Evolution of China's Water Footprint and Virtual Water Trade: A Global Trade Assessment

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Abstract: Water embodied in traded commodities is important for water sustainability management. This study provides insight into China's water footprint and virtual water trade using three specific water named Green, Blue and Grey. A multi-region input-output analysis at national and sectoral analysis levels from the years 1995 to 2009 is conducted. The evolution and position of China's virtual water trade across a global supply chain are explored through cluster analysis. The results show that China represented 11.2% of the global water footprint in 1995 and 13.6% in 2009. The green virtual water is the largest of China's exports and imports. In general, China is a net exporter of virtual water during this time period. China mainly imports virtual water from the USA, India and Brazil, and mainly exports virtual water to the USA, Japan and Germany. The agriculture sector and the food sector represent the sectors with both the largest import and export virtual water quantities. China's global virtual water trade network has been relatively stable from 1995 to 2009. China has especially close relationships with the USA, Indonesia, India, Canada, Mexico, Brazil and Australia. Trade relations, resource endowment and supply-demand relationships may play key roles in China's global virtual water footprint network rather than geographical location. Finally, policy implications are proposed for China's long term sustainable water management and for global supply chain management in general.

Keywords: water footprint; global supply chain; cluster analysis; virtual water trade; China

Introduction

Water is a fundamental natural resource for human and environmental development (Dalin et al., 2012). Water availability varies greatly across countries and global regions with uneven distribution. Water use also has different environmental impacts depending on the geographic location. Additionally water related issues constrain the sustainable development of countries or regions, with various socio-political issues arising, such as the water war between Central Asian countries (Ercin and Hoekstra, 2014). In order to alleviate water crises, international trade can play a significant role in water resources redistribution. This global redistribution can occur through traded commodities, which may contain large volumes of embodied upstream water use across the supply chain (Hoekstra, 2010; Zhang et al., 2016). Underlying international trade is the globalization of industrial supply chains, which should not go unrecognized in this discussion of international trade flows.

Water embodied in traded commodities is called "virtual water" (VW), which is defined as the volume of water required for the production of one commodity (Allan, 1997). The water footprint (WF) has been introduced to further identify anthropogenic (human) pressure on the natural environment. The WF is based on virtual water measures, it can also be used to quantify water resource gross requirements for products and services consumed by an individual, business, town, city or country (Chapagain and Hoekstra, 2002; Chapagain and Orr, 2008; Hoekstra et al., 2011). WF across global supply chains at the international level can be used to investigate water flows and the equity of water resources distribution across nations. The linkages between consumption behaviors, trade activities, and anthropogenic water use can also be evaluated (Chen and Chen, 2013; Chenoweth et al., 2014; Hoekstra and Mekonnen, 2012).

WF flows for China is especially pertinent due to water and other resource shortages from its rapid economic development and growing population (Dong et al., 2014). China has been one of the top water consumption countries in the world for the past two decades (Chen and Chen, 2013). Limited water resources have severely restricted development of its national economy (Chen et al., 2017a). China, as the 'world's manufacturer', supports its export production by consuming its natural resources and releasing vast amounts of pollutants (Geng et al., 2017; Liu et al., 2015). China's resource-intensive and export-oriented growth model has resulted in environmental degradation. Previous published research outcomes show that China is a net virtual water, virtual land, and embodied emissions exporting country through its international trade (Chen and Han, 2015; Chen et al., 2017b; Peters et al., 2011). In order to understand and manage China's and global water issues, China's water consumption across the global supply chain and international trade requires investigation.

With these issues in mind, the aims of this study are to: (1) holistically explore the trends and roles of China's water consumption from a global trade/supply chain perspective over a given time period; (2) identify the industrial sectors influencing China and its trade partners' virtual water flows; and (3) understanding China's dynamic trends of virtual water trade across the global supply chain and glean insights and policy directions. Although the goal of this study is to understand China's situation, the implications for other regions, policies, and supply chains will also be made evident.

The remainder of this paper begins with Section 2 which gives a brief review of virtual water and water footprint studies. Section 3 introduces the basic method and data sources of this study. The results are presented in Section 4. Finally, Section 5 discusses various policy, trade and supply chain implications, as well as limitations; Section 6 summarizes this study and provides directions for future study.

2 Review of virtual water and water footprint

Virtual water (VW) and water footprints (WF) emerged in the 1990s and 2000s, respectively (Allan, 1997; Chapagain and Hoekstra, 2002). VW quantifies total water consumed by product or service. Agriculture products and VW transfer between regions and countries have been a particular focus of most relevant studies. WF can be used to identify human pressure on the natural environment, quantifying water resource gross requirements for products and services consumed by an individual, business, town, city or country.

Three types of water resources are valued in VW and WF. These three water resources are green, blue and grey water. Green water is precipitation on land that does not run off or recharge the groundwater, but is stored in the soil or temporarily stays on the top of the soil or vegetation. Blue water is fresh water drawn from surface water and groundwater. Grey water is freshwater required to assimilate the load of pollutants based on existing water quality standards. It is necessary to know that grey water footprint is not an actual consumed quantity but a hypothetical amount to assimilate water pollution to certain predefined levels, therefore, it is used to show the economic burden on water use (Chapagain and Hoekstra, 2003; Hoekstra and Chapagain, 2008).

Studies on VW and WF have included global (Hoekstra and Mekonnen, 2012), regional (Vanham et al., 2013), specific countries (Schyns and Hoekstra, 2014), basin (Zhuo et al., 2014), city (Li et al., 2016), industry (Duarte et al., 2014), production (Rodriguez et al., 2015), and products perspectives (Schyns et al., 2017). Topics covered by the literature include water consumption, scarcity, efficiency, sustainable management and transfer. Bottom-up methods, also defined as a "production tree", and top-down Input-Output (I/O) analyses are widely used for quantifying VW and WF (Chapagain and Hoekstra, 2002; Ercin and Hoekstra, 2014;Cazcarro et al., 2012; Yang et al., 2013).

VW and WF can be jointly evaluated with trade transfer from global and regional perspectives. In China, water flows can be assessed from domestic or foreign trade perspectives. For China's domestic trade, several studies identified imbalanced exchanges with water resources between China's provinces and basins (Chen et al., 2017a; Deng et al., 2016; Dong et al., 2014; Jiang et al., 2015; Zhuo et al., 2016; Liu et al., 2017; Zhang and Anadon, 2014;Feng et al., 2012). Other studies investigated VW or WF for single cities and provinces and the influence of trade on their water resources (Dong et al., 2013; Wang et al., 2013; Zhang et al., 2011).

The VW and WF of China's international trade has also been investigated. Agricultural international trade has been the primary focus of most published studies

(Shi et al., 2014; Zhang et al., 2016; Zhang et al., 2017; Zhang et al., 2018). Several studies focused on China's import and export trade from a national level. For instance, Chen and Chen (2013) calculated the WFs of 112 countries (regions) and the VW trade using a multi-region I/O model with the Global Trade Analysis Project (GTAP) database. Results showed that India, the United States, and mainland China are the world's largest VW consumers, with 57% of the international VW flows from non-food trade. In addition, China's net import and export VW were evaluated for its trade partners. However, that study only evaluated a snapshot of a single year situation. Broader industry sectoral trade transfer between China and its partners were not considered.

China's VW export and import using I/O analysis from 2000 to 2012 was also evaluated in a recent study based on China's national input-output tables (Chen et al., 2017b). This study found that China was a net exporter of VW during this time period. VW exports were primarily to the USA, EU and Japan. China mainly imported VW from ASEAN countries, Brazil, and Korea. Sector of Textile, Garment and Leather Products was China's main industrial export sector, while agriculture was the main import sector. This study only applied a single region I/O model of China. It did not consider the complex interaction across the broader supply chain network; it investigated China's export and import VW from a sectoral perspective only, without investigating international sectoral relationships.

China's WF from production and consumption caused by foreign trade in 2012 was investigated based on a European database (Han et al., 2017). The results show that China was a net embodied water supplier in both final consumption based trade relations and in intermediate production-based ones. This study shows Pakistan, Myanmar and India were China's largest embodied water suppliers. Hong Kong, the United States, and Japan were its largest net recipients. The electrical and machinery sector and the agriculture sector were China's largest export and import VW sectors, respectively. This study identified the VW of China via international trade during a single year and did not distinguish relationships amongst the three specific VWs.

Under such a circumstance, in our study we seek to address the limitations and expand on existing studies relating to China's WF and VW flows from international trade. This study will investigate a perspective of China's WF and VW transfer across a broader international supply chain and trade partners from 1995 to 2009 based on a multi-region I/O model with the World Input-Output Database (WIOD). This study distinguishes between benchmarks for Blue, Green and Grey water consumption, respectively. VWs transfer between China and its partners from a sectoral perspective are also identified. China's VW trade flow evolution during this period is analyzed with the help of cluster analysis; a unique investigation not seen in other studies. The main innovation is that it is a temporal study, covering sectoral perspectives. Also, this study investigates green, blue and grey water resources so that more valuable policy insights can be obtained. In addition, cluster analysis is conducted to uncover the key features of China's VW so that the detailed water interaction between China and its trade partners can be presented for preparing sustainable water policies.

