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Assessing the Changes of China's Virtual Water Exports in 2002 and 2007

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ABSTRACT. An increase in virtual water export (VWE) could exacerbate the shortage of water resources in a water-stressed country. An analysis of VWE changes through time could be important for international trading strategies in water-stressed countries. China has been experiencing increased water shortages concurrent with astonishing economic growth. In this study, the VWE changes in China between 2002 and 2007 were quantitatively assessed. An input-output model was adopted to analyze the changes in VWEs including the contribution of each economic sector to such changes. The model indicated that the total VWE increased by 2.96×10^{10} m^3 in 2007 compared with export levels in 2002. Agriculture was the sector making the highest contribution (3.33×10^{10} m^3) to this increase. Instead of the previously published decomposition analysis method for VWE changes, a weighted average decomposition (WAD) method was introduced to further quantify the contributions of the three major driving factors to VWE. These driving factors included technological upgrade, structural adjustment, and variations in export volume. The results of WAD were also compared with a previous method in decomposition analysis of VWE changes, revealing that accuracy of results could be improved through the adoption of WAD. Moreover, the results showed that the change in export volume and structural change led to increases in the VWE of 1.41×10^{11} m^3 and 3.11×10^{10} m^3, respectively. Comparatively, technological change reduced the VWE by 1.43×10^{11} m^3.

Keywords: factor decomposition analysis, input-output analysis, virtual water export, water resource, weighted average decomposition

1. Introduction

Virtual water is defined as the reported water resources used in the production of goods and services (Allan, 1998). In essence this metric can be treated as an alternative proxy for actual water consumption. Therefore, virtual water trade can be used to address water related problems and facilitate the security of regional water resources (Wang et al., 2005; Liao et al., 2008; Mao and Yang, 2012; Reimer, 2012; Chen and Chen, 2013). For instance, a region with adequate water supplies for agricultural and manufacturing sectors could export relevant products to regions that lack sufficient water in producing similar products, indirectly relieving their demands for water (Yang et al., 2012; Wang et al., 2013). Such a trade pattern can be considered as a virtual water strategy, which is an alternative to high-cost water-transferring projects (Zhao et al., 2005; Verma et al., 2009; Zhao et al., 2010; Mao et al., 2011). On the other hand, if the virtual water exports (VWE), which means the outflow of virtual water along with the exports of goods and services, were too large in a water-stressed country/region, risks of water shortage would greatly be enhanced (Boelens and Vos, 2012; Zhao and Samson, 2012).

Since the introduction of the concept of virtual water, a number of studies have been performed on VWE around the world (Feng et al., 2012; Carr et al., 2013). For example, Hoekstra and Hung (2005) analyzed virtual water exports from 20 countries and claimed that 13% of the world's agricultural virtual water was tied to international trade. Dietzenbacher and Velázquez (2007) explored virtual water consumption in Andalusia and Spain and found that more than 50% of Andalusian virtual water was utilized for agricultural exports. Thus, in order to wisely allocate water to multiple sectors, exports of "high-water-cost" agricultural products needed to be reduced. Also, Chapagain and Hoekstra (2011) found that the virtual water related to international export was approximately 3.1×10^{28} m^3 per year, which was nearly 4% of the world water consumption per year. Zhao et al. (2009, 2010) developed an input-output method for calculating regional virtual water consumption and applied it to the Haihe River Basin, China, showing that VWE occupied a large proportion of the total virtual water consumption. A series of studies also showed that some regions in the Middle East and North Africa have not effectively controlled their VWE, which has intensified the severity of water shortages (Allan, 1998, 1999; Wheida and Verhoeven, 2007). However these Asian and African studies focused on VWE within a limited period, typically a year for a country or region, which restricts the interpretation of the results. To develop reasonable virtual water strategies and refine VWE, it is necessary to assess the changes of VWE over multiple years and identify the key economic sectors and driving factors. These changes and their contributions can be numerically modeled using decomposition analysis (Dietzen-

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bacher and Los, 1998; Kondo, 2005; Li, 2005).

However, there are remarkably few research studies examining multi-year changes in VWE and their driving factors. An assessment of temporal changes in VWE was performed by Kondo (2005), who analyzed export changes in Japan in 1980 and 2000. In Kondo's study, a structural decomposition analysis (SDA) model was used to analyze the driving factors' contribution to quantitative changes in VWE. Kondo's SDA model treated the SDA cross-term, which represents the combined contribution of driving factors, as "the error term". Therefore, this SDA is suitable for conditions under which the changes in factors are not significant. Mathematically, the cross-term is part of an integrated effect of driving factors, which is not effectively decomposed in the SDA (Dietzen-bacher and Los, 1998; Li, 2005). If the changes in factors are significant (for instance, a country's international trade increases greatly), the cross-term may become large and thus cannot be technically ignored.

China has had a rapid increase in international trade over the past 20 years, which can be directly linked to severe water shortages. For instance, the annual available volume of freshwater per capita in China (i.e., 2112 m^3) is much lower than the world average (i.e., 6,266 m^3) according to 2009 statistics (World Bank, 2010). China's water consumption is therefore of increasing concern, mainly due to its drastic growth in goods and service exports (Researching Group of Chinese Input-output Association, 2007; National Bureau of Statistics, 2011). To identify actual water consumption limitations and water resources management problems in China, VWE changes over multiple years should be analyzed. To date few researches in China have examined VWEs (Zhao et al., 2010; Zhang et al., 2012; Wang et al., 2013).

The objective of this study is to assess VWE changes in China during 2002 and 2007. An approach that can independently separate the various driving factors in VWE will be developed. To reduce the cross-term interference in Kondo's SDA model, a weighted average decomposition (WAD) method will be introduced into the analysis. WAD has already been effectively used to analyze changes of carbon emission (Li, 2005; Guan et al., 2008, 2014). Ultimately this case study in China can be a useful demonstration for VWE assessments in many other countries with rapidly developing international trade and severe water shortage problems.

