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# Reduction and reallocation of water use of products in Beijing

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## Highlights:

An indicator is introduced to study the water required for local production of final products.

Technical progress caused reductions in the internal water use of products in Beijing.

Production structure changes increased the internal water use of products in Beijing.

1 **Abstract:** The virtual water concept has received significant attention through  
2 manifesting the role of human activities such as consumption and international trade  
3 on water resources. However, few studies have focused on how the interactions of  
4 local supply chain exert impact on local water resources associated with virtual water  
5 flows. In this study, we introduce an indicator which is attached to the virtual water  
6 concept, termed the “internal water use of products” (IWUP), to examine the direct  
7 and indirect water use from local water supply for goods and services in Beijing for  
8 the years 1997, 2000, 2002, 2007, and 2010. This indicator links the pressure on local  
9 water resources to the final products with sectoral details, highlighting the importance  
10 of economic analysis in local water resource management. A structural decomposition  
11 analysis revealed that the increase in economic water productivity would have caused  
12 Beijing’s IWUP to decrease by 196% from 1997 to 2010, if other determining factors  
13 remained constant. Such great efficiency improvements have allowed Beijing to fulfill  
14 its objectives of economic growth, whilst in the meantime reducing the water used in  
15 production. However, we also found that production structure adjustment would  
16 increase the IWUP, mainly due to a shift from agricultural and industrial sectors to  
17 service sectors.

18 **Key words:** internal water use of products, virtual water, input-output analysis,  
19 structural decomposition analysis

# 1 **1 Introduction**

2       The imbalance of water supply and increasing water demand has become a  
3 serious problem for many local authorities (Llop, 2013; Zhao et al., 2015). It is widely  
4 known that most local water supply is used for the production of goods and services.  
5 However, less attention is given to the fact that this water is then embodied in goods  
6 and services to their places of consumption, which may be across local, regional and  
7 international boundaries. Such water flows along the economic supply chain from  
8 on-site (direct) water use to final products are not real water flows but virtual water  
9 flows. Introduced by Allan (Allan, 1992), the virtual water concept has since  
10 developed into two research areas, i.e. virtual water trade and water footprint. Virtual  
11 water trade studies focus on how water demand in one location can lead to freshwater  
12 depletion in other locations through trade (Yang et al., 2013a). Whilst, as a  
13 consumption-based indicator, water footprint is used to quantify the water use derived  
14 from consumption of final products (Feng et al., 2011; Hoekstra and Chapagain,  
15 2006). Both indicators appreciate the importance of extending the water study to  
16 global dimensions (Hoekstra and Mekonnen, 2012). However, few studies have  
17 focused on how the interactions of the local supply chain exert impact on local water  
18 resources associated with virtual water flows.

19       The effects of the supply chain can indirectly determine changes in water use.  
20 For example, it is a direct effect that expanded production in upstream sectors

1 increases on-site water use, and such expansion might be driven by increasing need  
2 for raw materials from local downstream industries. The above driving force can be  
3 attributed to indirect effects arising from supply chain interactions (Zhang, 2010).  
4 Policy makers usually acquire the information of direct effects. For example, in China  
5 water statistics provide the direct water use in each productive sector (defined  
6 hereafter as direct water use of products, DWUP). However, quantifying the changes  
7 in indirect effects, which are often ignored, can answer a series of questions relating  
8 to local economic and water management, such as how production structure  
9 adjustment can affect local water use, or what are the key sectors that drive the direct  
10 and indirect water use through the supply chain.

11 This paper aims to propose a framework to study the drivers of local water use  
12 changes derived from the interactions of the local economic system. First, we  
13 introduce a virtual water related indicator called the internal water use of products  
14 (IWUP). IWUP is defined as the water required to support local production of final  
15 products. ‘Internal’ means that no imported products are considered in the process.  
16 Both water footprint and IWUP underline the supply chain effects, but they have  
17 different scopes. The starting point of the water footprint is to highlight the  
18 consumption impact of a region to water resources wherever the production happens.  
19 Such impact is usually beyond a region’s territorial boundary through importing  
20 products. Whereas IWUP in turn traces how the water resources of a region are

1 influenced by final consumption and local supply chain effects, thus providing  
2 information of interrelationships between water use and local economy.

3       Second, we carry out a decomposition analysis to study the driving forces of  
4 changes in IWUP. There are two commonly used decomposition techniques: index  
5 decomposition analysis (IDA) and structural decomposition analysis (SDA) (Su and  
6 Ang, 2012). Detailed comparison of the two methods can be found in Hoekstra and  
7 van den Bergh (2003), and Su and Ang (2012). In short, IDA decomposes the  
8 resource use or emission without sector information, while SDA is associated with the  
9 input-output methodology incorporating the supply chain effects with detailed sector  
10 information. In this study, we use SDA with a single-region input-output (SRIO)  
11 analysis to quantify the drivers of IWUP changes. The SDA model has been widely  
12 employed to study the key drivers of energy use and carbon dioxide (CO<sub>2</sub>) emissions  
13 (Guan et al., 2008; O'Mahony et al., 2012; Wood, 2009), but has rarely been used for  
14 water, with a few notable exceptions for studies of water footprints (Guan et al., 2014;  
15 Zhang et al., 2012). The rationale of selecting the SRIO methodology and the  
16 comparison with other input-output techniques are presented in the Methodology  
17 section.