3 Method and data

3.1 Method

(1) Multi-region input-output analysis

Input-output analysis reveals interdependencies between different national and regional economies (Leontief, 1936) and can integrate environmental and economic data for a particular nation, region, province, or locality (Giljum, 2013). The multi-region input-output (MRIO) model integrates multiple country flows and incorporates both domestic and international supply chains (Tukker et al., 2016). The MRIO model is adopted in order to calculate water footprints across the whole supply chain including domestic production for final consumption and total direct and indirect water uses associated with imports for domestic use (Giljum, 2013).

In order to expand the MRIO model to the global level, bilateral trade values e^{rs} (exports from region r to s) are decomposed into exports for intermediate use ($A^{rs}x^{s}$) and for final consumption (y^{rs}). The standard MRIO model sums up intermediate and final consumption to arrive at total output in each region, expressed as:

$$x^{r} = Z^{rr} + y^{rr} + \sum_{s \neq r} e^{rs} = A^{rr}x^{r} + y^{rr} + \sum_{s \neq r} A^{rs}x^{s} + \sum_{s \neq r} y^{rs} \tag{1}$$

Where: x^{r} is the total output in region r; domestic intermediate consumption in region r is represented by the matrix Z^{rr} and domestic final consumption (households, governments and gross fixed capital formation) is represented by vector y^{rr} (both exclude imports). A^{rr} is a matrix composed of domestic direct requirement coefficients between different sectors in region r, while A^{rs} is the direct exported coefficients matrix from region r to s. By considering the equation in each region the expressed equation set in matrix form is shown in expression (2).

$$\begin{pmatrix} x^{1} \\ x^{2} \\ x^{3} \\ \vdots \\ x^{m} \end{pmatrix} = \begin{pmatrix} A^{11} & A^{12} & A^{13} & \cdots & A^{1m} \\ A^{21} & A^{22} & A^{23} & \cdots & A^{2m} \\ A^{31} & A^{32} & A^{33} & \cdots & A^{3m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A^{m1} & A^{m2} & A^{m3} & \cdots & A^{mm} \end{pmatrix} \begin{pmatrix} x^{1} \\ x^{2} \\ x^{3} \\ \vdots \\ x^{m} \end{pmatrix} + \begin{pmatrix} \sum_{r} y^{1r} \\ \sum_{r} y^{2r} \\ \sum_{r} y^{3r} \\ \vdots \\ \sum_{r} y^{mr} \end{pmatrix} \tag{2}$$

Where each block matrix A represents the interactions between industries (sectors) and countries. Diagonal matrix blocks represent domestic activities, off-diagonal matrix blocks are trade patterns between different regions. The footprint of country r (WF^{r}) can be calculated by using expression (3).

$$\begin{pmatrix} WF^{1r} \\ WF^{2r} \\ WF^{3r} \\ \vdots \\ WF^{mr} \end{pmatrix} = \begin{pmatrix} \hat{S}^{1} & 0 & 0 & \cdots & 0 \\ 0 & \hat{S}^{2} & 0 & \cdots & 0 \\ 0 & 0 & \hat{S}^{3} & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & \hat{S}^{m} \end{pmatrix} \left\{ \begin{pmatrix} I & 0 & 0 & \cdots & 0 \\ 0 & I & 0 & \cdots & 0 \\ 0 & 0 & I & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & I \end{pmatrix} - \begin{pmatrix} A^{11} & A^{12} & A^{13} & \cdots & A^{1m} \\ A^{21} & A^{22} & A^{23} & \cdots & A^{2m} \\ A^{31} & A^{32} & A^{33} & \cdots & A^{3m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A^{m1} & A^{m2} & A^{m3} & \cdots & A^{mm} \end{pmatrix} \right\}^{-1} \begin{pmatrix} y^{1r} \\ y^{2r} \\ y^{3r} \\ \vdots \\ y^{mr} \end{pmatrix} \tag{3}$$

Where WF^{mr} is a vector representing the water footprint in region r from resources extracted in region m. The sum of all elements in vectors WF^{1r} to WF^{mr} represent country r's water footprint. $\hat{S}^{m}$ is a diagonal matrix containing domestic resource and environmental coefficients for each industry (sector) in region m. Expression (3) provides a better understanding of national water footprints, which includes matrix multiplication of a domestic water resource coefficients matrix, a Leontief inverse matrix and domestic final consumption matrix. National water footprints link upstream supply chain resource extraction with final goods and services consumption.

(2) Cluster analysis

Networks exhibit a concentration of links within clusters. A cluster (community) is defined by having dense internal links and lower external link density. Cluster analysis can help identify hidden features of various flows. A two phased cluster analysis using weighted undirected networks is utilized in this study (Blondel et al., 2008; Gao et al., 2015).

The case of weighted undirected networks is shown in equation (4):

$$P = \frac{1}{2w} \sum_i \sum_j \left(w_{ij} - \frac{w_i w_j}{2w} \right) \partial(C_i, C_j) \tag{4}$$

Where w_{ij} shows the weight of the edge between i and j. w_i and w_j are node strengths of i and j respectively; $w_i = \sum_j w_{ij}$ and $w_j = \sum_i w_{ij}$ are the sum of the weights of the edges attached to the country. C_i is the community to which country i is assigned, and C_j is the community to which country j is assigned. The δ-function $\delta(u, v)$ is 1 if $u = v$; otherwise the δ-function $\delta(u, v)$ is 0, and $2w = \sum_i \sum_j w_{ij}$.

The clustering algorithm is divided in two phases that are repeated iteratively. First, it assigns a different community to each node. Then, for each node i it considers the neighbor j and evaluates the gain of modularity ΔP by placing i in the community of j. The node i is then placed in the community for which this gain is maximized, but only if this gain is positive. If no positive gain is possible, i stays in its original community. This process is applied repeatedly and sequentially for all nodes until no further improvement can be achieved; this step completes the first phase. The gain of modularity ΔP can be computed by expression (5):

$$\Delta P = \left[\frac{\Sigma_{in} + k_{i,in}}{2m} - \left(\frac{\Sigma_{tot} + k_i}{2m} \right)^2 \right] - \left[\frac{\Sigma_{in}}{2m} - \left(\frac{\Sigma_{tot}}{2m} \right)^2 - \left(\frac{k_i}{2m} \right)^2 \right] \tag{5}$$

Where Σ_{in} is the sum of the weights of the links inside community (C), Σ_{tot} is the sum of the weights of the links incident to nodes in community (C), k_i is the sum of the weights of node i, $k_{i,in}$ is the sum of the weights from i to nodes in community (C), and m is the sum of the weights of all the links in the network.

The second phase consists in building a new network whose community nodes are found during the first phase. In this way, the weights of the links between the new nodes are given by the sum of the weights of the links between nodes in the corresponding two communities. Once the second phase is completed, the first phase is reapplied to the resulting network, and this process is iterated. The two phases are iterated until there are no more changes and the maximum modularity is attained.

3.2 Data sources

The world input-output tables and water resources quantities for the years 1995 to 2009 were obtained from the World Input-Output Database (WIOD). WIOD is a project funded by the European Union's Seventh Framework Program for research and technological development, covering 35 sectors and 41 countries or regions (Timmer et al., 2015). In this study, we used the "release 2013" version, in which it includes the environmental accounts from 39 countries (The rest of world and Taiwan are excluded due to the purpose of this study focusing on exploring the specific country). This database has several variables. Particularly, this database provides readily available values for water use by different types and sectors. This study focuses on WFs including blue, green and grey. The original data from this database are processed according to Mekonnen and Hoekstra (2010). Natural resource extraction refers to the annual amounts of solid, liquid and gaseous raw materials extracted or moved from the natural environment by humans or human-controlled technologies (Genty et al., 2012). In this study, it comprises extracted resources which enter the economic system for further processing or direct consumption excluding the stock resources that never enter the economic system. All resource extraction coefficients are domestic extractions excluding imports.

4 Results

4.1 The role of China's water footprint and virtual water trade in a global network

The results show that global WF (Figure 1) increased by 1.4 times from 1995 to 2009. Approximately 90% of the WF was due to domestic consumption; leaving only 10% for transfer through international trade. Green WF accounted for a major portion of both domestic consumption and trade transfer.

Figure 2 shows China's WF in a global network. The results illustrate that China's WF increased between 1995 and 2009. China's WF represented 11.2% of global WF in 1995 and 13.6% in 2009. During this period, China's domestic WF, VW imports, and VW exports increased by 1.6 times, 2.9 times and 2.2 times, respectively from 1995 to 2009. For China's specific VWs import, we see Blue, Green and Grey VWs increased by 2.9 times, 2.9 times and 3.7 times, respectively. Green VW accounted for a main portion of total VW imports. Blue VW and Grey VW respectively followed in flows. China's exported VW showed Blue, Green and Grey VWs increasing at rates of 2.3 times, 1.9 times and 3.0 times over this period. Green VW also accounted for the largest portion of total VW exports. Grey VW was second and Blue VW was third in quantity.

