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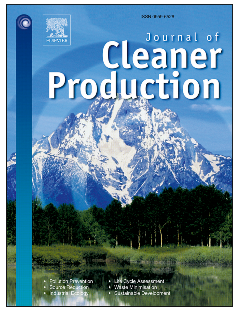

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Multi-scale input-output analysis of consumption-based water resources: method and application

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ABSTRACT

This work develops a method of multi-scale input-output analysis for the embodied water accounting of an economy. This method can distinguish between the different virtual water contents of imported and local products and is therefore capable of accurately estimating the virtual water that is embodied in trade. As a simplified model rather than a multi-regional input-output analysis, this method substantially

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minimizes the data requirements. With the support of averaged Eora global embodied water intensity databases for the world and Chinese economies, a three-scale embodied water input-output analysis of the Beijing economy in 2007 has been conducted. Dozens of virtual water flows that relate to the Beijing economy have been identified and analyzed. Only 15% of the total water resources embodied in Beijing's local final demand were from local water withdrawal; 85% were from domestically and internationally imported products. The virtual water import is revealed to play a more important role than physical water transfer in easing Beijing's water shortage. Since the average water use efficiency of the Beijing economy is much higher than that of the Chinese economy but somewhat lower that of the rest of the world, Beijing is suggested to shifting its imports to foreign countries to optimize global water use. The method developed can be useful for water saving strategies for multiple responsible entities holding different opinions, and it can be easily applied to the embodied water accounting of a sub-national or even smaller economic community.

Keywords

Multi-scale input-output analysis; Consumption-based water resources; Water resources embodied in trade; Virtual water strategy

1. Introduction

With the acceleration of globalization, cooperation, and specialization in the world economy, ever-increasing international and interregional trade have brought more trade imbalance issues concerning water resources. The water resources that are embodied in export, import, and bilateral trade have therefore attracted a significant amount of attention (Dalin et al., 2014; Hoekstra and Mekonnen, 2012). Among these studies, input-output analysis (IOA), and increasingly multi-region input–output (MRIO) analysis, plays an important role in tracing consumption-based water resource usage and in determining responsibility (Deng et al., 2015; Guan et al., 2014). Some water indicators, for example, the Water Stress Index (WSI) and the Water Exploitation Index (WEI) (Lenzen et al., 2013a; Pfister et al., 2009; Zhao et al., 2015) have also been attached to IOA to assist in the policy making.

Because the data support on a national level is relatively complete, the consumption-based water resources of countries around the world and the virtual water that is embodied in international trade have been successfully analyzed and estimated by MRIO analyses (Chen and Chen, 2013; Lenzen et al., 2013a). Based on available statistic trade data, some studies have made great contribution by connecting a national MRIO model to a global MRIO model with limited number of country groups to analyze regional virtual water flows (Cazcarro et al., 2016; Feng et al., 2011; Yu et al., 2010). However, for other sub-national or ever smaller regional economies where the detailed input-output data are not available, a complete water resource MRIO still presents difficulties. For example, the virtual water MRIO studies of Chinese regions either ignored international imported virtual water (Jiang et al., 2015; Zhao et al., 2015) or assumed that imported products and the locally produced products are homogenous (Deng et al., 2016).

Because of the lack of available data, some IOA based studies used the single-region input-output (SRIO) model to estimate the virtual water flow of an economy. The SRIO-based studies have either ignored imported virtual water (Zhao et al., 2016) or have made the water intensity for imports equal to that of local product (Guo et al., 2016; Renault, 2003; Zhao et al., 2009). Therefore, the SRIO can only estimate how much water is saved by importing a product instead of producing domestically, i.e., the water resources use that is avoided by imports (WAI). And it prevents estimation of the real virtual water transfer and the design of oriented virtual water strategies.

First presented by Chen and his colleagues, the method of multi-scale input-output (MSIO) was proposed to construct carbon emission intensity database and to support carbon emission accounting of a building (Chen et al., 2011). The present work contributes a universal multi-scale input-output (MSIO) method to analyze embodied water flows of an economy. It can distinguish between the different virtual water contents of the same products from different economies, which is superior to SRIO. In addition, because the averaged embodied water intensity databases for the world and for national economies have been used to estimate the virtual water that is embodied in trade, this method requires much less data than a complete MRIO analysis does. The MSIO can be easily applied to account the resource use of a sub-national or even a smaller economy according to individual need.

Beijing, as a megacity and the capital of China, has long suffered from water shortage because of a series of both natural and social economic factors, such as an unbalanced spatial distribution, heavy water pollution, a large population and rapid economic growth. It is reported that the groundwater reserves of Beijing (1.74 billion m^3 in 2015) has been declining over the past a few decades, the amount of which has been reduced by 9.48 billion m^3 since 1980 (BWA, 2015). The rivers with relative heavy water pollution (lower than V class water standard defined by Ministry of Environmental Protection of China) account for 39.7% of the total river length in 2015 (BWA, 2015). Aiming to demonstrate the MSIO method of water resources and assist water saving strategy design of Beijing, a case study has been conducted for a three-scale embodied water input-output analysis of the Beijing economy. The rest of the paper is organized as follows: Methodology and data sources are elaborated in Section 2. Section 3 presents the results of embodied water accounting of the Beijing economy. Section 4 discusses the advantages of the MSIO and contributes some virtual water strategies for Beijing to save water resources withdrawal. Finally, conclusions are drawn in Section 5.

2. Methods and materials

2.1 Multi-scale input-output (MSIO) analysis

2.1.1 Multi-scale ecological input-output table of an economy

To distinguish between the virtual water contents of local and imported products, a non-competitive ecological extended input-output table is considered as the basis of the MSIO analysis. Table 1 shows the general form of a multi-scale ecological input-output table of an economic system.