2. Methods

2.1. VWE Calculation based on the Input-Output Model

The input-output model is a widely accepted approach to calculate VWE within a continuous time period, and can provide data for assessing VWE changes (Zhao et al., 2009, 2010). Virtual water comprises "direct" (i.e., water consumed during the manufacturing of the final product) and "indirect" (i.e., water used in previous manufacturing stages) consumption in each economic sector. An input-output table will show material-product flows between sectors. Therefore, the VWE vector of each sector can be calculated through combining the input-output coefficient matrix of the input-output table, the direct water coefficient and the export vectors (Kondo, 2005; Zhao et al., 2009). The equations to compute VWE vectors are presented as follows (Leontief, 1970; Kanada, 2001; Kondo, 2005):

$$\mathbf{T} = \mathbf{t}\,[\mathbf{I}\text{-}\mathbf{A}]^{-1}\mathbf{m} \tag{1}$$

$$\mathbf{t} = [w_j/x_j] \tag{2}$$

$\boldsymbol{T}$ (m^3) is the total VWE ($\mathbf{n} \times 1$ dimensional vector; $\mathbf{n}$ is the number of sectors); $\boldsymbol{m}$ (RMB) is the export volume vector ($\mathbf{n} \times 1$); and $\boldsymbol{t}$ is the diagonal matrix of the direct water coefficient vector ($\mathbf{n} \times \mathbf{n}$ dimensional matrix), which means the amount of water consumed directly by each sector to produce one monetary unit of product. $\mathbf{A}$ is the input-output coefficient matrix ($\mathbf{n} \times \mathbf{n}$) from the input-output table, which shows the material-product relationships between each sector and can be seen as a symbol of industrial structure. The elements of matrix $\mathbf{t}$, w_j/x_j, are the direct water coefficients of sector j; w_j (m^3) is the direct water consumption of sector j; and x_j (RMB) is the total output of sector j. $\boldsymbol{I}$ is a unit diagonal matrix ($\mathbf{n} \times \mathbf{n}$). Kondo (2005) has presented a detailed description of the input-output model for VWE,

2.2. Factor Decomposition Analysis of VWE

2.2.1. SDA Model

Kondo (2005) noted that changes in VWE may result from the corresponding alteration of three driving factors, i.e., direct water coefficients, industrial structure and export volume. Contributions of these three factors can be determined by the following equations (Chen and Guo, 2000; Hoekstra and van den Bergh, 2003):

$$\begin{aligned}\Delta\mathbf{T} &= \mathbf{T}_1 - \mathbf{T}_0 = \mathbf{t}_1[\mathbf{I}\text{-}\mathbf{A}_1]^{-1}\mathbf{m}_1 - \mathbf{t}_0[\mathbf{I}\text{-}\mathbf{A}_0]^{-1}\mathbf{m}_0 = \mathbf{t}_1\mathbf{B}_1\mathbf{m}_1 - \mathbf{t}_0\mathbf{B}_0\mathbf{m}_0 \\ &= (\mathbf{t}_0 + \Delta\mathbf{t})(\mathbf{B}_0 + \Delta\mathbf{B})(\mathbf{m}_0 + \Delta\mathbf{m}) - \mathbf{t}_0\mathbf{B}_0\mathbf{m}_0 = \Delta\mathbf{t}\mathbf{B}_0\mathbf{m}_0 + \mathbf{t}_0\Delta\mathbf{B}\mathbf{m}_0 \\ &+ \mathbf{t}_0\mathbf{B}_0\Delta\mathbf{m} + \mathbf{e}\end{aligned} \tag{3}$$

$$\mathbf{e} = \Delta\mathbf{t}\Delta\mathbf{B}\mathbf{m}_0 + \Delta\mathbf{t}\mathbf{B}_0\Delta\mathbf{m} + \mathbf{t}_0\Delta\boldsymbol{B}\Delta\mathbf{m} + \Delta\mathbf{t}\Delta\mathbf{B}\Delta\mathbf{m} \tag{4}$$

where $\mathbf{T}_1$ is the total VWE during the final period (2007 in this study) and T_0 is that during the initial period (2002 in this study). $\Delta\mathbf{T}$ is the difference between them; $\mathbf{t}_1$ and $\mathbf{t}_0$ are the diagonal matrices of the direct water coefficient vectors during the final and initial periods, respectively; $\Delta\mathbf{t}$ is the difference between $\mathbf{t}_1$ and $\mathbf{t}_0$; $\mathbf{A}_1$ and $\mathbf{A}_0$ are the input-output coefficient vectors during the final and initial periods, respectively; $\mathbf{m}_1$ and $\mathbf{m}_0$ are the export volume vectors during the final and initial periods, respectively; and $\Delta\mathbf{m}$ is the difference between $\mathbf{m}_1$ and $\mathbf{m}_0$. To make the calculation clearer, $\mathbf{B}_1$ is used to represent $[\mathbf{I}\text{-}\mathbf{A}_1]^{-1}$, and B_0 is used to represent $[\mathbf{I}\text{-}\mathbf{A}_0]^{-1}$. ΔB is the difference between $\mathbf{B}_1$ and $\mathbf{B}_0$.

In Kondo's model, $\Delta\mathbf{t}\mathbf{B}_0\mathbf{m}_0$ is the change in VWE resulting from a change in the direct water coefficient representing the contribution of technological innovation; $\mathbf{t}_0\Delta\mathbf{B}\mathbf{m}_0$ is the change in VWE resulting from a change in industrial structure; and $\mathbf{t}_0\mathbf{B}_0\Delta\mathbf{m}$ is the change in VWE resulting from alterations in export volume. e is the cross-term, which is treated as an error term and ignored (Kondo, 2005). If **t**, **B**, and **m** changes slightly from the initial to the final period, such as in the case of Japan, e is small and can be ignored. In contrast, if **t**, **B**, or **m** changes substantially, such as in the case of a country with rapidly increasing international trade or changes in water-saving technologies, e will be too large to be considered a minor error term.