18       The mega-city of Beijing was chosen for a case study with the years 1997, 2000,  
19 2002, 2007, and 2010. The provision of sufficient water is becoming a great challenge  
20 for the world's large cities (Darrel Jenerette and Larsen, 2006). By 2050, 1 out of 3  
21 billion of the world's urban dwellers are expected to live in cities with perennial water

1 shortage (McDonald et al., 2011). Beijing, a mega-city of about 20 million inhabitants,  
2 is facing severe water shortage due to its rising population and poor freshwater  
3 availability. The data for 2010 shows that water availability for Beijing was only 140  
4 m<sup>3</sup>/capita (Beijing Water Resources Bureau, 1988-2012), much lower than the  
5 acknowledged water scarcity threshold of 1700 m<sup>3</sup>/capita (Falkenmark and Widstrand,  
6 1992). Since the late 1990s the city has suffered from ongoing drought, whilst during  
7 the period from 1997 to 2010, the population of Beijing has increased by 61% and the  
8 real gross domestic product (GDP) has increased more than fourfold (Beijing  
9 Municipal Bureau of Statistics, 1989-2013).

10 Several studies have shown water use increases in mega-cities, mainly due to  
11 population growth and industrial development (Darrel Jenerette and Larsen, 2006;  
12 Jury and Vaux, 2005). However, on-site water use for producing goods and services  
13 in Beijing has seen a declining trend. Between 1988 and 2010 the water use for  
14 agricultural and industrial production in Beijing decreased by 48% and 64%  
15 respectively (Beijing Water Resources Bureau, 1988-2012), and the declining trend  
16 has continued since then. Hence, it is interesting to examine the economic  
17 explanations for such a large decrease in water use against substantial economic  
18 growth.

## 1 **2 Methodology and data**

### 2 **2.1 Conceptual framework of water reallocation in the** 3 **supply chain of products**

4 In examining the factors contributing to changes in IWUP, we examined the total  
5 volume of freshwater used in all steps of the production supply chain. In particular,  
6 such accounting highlights the role of downstream industries on water demand. Such  
7 a role is also part of the extended producer responsibility, which refers to: “Producers  
8 of products should bear a significant degree of responsibility not only for the  
9 environmental impacts of their products downstream from the treatment and disposal  
10 of their products, but also for their upstream activities inherent in the selection of  
11 materials and in the design of products” (Lenzen et al., 2007).

12 In order to illustrate the above process we use a simple flow diagram of water  
13 reallocation in the supply chain of products (Fig. 1). Here, we assume there are only  
14 two sectors (Food and Food Processing) in a hypothetical region, and the Food sector  
15 produces wheat and maize for onward sale or further processing. The Food Processing  
16 sector produces the processed products using wheat and maize as raw materials. Here  
17 the water embodied in the imported products, which is also referred to as virtual water  
18 import (Hoekstra et al., 2011), is not considered in the process. Since we want to trace  
19 the virtual water flow from local water supply in the supply chain.

1 Fig. 1 shows that the total DWUP is  $130 \text{ m}^3$ , and the DWUP for the Food sector  
2 is  $100 \text{ m}^3$  ( $60 \text{ m}^3$  for wheat and  $40 \text{ m}^3$  for maize). However, as  $60 \text{ m}^3$  of water  
3 (embodied in the food products as raw materials) flows into Food Processing, the  
4 water use in producing the food products for final demand, i.e. the IWUP is actually  
5 only  $40 \text{ m}^3$  and the IWUP of Food Processing is  $90 \text{ m}^3$  (its DWUP is  $30 \text{ m}^3$ ). Hence,  
6 IWUP represents a real pressure on local water resources caused by local production  
7 activities. Meanwhile, it shows how the local water supply was reallocated among the  
8 supply chain to different sectors. Such a reallocation extends the producer  
9 responsibility for both direct and indirect water use.

## 10 **2.2 Top-down approaches in quantifying IWUP**

11 Top-down and bottom-up are two quantification approaches used in virtual water  
12 related studies (Yang et al., 2013a). The detailed comparison of the two approaches  
13 has been given by Yang et al. (2013a) and Feng et al. (2011). In a nutshell, a  
14 bottom-up method accounts for the water use for a single product with detailed  
15 descriptions of individual production processes. The top-down method usually refers  
16 to input-output analysis (IOA), which shows the interdependency among different  
17 economic sectors (Feng et al., 2011). An IOA has long been recognized as an  
18 appropriate tool to attribute resource use or pollution to final products in a consistent  
19 framework (Wiedmann, 2009).

1 In recent years, many studies have adopted SRIO to quantify water footprint and  
 2 virtual water trade (Guan and Hubacek, 2007; Guan et al., 2014; Zhao et al., 2009). A  
 3 major limitation of SRIO is the assumption that imported goods and services are  
 4 being produced using the same technology as the domestic technology in the same  
 5 sector (Wiedmann, 2009). SRIO can lead to errors in quantifying the virtual water  
 6 embodied in the imported goods and services, i.e. virtual water import (external water  
 7 footprint). A multi-region input-output model (MRIO) can overcome this limitation  
 8 by distinguishing between local and foreign production technology, but it  
 9 substantially increases the data requirement and computational complexity.