Countries can satisfy their water resource needs through international trade. The top ten China trading partners using both imported and exported VWs during this period are listed in Table A1 (Supporting Information SI). The USA, Australia, India, Indonesia, Japan, Korea, Brazil, Russia and Canada were the main Chinese exporting trade partners to China to help satisfy China's consumption needs. The USA, Australia, Japan, Korea, Canada, Italy, Germany, United Kingdom, and France were the main importing trade partners from China in order to meet with their water consumptions.

The import to export trade ratios of China's VW with its trade partners in the given period are in Table 1. The ratios with specific VW values are presented in Table A2 (SI).

Results show that China's VW had net export trends with all countries during this period with the exception of Brazil for the years 1998 to 2007, and India for 1996 to 1998, 2000 to 2001.

Four scale levels of China's net total VW exports can be identified in Table 1 (i.e. ratio ranges below 1, of 0.2~1, 0.1~0.2, 0.01~0.1, and 0~0.01). Greece and the Slovak Republic show the largest significant VW imports from China.

For specific VW trade of China, the total net export and net import situations with Blue VW, Green VW and Grey VW have similar patterns. Each shows that China is primarily a net exporter of VW (see Table A2). China showed a very high net exported grey VW to its trade partners during these periods. For example, during the 2009 China and Australia trade exchange, China had a net export of total VW; the import to export ratios of China's Blue, Green and Grey VWs were 0.06, 0.19 and 0.03, respectively. The result indicates that the products exported to Australia have a high pollution impact to China. EU countries were main net importers from China for each of the three VW types.

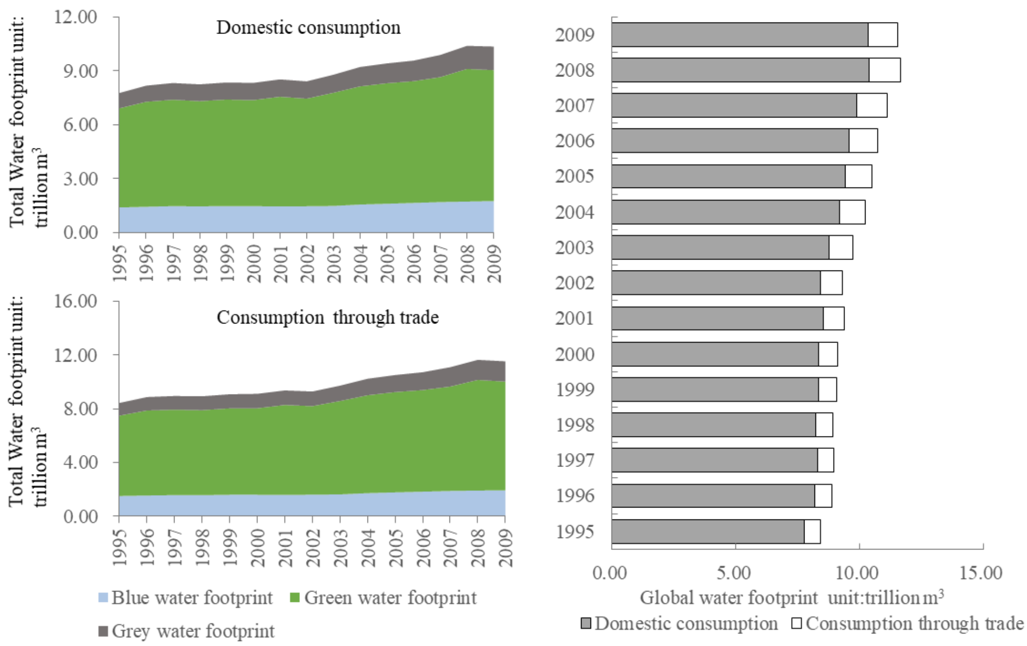


Figure 1 Global water footprint from 1995 to 2009

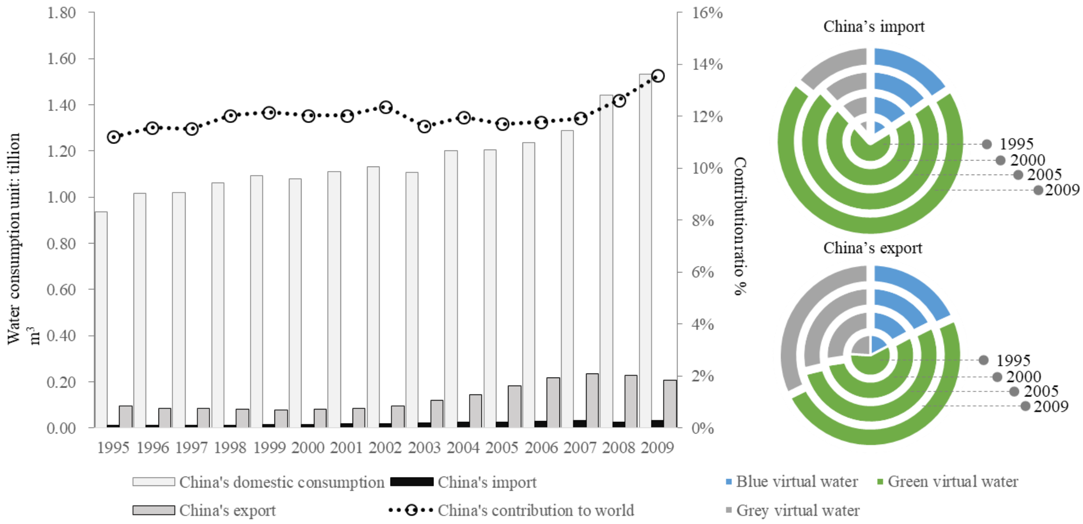


Figure 2 China's water footprint and virtual water trade in global network

Table 1 The total import to export ratios of China's virtual water from 1995 to 2009

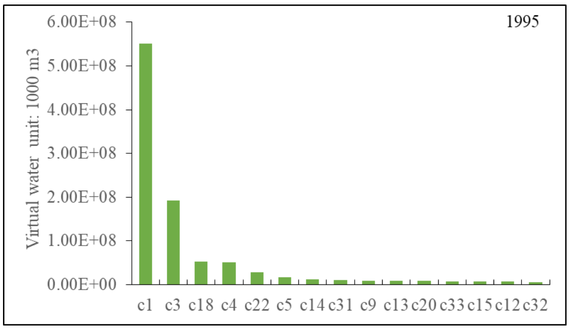
	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Australia (AUS)	0.54	0.53	0.47	0.49	0.55	0.51	0.55	0.38	0.40	0.24	0.18	0.10	0.11	0.10	0.12
Austria (AUT)	0.04	0.02	0.02	0.03	0.05	0.07	0.10	0.14	0.09	0.06	0.05	0.04	0.04	0.08	0.10
Belgium (BEL)	0.07	0.09	0.09	0.09	0.10	0.12	0.16	0.15	0.09	0.06	0.05	0.05	0.05	0.05	0.07
Brazil (BRA)	0.29	0.20	0.58	0.06	0.09	0.25	0.43	0.09	0.07	0.06	0.03	0.07	0.06	0.07	0.07
Bulgaria (BGR)	0.42	0.39	0.73	1.06	2.44	2.24	2.78	3.34	3.53	2.76	1.62	1.40	1.27	0.13	0.17
Canada (CAN)	0.05	0.07	0.11	0.11	0.09	0.12	0.13	0.10	0.08	0.07	0.08	0.07	0.07	0.08	0.11
Cyprus (CYP)	0.04	0.06	0.04	0.02	0.04	0.15	0.17	0.17	0.08	0.11	0.05	0.05	0.02	0.004	0.01
Czech Republic (CZE)	0.02	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.03	0.02	0.03	0.03	0.04
Denmark (DNK)	0.02	0.02	0.02	0.03	0.04	0.05	0.07	0.08	0.07	0.06	0.05	0.05	0.04	0.06	0.07
Estonia (EST)	0.04	0.07	0.14	0.11	0.10	0.17	0.20	0.22	0.22	0.16	0.10	0.09	0.12	0.23	0.21
Finland (FIN)	0.03	0.04	0.04	0.05	0.06	0.07	0.07	0.07	0.06	0.04	0.03	0.03	0.03	0.02	0.03
France (FRA)	0.04	0.04	0.14	0.22	0.06	0.13	0.06	0.07	0.05	0.03	0.04	0.11	0.03	0.03	0.08
Germany (DEU)	0.09	0.09	0.10	0.24	0.25	0.28	0.24	0.22	0.16	0.17	0.11	0.08	0.08	0.12	0.12
Greece (GRC)	0.07	0.07	0.11	0.08	0.08	0.09	0.11	0.10	0.07	0.06	0.05	0.06	0.07	0.08	0.08
Hungary (HUN)	0.03	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02
India (IND)	0.003	0.003	0.004	0.003	0.01	0.01	0.01	0.01	0.01	0.01	0.004	0.004	0.004	0.003	0.003
Indonesia (IDN)	0.07	0.08	0.11	0.06	0.15	0.17	0.12	0.14	0.07	0.07	0.07	0.11	0.12	0.14	0.20
Ireland (IRL)	0.47	0.34	0.48	0.95	0.58	0.60	0.78	0.51	0.46	0.59	0.63	0.38	0.46	0.25	0.18
Italy (ITA)	1.22	1.04	1.01	0.97	0.96	1.63	1.34	0.86	0.74	0.63	0.42	0.38	0.33	0.16	0.18
Japan (JPN)	0.03	0.03	0.03	0.04	0.07	0.16	0.25	0.09	0.08	0.08	0.08	0.05	0.04	0.03	0.05
Korea (KOR)	0.08	0.12	0.09	0.09	0.10	0.11	0.12	0.11	0.08	0.06	0.04	0.05	0.05	0.06	0.07
Latvia (LVA)	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.03	0.02	0.02	0.02	0.03	0.04	0.03
Lithuania (LTU)	0.10	0.09	0.09	0.14	0.08	0.08	0.10	0.10	0.11	0.11	0.09	0.08	0.08	0.14	0.17
Luxembourg (LUX)	0.08	0.13	0.02	0.02	0.17	0.05	0.12	0.23	0.16	0.07	0.03	0.02	0.01	0.02	0.03