2.2.2. Weighted Average Decomposition (WAD) within the SDA Model

Many methods have been used to decompose the overall change of variables into the independent contributions of driving factors. Two-polar (bipolar) decomposition analysis, a commonly used branch method of the Kondo's SDA model in the area of virtual water, attempts to decompose the contributions of factors by the average value of two decomposition forms based on the initial period and final period (see Zhang et al., 2012). This bipolar analysis has accuracy limitations (Dietzenbacher and Los, 1998; Li, 2005). If a variable is impacted by n factors, the factor decomposition of the variable has n! forms. Theoretically, for a driving factor, the contribution of its change to the overall impact can be measured more precisely using its average contribution in all the n! forms compared to using the average value of only two forms as in a bipolar decomposition analysis (Dietzenbacher and Los, 1998; Li, 2005; Minx et al., 2011). Li (2005) used WAD in a SDA model and proved that it had better accuracy in an economic decomposition analysis. The WAD method is introduced into this research and the calculation is as follows. The normal case decomposition form is:

$$y = \prod_{i=1}^{n} x_i \tag{5}$$

$$\Delta y = \prod_{i=1}^{n} x_{i1} - \prod_{i=1}^{n} x_{i0} = \sum_{i=1}^{n} E(\Delta x_i) \tag{6}$$

where y is the variable (VWE in this study) impacted by x_i (i = 1, 2, ,..., n) and x_i (i = 1, 2, ,..., n) is the i^{th} independent driving factor. Δy indicates the change in y caused by the changes in the factors from the initial period to the final period; x_{i1} is the i^{th} independent factor during the final period; x_{j0} is the j^{th} independent factor during the initial period. $E(\Delta x_i)$ is the contribution of the change in x_i to the change in y (Li, 2005).

Decomposing Eq. 6 from the initial period and the final period, respectively yields:

$$\Delta y = (\Delta x_1)\prod_{i=2}^{n} x_{i0} + x_{11}(\Delta x_2)\prod_{j=3}^{n} x_{j0} + \ldots + \prod_{k=1}^{n-2} x_{k1}(\Delta x_{n-1})x_{n0} + \prod_{l=1}^{n-1} x_{l1}(\Delta x_n) \tag{7}$$

$$\Delta y = (\Delta x_1)\prod_{i=2}^{n} x_{i1} + x_{10}(\Delta x_2)\prod_{j=3}^{n} x_{j1} + \ldots + \prod_{k=1}^{n-2} x_{k0}(\Delta x_{n-1})x_{n1} + \prod_{l=1}^{n-1} x_{l0}(\Delta x_n) \tag{8}$$

In the case of n factors, there will be n! decomposition forms analogous to Eq. 7 and Eq. 8 (Dietzenbacher and Los, 1998; Li, 2005; Guan et al., 2008). Combining all n! forms and merging similar items yields

$$\Delta y = \sum_{i=1}^{n} E(\Delta x_i) = \sum_{i=1}^{n}\sum_{s}[f(s)\prod_{\substack{j=1\\ j\neq i}}^{n} x_{ju}(\Delta x_i)] \tag{9}$$

$$f(s) = \frac{s!(n-s-1)}{n!} \tag{10}$$

where u equals 0 or 1 and s is the number of the cases in which u = 1 in each combination.

In terms of the decomposition analysis of changes in total VWE, x_i is **t**, **B** and **m**, while Δy is $\Delta\mathbf{T}$. According to Eq. 9 and Eq. 10, the decomposition analysis of changes in total volume of VWE is:

$$\Delta\mathbf{T} = \mathbf{T}_1 - \mathbf{T}_0 = \mathbf{t}_1\mathbf{B}_1\mathbf{m}_1 - \mathbf{t}_0\mathbf{B}_0\mathbf{m}_0 = E(\Delta\mathbf{t}) + E(\Delta\mathbf{B}) + E(\Delta\mathbf{m}) \tag{11}$$

$$E(\Delta\mathbf{t}) = \frac{0!(3-0-1)!}{3!}\Delta\mathbf{t}\mathbf{B}_0\mathbf{m}_0 + \frac{1!(3-1-1)!}{3!}\Delta\mathbf{t}\mathbf{B}_1\mathbf{m}_0 + \frac{1!(3-1-1)!}{3!}\Delta\mathbf{t}\mathbf{B}_0\mathbf{m}_1 + \frac{2!(3-2-1)!}{3!}\Delta\mathbf{t}\mathbf{B}_1\mathbf{m}_1 \tag{12}$$

$$E(\Delta\mathbf{B}) = \frac{0!(3-0-1)!}{3!}\mathbf{t}_0\Delta\mathbf{B}\mathbf{m}_0 + \frac{1!(3-1-1)!}{3!}\mathbf{t}_1\Delta\mathbf{B}\mathbf{m}_0 + \frac{1!(3-1-1)!}{3!}\mathbf{t}_0\Delta\mathbf{B}\mathbf{m}_1 + \frac{2!(3-2-1)!}{3!}\mathbf{t}_1\Delta\mathbf{B}\mathbf{m}_1 \tag{13}$$

$$E(\Delta\mathbf{m}) = \frac{0!(3-0-1)!}{3!}\mathbf{t}_0\mathbf{B}_0\Delta\mathbf{m} + \frac{1!(3-1-1)!}{3!}\mathbf{t}_1\mathbf{B}_0\Delta\mathbf{m} + \frac{1!(3-1-1)!}{3!}\mathbf{t}_0\mathbf{B}_1\Delta\mathbf{m} + \frac{2!(3-2-1)!}{3!}\mathbf{t}_1\mathbf{B}_1\Delta\mathbf{m} \tag{14}$$

which means:

