Faculty of Science, King Abdulaziz University, Jeddah, Saudi Arabia
[c] Department of Mathematics, Statistics and Physics, Qatar University, Doha 2713, Qatar
[d] Department of Mathematics, Quaid-i-Azam University, Islamabad, Pakistan
[e] School of Humanities and Economic Management, China University of Geosciences, Beijing 100083, PR China
[f] Institute of China's Economic Reform & Development, Renmin University of China, Beijing 100872, PR China
[g] School of Economics, Peking University, Beijing 100871, PR China

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ABSTRACT

The scheme of a three-scale input–output analysis is presented in this study to investigate the water use profile of the urban economy in Beijing. Defined as total water including direct and indirect water, embodied water for an urban economy supported by massive domestic and foreign trade can be decomposed into nine categories corresponding to three sources (local withdrawal, domestic imports, and foreign imports) and three destinations (local final demand, domestic exports, and foreign exports). Based on statistics for Beijing in 2010, the case urban economy is endowed with just 3.53 billion m^3 of local water withdrawal, whereas the total embodied water demand is estimated up to 13.61 billion m^3, almost quadruple the local water withdrawal. The extra 10.08 billion m^3 of indirect water use is obtained via cross-boundary trade. Overall, Beijing's total water demand is satisfied mainly by domestic imports by a share of more than 60%, and partly by foreign imports by a share of around 20%. The unintentionally induced water embodied in domestic and global trade plays an essential role in satisfying the water demand, which has essential implications for decision making to ease urban water scarcity.

1. Introduction

With the fact that only a tiny fraction of water resources on our globe is available for human beings' freshwater needs (Lambooy, 2011), fresh water is inevitably an critical natural resource. Movever, imbalanced distribution of fresh water aggravates the water crisis in many regions. Particularly with the fast-growing economy and increasing urban population, water shortage regions are facing increasingly severe water crisis. Under this circumstance, water grabbing through commodity trade has been deemed as an effective measure to meet the local fresh water requirements (Rulli et al., 2013).

The concept of virtual water was first put forward by Allan (1993), in the effort for water study to ease water shortage in the Middle East. After that, virtual water of different products, such as coffee, tea, rice, and meat, and virtual water in non-food products has been extensively analyzed (Chapagain and Hoekstra, 2003; Hoekstra and Chapagain, 2007; Hoekstra and Hung, 2002, 2005). Associated with virtual water, water footprint, defined as the volumes of water needed for the production of goods and services consumed by a country, region, sector/industry or individual, is deemed as an essential concept in the field of water resources accounting (Hoekstra et al., 2009). As ecosystem studies were extensively conducted, input–output analysis (IOA), a well-established top-down accounting method, was extensively employed for ecological elements accounting, stirring an accounting frenzy at various economic scales especially in the aspect of water resources accounting (Chen and Chen, 2012; Guan and Hubacek, 2007; Lenzen et al., 2013).

There are two distinctive IOA methods employed in water resources accounting. One is the environmentally-extended IOA method (Leontief, 1970, 1986) as an extension of the standard economic input–output table (Leontief, 1936). By assigning the sectorial direct water consumption to the final demand through the Leontief inverse, the environmentally-extended IOA has been

* Corresponding author at: Peking University, College of Engineering, Beijing 100871, PR China. Tel.: +86 10 62767167; fax: +86 10 62754280.
E-mail address: gqchen@pku.edu.cn (G.Q. Chen).

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applied to analyze water use on the global scale (Lenzen et al., 2013; Dalin et al., 2012), national scale (Dalin et al., 2014; Guan and Hubacek, 2007; Lenzen and Foran, 2001; Llop, 2008; Zhao et al., 2009), and urban scale in particular, by cases of Zhangye and Beijing, China (Wang et al., 2009; Wang et al., 2013; Zhang et al., 2011), Andalusia, Spain (Dietzenbacher and Velázquez, 2007; Velázquez, 2006) and Victoria, Australia (Lenzen, 2009).