Malta (MLT)	0.05	0.06	0.04	0.07	0.08	0.08	0.07	0.19	0.16	0.15	0.15	0.05	0.14	0.08	0.07
Mexico (MEX)	0.04	0.01	0.01	0.001	0.01	0.01	0.04	0.07	0.06	0.02	0.01	0.01	0.01	0.004	0.03
Netherlands (NLD)	0.10	0.12	0.10	0.06	0.08	0.09	0.07	0.06	0.05	0.05	0.03	0.03	0.03	0.03	0.04
Poland (POL)	0.02	0.04	0.08	0.02	0.003	0.01	0.02	0.02	0.01	0.03	0.07	0.04	0.04	0.01	0.01
Portugal (PRT)	0.08	0.10	0.12	0.11	0.12	0.14	0.16	0.15	0.16	0.14	0.11	0.10	0.09	0.09	0.09
Romania (ROU)	0.02	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.01	0.02
Russia (RUS)	0.06	0.08	0.09	0.08	0.07	0.11	0.14	0.24	0.15	0.15	0.09	0.11	0.11	0.05	0.06
Slovak Republic (SVK)	0.31	0.10	0.23	0.04	0.12	0.32	0.24	0.50	0.15	0.29	0.05	0.02	0.02	0.05	0.08
Slovenia (SVN)	0.10	0.06	0.08	0.15	0.32	0.27	0.22	0.15	0.10	0.10	0.08	0.06	0.03	0.03	0.06
Spain (ESP)	0.02	0.01	0.004	0.002	0.003	0.01	0.01	0.02	0.03	0.03	0.04	0.06	0.10	0.12	0.12
Sweden (SWE)	0.01	0.04	0.01	0.02	0.04	0.04	0.05	0.07	0.05	0.11	0.09	0.13	0.09	0.03	0.04
Turkey (TUR)	0.05	0.07	0.10	0.17	0.14	0.16	0.17	0.15	0.14	0.11	0.08	0.07	0.07	0.12	0.15
United Kingdom (GBR)	0.14	0.19	0.14	0.15	0.18	0.17	0.26	0.28	0.13	0.08	0.04	0.03	0.02	0.01	0.01
United States (USA)	0.09	0.10	0.13	0.10	0.09	0.09	0.09	0.07	0.07	0.05	0.05	0.05	0.06	0.06	0.07

Note: background color in Table 1 presents the net import and net export virtual water of China, this color presents China's net import, series of blue color presents China's net export, 0.2~1, 0.1~0.2, 0.01~0.1, 0~0.01

4.2 China's sectoral virtual water shift patterns with its main trade partners

It is critical to identify China's sectoral virtual water shift patterns with its main trade partners so that useful policies can be raised. Overall, China's sectors show net export VWs from 1995 to 2009, and their trends are increasing in the given period except for the agriculture sector. The Agriculture, Food, Vehicles sale, and Textiles sectors are the top four net exporting VW sectors from 1995 to 2009 (see Figure 3).



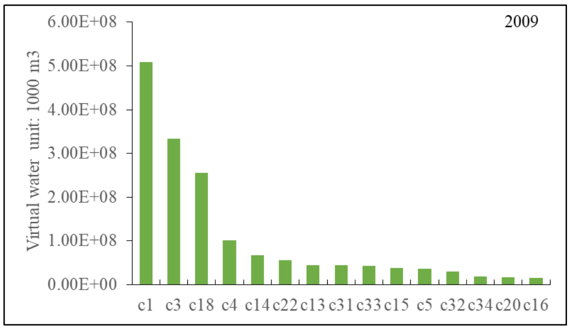


Figure 3 China's top 15 net export virtual water sectors from 1995 to 2009

(**c1**: Agriculture, Hunting, Forestry and Fishing (Agriculture sector); **c3**: Food, Beverages and Tobacco (Food sector); **c4**: Textiles and Textile Products (Textiles sector); **c5**: Leather, Leather and Footwear (Leather sector); **c9**: Chemicals and Chemical Products (Chemical sector); **c12**: Basic Metals and Fabricated Metal (Metal sector); **c13**: Machinery; **c14**: Electrical and Optical Equipment; **c15**: Transport Equipment; **c16**: Manufacturing; Recycling; **c18**: Sale, Maintenance and Repair of Motor Vehicles and Motorcycles (Vehicles Sale sector); Retail Sale of Fuel; **c20**: Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods (Other Sale sector 2); **c22**: Other Inland Transport; **c31**: Education; **c32**: Health and Social Work; **c33**: Other Community, Social and Personal Services (Other service sector); **c34**: Private Households with Employed Persons; more details of sectoral codes information could be found in (Genty et al., 2012))

In order to further explore VW shifts in trade between China and its trade partners, China's top 13 VW trade partners from the years of 1995 and 2009 are selected so that the sector flows perspectives can be presented. The flow results are shown in Figure 4a (1995) and Figure 4b (2009).

In terms of China's VW imports, the USA, Australia, India, Indonesia, Japan, Korea, Brazil, Russia and Canada were the largest exporters to China. A nuanced sectoral consumption evaluation between the years 1995 and 2009, shown in Table 2, illustrates that these countries' top 5 sectoral VW exporters to China either differed in rank order or had completely different sectors represented in the top 5. Take India (IND) as an example, the top 5 export VW sectors to China in 1995 included Agriculture sector (c1); Food sector (c3), Textiles sector (c4); Chemical sector (c9); and Manufacturing and Recycling sector (c16). The top IND VW exporting sectors in 2009 included Manufacturing and Recycling sector (c16); Food sector (c3); Agriculture sector (c1); Wood sector (c6); and Electrical and Optical Equipment sector (c14).

In addition, the top export (from trading partner countries to China) VW sectors showed diversity across countries. As an example, the USA, Indonesia, and Japan, respectively had, the Agriculture sector, Other Inland Transport sector, and Machinery sector as the top exporting VW sectors to China in 1995. These results reflect a diverse trade structure and final consumption between China and these trade partners. The three specific imported VW types (green, blue, grey) of sectors, had similar results.