$$E(\Delta\mathbf{t}) = \frac{1}{3}\Delta\mathbf{t}\mathbf{B}_0\mathbf{m}_0 + \frac{1}{6}\Delta\mathbf{t}\mathbf{B}_1\mathbf{m}_0 + \frac{1}{6}\Delta\mathbf{t}\mathbf{B}_0\mathbf{m}_1 + \frac{1}{3}\Delta\mathbf{t}\mathbf{B}_1\mathbf{m}_1 \tag{15}$$

$$E(\Delta\mathbf{B}) = \frac{1}{3}\mathbf{t}_0\Delta\mathbf{B}\mathbf{m}_0 + \frac{1}{6}\mathbf{t}_1\Delta\mathbf{B}\mathbf{m}_0 + \frac{1}{6}\mathbf{t}_0\Delta\mathbf{B}\mathbf{m}_1 + \frac{1}{3}\mathbf{t}_1\Delta\mathbf{B}\mathbf{m}_1 \tag{16}$$

$$E(\Delta\mathbf{m}) = \frac{1}{3}\mathbf{t}_0\mathbf{B}_0\Delta\mathbf{m} + \frac{1}{6}\mathbf{t}_1\mathbf{B}_0\Delta\mathbf{m} + \frac{1}{6}\mathbf{t}_0\mathbf{B}_1\Delta\mathbf{m} + \frac{1}{3}\mathbf{t}_1\mathbf{B}_1\Delta\mathbf{m} \tag{17}$$

where $E(\Delta\mathbf{t})$ is the contribution of the direct water coefficient change, which reflects the contribution of technological changes; $E(\Delta\mathbf{B})$ is the contribution of the structural change, which reflects the contribution of industrial structure changes in sectors; and $E(\Delta\mathbf{m})$ is the contribution of the export volume change, which reflects the contribution of the change in the volume of product and service export (Kondo, 2005).

3. Data Resource

3.1. Test Data

To test whether the WAD method was more accurate than Kondo's method in terms of the contribution analysis of each factor, a series of test data were generated. Suppose there were three sectors I, II, and III and that $\mathbf{t}_0$, $\mathbf{B}_0$ and $\mathbf{m}_0$ would represent the 2002 data and $\mathbf{t}_1$, $\mathbf{B}_1$ and $\mathbf{m}_1$ represented the corresponding 2007 data. WAD and Kondo's SDA analyses were used to evaluate these test data, and their results compared:

$$\mathbf{t}_0 = \begin{pmatrix} 1.5 & & \\ & 1.1 & \\ & & 1.2 \end{pmatrix} \text{ (unit: m}^3\text{/RMB)} \tag{18}$$

$$\mathbf{t}_1 = \begin{pmatrix} 5.0 & & \\ & 6.7 & \\ & & 3.8 \end{pmatrix} \text{ (unit: m}^3\text{/RMB)} \tag{19}$$

$$\mathbf{B}_0 = \begin{pmatrix} 0.19 & 0.14 & 0.15 \\ 0.12 & 0.16 & 0.17 \\ 0.13 & 0.10 & 0.18 \end{pmatrix} \tag{20}$$

$$\mathbf{B}_1 = \begin{pmatrix} 0.98 & 0.95 & 0.96 \\ 0.93 & 0.94 & 0.98 \\ 0.92 & 0.90 & 0.97 \end{pmatrix} \tag{21}$$

$$\mathbf{m}_0 = \begin{pmatrix} 20 \\ 21 \\ 22 \end{pmatrix} \text{ (unit: RMB)} \tag{22}$$

$$\mathbf{m}_1 = \begin{pmatrix} 44 \\ 40 \\ 41 \end{pmatrix} \text{ (unit: RMB)} \tag{23}$$

3.2. Chinese VWE Data

In this study, the VWEs of China's 17 main economic sectors were studied. The input-output coefficient matrix, total output vector and export volume vector for these 17 sectors listed in the 2002 and 2007 national input-output tables were used which represented the latest available official input-output tables (National Bureau of Statistics, 2003; National Bureau of Statistics, 2008b). The direct water consumption data was derived from the China Water Resources Bulletin of 2002 and 2007 (Ministry of Water Resources, 2003; Ministry of Water Resources, 2008). The direct water consumption in this study only concerned surface water and groundwater. Precipitation and soil moisture was not considered because many sectors and services mainly use surface water and groundwater; an exception was agriculture and the sectors that depend on agricultural raw materials (Zhao et al., 2010; Zhang et al., 2012). Including precipitation and soil moisture would have increased the share of agricultural water consumption greatly and cause biased conclusions in estimating the value of water use across different sectors (Zhao et al., 2010).

Table 1. Analysis of Test Data Using the WAD Method

Sector	$E(\Delta\mathbf{t})$		$E(\Delta\mathbf{B})$		$E(\Delta\mathbf{m})$		$\Delta\mathbf{T}$ (m^3)
	Volume (m^3)	CRS (%)	Volume (m^3)	CRS (%)	Volume (m^3)	CRS (%)	
I	199.40	33.95	259.88	44.25	128.06	21.80	587.34
II	312.62	39.83	316.55	40.33	155.67	19.83	784.84
III	141.08	32.71	197.07	45.69	93.22	21.61	431.36
Total	653.01	36.21	773.50	42.89	376.95	20.90	1803.54

*Volumes were computed by Equations 15 to 17. The columns of CRS (contribution rate to sector) show the proportion of $E(\Delta\mathbf{t})$, $E(\Delta\mathrm{B})$ and $E(\Delta\mathbf{m})$ in $\Delta\mathbf{T}$ in each sector respectivly. CRS = Volume/($\Delta\mathbf{T}$)×100%. For example, in sector I, the volume of $E(\Delta\mathbf{t})$ was 199.40 m^3, and the proportion of this $E(\Delta\mathbf{t})$ in its $\Delta\mathbf{T}$ (587.34 m^3) was 33.95%.