The illustrated system is divided into n_0 industrial sectors, which are simultaneously sustained by local and imported products. The imports are assumed to be from *m* external economic systems, and the economic system in the S_h scale is divided into n_h industrial sectors. $z_{i,j}^{L}$ and $z_{i,j}^{S_h}$ represent local products and imported product of the S_h scale from Sector *i* that are used as intermediate inputs for local Sector *j*. y_i^L and $y_i^{S_h}$ represent local products and imported products of the S_h scale from Sector *i* to satisfy the local final use. The local products from local Sector *i* that satisfy external use in the external economic system are represented as exports, e_i^L. Imported products are also re-exported to the external economic systems (see $e_i^{S_h}$). Finally, x_i represents the total output of the *i*-th local sector, and $F_{k,j}$ represents the *k*-th water resources flow that is consumed by the *j*-th local sector.

Table 1

Multi-scale ecological input-output table of an economic system[1]

Input \ Output		Intermediate use: Sector 1	Intermediate use: …	Intermediate use: Sector n_0	Final use: Local final consumption	Final use: Export	Output
Local inputs	Sector 1	$z_{1,1}^L$	…	z_{1,n_0}^L	y_1^L	e_1^L	x_1
	⋮	⋮	…	⋮	⋮	⋮	⋮
	Sector n_0	$z_{n_0,1}^L$	…	z_{n_0,n_0}^L	$y_{n_0}^L$	$e_{n_0}^L$	x_{n_0}
Imported inputs from S_1	Sector 1	$z_{1,1}^{S_1}$	…	$z_{1,n_0}^{S_1}$	$y_1^{S_1}$	$e_1^{S_1}$	
	⋮	⋮	…	⋮	⋮	⋮	
	Sector n_1	$z_{n_1,1}^{S_1}$	…	$z_{n_1,n_0}^{S_1}$	$y_{n_1}^{S_1}$	$e_{n_1}^{S_1}$	
⋮	⋮	⋮	⋮	⋮	⋮	⋮	

Imported inputs from S_m	Sector 1	$z_{1,1}^{S_m}$	…	$z_{1,n_0}^{S_m}$	$y_1^{S_m}$	$e_1^{S_m}$
	⋮	⋮	…	⋮	⋮	⋮
	Sector n_m	$z_{n_m,1}^{S_m}$	…	$z_{n_m,n_0}^{S_m}$	$y_{n_m}^{S_m}$	$e_{n_m}^{S_m}$
Direct water resources withdrawal	Water type 1	$F_{1,1}$	…	F_{1,n_0}		
	⋮	⋮	…	⋮		
	Water type p	$F_{p,1}$	…	F_{p,n_0}		

[1] The added value part is omitted as it is not involved in the basic formulation.

2.1.2 The basis formulas of multi-scale input-output analysis

Figure 1 shows the water resources input and output flows of a typical industrial sector i in an economic system (only the k-th water flow is considered). $\varepsilon_{k,j}^{L}$ and $\varepsilon_{k,j}^{S_h}$ represent the k-th embodied water resource intensities of local products from Sector j and imported products from Sector j of the economic system in the S_h scale. Here, the embodied water intensity is principally defined as the marginal water cost when the total amount of a product changes by an incremental unit.

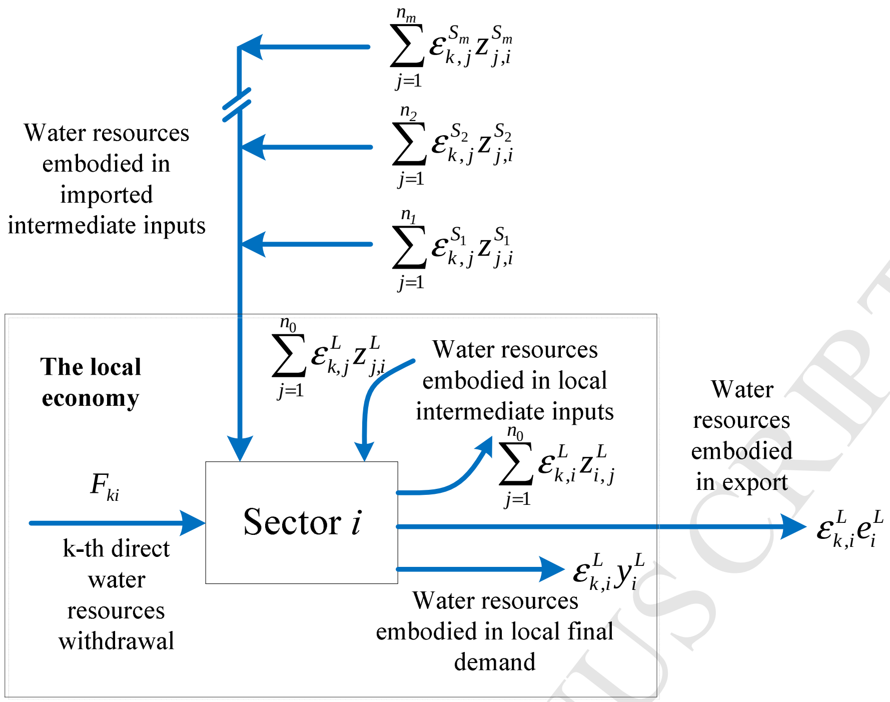

Figure 1. The virtual water balance of an industrial sector in an economic system

According to conservation law, the physical embodied water balance equation for local Sector *i* can be written as

$$F_{k,i}+\sum_{j=1}^{n_0}(\varepsilon_{k,j}^{L}z_{j,i}^{L})+\sum_{h=1}^{m}\sum_{j=1}^{n_h}(\varepsilon_{k,j}^{S_h}z_{j,i}^{S_h})=\varepsilon_{k,i}^{L}\left(\sum_{j=1}^{n_0}z_{i,j}^{L}+y_i^L+e_i^L\right). \qquad (1)$$