Another is the systems IOA, as originally illustrated for energy study by Costanza (1980) and Odum (1983). Derived as a combination of Odum's biophysical balance in systems ecology (Odum, 1983) and Leontief's input–output model (Leontief, 1986), systems IOA has been rigorously developed to investigate various ecological elements at multiple economic scales, and furthermore was specifically applied to analyze water use on the global scale (Chen and Chen, 2012; Chen et al., 2012), national scale (Chen and Chen, 2010; Chen and Han, 2015; Chen et al., 2010), and urban scale (Han et al., 2014; Chen and Li, 2015; Zhou et al., 2010).

The urban economy in Beijing suffers a severe water crisis due to endogenous water shortage, population explosion and economy booming. According to Beijing Water Resources Bulletin 2010 (Beijing Water Authority, 2010), the direct water withdrawal throughout the whole year is 3.52 billion cubic meters (m^3 hereafter), and the local water supply capability is 1.40 billion m^3. In this study, all the direct water withdrawal is considered as local water withdrawal to avoid misunderstanding. Till now, this gap (2.38 million m^3) is mainly filled by over-drafting groundwater and transferring water from surrounding water scarce provinces (e.g., Hebei and Shanxi). As a consequence, over-exploitation of ground water makes ground water depth decrease at a speed of 1.1 m/year and forms a subsidence area of 2.65 billion square meters (Beijing Water Authority, 2010). To solve this problem, the Middle Route of South-to-North Water Transfer Project has been put into service since 2008, and one billion m^3/year of water is planned to be sent to Beijing since 2014 (Beijing Municipal Government, 2011).

IOA has been employed to investigate Beijing's water use, especially for the year of 2002 and 2007 (Han et al., 2014; Zhou et al., 2010). Besides, an interregional input–output analysis was performed to investigate interregional water resources connections between Beijing and other regions in China (Dalin et al., 2014; Zhang et al., 2011). In addition to the static analysis, the decomposition analysis on the water use change in the period of 1997–2007 was performed (Zhang et al., 2012). Even though contributed significantly to in-depth analysis of water shortage in Beijing economy, the existing studies did not cast light on the impacts from domestic and foreign trade on local water use. To provide comprehensive policy recommendations, it is significant to identify water sources and destinations for water scare regions, in particular that embodied in booming global and domestic trade activities (Wang et al., 2013; Zhang et al., 2011).

The present work takes Beijing as a case to carry out a three-scale systems analysis for urban scale water resources use in light of national and global water intensity databases. An elaborated assessment on intensity inventory, final demand, and trade of Beijing economy in the year of 2010 is conducted, and discussions on water imbalance embodied in trade and Beijing economy's water balance are given as an empirical application to the systems IOA method for an urban economy.

2. Method and data sources

Derived as a combination of Odum's biophysical balance in systems ecology (Odum, 1983) and Leontief's input–output model (Leontief, 1986), the three-scale systems IOA method and related data sources are presented below.

Table 1
Three-scale systems input–output table.

Input/output		Intermediate use	Final demand
		Sector 1 ... Sector n	Sector 1 ... Sector n
Local inputs	Sector1 ... Sector n	z_{ij}^L	fd_i^L
Domestic imports	Sector1 ... Sector n	z_{ij}^D	fd_i^D
Foreign imports	Sector1 ... Sector n	z_{ij}^F	fd_i^F
Ecological inputs	Water	w_i	

2.1. Method

A three-scale systems input–output table for an typical urban economy is built to integrate the economy and its physical driving force of the water resources as presented in Table 1 for an economy with n sectors (Chen et al., 2013). For brevity, the rest of the mainland China except Beijing is put on the domestic scale, and the rest of the world except the mainland China is on the global scale.

Correspondingly, the water flows across the boundary of an urban economy are depicted in Fig. 1, in which w_i, $\sum_{j=1}^{n}\varepsilon_j^L z_{j,i}^L$, $(\sum_{j=1}^{n}\varepsilon_j^D z_{j,i}^D+\varepsilon_i^D fd_i^D)$, and $(\sum_{j=1}^{n}\varepsilon_j^F z_{j,i}^F+\varepsilon_i^F fd_i^F)$, respectively, represent local water withdrawal, water embodied in local intermediate use, in domestic imports, and in foreign imports of Sector i; $\varepsilon_i^L(\sum_{j=1}^{n} z_{i,j}^L + fd_i^L)$, $\varepsilon_i^L ex_i^D$, and $\varepsilon_i^L ex_i^F$, respectively, represent water embodied in local outputs, in domestic exports, and in foreign exports of Sector i.