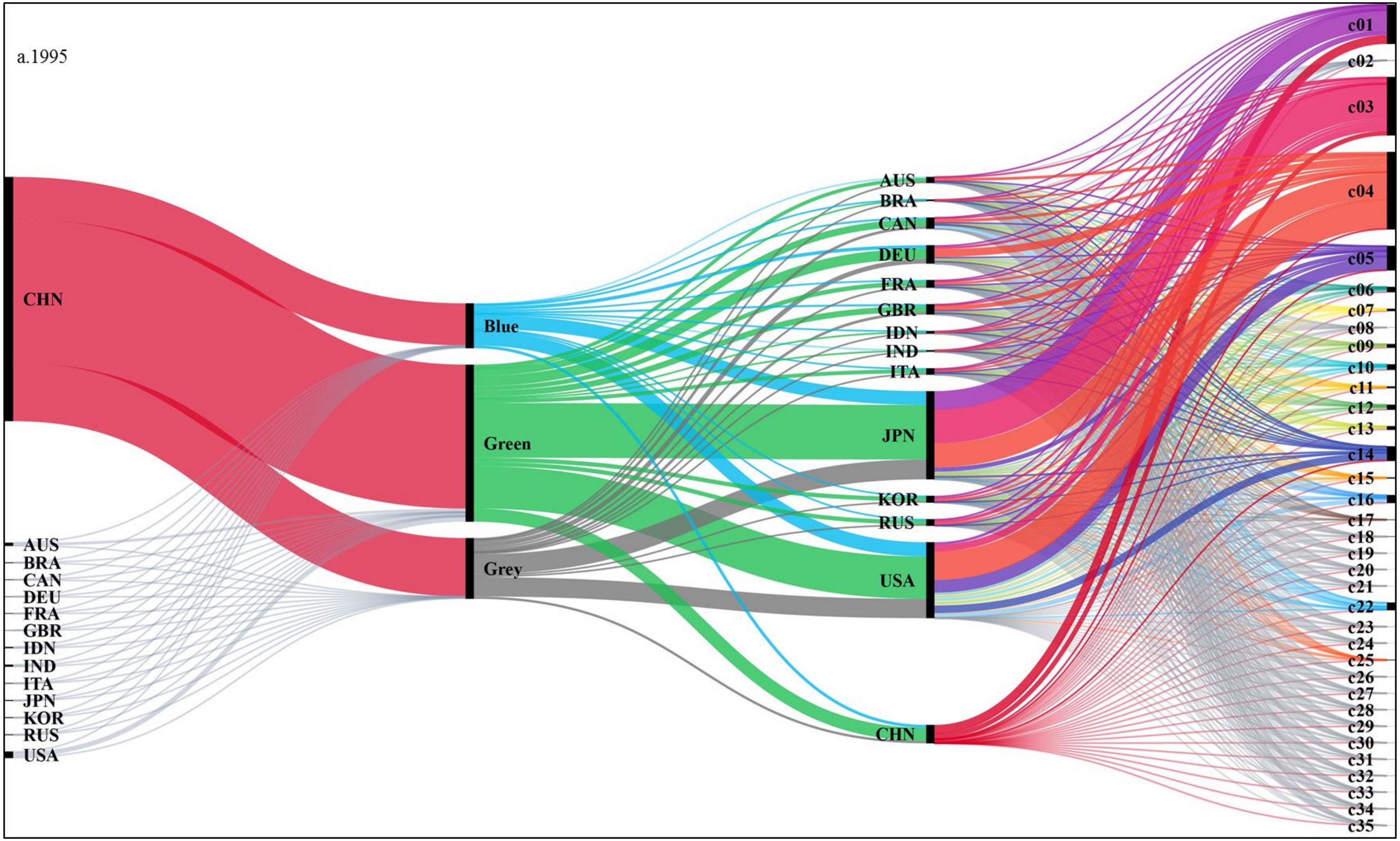
Looking at China's export VW, China mainly exported to the USA, Australia, Japan, Korea, Canada, Italy, Germany, United Kingdom, and France. Overall, the Food, and Textiles sectors were the top VW export sectors from China to these partner countries. China's top exporting sectors to these trading partner remained relatively stable from 1995 to 2009. The major exceptions were the USA, Japan and Canada. As an example, the Textiles sector was the largest VW export sector from China to the USA in 1995, while the Electrical and Optical Equipment sector was the top VW export sector from China to the USA in 2009.

The structure (order) of the top 5 export VW sectors differed in the period of 1995 -2009. The structures were diverse across the different countries as well. Structural situations for total VW exports were similar for each of the three specific (green, blue, grey) VW exports.

Table 2 Top 5 sectors with import and export virtual water of selected countries in 1995 and 2009 (Unit: 1000 m^3)

China's import									
USA		**AUS**		**IND**		**IDN**		**JPN**	
1995	2009	1995	2009	1995	2009	1995	2009	1995	2009
c1(1.2E+06)	c3(1.7E+06)	c1(8.0E+05)	c3(2.9E+05)	c1(4.4E+05)	c16(2.6E+05)	c22(1.5E+05)	c3(1.9E+05)	c13(8.2E+04)	c14(2.9E+05)
c3(5.7E+05)	c1(1.0E+06)	c3(1.5E+05)	c1(1.8E+05)	c3(7.0E+04)	c3(1.8E+05)	c3(1.3E+05)	c14(6.2E+04)	c14(6.0E+04)	c13(1.7E+05)
c13(6.5E+04)	c15(2.2E+05)	c4(3.4E+04)	c22(1.2E+05)	c4(5.5E+04)	c1(1.7E+05)	c1(9.7E+04)	c22(5.9E+04)	c3(3.4E+04)	c15(9.8E+04)
c14(5.5E+04)	c13(1.8E+05)	c22(3.2E+04)	c9(1.3E+04)	c9(3.6E+04)	c6(6.4E+04)	c9(4.8E+03)	c1(3.5E+04)	c12(1.6E+04)	c3(7.0E+04)
c4(4.3E+04)	c14(1.3E+05)	c14(5.0E+03)	c13(1.1E+04)	c16(1.2E+04)	c14(6.1E+04)	c6(4.1E+03)	c13(3.0E+04)	c4(1.4E+04)	c9(3.8E+04)
KOR		**BRA**		**RUS**		**CAN**			
1995	2009	1995	2009	1995	2009	1995	2009		
c3(9.1E+04)	c14(3.8E+05)	c3(1.7E+05)	c3(4.7E+03)	c1(8.4E+04)	c3(4.2E+05)	c3(5.6E+04)	c1(3.1E+05)		
c4(3.4E+04)	c3(2.1E+05)	c1(2.8E+04)	c15(4.4E+04)	c13(7.3E+04)	c1(1.0E+05)	c22(5.2E+04)	c3(2.7E+05)		
c13(2.7E+04)	c13(1.7E+05)	c13(2.3E+03)	c1(4.2E+04)	c3(2.7E+04)	c13(5.0E+04)	c1(2.2E+04)	c22(1.1E+05)		
c5(2.1E+04)	c15(7.3E+04)	c5(1.2E+03)	c13(7.0E+03)	c14(7.4E+03)	c9(2.2E+04)	c14(1.3E+04)	c14(4.3E+04)		
c14(1.6E+04)	c4(2.7E+04)	c15(9.2E+02)	c14(5.6E+03)	c12(6.4E+03)	c22(3.5E+03)	c6(7.2E+03)	c13(3.3E+04)		
China's export									
USA		**AUS**		**FRA**		**ITA**		**JPN**	
1995	2009	1995	2009	1995	2009	1995	2009	1995	2009
c4(8.7E+06)	c14(1.3E+07)	c4(8.6E+05)	c4(2.0E+06)	c4(6.9E+05)	c4(2.6E+06)	c4(5.1E+05)	c4(1.6E+06)	c3(1.1E+07)	c4(7.3E+06)
c5(4.0E+06)	c4(1.2E+07)	c3(3.1E+05)	c14(9.1E+05)	c3(4.1E+05)	c14(1.2E+06)	c1(4.5E+05)	c14(5.9E+05)	c4(7.4E+06)	c3(6.5E+06)
c14(2.3E+06)	c5(6.2E+06)	c5(1.1E+05)	c3(7.6E+05)	c1(3.3E+05)	c5(5.5E+05)	c22(2.8E+05)	c5(5.7E+05)	c1(5.6E+06)	c14(3.9E+06)
c3(2.2E+06)	c16(4.4E+06)	c22(1.0E+05)	c22(2.9E+05)	c5(3.0E+05)	c3(5.0E+05)	c5(1.7E+05)	c3(3.2E+05)	c5(1.3E+06)	c5(1.9E+06)
c16(1.4E+06)	c3(4.3E+06)	c14(1.0E+05)	c16(2.8E+05)	c14(1.8E+05)	c16(3.7E+05)	c3(1.4E+05)	c13(2.2E+05)	c14(6.6E+05)	c1(1.5E+06)
KOR		**GBR**		**DEU**		**CAN**			