Table 2. Analysis of Test Data Using the Kondo's SDA Model

Sector	$E(\Delta\mathbf{t})$		$E(\Delta\mathbf{B})$		$E(\Delta\mathbf{m})$		E		$\Delta\mathbf{T}$ (m^3)
	Volume (m^3)	CRS (%)	Volume (m^3)	CRS (%)	Volume (m^3)	CRS (%)	Volume (m^3)	CRS (%)	
I	35.14	5.98	75.95	12.93	15.11	2.57	461.15	78.51	587.34
II	53.20	6.78	55.44	7.06	10.07	1.28	666.14	84.88	784.84
III	22.52	5.22	59.98	13.9	10.13	2.35	338.74	78.53	431.36
Total	110.86	6.15	191.36	10.61	35.30	1.96	1466.02	81.29	1803.54

*Volumes were computed by Eqations 3 and 4. The columns of CRS (contribution rate to sector) show the proportion of $E(\Delta\mathbf{t})$, $E(\Delta\mathbf{B})$, $E(\Delta\mathbf{m})$ and e in $\Delta\mathbf{T}$ in each sector respectivly. CRS = Volume/($\Delta\mathbf{T}$)×100%. For example, in sector I, the volume of $E(\Delta\mathbf{t})$ was 35.14 m^3, and the proportion of this $E(\Delta\mathbf{t})$ in its $\Delta\mathbf{T}$ (587.34 m^3) was 5.98%.

4. Results and Discussion

4.1. Method Comparison

The test data were computed by both the WAD and Kondo's SDA protocols (Tables 1 and 2). Table 1 shows the contributions of $E(\Delta\mathbf{t})$, $E(\Delta\mathbf{B})$, and $E(\Delta\mathbf{m})$ in each sector. For each row of Table 1, the sum of the volume of $E(\Delta\mathbf{t})$, $E(\Delta\mathbf{B})$, and $E(\Delta\mathbf{m})$ was equal to ΔT. For instance, for sector I, the increases in $E(\Delta\mathbf{t})$, $E(\Delta\mathbf{B})$, and $E(\Delta\mathbf{m})$ were 199.40, 259.88, and 128.06 m^3, corresponding to 33.95, 44.25, and 21.80% of the total change (587.34 m^3), respectively. However, for each row of Table 2, because the factor decomposition of the Kondo's method was imprecise, the error term was relatively large, corresponding to over 78% of the change, and the sum of $E(\Delta\mathbf{t})$, $E(\Delta\mathbf{B})$, and $E(\Delta\mathbf{m})$ was less than 23% of $\Delta\mathbf{T}$, which was not consistent with the actual VWE changes nor explain the change from $\mathbf{T}_0$ to $\mathbf{T}_1$. For example, in sector I, the increases in $E(\Delta\mathbf{t})$, $E(\Delta\mathbf{B})$, and $E(\Delta\mathbf{m})$ were only 5.98, 12.93, and 2.57% of total change, respectively, whereas e represented 78.51%.

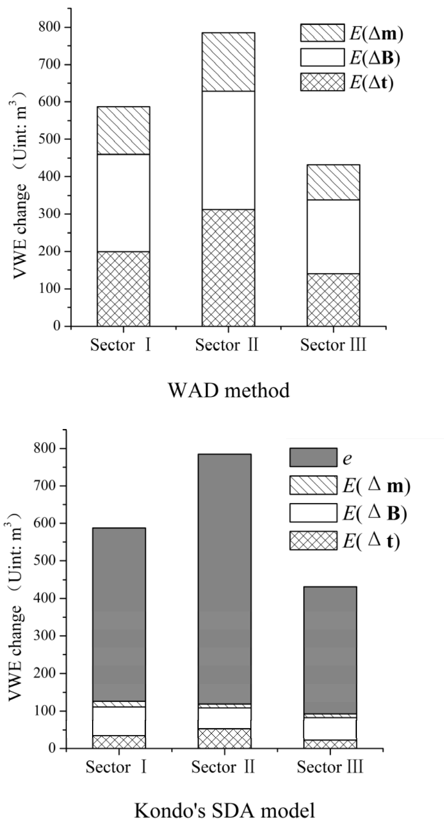

Figure 1. Comparison of the WAD method and Kondo's SDA model.

Comparing Tables 1 and 2, the results of the WAD method reflected the overall changes (Δ**T**) without any error term, whereas Kondo's SDA model included the error term *e*, which was much larger than other terms because **t**, **B**, and **m** in the test data all increased dramatically (Figure 1). This finding demonstrates that the SDA model is not accurate when factors change significantly, which makes the cross-term too large to be ignored.

To further compare the performance of the Kondo's SDA model and the WAD method, the total VWE changes in 17 sectors from 2002 to 2007 were computed (Tables 3 and 4). In Table 4, the *E*(Δ**t**), *E*(Δ**B**), and *E*(Δ**m**) calculated by the Kondo's SDA model all had large deviations from the WAD data in Table 3 due to the existence of *e*, the error term. In Table 4, the results for each sector generally had a large error. In most sectors, *e* exceeded 100% and even reached > 33000% in the sector of non-metallic mineral products. The total volume of *e* was as large as 1.24×10^{10} m^3, which was 418% of the total volume of VWE, so in the case of China it should not be ignored. As mentioned above, if **t**, **B**, and **m** had changed little, *e* was small enough to be ignored, whereas if **t**, **B**, or **m** exhibited obvious changes, the cross-term, *e*, would likely be too large a contribution to be considered an error term and neglected. The results demonstrate that the WAD method is a better application and more suitability compared to Kondo's SDA model when studying VWE variations when the factors change substantially. This discrepancy would be even more evident in data from countries with a large increase in international trade or fast-growing technologies.

4.2. VWE Changes in China

Based on analysis using the input-output method, the total VWE was 1.01×10^{11} m^3 and 1.31×10^{11} m^3 during 2002 and 2007, respectively. Correspondingly, the total VWE increased by 2.96×10^{10} m^3 from 2002 to 2007. This increase of VWE was equal to 92% of the Chinese direct water consumption increase during the same period (3.22×10^{10} m^3) and 5.1% of the total direct water consumption of China in 2007 (5.82×10^{11} m^3) (National Bureau of Statistics, 2008a).