The balance of both the water and monetary flows of Sector i, respectively, requires:

$$w_i+\sum_{j=1}^{n}\varepsilon_j^L z_{j,i}^L+\left(\sum_{j=1}^{n}\varepsilon_j^D z_{j,i}^D+\varepsilon_i^D fd_i^D\right)+\left(\sum_{j=1}^{n}\varepsilon_j^F z_{j,i}^F+\varepsilon_i^F fd_i^F\right)=\varepsilon_i^L x_i \quad (1)$$

$$x_i=\sum_{j=1}^{n} z_{i,j}^L+fd_i^L+ex_i^D+ex_i^F \quad (2)$$

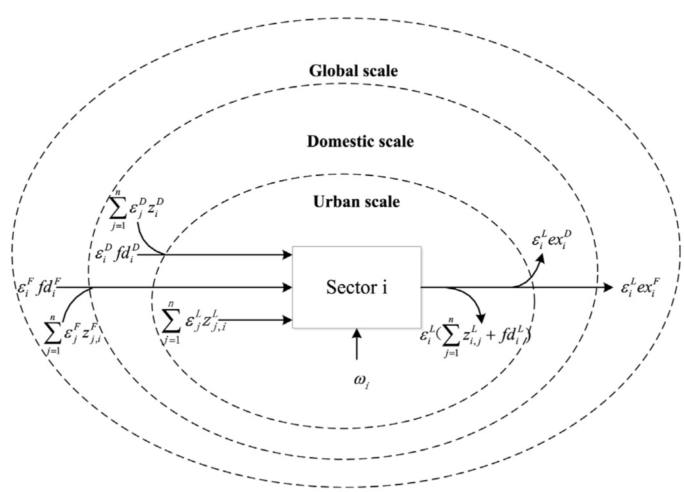

Fig. 1. Ecological flows for a typical sector in an urban economy.

where w_i represents the local water withdrawal derived by Sector i, ε_j represents the embodied water intensity of Sector j, $z_{j,i}$ represents the output from Sector j to i, fd_i represents the final demand of Sector i, x_i represents the gross output of Sector i, ex_i represents the export of Sector i, and superscript L, D, and F, respectively, represent local, domestic and foreign scales. It is assumed that the embodied intensities are equal for all commodities from the same economic sector.

Subsequently, the matrix form for (1) can be expressed as:

$$x_i = \sum_{j=1}^{n} z_{i,j}^{L} + fd_i^{L} + ex_i^{D} + ex_i^{F} \quad (3)$$

in which, $W = [w_i]_{1\times n}$, $E = [\varepsilon_i]_{1\times n}$, $Z = \left[z_{j,i}\right]_{n\times n}$, $IM = Z + \widehat{FD}$, diagonal matrices $\widehat{FD} = \left[fd_{i,j}\right]_{n\times n}$, where $i, j \in (1, 2, \ldots, n)$, $fd_{i,j} = fd_i$ $(i = j)$, and $fd_{i,j} = 0$ $(i \neq j)$, and $\hat{X} = \left[x_{i,j}\right]_{n\times n}$, where $x_{i,j} = x_i$ $(i = j)$, and $x_{i,j} = 0$ $(i \neq j)$.

With properly given local water withdrawal matrix W, local intermediate inputs matrix Z^L, imports matrices IM^D and IM^F, gross outputs matrix $\hat{X}$, and global and domestic embodied intensity matrices E^F and E^D, the local embodied water intensity matrix is obtained as:

$$E^L = (W + E^D IM^D + E^F IM^F)(X - Z^L)^{-1} \quad (4)$$

Thus, based on the three-scale systems analysis, water use reflected in intermediate use and final demand can be traced back to local water withdrawal, water embodied in domestic imports, and in foreign imports.

2.2. Data sources

According to the physical entry scheme, the detailed data of urban, national, and global scales are introduced below.