Based on the basic economic balance of an input-output table (see Table 1), it is understood that

$$x_i=\sum_{j=1}^{n_0}z_{i,j}^{L}+y_i^L+e_i^L. \qquad (2)$$

For the entire economic system that is complemented by water resource flows of *p* types as an economic-ecological integration, an aggregate matrix equation can be induced as

$$\mathbf{F}+\boldsymbol{\varepsilon}^{\mathbf{L}}\mathbf{Z}^{\mathbf{L}}+\sum_{h=1}^{m}(\boldsymbol{\varepsilon}^{S_h}\mathbf{Z}^{S_h})=\boldsymbol{\varepsilon}^{\mathbf{L}}\mathbf{X}, \qquad (3)$$

in which

$$\mathbf{F} = \left[F_{k,i}\right]_{p\times n_0},$$

$$\boldsymbol{\varepsilon}^{\mathbf{L}} = \left[\varepsilon_{k,i}^{L}\right]_{p\times n_0},\ \mathbf{Z}^{\mathbf{L}} = \left[z_{i,j}^{L}\right]_{n_0\times n_0},\ \boldsymbol{\varepsilon}^{S_h} = \left[\varepsilon_{k,i}^{S_h}\right]_{p\times n_h},\ \mathbf{Z}^{S_h} = \left[z_{i,j}^{S_h}\right]_{n_h\times n_0},$$

$\mathbf{X} = \left[x_{i,j}\right]_{n_0\times n_0}$, where $x_{i,j} = x_i$ when $i = j$, and $x_{i,j} = 0$ when $i \neq j$.

2.1.3 The embodied water intensity database based on the MSIO analysis

The embodied water intensity matrix for local products, as the basis for estimating the virtual water resource flows, can be given based on Eq. (3) as

$$\boldsymbol{\varepsilon}^{\mathbf{L}} = (\mathbf{F} + \sum_{h=1}^{m}(\boldsymbol{\varepsilon}^{S_h}\mathbf{Z}^{S_h}))(\mathbf{X} - \mathbf{Z}^{\mathbf{L}})^{-1}. \quad (4)$$

It can be seen that the direct water withdrawal data, non-competitive economic input-output data and the embodied water intensity matrixes for imported products are the preconditions for obtaining the embodied water intensity database of local products. As long as the embodied water intensity database of local products is obtained, the water resources that are embodied in the final demand and the exports can be calculated accordingly. After several deformations, Eq. (4) can also be rewritten as the following to make it easier to understand:

$$\boldsymbol{\varepsilon}^{\mathbf{L}} = (\mathbf{F} + \sum_{h=1}^{m}(\boldsymbol{\varepsilon}^{S_h}\mathbf{Z}^{S_h}))\mathbf{X}^{-1}(\mathbf{I} - \mathbf{A}^{\mathbf{L}})^{-1}, \quad (5)$$

where $\mathbf{A}^{\mathbf{L}} = \mathbf{Z}^{\mathbf{L}}\mathbf{X}^{-1}$ is a coefficient matrix that describes the inputs in the production of these sectors, and $(\mathbf{I} - \mathbf{A}^{\mathbf{L}})^{-1}$ is the so-called Leontief inverse (Miller and Blair, 2009). The equation is formally the same as the basis formula in universal environmental input-output analysis (EIOA). In EIOA, only $\mathbf{F}\mathbf{X}^{-1}$ as direct water use coefficients is applied to calculate the water resources embodied in final demand. However, besides the local water withdrawal, some of the water resources that are embodied in local products have originated from external economies by means of imported intermediate input. Therefore, in Eq. (5), the "direct" water use coefficients include not only the coefficients that originate from direct local water withdrawal ($\mathbf{FX}^{-1}$) but also the coefficients that originate from external water imports ($\sum_{h=1}^{m}(\boldsymbol{\varepsilon}^{S_h}\mathbf{Z}^{S_h})\mathbf{X}^{-1}$). They together constitute the total water coefficients (internal and external) of local products. $\varepsilon^{L,L}$ ($\mathbf{FX}^{-1}(\mathbf{I}-\mathbf{A}^{\mathbf{L}})^{-1}$) and ε^{L,S_h} ($\sum_{h=1}^{m}(\boldsymbol{\varepsilon}^{S_h}\mathbf{Z}^{S_h})\mathbf{X}^{-1}(\mathbf{I}-\mathbf{A}^{\mathbf{L}})^{-1}$) are used to denote local (with direct water withdrawal) and external (with imported intermediate input in S_h scale) embodied water intensities of local products.

2.2 Data source

Based on the MSIO method illustrated in Section 2.1, the three-scale embodied water input-output analysis of the Beijing economy in 2007 is performed as a case study. There are three types of essential databases for MSIO analysis. The first database is a direct water use matrix for the Beijing economy in 2007. The ecological input-output analysis assumes that the water transfer in an economic system has been approximately covered by the input-output data among different industrial sectors. For example, the tap water fee indicating the water transfer from the water supply industry to other industries has been itemized as the intermediate output of the water supply industry in the statistics data. As the physical entry of water resources to human society, the direct water withdrawal data – rather than direct water consumption – are therefore concerned in this work. The statistical data that was contributed by the Second National Economic Census of China has been referred to (see SI, Table S4) (CECY, 2010). Total water resource consumption has been divided into three types of water usage according to different withdrawal purposes. Agricultural water is for agricultural water requirements, mainly irrigation. Industrial water is for industrial production processes, for example, washing coal or cooling generator systems. Domestic water refers to daily water use by residents.

The second database is the economic input-out table. The official economic input-output table for the Beijing economy in 2007 has been adopted (BSB, 2009). This monetary input-output table is in units of Chinese Yuan (referred to as Yuan hereafter). There are 42 industrial sectors in the table, which can be found in Support Information (SI), Section S1.1. It is a competitive input-output table that does not distinguish between local and imported products. By assuming that the imported products have been distributed to intermediate input and final use with the same ratio of local products (Guan et al., 2014; Shao et al., 2016; Weber et al., 2008), it is transformed into a non-competitive input-output table. The intermediate input-output matrix and final use matrix of local products, domestic imported products, and foreign imported products can be obtained accordingly. For example, the foreign-imported intermediate input-output matrix, $\mathbf{Z^M}$, can be calculated as

$$z_{i,j}^{M} = z_{i,j}\left(\frac{x_i^M}{x_i + x_i^D + x_i^M}\right) \quad (6)$$

where $z_{i,j}$ is the total intermediate input from Sector i to Sector j, x_i is the total output of Sector i, x_i^D is the domestically imported economic flow of Sector i, and x_i^M is the foreign-imported economic flow of Sector *i*. Meanwhile, the final demand of Sector *i* from foreign imports, $\mathbf{F^M}$, is expressed as

$$f_{i,k}^{M} = f_{i,k}\left(\frac{x_i^M}{x_i + x_i^D + x_i^M}\right) \tag{7}$$

where $f_{i,k}$ is the *k*-th final consumption of Sector *i*.