10 Our study employed a SRIO to account for the IWUP. As IWUP doesn't contain  
 11 the virtual water import, the above mentioned limitation of SRIO has no effect on the  
 12 IWUP. Following the framework in Fig. 1, we present the formula of calculating  
 13 IWUP associated with a SRIO. Local goods and services are consumed by two kinds  
 14 of consumers (**f**): consumers in the local region, which represent internal final demand  
 15 (**i**), and consumers in other regions, which represent export (**e**). So the IWUP can be  
 16 expressed as:

$$17 \quad \mathbf{iwup} = \mathbf{d} \cdot \mathbf{L} \cdot \mathbf{f} = \mathbf{d} \cdot (\mathbf{I} - \mathbf{A})^{-1} \cdot (\mathbf{i} + \mathbf{e}) \quad (1)$$

18 Where **iwup** is the vector of IWUP, **d** is the vector of direct water use intensity,  
 19 which is calculated as the per unit output of the direct water use of products (DWUP).  
 20 The reciprocal of **d** is the economic water productivity.  $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$  is the Leontief  
 21 inverse matrix. **I** represents the identity matrix and **A** represents the technical

1 coefficient matrix that contains the inputs of each sector per unit of their output in  
 2 monetary terms.  $\mathbf{f}$  is the vector for total final demand, and can be divided into  $\mathbf{i}$  and  $\mathbf{e}$ .  
 3  $\mathbf{i}$  is the vector for internal final demand, indicating the local production that is used for  
 4 local consumption, and  $\mathbf{e}$  is the vector for exports.

## 5 **2.3 Structural decomposition method**

6 We used a structural decomposition analysis to study the driving forces that  
 7 determine the change of IWUP. The approach changes the multiplicative factors into  
 8 additive parts following Hoekstra and van den Bergh (2003). According to equation  
 9 (1), we divided the change in IWUP into four driving forces: direct water use intensity  
 10 ( $\mathbf{d}$ ), production structure adjustment ( $\mathbf{L}$ ), internal final demand ( $\mathbf{i}$ ), and exports ( $\mathbf{e}$ ).  
 11 Among the driving forces,  $\mathbf{d}$  reflects the effects of technological improvements on  
 12 water use efficiency. The Leontief inverse matrix  $\mathbf{L}$  is a reflection of the economic  
 13 production structure (De Haan, 2001; Guan et al., 2008). The change in IWUP from  
 14 time 0 to time 1 can be decomposed into the selected driving forces using the  
 15 following equations:

$$\begin{aligned}
 \Delta \mathbf{iwup} &= \mathbf{iwup}_1 - \mathbf{iwup}_0 \\
 &= (\mathbf{d}_1 \cdot \mathbf{L}_1 \cdot \mathbf{f}_1) - (\mathbf{d}_0 \cdot \mathbf{L}_0 \cdot \mathbf{f}_0) \\
 &= \Delta \mathbf{d} \cdot \mathbf{w}_d + \Delta \mathbf{L} \cdot \mathbf{w}_l + \Delta \mathbf{f} \cdot \mathbf{w}_f
 \end{aligned}
 \tag{2}$$

17 Where subscripts 0 and 1 represent the two points in time.  $\mathbf{w}_d$ ,  $\mathbf{w}_l$ , and  $\mathbf{w}_f$  are weights  
 18 to be solved for the direct water consumption intensity, the Leontief inverse matrix,

1 and the total final demand, respectively.  $\Delta \mathbf{d} = \mathbf{d}_1 - \mathbf{d}_0$ ,  $\Delta \mathbf{L} = \mathbf{L}_1 - \mathbf{L}_0$ , and  $\Delta \mathbf{f} = \mathbf{f}_1 - \mathbf{f}_0$ .

2 One of the solutions to equation (2) can be shown as follows:

$$\begin{aligned}
 & \Delta \mathbf{i} \mathbf{w} \mathbf{u} \mathbf{p} = \mathbf{i} \mathbf{w} \mathbf{u} \mathbf{p}_1 - \mathbf{i} \mathbf{w} \mathbf{u} \mathbf{p}_0 \\
 & = (\mathbf{d}_1 \cdot \mathbf{L}_1 \cdot \mathbf{f}_1) - (\mathbf{d}_0 \cdot \mathbf{L}_0 \cdot \mathbf{f}_0) \\
 3 \quad & = \Delta \mathbf{d} \cdot \mathbf{L}_1 \cdot \mathbf{f}_1 + \mathbf{d}_0 \cdot \mathbf{L}_1 \cdot \mathbf{f}_1 - \mathbf{d}_0 \cdot \mathbf{L}_0 \cdot \mathbf{f}_0 \quad (3) \\
 & = \Delta \mathbf{d} \cdot \mathbf{L}_1 \cdot \mathbf{f}_1 + \mathbf{d}_0 \cdot \Delta \mathbf{L} \cdot \mathbf{f}_1 + \mathbf{d}_0 \cdot \mathbf{L}_0 \cdot \mathbf{f}_1 - \mathbf{d}_0 \cdot \mathbf{L}_0 \cdot \mathbf{f}_0 \\
 & = \Delta \mathbf{d} \cdot \mathbf{L}_1 \cdot \mathbf{f}_1 + \mathbf{d}_0 \cdot \Delta \mathbf{L} \cdot \mathbf{f}_1 + \mathbf{d}_0 \cdot \mathbf{L}_0 \cdot \Delta \mathbf{f}
 \end{aligned}$$

4 In equation (3), the solved weights are:  $\mathbf{w}_d = \mathbf{L}_1 \cdot \mathbf{f}_1$ ,  $\mathbf{w}_l = \mathbf{d}_0 \cdot \mathbf{f}_1$ , and  $\mathbf{w}_f = \mathbf{d}_0 \cdot \mathbf{L}_0$ .