2.2.1. Urban scale data

The urban scale data refer to the economic data and local water withdrawal data. Beijing extended input–output table 2010 is the latest and most detailed one with 42 economic sectors as listed in Appendix Table A.1, issued by Beijing Statistics Bureau (BSY). In this case, the data on local water withdrawal, which includes those directly delivered into the major water users in terms of agricultural production, industrial production, municipal ecological protection, and household use, are derived from Beijing Statistical Yearbook (BSY, 2011), of which the amounts are 1.24E+09 m^3, 5.80E+08 m^3, 2.70E+08 m^3, and 1.39E+09 m^3, respectively. It is assumed that water used for agricultural production is directly exploited by cultivators and distributed to *Agriculture Sector*, while that for household use is exploited and pretreated by waterworks, which is distributed to *Water Production and Supply Sector*. Water utilized for industrial production is distributed to the secondary industry except *Water Production and Supply Sector* on the basis of the weighting coefficient of each sector. Municipal ecological water use, only containing the water used for artificial environmental engineering and supplement for rivers, lakes and wetlands, is distributed to *Public Facilities Management Sector*. Considering the limited availability of data, only surface water and ground water consumed during production process are considered in this study.

2.2.2. National scale data

China's embodied intensity inventory for the year of 2010 can be derived as relevant studies (Chen and Chen, 2012; Chen et al., 2012; Shao, 2014). The national scale data are adjusted to 42 sectors to comply with Beijing extended input–output table 2010, and the corresponding sector incorporation and allocation are carried out with details presented in Appendix Table A.1.

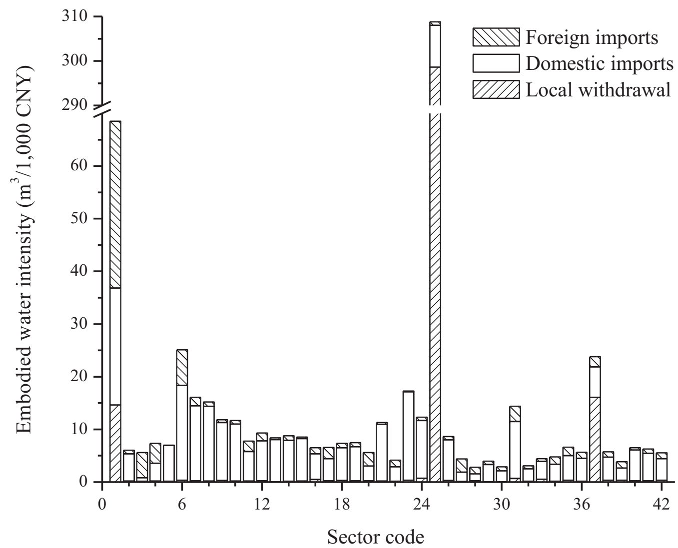

Fig. 2. Embodied water intensities by sector.

2.2.3. International scale data

The global water intensity inventory for the year of 2010 can be derived as the relevant studies (Chen and Chen, 2010; Chen et al., 2010; Shao, 2014), with corresponding sector incorporation and allocation to 42 sectors presented in Appendix Table A.1. Detailed import trade data can be integrated with the local input–output table through China's customs statistics yearbook or estimated based on each sector's weighting coefficient in the urban economic structure. In this study, each sector's intermediate import data are estimated by the weighting coefficient of each sector in Beijing's economic structure, with details given in Supplementary Material.

3. Results and discussion

Based on the described method and data sets, the three-scale systems IOA method is conducted with results and discussion presented below.

3.1. Embodied water intensity

The three-scale embodied water intensity inventory of Beijing's 42 economic sectors is presented in Fig. 2, in which three sources in terms of local water withdrawal, domestic imports (water embodied in domestic imports), and foreign imports (water embodied in foreign imports) are considered. The intensity of Sector 25 (*Water Production and Supply*) is much higher than that of the other sectors mainly due to the distribution of local water inputs for household use, and the special situation is also noticed for Sector 37 (*Public Facilities Management*) due to the distribution of local water inputs for municipal ecological protection.