The last data source concerns the embodied water intensity databases for the domestic and foreign imported products of the Beijing economy. The results from an MRIO analysis to estimate the embodied water intensity database for 26 sectors of 186 countries all over the world in 2007 on the basis of the Eora global MRIO database have been referred to (Lenzen et al., 2012; Lenzen et al., 2013b; Shao, 2014). According to the multi-scale input-output scheme, in principle, the databases should represent the rest of the world excluding the Chinese economy (because the products from the Chinese economy are considered to be domestic imported products) and the rest of China excluding the Beijing economy to estimate the virtual water that is embodied in foreign and domestic imports. With respect to the former, the average embodied water intensity for the 26 sectors in the other 185 nations of the world economy has been applied to estimate water resources embodied in foreign imported products (see SI, Table S2). However, regarding the latter, excluding the Beijing economy from the Chinese database is difficult. Therefore, the embodied water intensity for 26 sectors of the Chinese economy, as part of the results of the global MRIO analysis, has been applied to estimate to estimate water resources embodied in domestic imported products (see SI, Table S3). Because the share of the Beijing economy is a small part of the Chinese economy (the GDP ratio is approximately 3%), the deviation that the assumption presents can be ignored.

3. Results

3.1 The embodied water intensity of the Beijing economy

In 2007, Beijing has withdrawn 3.21 billion m^3 water. Meanwhile, the consumption-based water resources of Beijing is estimated as 11.28 billion m^3 water, approximately 3.51 times higher than the production-based water resources withdrawal. The embodied water intensities of all economic sectors in the Beijing economy in 2007 in the form of water resource withdrawal initiated by the final consumption of one unit product (this work uses the monetary unit) are shown in Figure 2 (the values can be found in SI, Table S5).

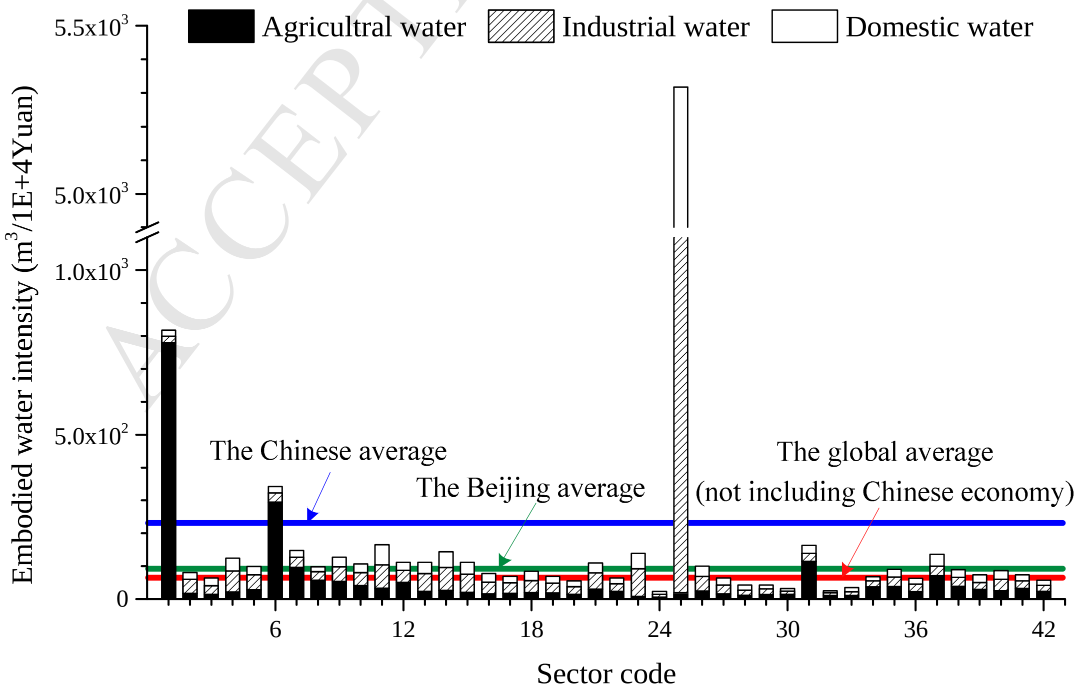

Figure 2. The embodied water intensity of the Beijing economy in 2007

Among the 42 industrial sectors, Sector 25 (Production and Distribution of Water) has the highest embodied water intensity, and Sector 1 (Agriculture, Forestry, Animal Husbandry and Fishery) ranks second. It is because these two industries have withdrawn abundant raw water resources, accounting for more than 85% of the total freshwater withdrawal. The final products that are supplied by these sectors, such as tap water, foods, and tobacco, are water-intensive products. Beijing can increase imports of these products to save local water resources. Although many industries seem irrelevant to agriculture, every sector has embodied agricultural water intensity. The advantage of input-output analysis is that it can reveal the complex technical and economic interactions of different industries.

A key theoretical premise of this study is that, because of the variation in technological efficiency and the diversity of economic structure, the same type of products that are produced in different communities have different embodied water intensities, i.e., virtual water contents. The obtained results agree with this premise (see the comparisons of Tables S2, S3, and S4 in SI). The average output-valued embodied water intensity for the entire global economy (not including the Chinese economy), the Chinese economy, and the Beijing economy in 2007 have been estimated as 71.69 m^3/1E+04 Yuan, 235.72 m^3/1E+04 Yuan, and 91.97 m^3/1E+04 Yuan (the former two are calculated from the embodied water intensity database of the Chinese economy and the rest of the global economy in 2007; see Figure 2). It can be observed that the average water use efficiency of the Beijing economy is much higher than that of the Chinese economy but somewhat lower that of the rest of the world. Thus, on average, China needs more than twice as many water resources as Beijing to have the same economic output value.