5 However, such a solution is not unique. Different solutions can be obtained by simply

6 changing the permutation of the three multiplied variables, i.e.  $\mathbf{d}$ ,  $\mathbf{L}$ , and  $\mathbf{f}$ . For  $n$

7 multiplicative variables, there are  $n!$  solutions (Dietzenbacher and Los, 1998). In our

8 case, there are  $3! = 6$  solutions. Diezenbacher and Los (1998) solved the problem with

9 a ‘two polar’ method by calculating the mean of all solutions. One attribute of the

10 ‘two polar’ method is that each solution has a ‘mirror image’. De Haan (2001)

11 presented a sensitivity analysis to show that the ‘mirror image’ decomposition forms

12 substantially diminish the percentage deviation from the average estimate. Due to its

13 good performance, this method has been widely used in structural decomposition

14 analysis (De Haan, 2001; Guan et al., 2008; Su and Ang, 2012). The solution in our

15 case with the ‘two polar’ method is shown in Equations (4) to (7). It is worth

16 mentioning that we further decomposed the final demand ( $\mathbf{f}$ ) into internal final

17 demand ( $\mathbf{i}$ ) and exports ( $\mathbf{e}$ ) to emphasize the effects of exports.

$$18 \quad \Delta \mathbf{d} \cdot \mathbf{w}_d = \Delta \mathbf{d} \cdot (\mathbf{1}/3 \mathbf{L}_0 \cdot \mathbf{f}_0 + \mathbf{1}/6 \mathbf{L}_0 \cdot \mathbf{f}_1 + \mathbf{1}/6 \mathbf{L}_1 \cdot \mathbf{f}_0 + \mathbf{1}/3 \mathbf{L}_1 \cdot \mathbf{f}_1) \quad (4)$$

$$\Delta L \cdot w_f = \Delta L \cdot (1/3d_0 \cdot f_0 + 1/6d_0 \cdot f_1 + 1/6d_1 \cdot f_0 + 1/3d_1 \cdot f_1) \quad (5)$$

$$\Delta i \cdot w_f = \Delta i \cdot (1/3d_0 \cdot L_0 + 1/6d_0 \cdot L_1 + 1/6d_1 \cdot L_0 + 1/3d_1 \cdot L_1) \quad (6)$$

$$\Delta e \cdot w_f = \Delta e \cdot (1/3d_0 \cdot L_0 + 1/6d_0 \cdot L_1 + 1/6d_1 \cdot L_0 + 1/3d_1 \cdot L_1)$$

(7)

## 2.4 Data

The SRIO table for China is officially compiled every five years, and the most up-to-date one is from 2007 (IO table in 2012 is still in compilation). Since the input-output (IO) table and water use data before 1997 is unreliable, our study chose the IO tables in years 1997, 2002, and 2007, and an extended table in 2000 and 2010, which were derived from the IO tables in 1997 and 2007 respectively. 14 sectors were grouped according to the IO table for Beijing and available sectoral water use data. These were (1) Agriculture, (2) Mining, (3) Food and tobacco processing, (4) Textile, leather, and other fiber products, (5) Lumbering and paper products, (6) Petroleum processing and coking, (7) Chemicals, (8) Non-metal mineral products, (9) Metal products, (10) Machinery and equipment, (11) Electricity, gas, and water production and supply, (12) Construction, (13) Wholesale and retail trade and passenger transport, and (14) Other services. Among these, sectors (2) to (12) are defined as Industrial sectors, and sectors (13) to (14) are Service sectors.

In this study, local water supply is defined as water abstracted locally or transferred from outside the regional boundary into the local water supply system.

1 Water use is defined as the gross quantity of water distributed to users, including  
2 water lost in distribution, such as through leakage. The water use data of the  
3 Agriculture, Industry and Service sectors is taken from the Beijing Water Resources  
4 Bulletin (Beijing Water Resources Bureau, 1988-2012). The breakdown of water use  
5 to Industrial sectors is derived from the Beijing Economic Census Yearbook (Beijing  
6 Municipal Statistics Bureau, 2004). The breakdown of water use to Service sectors is  
7 taken from Zhao et al.(2010). The water supply of Beijing comes from surface water,  
8 ground water, transferred water, and recycled water. Recycled water including reused  
9 rainfall and sewage water is an important source of Beijing's water supply (Wu and  
10 Chau, 2006), accounting for 14% of total water supply in 2010.

## 11 **3 Results**

### 12 **3.1 Direct water use of products**

13 DWUP represents the water used directly by each sector. It can be seen in Table  
14 1 that DWUP is unevenly distributed amongst the 14 sectors. Agriculture uses most of  
15 the DWUP, accounting for 47.2% based on the average for the five years considered.  
16 This is followed by Electricity, gas, and water production and supply (19.2%), and  
17 Wholesale, retail trade and passenger transport (19.6%). Combined, these three  
18 sectors used an average of 86% of the total DWUP based on the five years of  
19 available data.