Except for Sector 25 and 37, Beijing's sectoral intensities are close to the global and domestic sectoral average, with details shown in Appendix Table A.2. Overall, the embodied water intensity of the primary industry in Beijing (68.52 m^3/1,000 CNY) is much higher than that of the secondary industry (9.93 m^3/1,000 CNY) and of the tertiary industry (4.97 m^3/1,000 CNY). However, taking into account of both the domestic and global average intensities, the intensity of secondary industry in Beijing is comparatively low, while that of the tertiary industry is comparatively high. As for the

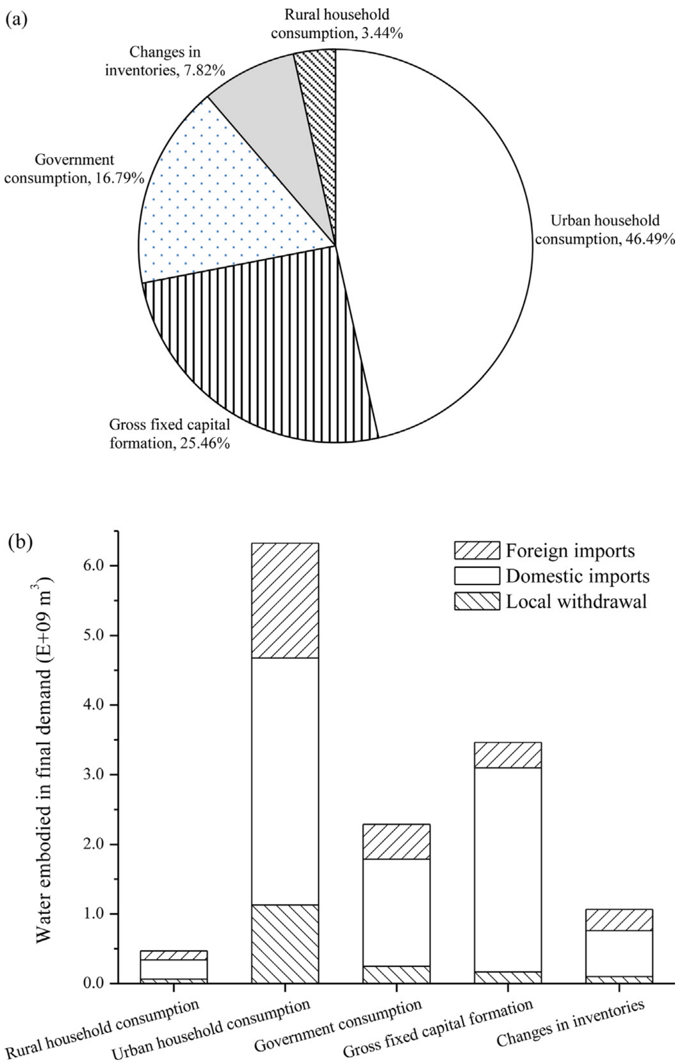

Fig. 3. The components of embodied water by final demand category.