The significant gap between the Chinese and Beijing economies is mainly a reflection of the embodied agricultural water intensity, where China's average value is 161.59 m^3/1E+04 Yuan and Beijing's average value is only 41.04 m^3/1E+04 Yuan (which is even lower than the average value of the rest of the world). In 2012, over 88% of the total agricultural area in Beijing had adopted water-efficient irrigation, and the coefficient of irrigation agricultural water was as high as 0.70 in 2013 (Geng, 2014). At the same time, agricultural water use in Beijing has continually dropped since 2001 (CSY, 2015). With regard to China, the coefficient was only 0.52 in 2013 (Geng, 2014). The Chinese government plans to increase this coefficient to over 0.60 in 2030 according to the national policy referred to as "the Strictest Water Resources Management System" (SCC, 2012); the implementation of this policy was also emphasized in a recently launched draft of the five-year-plan for China. Smooth implementation of the plan will contribute to a lower embodied water intensity of China.

3.2 Water resources embodied in the final demand of the Beijing economy

One of the most important core issues in ecological economics is that the use of resources, such as water resource withdrawal, and environmental emissions, such as greenhouse gas emissions, are driven by human final demand or final consumption.

All embodied water flows related to the Beijing economy have been calculated and are illustrated in Figure 3 (the definitions and values of the embodied flows are shown in SI, Table S6). Essentially, the final consumption of Beijing is simultaneously met by foreign imported, domestic imported and local products. However, local products, which were emphasized in Section 2.1, involve local, domestic, and global embodied water intensities through direct water withdrawal, domestic, and foreign imported intermediate inputs, respectively. Therefore, part of the embodied water of the local products has also originated from domestic and foreign imported embodied water. This is often ignored in previous studies, and the MSIO has made it possible to identify and calculate it in the present work.

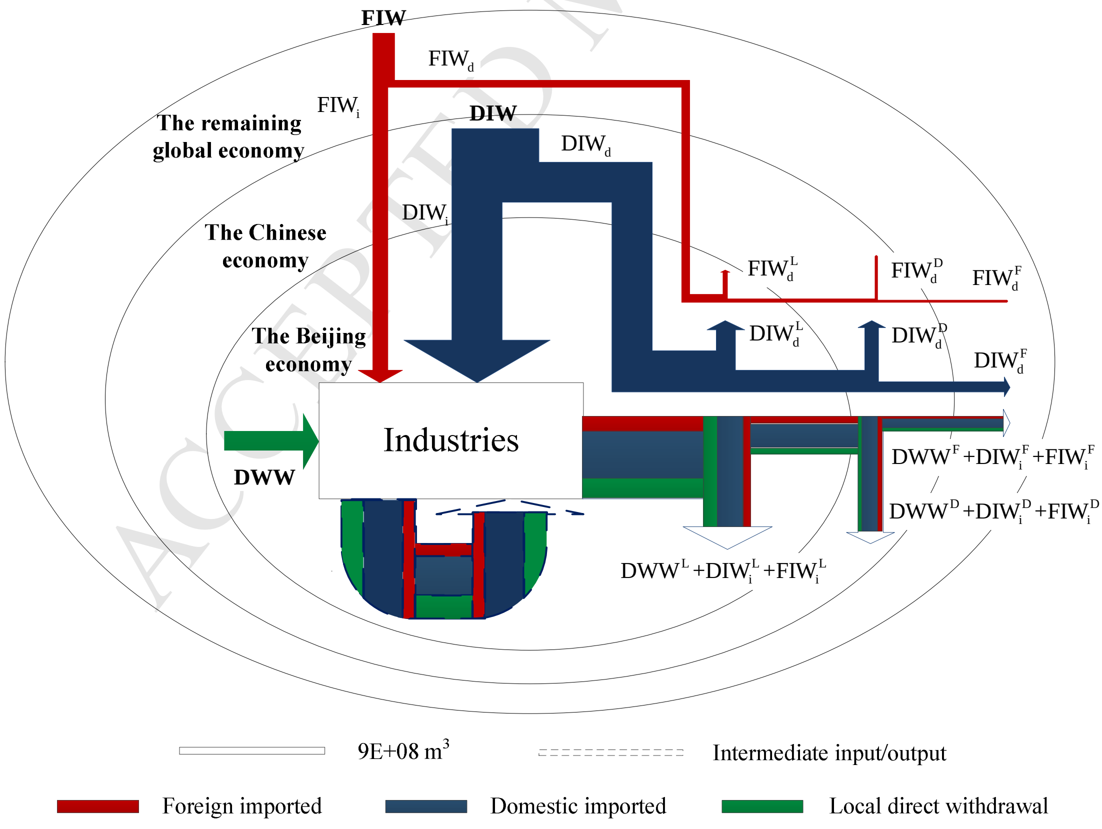

Figure 3. The embodied water flows of the Beijing economy in 2007 (DWW: direct water withdrawal; FIW: foreign imported water resources; DIW: domestically imported water resources; Superscript L/D/F: water resources embodied in local final demand/domestic export/foreign export; subscript d: direct imported water resources; Subscript i: indirect imported water resources through imported intermediate inputs)

According to the results, less than 1/5 of the total water resources that are embodied in Beijing's local final demand have been met by direct local water withdrawal (DWW^L). Concerning domestic imported water (DIW^L), in addition to the 3.17 billion m^3 of ostensible embodied water that is supplied by direct domestic import (DIW_d^L), another 4.10 billion m^3 of water resources have also been supplied through intermediate industrial processes (DIW_i^L). The invisible or indirect embodied water of local products that originated from domestic import is even larger than the obvious or direct embodied water. Together, they supply more than approximately 3/5 of the total embodied water of Beijing's local final consumption. The situation for foreign imported water that is embodied in local final consumption is similar (FIW^L); the ostensible (FIW_d^L) and unapparent embodied water resources (FIW_i^L) are 0.65 billion m^3 and 1.20 billion m^3, accounting for approximately 16% of the total embodied water of local final consumption.