1995	2009	1995	2009	1995	2009	1995	2009
c3(7.0E+05)	c3(1.5E+06)	c4(1.3E+06)	c4(3.2E+06)	c4(2.4E+06)	c4(3.8E+06)	c22(1.1E+06)	c4(1.7E+06)
c1(5.1E+05)	c4(1.0E+06)	c5(3.2E+05)	c14(9.4E+05)	c3(7.4E+05)	c14(2.7E+06)	c4(9.6E+05)	c22(1.5E+06)
c4(4.8E+05)	c14(9.6E+05)	c1(2.8E+05)	c3(5.8E+05)	c14(4.9E+05)	c3(1.3E+06)	c3(4.0E+05)	c14(1.2E+06)
c5(1.4E+05)	c1(5.1E+05)	c14(2.4E+05)	c5(5.5E+05)	c5(4.9E+05)	c16(8.7E+05)	c5(3.2E+05)	c3(1.1E+06)
c14(7.1E+04)	c5(4.2E+05)	c3(2.1E+05)	c16(5.0E+05)	c1(4.6E+05)	c5(7.5E+05)	c10(1.1E+05)	c5(7.4E+05)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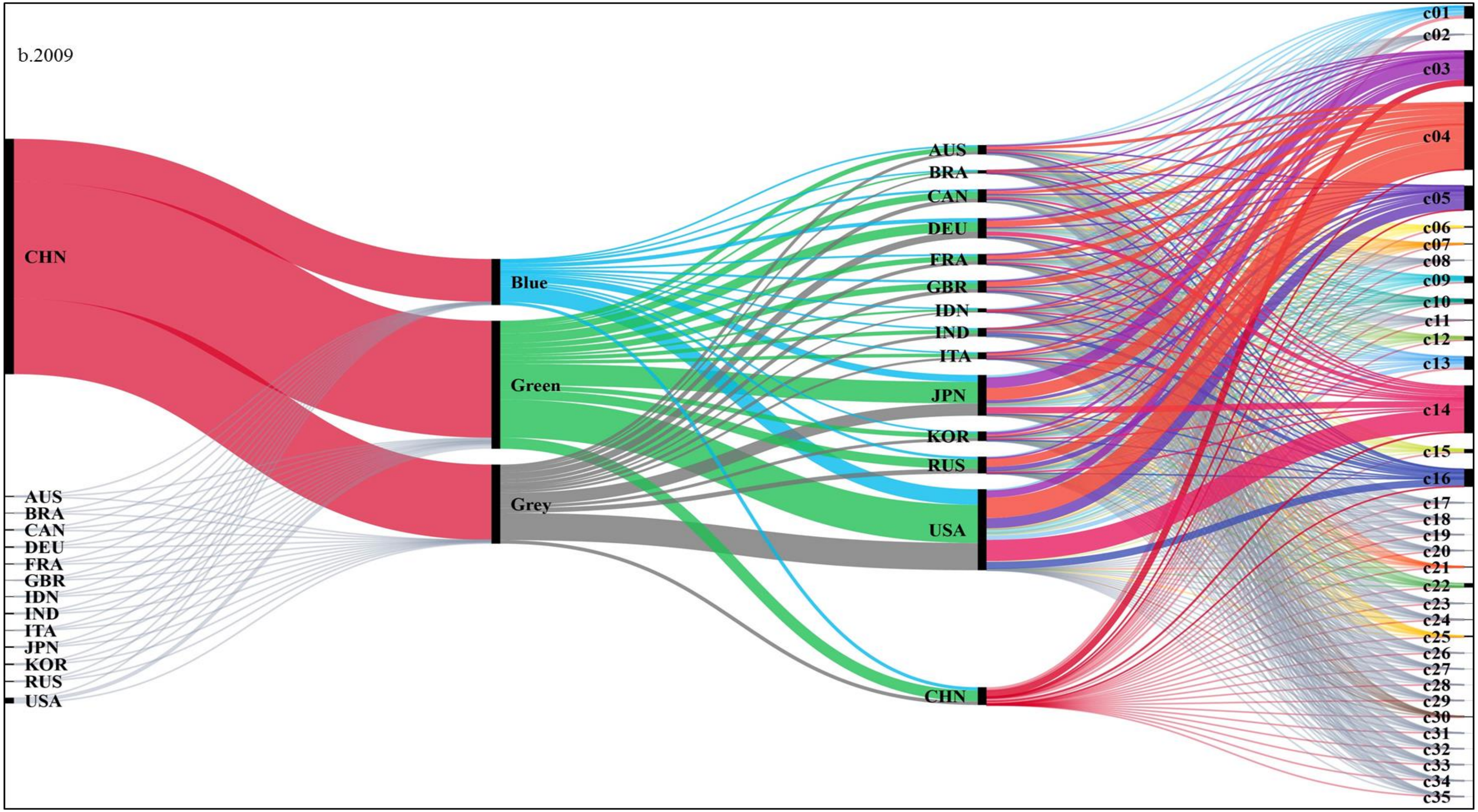

Figure 4 Virtual water shift patterns between China and its selected trade partners in 1995 (top) in 2009 (bottom)

4.3 Understanding the dynamic virtual water of China with its trade partners

Figure 5 illustrates the results of partner China's VW import cluster trends from 1995 to 2009; over four time periods 1995, 2000, 2005, 2009. The entire VW network is clustered into three sub-networks in each year.

The results show that China has been in the same cluster as the USA, Indonesia, India, Canada, Mexico, Brazil and Australia over the time periods. China has a close VW trading relationship with each of these countries, and weaker VW trading relationships with nations outside this cluster. Geographical location was not a key factor influencing China's VW trade. For example, geographically China is closer in proximity to Japan than the USA, except China and the USA belong to the same cluster.

Several factors may influence the formation of China's VW cluster, such as trade relations, resource endowments and supply-demand relationships. For trade relations, trade agreements and good diplomatic relationships play a key role between countries and could be causes of extra VW transfer. For example, the United States-Mexico trade agreement for agriculture (part of the North American Free Trade Agreement), has led to greater internal North American trade, in this circumstance, VW transfers through traded commodities (Dalin et al., 2012). China has a good diplomatic relationship with Australia, both countries have been building a Free Trade relationship since 2005. During this process, China imported more agriculture products from Australia, which embodied more virtual water as well. Resource endowment could be the other driving factor for countries' VWs within this cluster. India and Brazil are rich in agricultural products. They were the main trade partners exporting agriculture products (such as cotton and soybean) to China. Again, agriculture products embodied more virtual water, resulting in greater VW transfer between these countries. In addition, China's increased desire for more diverse products is satisfied by these countries, exhibiting stronger trade relationships.

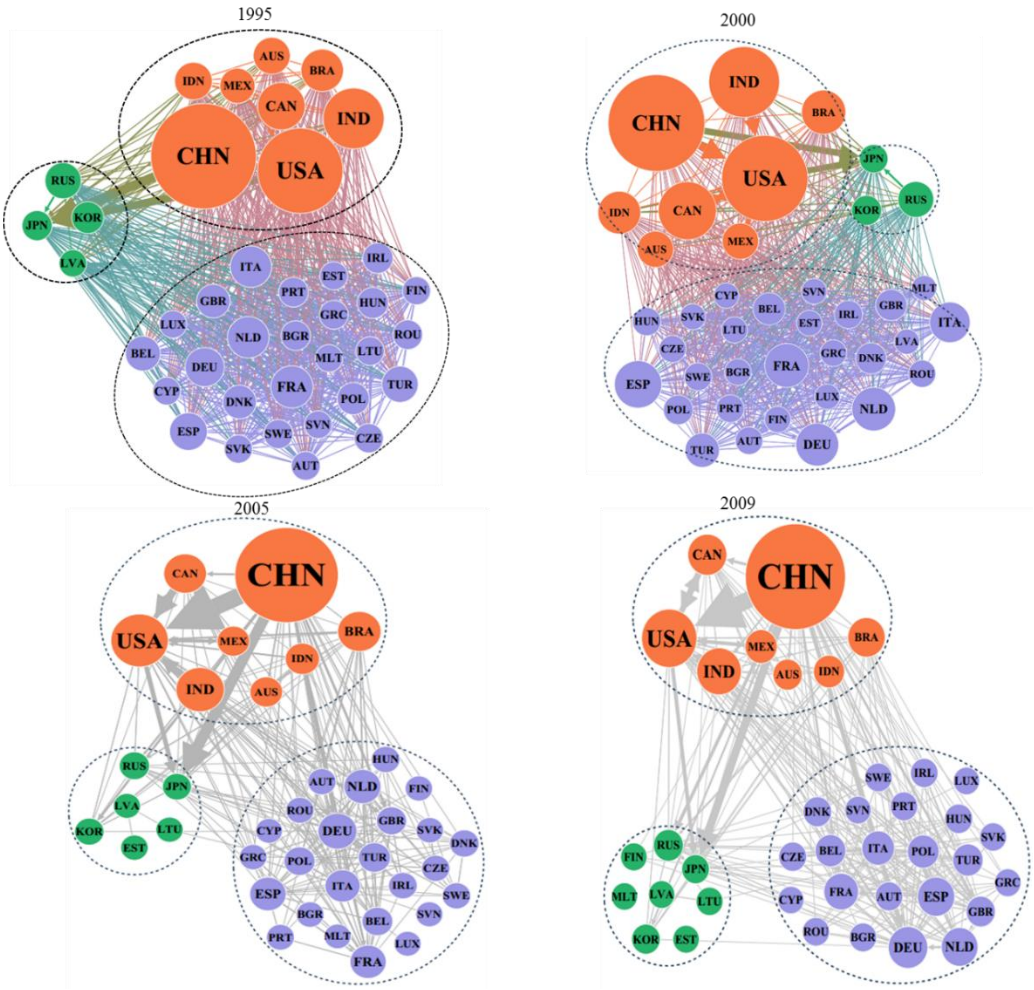

Figure 5 Cluster trends of China's virtual water from 1995 to 2009 for selected years (The circles with the same color located in the same cluster, the size of the circle presents the total export VW of this country, the size of country's arrow presents the export VW to each partner)

5 Discussions

5.1 Policy implications

Supply chains encompass activities and processes far beyond local activities. Global supply chains greatly influence national WFs; and are the foundation of most international trade. Closely tied to increases in globalization, China's VW trade also experienced increasing trends from 1995 to 2009. China was a net VW exporter during this period. China's major import partners from the USA, India, Brazil and mainly exporting to the USA, Japan and Germany is consistent with the findings of previous studies (e.g., Chen and Chen, 2013; Han et al., 2017).