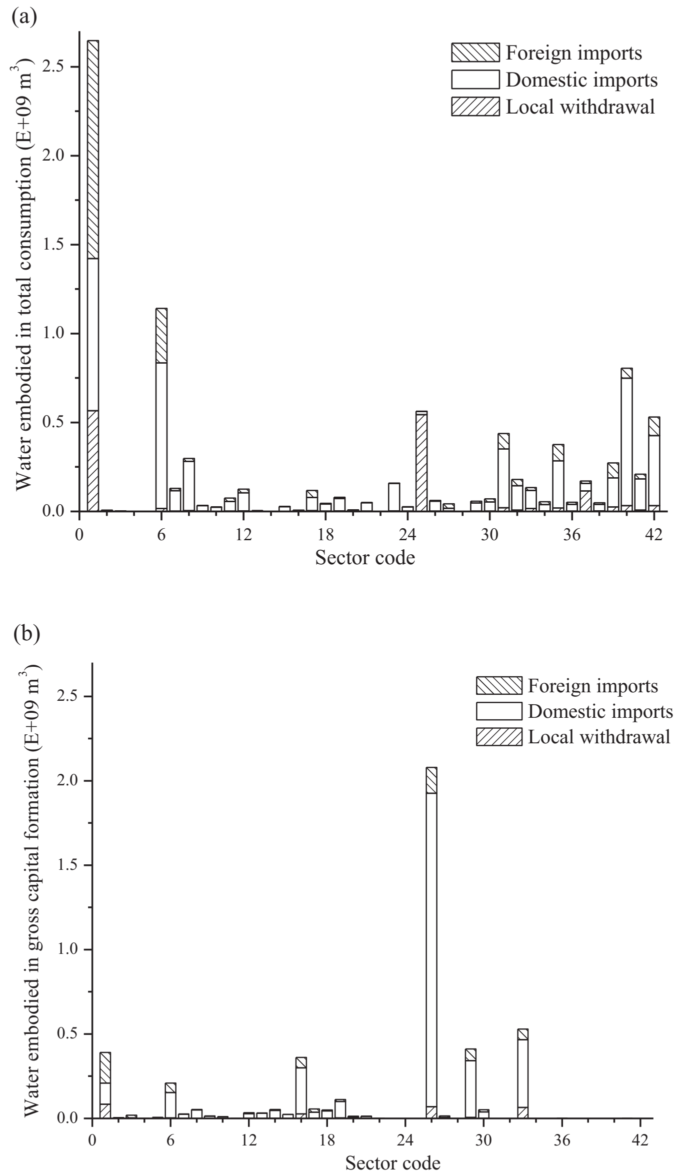

Fig. 4. Water embodied in (a) Total consumption and (b) Gross capital formation.

intensity of primary industry, it is in the middle level between the global and domestic average.

Since the late 1990s (first started in 1985), the scale of agriculture in Beijing has been severely restricted, and enterprises with high consumption and high pollution were gradually shut down or moved out of Beijing. As a result, domestic imports contribute a large share to the embodied water intensity of Beijing's most sectors. In addition, several specific sectors' intensities such as Sector 25 (*Water Production and Supply*) are dominated by local water withdrawal. Compared with the water embodied in domestic imports, the water embodied in foreign imports contributes relatively small to many sectors' embodied water intensities.

3.2. *Water embodied in final demand*

The total local water withdrawal is 3.53 billion m^3 (Beijing Water Authority, 2010), and the local embodied water demand is quantified as 13.61 billion m^3, almost quadruple the local water withdrawal. Regarding the five final demand categories shown in Fig. 3(a), the volume of water embodied in urban household consumption is the largest, accounting for 46.49% of the total, followed by that embodied in Gross fixed capital formation for 25.46%. By industry, the secondary and tertiary industries, respectively, contribute 44. 97% and 32.71% to the water embodied in final demand. It is noting that the water embodied in the secondary industry is slightly larger than that embodied in tertiary industry, even though the tertiary industry has already held a fundamental position in Beijing economy with a share of up to 59.07%. This phenomenon is mainly due to tertiary industry's smallest water occupation per capital unit in all the three industrial typologies.

Sectoral water embodied in final demand from the three sources is depicted in Fig. 3(b), with detailed data listed in Appendix Table A.3. From the systems perspective, domestic imports contribute about 70% to the water embodied in Beijing's final demand. As Beijing's heavy needs of resources use are mainly satisfied by domestic provinces and cities, water embodied in final demand is basically influenced by domestic imports, especially Sector 5 (*Other Minerals Mining*). As the largest component, water embodied in Urban household consumption mainly comes from domestic imports with a proportion of 56.05%, followed by foreign imports of 26.08%. As for the other final demand categories, domestic imports contribute about 85% to the water embodied in Gross fixed capital formation, and foreign imports contribute more than 25% to the water embodied in Changes in inventories.

Fig. 4 presents the water embodied in total consumption and gross capital formation. Sector 1 (*Agriculture*), 6 (*Food Processing*),

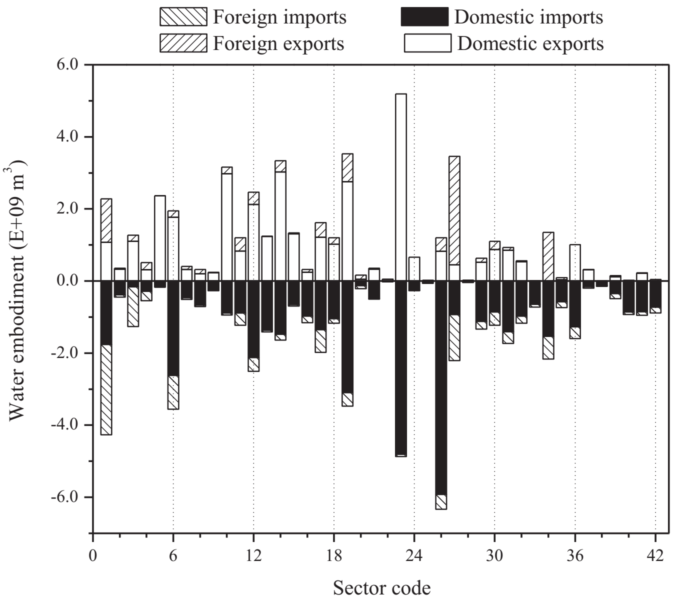

Fig. 5. Water embodied in trade by sector.