Beijing's local final demand includes rural household consumption, urban household consumption, government consumption, fixed capital formation, and inventory increase. In addition, local products have also been exported to other

Chinese regions and foreign countries, and together, they form the final use of local products (see Figure 4). The water resources that are embodied in urban household consumption are approximately 12 times higher than the water resources of rural household consumption. The ratio of the urban population to rural population is only approximately 5.45, which reveals the significant gap between the standards of resource use of urban and rural people.

Like local final consumption, the water resources that are embodied in total domestic and foreign exports each constitute five components. Except for the embodied water that is directly supplied by direct local water withdrawal (DWW^D and DWW^F) and domestic (DIW_d^D and DIW_d^F) and foreign imported products (FIW_d^D and FIW_d^F), a significant portion of the domestic and foreign exports' embodied water that is supplied by local products also originates from domestic (DIW_i^D and DIW_i^F) and foreign imported intermediate inputs (FIW_i^D and FIW_i^F). Local freshwater withdrawal and domestic and foreign imports' embodied water account for 10.56%, 72.26%, and 17.18% of the total domestic export water. With respect to foreign export water, the ratios are essentially the same. Nearly half (47%) of the 21.35 billion m^3 of virtual water resources related to Beijing (direct water withdrawal plus domestic imported water plus domestic imported water, DWW+DIW+FIW) has been re-exported or re-located to external economies.

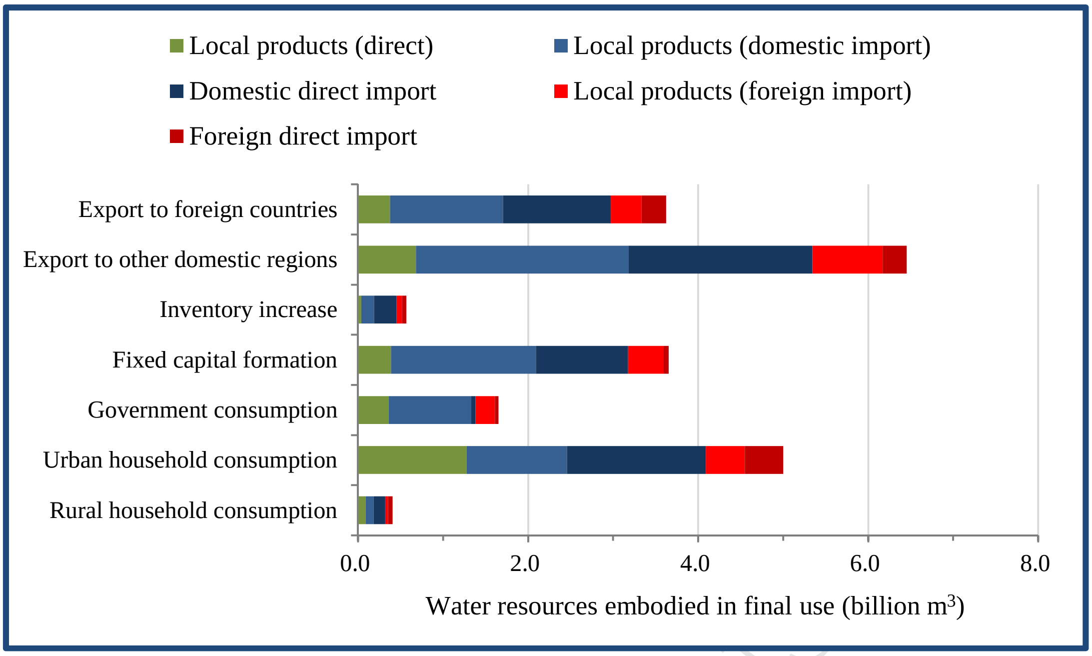

Figure 4. Water resources embodied in the final use of the Beijing economy in 2007

3.3 Embodied water trade balance of the Beijing economy

Beijing has 14.53 billion m^3 of domestic imported water from other Chinese regions, which is approximately 2.25 times greater than domestic exported embodied water. Regarding foreign trade, foreign exported embodied water is slightly higher (0.18%) than foreign imported embodied water. Domestic imported water is also 4 times greater than foreign imported water. Concerning domestic and foreign exported water, the ratio is only approximately 1.78. Overall, total water resources embodied in domestic trade is 2.90 times greater than the total water resources of foreign trade.

Figure 5 shows the water balance of each industry in the Beijing economy in 2007. Overall, the primary industry and most secondary industries are embodied water net importers, and most tertiary industries are embodied water net exporters. Sector 1 (Agriculture, Forestry, Animal Husbandry and Fishery) involves the largest embodied water trade and is also the largest embodied water importer. It may because agriculture is a water-intensive industry, and its embodied water intensity is the second largest after the water industry. This result also indicates that Beijing, as a megacity, is highly dependent on imported agricultural products.

Sector 19 (Manufacture of Communication Equipment, Computer and Other Electronic Equipment) is the second largest embodied water trader and also exports the most embodied water among all industries. Unlike the agriculture industry, Sector 19's embodied water import and export are both very large, although the former is approximately 20% larger than the latter. The industry involves many high-tech products, whose trade deals have led to the massive embodied water flows.