Given that WF is a measure of water consumption, there are policy implications for water resource consumption management. The increases in global consumption make water resources conservation policies more difficult to manage. Although China can put some policies in place for water consumption of its own population and its own resources, developing policies for trade and WF is a complex proposition and careful thought on regulatory or policy measures are needed. For example, an information based or eco-labeling policy on WF of certain industrial sectors and products may be implemented. WF labels on products can be helpful for sustainable consumption, it could both increase public awareness of the environmental impacts associated with production as well as support producers who provide sustainable products (Leach et al., 2016). At the same time, capacity-building efforts should be made so that the Chinese consumers can increase their water saving awareness through behaviors changes, such as TV, radio and Internet promotion, regular workshops, pamphlets, public placards and billboards, etc. In addition, economic instruments should be adopted, such as water resource tax, differentiated water prices for different water uses, so that the general public can realize that water is not a free good, but contains certain economic value.

The feasibility of this solution may be called into question and may be dependent on country and product or material characteristics. There could be situations where requiring WF labels for products and its potential enforcement, may be seen as a trade barrier and unfair trade practice; putting additional costs on products to and from countries (Farnia et al., 2018). Some countries may be unduly burdened, while other countries may not feel the brunt of these regulations, providing an uneven playing field, especially to water-stricken developing countries (Postle, et al., 2012). Another issue with water footprint eco-labelling is the unawareness of most consumers concerning the WF labeling concept and the unresolved issues on transparency and reliability of data (Symeonidou and Vagiona, 2018). A policy implication here is for China to support initiatives to globally harmonize how water issues are addressed in product ecolabelling.

In terms of the three specific VW types in China, green VW was the main imported and exported VW type. This finding is consistent with previous studies (e.g. Hoekstra and Mekonnen, 2012). An interesting finding in this study is that for China's import, blue VW is more than grey VW, but alternatively for China's export, an opposite trend occurred where China needed more freshwater to assimilate the load of pollutants based on existing ambient water quality standards. Given China's reputation as the "world's factory", pollutant emissions from Chinese production may also be significant. This leads to a greater grey VW exported from China.

A major implication is that China needs to improve its technology towards cleaner production at the industry level, especially for high polluting industries. For example, L'Oreal, a cosmetics manufacturer incorporated grey water footprints into eco-design (GWFE) of products (L'Haridon et al., 2018). Developing and disseminating such eco-design tools to grey water sensitive industrial sectors may help.

Freshwater would be saved from cleaner production and reducing polluting emissions, leading to decreased grey WF. Fewer polluting emissions means less grey water because fresh water is not needed to clean processes. At the operational level tools for managing internal production processes such as process integration and water pinch analysis techniques can also provide improvements in industrial practices for sectors with grey water heavy WF (Skouteris, et al., 2018).

Reducing emissions and cleaner production exemplifies the complex systemic connections between different environmental indicators such as CO_2 emissions, SO_2 emissions, water footprints, virtual land, and hazardous pollutant emissions. Changes in policies and technologies affecting one indicator could affect other environmental indicators. Governments can holistically manage resources and environmental issues by promoting joint policies to take advantages of co-benefits and spillover effects (Liu et al., 2015), as with the food-energy-water nexus efforts (Albrecht et al., 2018). Another related policy direction, especially in China, is that industries should continue to implement circular economy principles for preventing resources and environmental loss from production (Geng and Doberstein, 2008). Circular economy principles have been a mainstay of economic and environmental policies in China for over a decade. Particularly, at the industrial park level, many water reuse and recycling opportunities exist among different industrial water users and should be encouraged through the expansion of water cascading. For instance, the Tianjin Economic Development Area (TEDA, China's largest industrial park in terms of the total industrial output), established a wide water recycling network among its tenants, leading to significant reduction of both freshwater consumption and wastewater discharge (Geng and Yi, 2006; Geng et al., 2007).

From sectoral perspective, China's VW flows showed significant diversity across sectors. Such results indicate variations in trade structures can influence VW transfer between countries. One of the observations made is that over time there is a shift in ranking of commodities traded, maybe due to country economic development evolution. The shifts are more than subtle in some cases with some commodities becoming more prevalent. Sectors have different levels of consumption for each water type. For example, the agriculture sector has greater green water consumption (Rost et al., 2008). As China's economy has matured, greater trade in non-agriculture and non-food sectors means that there is a shift away from green water flows. In strategic economic policy settings as economies develop, careful sectoral environmental water implications should be considered. Linking sectoral economic development shifts to WF is necessary to identify true overall social, environmental, and economic costs. The relative ease and feasibility of such an initiative can be questioned, but as the sectoral trading shifts due to economic policies, there will also be shifts in water flows. Raising awareness of these relationships is an initial step.

China's VW cluster is identified in this study; implying that some countries are more influenced or can more influence China's water policy. Changes in one country can have greater effects on countries within the same cluster than countries outside this cluster. Therefore, China's WF should be carefully considered when trade agreements are formed with these countries. The VW cluster network can identify impacts between countries, particularly for crises (water crises especially) within countries. Transferring and collaborating on water resources technology between countries and/or sectors can benefit all partners to broadly reduce WF. China should take advantage of its relationships with its VW cluster, adopting and collaborating on advanced technology and globally decreasing WF. For these specific partner countries, China should complete economic risk assessments regarding their water use and allocation, or apply a water risks and sustainability audit, within the framework of international cooperation, for economic relationships and projects with its partner countries.

5.2 Limitations

Research limitations do exist for this study. For example, capturing international trade flows relies on more accurate data, particularly those data related with more detailed sectoral import and export information. Unfortunately, our adopted database cannot provide these data (Yang et al., 2013). The water consumption data from WIOD are estimated data, rather than the real data. Therefore, elements such as annual climate changes, land use changes and technology improvements are not considered. Under such a circumstance, it may be necessary to get the real water consumption data so that the results can be more accurate and reliable.

Also, the MRIO data used in this study were from 1995 to 2009. This dataset may not represent the most recent structural, institutional, and technological capabilities of investigated nations. It is critical to initiate more studies by using more recent data, especially given the current trade skirmishes among several major economies.

In addition, there are concerns of proportionality and linearity assumptions amongst the inputs and outputs (Acquaye et al., 2016). Although some researchers have supported the use of linear approximations (e.g. Hendrickson et al., 1998), such problems still exist due to the lack of data (Tukker and Dietzenbacher, 2013).

Finally, economic valuation was not conducted in this study. Several economic valuation methods exist and can help further investigate price elasticity (e.g. Dietzenbacher and Velázquez, 2007; Bae and Dall'erba, 2018). It would be crucial to have further studies to see the cost and price perspectives associated with these identified water flows.

6. Conclusions

This study evaluates China’s WF and VW trade evolution from 1995 to 2009 based on MRIO and cluster analysis. The major contribution, going beyond previous studies, is to provide a time series analysis of China’s WF in a global supply chain. This analysis reveals China’s VW evolutionary shifts between China and its main trade partners at various sectoral levels. Part of this analysis identifies three specific WFs. The longitudinal and nuanced study provides some insights for future water management. Another contribution is to identify potential driving forces for China’s VW evolution pattern through cluster analysis. This analysis reveals a complex VW network between China and its trade partners. Key VW exchange paths can be identified. This information provides a targeted way for China to adjust its WF policies.

With this study, the main findings include:

As economic development and population increase, the global WF has increased by 1.4 times between 1995 and 2009; it is unlikely that this trend will end. Approximately 90% of WF is caused by country domestic consumption, only 10% of consumption is from international trade. China’s WF experienced increasing trends from 1995 to 2009, global WF was 11.2% caused by China in 1995 and 13.6% caused by China in 2009. Substantial increases through international trade is likely to occur as global trade increases with China.

For China’s specific imported VWs, the rank was green VW, blue VW and grey VW, China’s export ranks were green VW, grey VW and bBlue VW. In general, China is a net VW exporter. China mainly imports virtual water from the USA, Australia, India, Indonesia, Japan, Korea, Brazil, Russia and Canada, and mainly exports to the USA, Australia, Japan, Korea, Canada, Italy, Germany, United Kingdom and France.

The agriculture sector, and food sector were the top VW sectors with both imports and exports. The VW shift patterns between China and its trade partners showed diversity at the sectoral level due to diverse trade structures. China's global VW network was relatively stable from 1995 to 2009. In order to decrease China's WF, sustainable consumption should be advocated, technology with water utilization should be improved, and collaborative policies that target multiple dimensions of environmental and resources management should be proposed.