Table 3 shows that the VWEs in 11 sectors increased from 2002 to 2007. The top three sectors in terms of contribution to this increase were agriculture; wholesale, retail trade, accommodation, and catering; and wood and paper. These three sectors occupied 121.59% of the increase in total VWE. Agriculture (3.33×10^{10} m^3) contributed the most to the total VWE increase (112.50%), with *E*(Δ**t**) being -124.94% (negative value indicated direction of change was opposite to total change), *E*(Δ**B**) 38.48%, and *E*(Δ**m**) 186.46%.. Therefore, the export of agriculture should be reduced or changed to save water resources. The contribution of the wholesale, retail trade, accommodation, and catering sector (1.44×10^9 m^3) and the wood and paper sector (1.25×10^9 m^3) to the VWE were 4.86 and 4.23% of the total change, respectively. The contributions of these two sectors were substantially lower than that of agriculture. The lower contributions of other economic sectors further demonstrate the significance of reducing the VWE in agricultural products.

Although the total VWE increased from 2002 to 2007, six sectors still made negative contributions to the increase of VWEs: electricity, heat, and water; coke, gas, and oil processing; chemical industry; metal products; machinery and equipment manufacturing; and building industry. The top three sectors by (negative) contribution were the chemical industry (-4.11×10^9 m^3), metal products (-2.97×10^9 m^3,) and electricity, heat, and water (-1.99×10^9 m^3), whose contributions were -13.87, -10.03, and -6.71%, respectively. Compared with the positive contribution of agriculture, the negative contributions of these sectors were small. However, they were still greater than the positive contribution of some sectors to the overall VWE. Therefore, the government should encourage these sectors to continue to save water resources in their production processes.

4.3. Factor Decomposition Analysis of the VWE Changes in China

E(Δ**t**), *E*(Δ**B**), and *E*(Δ**m**) all play important roles in the total change of VWE. *E*(Δ**t**), which reflects the contribution of technology, decreased because of new developments in water saving (-1.43×10^{11} m^3). However, the growth in the volume of VWE caused by the structural changes in sectors (*E*(Δ***B***), 3.11×10^{10} m^3) and the increase in the total export

Table 3. Analysis of Virtual Water Export from 2002 to 2007 with the WAD Method

Sector	E(Δ**t**)			E(Δ**B**)			E(Δ**m**)			Δ**T**	
	Volume (10^6 m^3)	CRS (%)	CRF (%)	Volume (10^6 m^3)	CRS (%)	CRF (%)	Volume (10^6 m^3)	CRS (%)	CRF (%)	Volume (10^6 m^3)	CRF (%)
Agriculture	-41654.30	-124.94	29.16	12828.83	38.48	41.25	62163.71	186.46	43.96	33338.24	112.50
Mining industry	-2144.01	-788.08	1.50	697.33	256.32	2.24	1718.73	631.76	1.22	272.05	0.92
Food and tobacco	-492.78	-325.48	0.34	214.23	141.50	0.69	429.95	283.98	0.30	151.40	0.51
Textile, clothing, and leather	-384.46	-36.66	0.27	191.64	18.28	0.62	1241.38	118.39	0.88	1048.57	3.54
Wood and paper	-958.30	-76.51	0.67	310.47	24.79	1.00	1900.37	151.72	1.34	1252.53	4.23
Electricity, heat and water	-47313.08	2380.04	33.12	15389.27	-774.14	49.48	29935.90	-1505.90	21.17	-1987.91	-6.71
Coke, gas and oil processing	-4724.00	1458.57	3.31	1206.59	-372.54	3.88	3193.53	-986.03	2.26	-323.88	-1.09
Chemical industry	-16247.26	395.19	11.37	1511.53	-36.77	4.86	10624.42	-258.42	7.51	-4111.30	-13.87
Non-metallic mineral products	-354.25	-32924.34	0.25	45.37	4216.28	0.15	309.96	28808.06	0.22	1.08	0.00
Metal products	-16363.74	550.67	11.45	2160.76	-72.71	6.95	11231.39	-377.96	7.94	-2971.58	-10.03
Machinery and manufacturing	-1543.76	3800.49	1.08	128.58	-316.54	0.41	1374.56	-3383.95	0.97	-40.62	-0.14
Building industry	-6.80	389.66	0.00	-5.65	323.60	-0.02	10.70	-613.26	0.01	-1.74	-0.01
Transportation, etc**.	-2622.94	-664.65	1.84	111.82	28.34	0.36	2905.76	736.31	2.06	394.64	1.33
Wholesale, etc***	-6432.44	-446.58	4.50	-2985.13	-207.25	-9.60	10857.96	753.82	7.68	1440.39	4.86
Real estate and renting	-940.25	-95.90	0.66	-807.60	-82.37	-2.60	2728.35	278.26	1.93	980.50	3.31
Financial sector	-506.38	-413.27	0.35	31.80	25.96	0.10	597.10	487.32	0.42	122.53	0.41
Other Services	-171.99	-248.09	0.12	71.30	102.84	0.23	170.01	245.25	0.12	69.32	0.23
Total	-142860.73	-482.08	100	31101.15	104.95	100	141393.77	477.13	100	29634.20	100

*The Volumes were computed by Equations 16 to 17. CRS = Volume/(Δ**T**) × 100%. CRF = (Volume/Total Volume) × 100%. For example, in the sector of agriculture, the volume of E(Δ**t**) was -4.17 × 10^{10} m^3; the proportion of this E(Δ**t**) in the Δ**T** in agriculture (3.33 × 10^{10} m^3) was -124.94%; the proportion of this E(Δt) in the total E(Δt) (-1.43 × 10^{11} m^3) was 29.16%.
**Postal services, information transmission, computer services and software.
***Retail trade, accommodation and catering.

volume (E(Δ***m***), 1.41 × 10^{11} m^3) were larger; thus, the overall VWE continued to grow. The total contribution of E(Δ**t**), E(Δ**B**), and E(Δ**m**) were -482.08, 104.95, and 477.13%, respectively. Technological improvements should be encouraged to save more water resources. Because the exports of these sectors play important roles in the Chinese export economy and the export volume cannot currently be decreased, China could charge VWE levies on those sectors with large consumption levels or make water-saving technical support agreements with the countries that benefit from Chinese VWE. Although E(Δ**B**) was lower than E(Δ**t**) and E(Δ**m**), its absolute value was still high, and the industrial structure should be adjusted to make these sectors more efficient in water-savings.