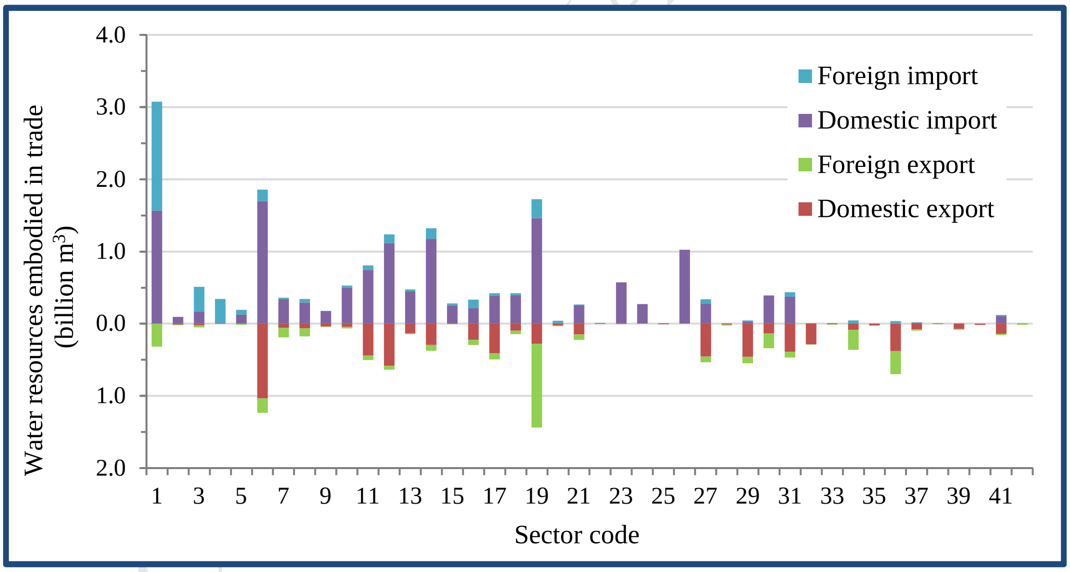

Figure 5. The water trade balance of the Beijing economy in 2007

Sector 6 (Manufacture of Foods and Tobacco) ranks third and is also the second largest embodied water importer and exporter after Sectors 1 and 19, respectively. For most industries, the water that is embodied in domestic trade is greater than the water that is embodied in foreign trade. Because there are typically more barriers in international trade than in domestic trade, this result is reasonable. However, Sector 19 is the opposite. This contrast may be because the production advantage of sector 19 is sufficiently distinct to offset tariffs and the different preferences of domestic and foreign customers.

4. Discussion

4.1 Comparing this study to other related studies

According to different measures to estimate the virtual water resources that are embodied in imports, there are four IOA methods that can be applied to analyze the consumption-based water resources use of an economy:

(1) SRIO (Single Regional Input-Output Analysis)

The water resources that are embodied in imports are ignored. Only the local water resources are concerned.

(2) SRIO-r (Single Regional Input-Output Analysis-revised)

The water intensities for imports are assumed equal to that of local products. The water resources use that is avoided by imports (WAI) rather than that is embodied in imports is calculated.

(3) MRIO (Multi-Region Input-Output Analysis)

The same products from different countries are treated as completely different types of products. The water resources that are embodied in imported products for meeting local final demand are calculated.

(4) MSIO (Multi-Scale Input-Output Analysis)

The output-averaged embodied water intensity databases for the external economies are applied to estimate the water resources that are embodied in imports.

In order to illustrate the differences between these IOA methods, they have been applied separately to analyze the consumption-based water resources of the Beijing economy in 2007. The results are compared in Table 2 (since a complete MRIO analysis needs massive data to perform, here this paper only compares the results of the former three methods; the differences between MSIO and MRIO are discussed later in theory).

Table 2

Water resources accounting results based on different IOA methods

IOA method	Embodied water intensity (m^3/1E+04 Yuan)	Water resources embodied in local final demand (billion m^3)	Water resources embodied in total final use (billion m^3)	Water resources embodied in domestic imports (billion m^3)	Water resources embodied in foreign imports (billion m^3)
SRIO	21.39	2.15	3.21	-	-
SRIO-r	21.39	2.15	3.21	1.06 (WAI)	2.26 (WAI)
MSIO	91.97	11.28	21.35	14.53	3.62

It can be seen that in general the results of SRIO and SRIO-r are much lower than that of MSIO. It is because the SRIO and the SRIO-r have ignored and underestimated the water resources that are embodied in imports. As indicated in Eq. (5) and the related descriptions in Section 2.1, the embodied water intensity of Beijing local products consists of local (with direct water withdrawal), domestic (with domestic imported intermediate input), and global (with foreign imported intermediate input) embodied water intensities (see SI, Section S2 and Figure S1). The intensities obtained from SRIO and SRIO-r are equal, which is indeed the local embodied water intensity of MSIO. Therefore the results of SRIO and SRIO-r are only part of the results of MSIO, and the MSIO can provide us with additional information on imported water resources that is embodied in local products.

Although in theory the MRIO is more accurate than the MSIO with respect to regional resolution, the size of their basis data differs by orders of magnitude. For example, in this study, on the basis of the existing world and Chinese embodied water intensity datasets (which are typically drawn from previous MRIO analysis), 6,174 embodied water flows have been analyzed to obtain the final results. However, an MRIO analysis that connects all Chinese provinces to all countries may involve over 70 million economic flows (assuming that each Chinese region has 30 sectors and 5 types of final demand and each country has 57 sectors and 3 types of final demand). Nearly half of the data required, i.e., economic trade flows between Chinese region and foreign countries, cannot be found in the existing databases or studies, and many assumptions must be made.

Since the MSIO can distinguish between the different embodied water resources of imported products and local products, it was proved to be superior to the SRIO. However, MSIO is not a perfect method. And the present study also involves a few uncertainties. For example, the aggregation error in connecting 26 sectors-based Eora intensity database to 42 sectors-based Beijing input-output data. When the MRIO data are not available or reliable, the MSIO can be served as a compromised but efficient way to address consumption-based environmental issues. The advantage of MSIO will be even more prominent when it needs to conduct an embodied water analysis for a sub- national or even a small economy. The obtained embodied water intensity database would be very useful for water footprint analysis of an engineering system, e.g., a wastewater treatment plant, a building, too (Meng et al., 2014; Shao and Chen, 2013, 2016).

Some previous studies have analyzed the carbon emissions and embodied water of the Beijing economy by MSIO (Chen et al., 2013; Guo et al., 2012; Han et al., 2015). However, these studies have certain limitations. First, China's economy was not excluded from the averaged database of the world economy. Second, the database for the Chinese economy that was applied was derived from a single-region analysis that did not distinguish between import products and local products. These limitations created deviations in the final results.