1           The total DWUP decreased by 21% from 1997 to 2010. The main contributor to  
2 the decline in total DWUP was agriculture, accounting for 52% (from 1812 million  
3 m<sup>3</sup> to 1140 million m<sup>3</sup>) of the sectors with decreased DWUP between 1997 and 2010.  
4 The decrease is largely due to the decline of agricultural production in Beijing,  
5 especially grain production. The production volume of major grain crops decreased  
6 from 2.37 million tons in 1997 to 1.16 million tons in 2010, and available arable land  
7 decreased by 32%. The share of agriculture in total GDP decreased from 3.7% to 0.9%  
8 between 1997 and 2010 (Beijing Municipal Bureau of Statistics, 1989-2013). Another  
9 contributor to the total DWUP decrease is Electricity, gas, and water production and  
10 supply. About 46% of the decrease was attributed to this sector (from 863 million m<sup>3</sup>  
11 to 276 million m<sup>3</sup>) between 1997 and 2010. This is partly attributed to Beijing's effort  
12 to improve water use efficiency for electricity production since 2002. For example, it  
13 has changed its thermal power plants from once-through cooling systems to open  
14 cycle cooling systems (Du, 2006). Despite the downward trend for total DWUP, the  
15 DWUP of the two service sectors increased by 77% from 1997 to 2010. The increase  
16 is mainly due to Beijing's rapid urban development during the period (Yang et al.,  
17 2013b).

### 18 **3.2 Internal water use of products**

19           DWUP turns into an identical volume of virtual water after being 'embodied' in  
20 the supply chain of products. This virtual water is reallocated to different sectors and

1 finally flows to consumers as IWUP. The process is shown as a matrix in Table 2 for  
2 the situation in 2010. Each column of the matrix demonstrates how the DWUP of a  
3 sector is reallocated to all sectors in a virtual form. While each row of the matrix  
4 shows how much virtual water is needed from all sectors to fulfill the final demand of  
5 consumers of a sector. As a result, the total IWUP is equal to the total DWUP, but  
6 they differ at the sectoral level (see Table 1 and Table 2).

7 The IWUP of each sector shows the extent of pressure on local water resources  
8 derived from the final products of that sector. Based on the five years' average, the  
9 top five sectors of IWUP are Agriculture (29%); Other services (25%); Wholesale,  
10 retail trade and passenger transport (13%); Food and tobacco processing (12%); and  
11 Construction (6.5%). It was also found that there are sectors with IWUP significantly  
12 larger than their DWUP, namely: Food and tobacco processing, Machinery and  
13 equipment; Construction; and Textile, leather, and other fiber products. These sectors  
14 are characterized by being 'downstream' of the supply chain, and require a large  
15 amount of indirect water from 'upstream' activities. Traditionally, these sectors are  
16 considered to be less water intensive. However, by considering both direct and  
17 indirect water needs in the sector, they become much more water intensive. For  
18 example, in 2010 the DWUP of Food and tobacco processing was only 31.1 million  
19 m<sup>3</sup>, but the IWUP of this sector was 172.5 million m<sup>3</sup>, nearly 5.5 times of its DWUP.

20 Our analysis showed that eight of the sectors under study decreased their IWUP  
21 between 1997 and 2010; the rate of reduction ranging from 27%-91%. Amongst these,

1 56% of the total decrease came from Agriculture (23%) and Food and tobacco  
2 processing (33%). This is explained by the large drop in DWUP for the Agriculture  
3 sector. Four sectors increased their IWUP and, amongst these, the two service sectors  
4 contributed 88% to the increase.

### 5 **3.3 Decomposition analysis of internal water use of products**

6 The structural decomposition analysis for 1997, 2000, 2002, 2007, and 2010  
7 showed the significant contribution of increasing economic water productivity in  
8 decreasing the total IWUP, despite the offset effects caused by the change in the three  
9 other determining factors (i.e. production structure adjustment, internal final demand,  
10 and exports) (Fig. 2). The improvement of economic water productivity would have  
11 caused Beijing's IWUP to decrease by 6987 million m<sup>3</sup> (196%) during the study  
12 period if other determining factors had remained constant. These great efficiency  
13 improvements has allowed Beijing to further develop its economy without increasing  
14 its water use in the production of goods and services. Consequently, Beijing has  
15 expanded its economic output for both internal final demand and export. For internal  
16 final demand, the change would have increased the total IWUP by 66 % above the  
17 1997 level, if other determining factors remained constant. The increased export of  
18 goods and services in the period led to an 85% increase in total IWUP.

19 It is generally believed that Beijing has significantly reduced its water use due to  
20 production structure adjustments through developing service sectors (Yang et al.,

1 2013b). From 1997 to 2010, the share of agriculture in total GDP decreased from 3.7%  
2 to 0.9%, while the share of industry decreased from 37.6% to 24% (Beijing Municipal  
3 Bureau of Statistics, 1989-2013). The changes have resulted in the service sectors  
4 dominating GDP with a share of 75.1% in 2007, compared with 58.7% in 1997  
5 (Beijing Municipal Bureau of Statistics, 1989-2013). However, the results of our  
6 analysis show that with other determining factors remaining constant, the production  
7 structure adjustment would have caused the IWUP to increase by 24% (842 million  
8 m<sup>3</sup>) between 1997 to 2010. Since the service sectors are water intensive in terms of  
9 IWUP, the production structure adjustment to more service-based activities leads to  
10 more IWUP.