and 40 (*Health*) are found as the biggest three water consumers, and their trade patterns should be given further attention especially in terms of trade structure adjustments. Besides, Sector 26 (*Construction*), 33 (*Real Estate*), and 29 (*Information*) stock a large amount of water embodied in Gross capital formation, with amounts of 2.08 billion, 0.53 billion, and 0.41 billion m^3, respectively. From the systems perspective, water embodied in domestic imports contributes about 60% to the total water embodied in Total consumption, while that proportion for Gross capital formation reaches 80%.

3.3. Water embodied in imports and exports

Water embodied in imports reaches 56.77 billion m^3, almost quadruple the water embodied in final demand. Considering the total volume of water embodied in imports, domestic imports (44.68 billion m^3) are much larger than the foreign imports (12.08 billion m^3). By industry, the primary, secondary, and tertiary industries, respectively, contribute 7.52%, 63.34% and 29.14% to the water embodied in imports. Because of the fact that agricultural production capacity is limited and heavy industries are being gradually moved out, Beijing is highly dependent on the water embodied in trade from primary and secondary industries.

Exports embody 46.69 billion m^3 of water (including those to foreign countries and regions, and to domestic provinces and cities). Sector 23 (*Electric Power*) is noticed as the largest water exporting sector, with all goods exported to domestic regions. By industry, the secondary industry contributes more than 70% to the total water embodied in exports, followed by 21.27% by the tertiary industry and by 4.89% by the primary industry. Due to Beijing's significant role in China, water embodied in domestic exports is triple that in foreign exports. Yet considering the primary industry separately, the water embodied in domestic and global exports are comparable.

3.4. Water imbalance in trade

As a net importer, water embodied in Beijing's commodity trade amounts to 103.45 billion m^3, and the net water imports along with the merchandise flows reach 10 billion m^3. The water imbalance embodied in trade of the 42 economic sectors is presented in Fig. 5, with quantitative details presented in Appendix Table A.4.

Among the 42 sectors, there are 12 with embodied water surplus while the other 30 with deficit. Sector 26 (*Construction*) is the leading embodied water importer (6.33 million m^3 of total embodied water imports) and the leading trade deficit receiver (5.13 million m^3 of net embodied water imports), in contrast to Sector 23 (*Electric Power*) as the leading exporter (5.19 million m^3 of total embodied water exports) and Sector 10 (*Paper Products*) the leading trade surplus receiver (2.22 million m^3 of net embodied water exports). By industry, most secondary industrial sectors are net embodied water importers, while most tertiary industrial sectors are net embodied water exporters.

Sector 23 (*Electric Power*), 10 (*Paper Products*), and 29 (*Telecommunications Equipment*) are noticed as the largest three water exporting sectors, and their corresponding intensities are 17.31, 11.69, and 3.98 m^3/1000 CNY, respectively. Compared with the global and domestic average, the intensities of Sector 10 and 23 are in the middle level, while the water utilization efficiency in Sector 29 remains to be improved. Sector 1 (*Agriculture*), 6 (*Food Processing*), and 40 (*Health*), as the biggest three water consumers, can consciously reduce embodied water exports and increase imports through trade activities. From Fig. 5, all the three sectors are net importers, however, there are still more than 4.25 million m^3 of water exported through merchandise trade in particular in Sector 1 and 6. Thus, to practically save urban scale water resources use, adjusting economic trade can be feasible and effective, considering the huge amount of water embodied in trade activities.

3.5. Water balance in Beijing economy

Based on the three-scale analysis method, the water embodied in local final demand, domestic exports, and foreign exports can be traced back to local water withdrawal, water embodied in domestic imports, and in foreign imports, as depicted in Fig. 6 with details shown in Appendix Table A.5.