4.2 Virtual water strategy of the Beijing economy

Beijing and other northern Chinese regions have long suffered from water shortage. Given that the southern regions have more than enough water resources, the Chinese government launched the nationwide "South-to-North Water Transfer Project" (SNWTP) in 2002 after over fifty years of discussion and planning (Li, 2016). The middle route of the SNWTP officially began operations in December 2014 after twelve years of construction (Li, 2016). Approximately 1.9 billion m^3 of freshwater has been distributed to Beijing during the past two year, which has alleviated the local water shortage and groundwater overdraft (Li, 2016). Over 70% of Beijing's tap water is currently from the SNWTP (Li, 2016), and a rise in the groundwater level has been observed for the first time in 16 years (STD, 2015).

According to the results, in 2007, Beijing domestically and internationally imported 14.53 and 3.62 billion m^3 of embodied or virtual water. The net import is approximately 8 billion m^3 of virtual water (all from domestic imports). It can be seen that virtual water transfer plays a more important role than physical water transfer in easing Beijing's water shortage. This conclusion is consistent with that of Zhao et al. (Zhao et al., 2015). Improving local water use efficiency can be considered the most fundamental and sustainable measure to reduce direct water withdrawal of Beijing. Since Beijing relies heavily on domestic imported water resources and the Chinese average embodied water intensity is much higher that the Beijing average and the global average, Beijing would also benefit a lot from the improvement of water use efficiency on the domestic level. Beijing can invest in or spread water-saving technology in other Chinese regions to reduce the Chinese average embodied water intensity.

The concept of virtual water was first proposed by Allan in 1998 and has been considered essential to a strategic solution for water-scarce regions (Allan, 1998). Because all products (mainly agricultural products in early research) consume water resources during production in the form of virtual water or embodied water, the water-scarce problem can be settled through the commercial trade of water-intensive products. Since the cost of physical transport of water resources is very high, virtual water strategy can be considered as an alternative and better way to alleviate Beijing's water shortage problem. The MSIO-based results can be very helpful in the design of water saving strategies for multiple responsible entities holding different opinions. Concerning reducing Beijing's local water resource withdrawal only, Beijing should enlarge its imports of Sector 1 (agricultural products), 6 (foods and tobacco), 4 (metal ores), and 7 (textile products). It is because these products have the largest local embodied water intensities, and they can be easily substituted by imported like products.

However, for the entirely different matter of global water saving, the production of high-intensity products should be allocated to economies with high water production efficiency or low water intensity. Whether Beijing should import or where it should import from should also depend on water use efficiency. Since the average water use efficiency of the Beijing economy is much higher than that of the Chinese economy but somewhat lower that of the rest of the world, Beijing should enlarge its international imports and reduce its domestic imports.

5. Conclusions

Virtual water accounting has been a research hotspot in water resource management field. This work contributed a multi-scale input-output (MSIO) analysis method to account the consumption-based water resources of an economy. It can distinguish the different virtual water contents of imported products and local products. Compared with the single region input-output analysis (SRIO) method, the

MSIO can improve the accounting accuracy. Meanwhile, it requires much less data than a complete MRIO analysis does.

The framework and algorithm of the MSIO method for water resources accounting of an economy were presented in detail in Section 2.1. In order to illustrate the MSIO method, a three-scale embodied water input-output analysis of the Beijing economy in 2007 was performed as a case study. On the basis of an Eora global MRIO analysis, the output-weighting averaged embodied water resources intensity database for the 26 sectors in the other 185 nations (excluding China) of the world economy was applied to estimate the water resources embodied in the foreign imports of Beijing. Meanwhile, the database for the Chinese economy as a part of the MRIO analysis results was applied to estimate the embodied water resources of Beijing's domestic imports.

The consumption-based water resources consumption of Beijing was estimated as 11.28 billion m^3, which was 3.51 times higher than the production-based water resources withdrawal in 2007 (3.21 billion m^3). It is revealed that the average water use efficiency of the Beijing economy (109 Yuan/m^3) is much higher than that of the Chinese economy (42 Yuan/m^3) but somewhat lower that of the rest of the world (139 Yuan/m^3). Among the total amount of 21.35 billion m^3 water resources that were related to Beijing, 15% were from direct water withdrawal, 68% were from domestically imported virtual water resources, and 17% were from international imported virtual water resources. Over 1/2 of these water resources have been embodied in Beijing's local final demand, only 30% have been exported to other regions in China, and 17% have been exported to other countries.

In 2007, Beijing imported 14.53 billion m^3 water resources from other Chinese regions, which was approximately 2.25 times greater than domestic exported embodied water (6.45 billion m^3). Meanwhile, the foreign imported embodied water (3.62 billion m^3) was more or less the same as foreign exported embodied water (3.62 billion m^3). It is revealed that the primary industry and most secondary industries were embodied water net importers, and most tertiary industries were embodied water net exporters.

The differences between different IOA methods are discussed in the last section. According to the results of this paper, the net virtual water import of Beijing was approximately 8 billion m^3 (all from domestic imports) in 2007. It is much larger than the physical water transfer of Beijing during 2015-2016 (approximately 1.9 billion m^3) from the nationwide "South-to-North Water Transfer Project". The virtual water transfer is revealed to play an important role in easing Beijing's water shortage. According to the results, in order to save local water resources withdrawal, Beijing should enlarge its imports of Sector 1 (agricultural products), 6 (foods and tobacco), 4 (metal ores), and 7 (textile products). On the other hand, in order to improve the water use efficiency worldwide and maximize water conservation, Beijing should enlarge its international imports and reduce its domestic imports.

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- A multi-scale input-output analysis method (MSIO) has been contributed.
- The MSIO can greatly minimizes the data requirements compared to the MRIO method.
- Water resources embodied in final demand and trade of Beijing have been analyzed.
- Averaged embodied water databases for the world and Chinese economies were applied.
- More than 3/5 of local final demand's embodied water were domestically imported.