## 11 **4 Discussion**

12 Traditionally, environmental impacts are allocated to their immediate producers  
13 (Lenzen et al., 2007). Using IWUP as an indicator, our results highlight the water use  
14 in final products derived from local water supply. This on the one hand helps address  
15 the extended producer responsibility, and on the other hand shows the pressure on  
16 local water resources caused by final products. The pressure can be further broken  
17 down to sectors, showing the pulling effects of final products with sector details.

18 The driving forces of the downward trend in IWUP were analyzed with a  
19 structural decomposition analysis. Our results showed that technical improvements  
20 have significantly reduced water use in Beijing, causing reductions in both the total

1 DWUP and IWUP. However we also found that production structure adjustment, in  
2 itself, has increased the IWUP. One production structure adjustment in Beijing is the  
3 shift from agricultural and industrial based activity to service based activity. The  
4 service sectors in Beijing have greatly expanded since 1995 (Yang et al., 2013b). The  
5 latest economic plans for Beijing have continued to call for the expansion of the  
6 service sector. For example, the ‘Outline of the Eleventh Five-Year Plan of Beijing’  
7 (2006-2010) urged to “speed up the development of modern services” (Beijing  
8 Municipal Government, 2005), while the ‘Outline of  
9 the Twelfth Five-Year Plan of Beijing’ (2011-2015) emphasizes the need to “make  
10 the service sector big” (Beijing Municipal Government, 2011). However, what is  
11 often neglected is that service sectors will drive manufacturing output indirectly  
12 through the input of intermediate products from other water intensive industries (Suh,  
13 2006), hence increasing indirect water use. In our case, the service sectors would have  
14 resulted in a 12% increase in IWUP from 1997 to 2010, assuming the IWUP of the  
15 other sectors remained constant. So the development of the service sector should be  
16 undertaken more carefully, considering the full effect on local upstream sectors,  
17 which may be water intensive.

18 Our results show that the IWUP of Beijing decreased between 1997 and 2010.  
19 However, several studies have reported an increase in Beijing’s water footprint based  
20 on SRIO analysis in recent years (Wang et al., 2013; Zhang et al., 2011). The main  
21 reason for the difference is that the IWUP has a different perspective compared with

1 the water footprint. First, the IWUP incorporates the water ‘embodied’ in internal  
2 final demand and export, thus reflecting the local water use reallocation to final  
3 products among different economic sectors. Zhang et al. (2012) and Wang et al. (2013)  
4 calculated the water footprint from a consumption perspective, which refers to the  
5 water ‘embodied’ in internal final demand and imports. Second, water footprint  
6 accounting utilising SRIO analysis has to assume that the imported products have the  
7 same production technology as the local products, while the IWUP is free from such  
8 an assumption. More importantly, although both the IWUP and water footprint  
9 address the supply chain effect, the IWUP is easier to incorporate into water  
10 management since it is directly related to local water use.

11 This study, nevertheless, contains several limitations. First, the study used an  
12 IOA to calculate the IWUP. The general limitations and assumptions rooted in the  
13 IOA also apply to the quantification of the IWUP, such as the assumptions of  
14 homogeneity (i.e. each sector produces a single product, and all output uses the same  
15 processes and technology), and linear production functions (Bicknell et al., 1998).  
16 Overcoming the limitations of these assumptions is beyond the scope of this study. In  
17 addition, the quantification with sectoral aggregation in this study may decrease the  
18 accuracy of the results (Baiocchi and Minx, 2010). Second, water use changes are not  
19 only determined by economic driving forces, but also the changes in water supply  
20 which can be linked to other factors, including climate change. For example,

1 agricultural water use may be decreased during a drought year because of lack of  
2 water.

### 3 **5 Conclusions**

4 The virtual water concept has received extensive attention through manifesting  
5 the role of human activities such as consumption and international trade on water  
6 resources. In this study, a new indicator attached to the virtual water concept was  
7 introduced to show how local economic systems reallocate the on-site water use to  
8 final products through virtual water flows. A SDA was used to evaluate the economic  
9 determinants (technological improvements, production structure adjustments, internal  
10 final demand, and exports) that underlie the changes in the IWUP with sector details.  
11 Such an attempt highlights the importance of incorporating economic drivers into  
12 local water management. The results can support decision making in balancing the  
13 trade-offs between local economic development and water resource depletion. It  
14 should be mentioned that such decision making is a multi-criteria problem, and has to  
15 be made by incorporating other relevant criteria with the participation of stakeholders  
16 (Zhao et al., 2006).