From the results, Beijing's local water withdrawal is 3.53 billion m^3, and the local embodied water demand is quantified nearly quadruple its local water withdrawal. The water embodied in domestic imports and foreign imports are, respectively, quantified

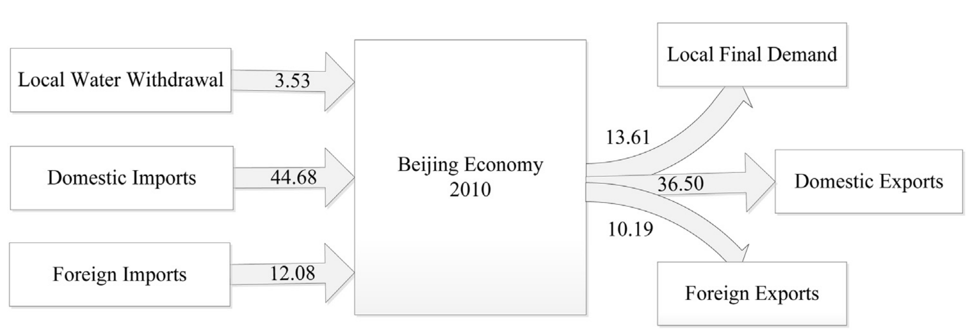

Fig. 6. Water flows associated with Beijing economy 2010 (unit: billion m^3).

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as 44.68 and 12.08 billion m^3, both of which are much higher than the local water withdrawal. Meanwhile, water embodied in domestic exports and foreign exports are respectively quantified as 36.50 and 10.19 billion m^3. Thus, it is worth noting that, from Beijing's water balance sheet, Beijing's huge water demand is mainly satisfied by domestic imports and foreign imports with shares of 60.10% and 13.89%, respectively. As normal practice, great concern has been paid to Beijing's extremely limited fresh water resources and rising water demand, and in this case water-saving strategies on reducing direct water consumption and increasing water utilization efficiency are suggested (Beijing Municipal Government, 2011, 2012). However, as indirect water associated with trade flows becomes even more significant than local direct water, the water embodied in trade should deserve much more attention.

From embodied water intensity inventory for Beijing economy, the primary industry's embodied water intensity is much higher than that of the secondary industry and of the tertiary industry. Thus, in consideration of primary industry's high intensity, importing primary products from other countries and regions is an inevitable measure to alleviate Beijing's water shortage pressure. As for the secondary industry, more than 70% of the local embodied water demand is from domestic economy, and only 5.24% is derived from local water withdrawal. As industries with high consumption and high emissions are being gradually moved out of Beijing, trends of external dependence of water resources will become more evident. Meanwhile, the tertiary industry, with the lowest embodied water intensity, will gradually dominate the urban economy. In this case, water embodied in production process and in intermediate inputs should be strictly controlled, and the water utilization efficiency of the tertiary industry should be further increased in the process of industrial upgrading.

4. Concluding remarks

The present work draws a holistic picture of urban water use balance based on a three-scale systems IOA method and provides an insight into the urban water use in context of regionalization and globalization of water resources use. From the perspective of systems theory, trade flows in and out of the urban economy are associated with massive water resources, which have essential implications to relocate urban scale water resources with that in the domestic and global economies.

With regard to urban water balance, the local embodied water demand for Beijing is nearly quadruple its local water withdrawal, and the water embodied in domestic and foreign imports plays an essential role in Beijing's huge water demand. With the three-scale system analysis, proper decisions on water-saving strategy can be made from the perspective of embodiment. It is obvious that obtaining embodied water resources through trade is essential for water scare economies in particular for Beijing. For now Beijing has gradually formed an economic structure to obtain embodied water from trade, and in the following process of structural adjustment, water demand embodied in total consumption should be placed with the first priority. Meanwhile, as the urban economy is dominated by tertiary industry, which is characterized as demand for a large amount of embodied water but a relatively small amount of direct water, water utilization efficiency in the tertiary industry in particular those embodied in the production process and in intermediate inputs should be further increased. In the context of globalization, urban economy with water shortage should draw support from their booming trade activities to rebalance water resources use, which will play an essential role in satisfying the water demand and have essential implications for decision making to ease urban water scarcity.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolmodel.2015.05.024

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