E(Δ**t**), E(Δ**B**), and E(Δ**m**) made different contributions to the changes in VWE across different sectors. The E(Δ**t**) of each sector decreased, which corresponded to a positive contribution to water saving. In terms of volume changes, the E(Δ**t**) in agriculture (-4.17 × 10^{10} m^3); electricity, heat, and water (-4.73 × 10^{10} m^3); and metal products (-1.64 × 10^{10} m^3) decreased dramatically, corresponding to 29.16%, 33.12%, and 11.45% of the total change of E(Δ**t**). The other sectors, such as building industry (-6.80 × 10^6 m^3), decreased less. E(Δ**t**) made different contributions to the VWE changes in different sectors. E(Δ**t**) in the sector of non-metallic mineral products (32924%); the sector of electricity, machinery, and equipment manufacturing (3800%); and the sector of heat and water (2380%) contributed more to water saving than E(Δ**t**) in other sectors. The decrease in E(Δ**t**) was due to improvements in water-saving technology and the reduction in intentional water consumption in response to government regulation. According to the national Tenth Five-Year Plan (2001-2005) and Eleventh Five-Year Plan (2005-2010), both enterprises and governments emphasized the importance of water-saving technology (National Bureau of Statistics, 2011), which should be retained to serve more water resources in the future.

E(Δ**B**) increased in 14 sectors. The top three were agriculture (1.28 × 10^{10} m^3); electricity, heat, and water (1.54 × 10^{10} m^3); and metal products (2.16 × 10^9 m^3). These three sectors, represent 41.25, 49.98, and 6.95% of the total change in E(Δ**B**). In contrast, E(Δ**B**) declined in the following sectors: real estate and renting (-8.08 × 10^8 m^3 [-9.60%]); building Industry (-5.65 × 10^6 m^3 [-2.60%]); and wholesale, retail trade, accommodation, and catering (-2.99 × 10^6 m^3 [-0.02%]). Further, increase in E(Δ**B**) were more concerning in other sectors, such as in non-metallic mineral products (4216%); electricity, heat, and water (774%); and coke, gas, and oil processing (372%). Only E(Δ**B**) changes in the building industry (323%); wholesale, retail trade, accommodation, and catering (207%); and real estate and renting (82.37%) contributed to the prevention of a VWE increase. The data showed that the rapid growth of the total structural change (E(Δ**B**)) over the 5 years studied was primarily caused by changes in the industrial structures of agriculture and manufacturing (Table 3). The analysis shows that these two sectors over the 2002 to 2007 period used more intermediate products containing more virtual water. It seems that the national Tenth

Table 4. Analysis of Virtual Water Export from 2002 to 2007 with the Kondo's SDA Model

Sector	$E(\Delta\mathbf{t})$			$E(\Delta\mathbf{B})$			$E(\Delta\mathbf{m})$			e			$\Delta\mathbf{T}$	
	Volume (10^6 m^3)	CRS (%)	CRF (%)	Volume (10^6 m^3)	CRS (%)	CRF (%)	Volume (10^6 m^3)	CRS (%)	CRF (%)	Volume (10^6 m^3)	CRS (%)	CRF (%)	Volume (10^6 m^3)	CRF (%)
AG	-21564.20	-64.68	36.50	9085.29	27.25	33.72	72194.00	216.55	38.85	-26376.85	-79.12	21.26	33338.24	112.50
MI	-749.20	-275.38	1.27	557.49	204.92	2.07	2198.09	807.96	1.18	-1734.33	-637.49	1.40	272.05	0.92
FT	-222.34	-146.86	0.38	177.80	117.44	0.66	490.01	323.65	0.26	-294.06	-194.23	0.24	151.40	0.51
TCL	-198.15	-18.90	0.34	117.90	11.24	0.44	1309.35	124.87	0.70	-180.54	-17.22	0.15	1048.57	3.54
WP	-426.72	-34.07	0.72	179.95	14.37	0.67	2168.50	173.13	1.17	-669.19	-53.43	0.54	1252.53	4.23
EHW	-14866.53	747.85	25.16	14287.55	-718.72	53.02	39638.30	-1993.96	21.33	-41047.23	2064.84	33.08	-1987.91	-6.71
CGO	-1677.24	517.86	2.84	1097.54	-338.88	4.07	4505.91	-1391.23	2.42	-4250.09	1312.25	3.43	-323.88	-1.09
CI	-6971.71	169.57	11.80	1526.31	-37.12	5.66	17681.24	-430.06	9.51	-16347.14	397.61	13.17	-4111.30	-13.87
NMP	-140.28	-13037.5	0.24	37.07	3445.20	0.14	464.31	43153.8	0.25	-360.03	-33461.53	0.29	1.08	0.00
MP	-5345.30	179.88	9.05	1995.22	-67.14	7.40	18621.97	-626.67	10.02	-18243.47	613.93	14.70	-2971.58	-10.03
MEM	-610.83	1503.78	1.03	99.79	-245.66	0.37	2130.07	-5243.90	1.15	-1659.64	4085.78	1.34	-40.62	-0.14
BI	-4.56	261.49	0.01	-4.24	243.32	-0.02	17.92	-1027.18	0.01	-10.86	622.37	0.01	-1.74	-0.01
TPIC	-1223.15	-309.94	2.07	113.00	28.63	0.42	4209.30	1066.62	2.26	-2704.50	-685.31	2.18	394.64	1.33
WRAC	-4193.04	-291.11	7.10	-1924.75	-133.63	-7.14	15497.91	1075.95	8.34	-7939.72	-551.22	6.40	1440.39	4.86
RER	-544.67	-55.55	0.92	-462.42	-47.16	-1.72	3720.36	379.44	2.00	-1732.77	-176.72	1.40	980.50	3.31
FS	-238.99	-195.05	0.40	16.98	13.85	0.06	826.04	674.16	0.44	-481.50	-392.97	0.39	122.53	0.41
OS	-105.49	-152.17	0.18	46.46	67.02	0.17	174.64	251.92	0.09	-46.29	-66.77	0.04	69.32	0.23
Total	-59082.4	-199.37	100	26946.9	90.93	100	185847.9	627.14	100	-124078.2	-418.70	100	29634.2	100