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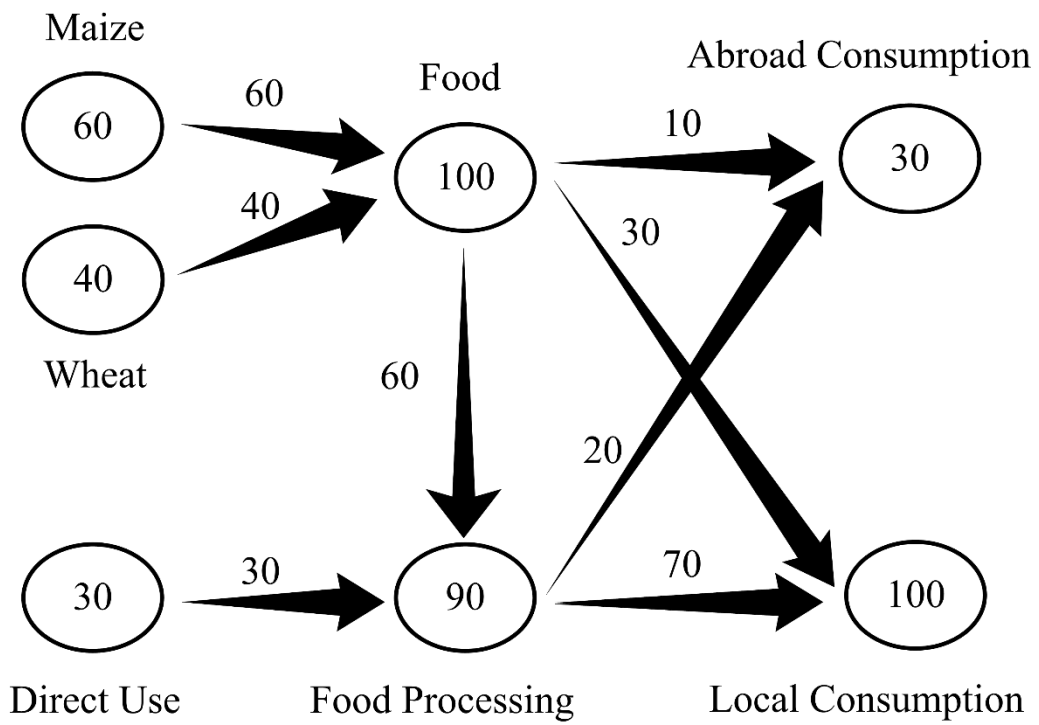
20

**Table 1 Direct water use of products (DWUP) VS. Internal water use of products (IWUP). Unit: million m<sup>3</sup>**

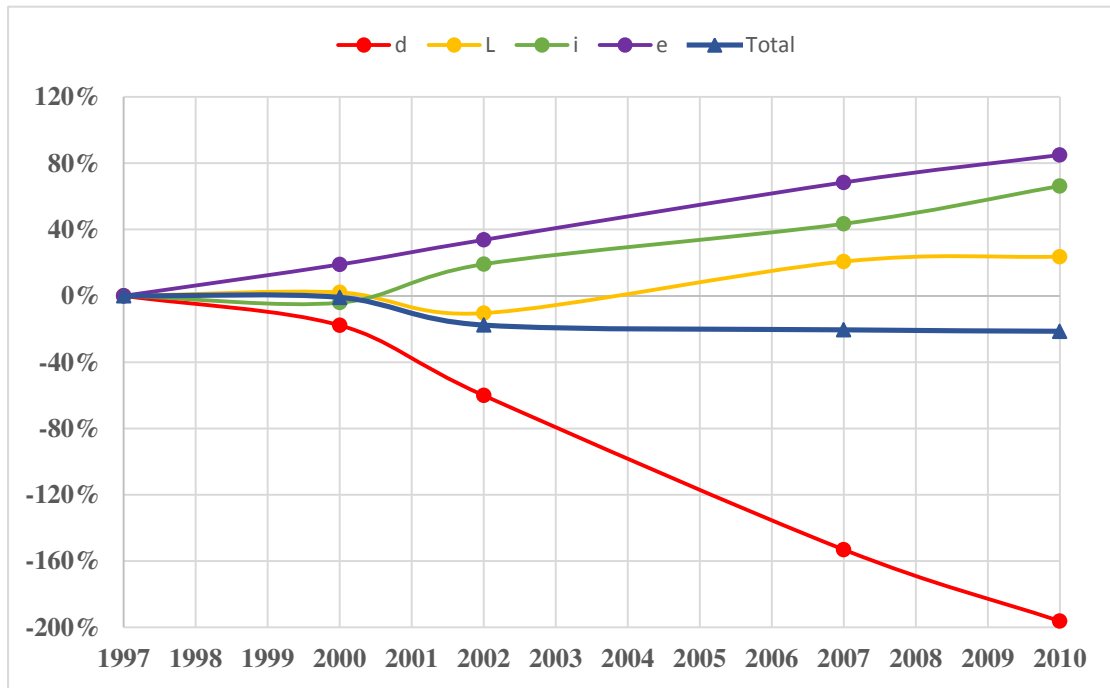
	1997		2000		2002		2007		2010	
	DWUP	IWUP	DWUP	IWUP	DWUP	IWUP	DWUP	IWUP	DWUP	IWUP
<b>Sec1:Agriculture</b>	1812	1071.4	1649	924.5	1545	1207.3	1244	523	1140	781.7
<b>Sec2:Mining</b>	6	3.2	5.7	1.7	4.1	1.8	3.1	3.1	6.5	29.5
<b>Sec3:Food and tobacco processing</b>	26.7	580.6	25.5	522.6	18.3	220.4	13.9	331.6	31.1	172.5
<b>Sec4:Textile, leather, and other fiber products</b>	10.9	118.5	10.5	65.7	7.5	40	5.7	18.3	5.9	12.5
<b>Sec5:Lumbering and paper products</b>	10.4	17.9	10	21.4	7.2	10.2	5.5	6.4	9.2	5.5
<b>Sec6:Petroleum processing and coking</b>	6.6	1.8	6.3	3.3	4.5	14.2	3.5	13.4	12.7	15.2
<b>Sec7:Chemicals</b>	29.9	43.4	28.6	31.6	20.5	104.9	15.7	66.5	38.1	55.5
<b>Sec8:Non-metal mineral products</b>	29.8	21.3	28.5	20.4	20.5	4.2	15.6	10	15.5	7.9
<b>Sec9:Metal products</b>	71.7	39.8	68.5	16.7	49.1	33.7	37.5	18.9	63.5	19.1
<b>Sec10:Machinery and equipment</b>	44.5	165.0	42.6	118.6	30.5	140.4	23.3	128.2	51.4	169.4
<b>Sec11:Electricity, gas, and water production and supply</b>	863.4	352.1	825.7	236.9	591.8	63.5	451.3	71	276.1	33.4
<b>Sec12:Construction</b>	14.1	228.1	18	267.4	13.8	203.4	22.1	167.9	25.1	155.6
<b>Sec13:Wholesale, retail trade and passenger transport</b>	466	282.9	594.3	385.2	455	346.4	726.7	515.2	826.7	441.8
<b>Sec14:Other services</b>	168.1	634.3	214.4	911.8	164.2	541.4	262.2	956.6	298.2	900.4
<b>Total volume</b>	3560.3	3560.3	3527.7	3527.7	2932	2932	2830	2830	2800	2800

**Table 2 Water reallocation from DWUP to IWUP among sectors** (Each column demonstrates how the DWUP of a sector is reallocated to all sectors in a virtual form. Each row shows how much virtual water is need from all sectors to fulfill the final demand of consumers of a sector)  
**Unit: million m<sup>3</sup>**

	<b>Sec1</b>	<b>Sec2</b>	<b>Sec3</b>	<b>Sec4</b>	<b>Sec5</b>	<b>Sec6</b>	<b>Sec7</b>	<b>Sec8</b>	<b>Sec9</b>	<b>Sec10</b>	<b>Sec11</b>	<b>Sec12</b>	<b>Sec13</b>	<b>Sec14</b>	<b>IWUP</b>
<b>Sec1</b>	773.64	0.08	0.11	0.00	0.03	0.08	0.25	0.02	0.26	0.08	3.08	0.01	3.36	0.71	<b>781.7</b>
<b>Sec2</b>	1.49	3.87	0.03	0.02	0.10	0.47	0.22	0.05	0.48	0.23	11.49	0.02	10.11	0.91	<b>29.5</b>
<b>Sec3</b>	124.91	0.09	24.38	0.02	0.22	0.09	0.59	0.19	0.91	0.19	5.25	0.02	14.42	1.19	<b>172.5</b>
<b>Sec4</b>	2.68	0.01	0.01	4.85	0.04	0.02	0.13	0.01	0.07	0.04	0.92	0.01	3.51	0.24	<b>12.5</b>
<b>Sec5</b>	0.63	0.01	0.00	0.02	1.86	0.01	0.16	0.01	0.20	0.02	0.98	0.00	1.46	0.11	<b>5.5</b>
<b>Sec6</b>	0.55	0.09	0.01	0.00	0.02	6.88	0.08	0.01	0.09	0.05	1.51	0.01	5.62	0.28	<b>15.2</b>
<b>Sec7</b>	16.76	0.12	0.07	0.02	0.10	0.24	17.18	0.07	0.49	0.17	9.70	0.02	9.68	0.91	<b>55.5</b>
<b>Sec8</b>	0.34	0.05	0.01	0.00	0.02	0.02	0.11	3.77	0.12	0.04	1.33	0.00	1.94	0.15	<b>7.9</b>
<b>Sec9</b>	0.34	0.15	0.01	0.00	0.02	0.03	0.08	0.02	14.60	0.06	1.32	0.00	2.28	0.23	<b>19.1</b>
<b>Sec10</b>	11.13	0.31	0.18	0.16	0.52	0.42	3.28	0.86	10.19	34.13	20.40	0.13	81.84	5.86	<b>169.4</b>
<b>Sec11</b>	0.46	0.09	0.01	0.01	0.02	0.02	0.07	0.02	0.17	0.08	29.89	0.01	2.00	0.53	<b>33.4</b>
<b>Sec12</b>	18.47	0.49	0.17	0.12	1.05	0.83	2.04	7.53	16.67	2.04	23.39	21.65	54.60	6.54	<b>155.6</b>
<b>Sec13</b>	30.71	0.22	0.51	0.11	0.74	1.35	1.76	0.34	2.89	2.30	24.01	0.38	361.50	14.97	<b>441.8</b>
<b>Sec14</b>	157.90	0.87	5.57	0.60	4.47	2.29	12.16	2.60	16.35	12.01	142.81	2.83	274.35	265.62	<b>900.4</b>
<b>DWUP</b>	<b>1140</b>	<b>6.5</b>	<b>31.1</b>	<b>5.9</b>	<b>9.2</b>	<b>12.7</b>	<b>38.1</b>	<b>15.5</b>	<b>63.5</b>	<b>51.4</b>	<b>276.1</b>	<b>25.1</b>	<b>826.7</b>	<b>298.2</b>	<b>2800</b>



**Fig. 1 A simple framework of virtual water flow in the supply chain of products**



**Fig 2. Structural decomposition analysis of Beijing's IWUP from 1997 to 2010.**

The blue line shows the percentage change in IWUP from 1997 to 2010. Other colored lines represent the contribution to change from direct water use intensity (red), production structure adjustment (orange), internal final demand (green), and export (purple).