*The Volumes were computed by Equations 3 and 4. CRS = Volume/($\Delta\mathbf{T}$) × 100%. CRF = (Volume/Total Volume) × 100%. For example, in the sector of agriculture, the volume of $E(\Delta\mathbf{t})$ is -2.16 × 10^{10} m^3; the proportion of this $E(\Delta\mathbf{t})$ in the $\Delta\mathbf{T}$ in agriculture (3.33 × 10^{10} m^3) was -64.68%; the proportion of this $E(\Delta\mathbf{t})$ in the total $E(\Delta\mathbf{t})$ (-5.91 × 10^{10} m^3) was 36.50%. AG: Agriculture; MI: Mining industry; FT: Food and tobacco; TCL: Textile, clothing and leather products; WP: Wood and paper; EHW: Electricity, heat and water; CGO: Coke, gas and oil processing; CI: Chemical industry; NMP: Non-metallic mineral products; MP: Metal products; MEM: Machinery and equipment manufacturing; BI: Building industry; TPIC: Transportation, postal services, information transmission, computer services and software; WRAC: Wholesale, retail trade, accommodation and catering; RER: Real estate and renting; FS: Financial sector; OS: Other Services.

Five-Year Plan (and Eleventh Five-Year Plan, data not shown) did not address the relationship of industrial structure and VWE as energy consumption and carbon emission (National Bureau of Statistics, 2011). Therefore, the sectors' industrial structure should be adjusted to become more water-saving.

The change in export volume ($E(\Delta\mathbf{m})$) increased in all 17 sectors, especially in agriculture (6.21 × 10^{10} m^3 [43.96%]); electricity, heat, and water (3.00 × 10^{10} m^3 [21.17%]); and metal products (1.12 × 10^{10} m^3 [7.94%]). China entered into the World Trade Organization at the end of 2001, triggering an explosion in exports (National Bureau of Statistics, 2008a). The contributions of $E(\Delta\mathbf{m})$ to the total VWE varied by sector. The increases due to $E(\Delta\mathbf{m})$ comprised over 100% of the total VWE changes and offset the decreases due to $E(\Delta\mathbf{t})$ in 11 of 17 sectors, especially in the sectors of non-metallic mineral products (28808%); electricity, heat, and water (1505%); and machinery and equipment manufacturing (3383%), which are known for high content of virtual water in the final products (Zhao et al., 2009, 2010). Consequently, the government could impose VWE levies on these sectors to manage $E(\Delta\mathbf{m})$.

Our analysis found several limitations in the metrics. Although the computation of the input-output model for VWE is direct, it is still limited by specific data requirements which depend on accurate data in the input-output tables. The input and output of each economic activity, circulation progress, process of economic activities, and production progress process have to be accounted for (Leontief, 1970; Zhao et al., 2010). In this study, we used the latest available input-output tables from 2002 and 2007, and combined the sectors into 17 economic units; some aggregation errors were inevitable. There are also limitations affecting the analysis of virtual water import. The virtual water content of imported products was not examined because it should be calculated in concordance with the countries or regions where they were made. Therefore, a complete understanding of virtual water imports and exports at the global scale should be a future developmental direction in virtual water research.

5. Conclusions

Virtual water exports (VWEs) in the future could exacerbate the shortage of water resources in China. To understand past Chinese VWE changes [2002 and 2007] and facilitate reasonable virtual water strategies including water resources management, it was necessary to analyze the changing VWE contributions of each economic sector. Furthermore, it was important to assess the contributions of three major driving factors to the VWE changes, including: the direct water coefficient change to reflect technological upgrade; the structural adjustment to reflect the industrial structure changes in sectors; and the export volume change to reflect the change in the volume of product and service export. The weighted average decomposition (WAD) method, a development of structural decomposition analysis (SDA) model, was introduced to determine the contributions of the three factors quantitatively.

The following conclusions were reached:

(1) Compared with the previous SDA model (Kondo, 2005) for the decomposition analysis of VWE changes, the introduced WAD method is stricter and more accurate, especially when the factors influencing the VWE changes increase significantly. The WAD method is recommended for future research on analyzing the changes in virtual water trades in other countries or regions, especially those with large increases in international trade or fast-growing technologies.

(2) The agricultural sector in 2002 and 2007 made a dominant contribution (3.33×10^{10} m^3) to the increase of the total VWE (2.96×10^{10} m^3). Therefore, the export of agricultural products should be controlled to reduce the water shortage in China.

(3) The total VWE increased by 2.96×10^{10} m^3 between 2002 and 2007. This increase was mainly due to changes in export volume and the structural change, which lead to an increase of VWE by 1.41×10^{11} and 3.11×10^{10} m^3, respectively. The direct water coefficient change had a positive contribution to reducing the VWE, suggesting the potential to reduce water export by 1.43×10^{11} m^3. Thus, the contribution of technological changes is quite effective at offsetting the increase of VWE caused by the export volume increase. From the perspective of globalization and the development of international trade, the export volume of goods and services will continue to increase. Therefore, technological improvements should be enhanced to offset the increase in VWE caused by the export volume increase.

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