The results of this study show some significant insights for managing WF and trade at international, national, and sectoral levels. Policies affecting the facility level to international trade agreements can all influence the trading relationship. Although water is one of the world's most sensitive and important resources, especially at the global level, it is not clear that any countries or trade agreements focus specifically on the WF of products, materials, and commodities that are traded. This paper sought to show through some evidences and findings that trade can greatly affect and be affected by WF.

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Reference

Acquaye A, Feng K, Oppon E, Salhi S, Ibnmohammed T, Genovese A, et al. Measuring the environmental sustainability performance of global supply chains: A multi-regional input-output analysis for carbon, sulphur oxide and water footprints. Journal of Environmental Management 2016;187:571-85.

Albrecht TR, Crootof A, Scott CA. The Water-Energy-Food Nexus: A systematic review of methods for nexus assessment. Environmental Research Letters 2018; 13(4): 1-26.

Allan JA. 'Virtual water': a long term solution for water short Middle Eastern economies? Paper presented at the 1997 British Association Festival of Science, University of Leeds, 1997.

Bae J, Dall'erba S. Crop production, export of virtual water and water-saving strategies in Arizona, Ecological Economics 2018; 146: 148-156.

Blondel VD, Guillaume JL, Lambiotte R, Lefebvre E. Fast unfolding of communities in large networks. Journal of Statistical Mechanics Theory & Experiment 2008; 2008: 155-168.

Cazcarro I, Duarte R, Sánchez-Chóliz J. Water flows in the Spanish economy: agri-food sectors, trade and households diets in an input-output framework. Environmental Science & Technology 2012; 46: 6530.

Chapagain AK, Hoekstra AY. Virtual Water Trade: A Quantification of Virtual Water Flows Between Nations in Relation to International Crop Trade. Water Research Report Series. IHE Delft. 2002.

Chapagain AK, Hoekstra AY. Virtual Water Flows Between Nations in Relation to Trade in Livestock and Livestock Products. 2003.

Chapagain AK, Orr S. UK Water Footprint: the impact of the UK's food and fibre consumption on global water resources. 2008; 1.

Chen GQ, Han MY. Virtual land use change in China 2002-2010: Internal transition and trade imbalance. Land Use Policy 2015; 47: 55-65.

Chen W, Wu S, Lei Y, Li S. China's water footprint by province, and inter-provincial transfer of virtual water. Ecological Indicators 2017a; 74: 321-333.

Chen W, Wu S, Lei Y, Li S. Virtual water export and import in china's foreign trade: A quantification using input-output tables of China from 2000 to 2012. Resources Conservation & Recycling 2017b.

Chen ZM, Chen GQ. Virtual water accounting for the globalized world economy: National water footprint and international virtual water trade. Ecological Indicators 2013; 28: 142-149.

Chenoweth J, Hadjikakou M, Zoumides C. Quantifying the human impact on water resources: a critical review of the water footprint concept. Hydrology and Earth System Sciences 2014; 18(6): 2325-2342.

Dalin C, Konar M, Hanasaki N, Rinaldo A, Rodrigueziturbe I. Evolution of the global virtual water trade network. Proceedings of the National Academy of Sciences of the United States of America 2012; 109: 5989-94.

Deng G, Ma Y, Li X. Regional water footprint evaluation and trend analysis of China-based on interregional input–output model. Journal of Cleaner Production 2016; 112: 4674-4682.

Dietzenbacher E, Velázquez E. Analysing Andalusian virtual water trade in an input-output framework. Regional Studies 2007; 41: 185-196.

Dong H, Geng Y, Fujita T, Fujii M, Hao D, Yu X. Uncovering regional disparity of China's water footprint and inter-provincial virtual water flows. Science of the Total Environment 2014; 500-501: 120-130.

Dong H, Geng Y, Sarkis J, Fujita T, Okadera T, Xue B. Regional water footprint evaluation in China: a case of Liaoning. Science of the Total Environment 2013; 442: 215-224.

Duarte R, Pinilla V, Serrano A. The water footprint of the Spanish agricultural sector: 1860-2010. Ecological Economics 2014; 108: 200-207.

Ercin AE, Hoekstra AY. Water footprint scenarios for 2050: a global analysis. Environment International 2014; 64: 71-82.

Farnia F, Marcellis-Warin ND, Warin T. Technical Barriers to Trade: A Canadian Perspective on Ecolabelling. Global Economy Journal 2018; 18(1): 1-21.

Feng K, Siu YL, Guan D, Hubacek K. Assessing regional virtual water flows and water footprints in the Yellow River Basin, China: A consumption based approach. Applied Geography 2012; 32: 691-701.

Gao C, Sun M, Shen B. Features and evolution of international fossil energy trade relationships: A weighted multilayer network analysis. Applied Energy 2015; 156: 542-554.

Geng Y, Yi J. Integrated water resources planning and management at the industrial park level: a case of TEDA. International Journal of Sustainable Development and World Ecology 2006; 13(1): 37-

51.
Geng Y, Cote R, Fujita T. A quantitative water resource planning and management model for an industrial park level. Regional Environmental Change 2007; 7:123-135.
Geng Y, Doberstein B. Developing the circular economy in China: Challenges and opportunities for achieving 'leapfrog development'. International Journal of Sustainable Development & World Ecology 2008; 15: 231-239.
Geng Y, Tian X, Sarkis J, Ulgiati S. China-USA Trade: Indicators for Equitable and Environmentally Balanced Resource Exchange. Ecological Economics 2017; 132: 245-254.
Genty A, Arto I, Neuwahl F. Final database of environmental satellite accounts: technical report on their compilation, WIOD Deliverable 4.6, Documentation. http://www.wiod.org/publications/source_docs/Environmental_Sources.pdf 2012.
Giljum S, Lutter S, Bruckner M, Aparcana S. A review and evaluation of available methods and data to calculate footprint-type (consumption-based) indicators for materials, water, land and carbon. Sustainable Europe Research Institute (SERI) 2013.
Han M, Dunford M, Chen G, Liu W, Li Y, Liu S. Global water transfers embodied in Mainland China’s foreign trade: Production-and consumption-based perspectives. Journal of Cleaner Production 2017; 161: 188-199.
Hendrickson C, Horvath A, Joshi S. Economic input-output models for environmental life-cycle assessment. Environmental Science & Technology 1998; 32 (7): 184-191.
Hoekstra AY. The Relations Between International Trade and Freshwater Scarcity. World Trade Organization 2010.
Hoekstra AY, Chapagain AK. Globalization of water: Sharing the planet’s freshwater resources, Blackwell Publishing, Oxford, UK. 2008.
Hoekstra AY, Chapagain AK, Aldaya MM, Mekonnen MM. The water footprint assessment manual: Setting the global standard, Earthscan, London, UK. 2011.
Hoekstra AY, Mekonnen MM. The water footprint of humanity. Proceedings of the National Academy of Sciences of the United States of America 2012; 109: 3232-3237.
Jiang Y, Cai W, Du P, Pan W, Wang C. Virtual water in interprovincial trade with implications for China's water policy. Journal of Cleaner Production 2015; 87: 655-665.
Leach AM, Emery KA, Gephart J, Davis KF, Erisman JW, Leip A, et al. Environmental impact food labels combining carbon, nitrogen, and water footprints. Food Policy 2016; 61: 213-223.
Leontief WW. Quantitative Input-Output Relations in the Economic System of the United States. Review of Economics & Statistics 1936; 18: 105-125.
L'Haridon J, Martz P, Chenéble JC, Campion JF, Colombe L. Ecodesign of cosmetic formulae: methodology and application. International Journal of Cosmetic Science 2018; 40(2): 165-177.
Li H, Liu G, Yang Z, Hao Y. Urban Gray Water Footprint Analysis Based on Input-Output Approach. Energy Procedia 2016; 104: 118-122.
Liu J, Mooney H, Hull V, Davis SJ, Gaskell J, Hertel T, et al. Systems integration for global sustainability. Science 2015; 347(6225): 1258832.
Liu X, Klemeš JJ, Varbanov PS, Čuček L, Qian Y. Virtual carbon and water flows embodied in international trade: areview on consumption-based analysis. Journal of Cleaner Production 2017; 146: 20-28.
Liu Z, Davis SJ, Feng K, Hubacek K, Liang S, Anadon LD, et al. Targeted opportunities to address the climate-trade dilemma in China. Nature Climate Change 2015; 1-6.

Mekonnen M, Hoekstra A. The green, blue and grey water footprint of crops and derived crop products. Value of water research report series no.47, volume I and II. Unesco-IHE, Delft, the Netherlands. 2010.

Peters GP, Minx JC, Weber CL, Edenhofer O. Growth in emission transfers via international trade from 1990 to 2008. Proceedings of the National Academy of Sciences 2011; 108: 8903-8908.

Postle M, George C, Upson S, Hess T, Morris J. Assessment of the efficiency of the water footprinting approach and of the agricultural products and foodstuff labelling and certification schemes. Report for the European Commission, DG Environment. 2012.

Rodriguez CI, Galarreta VARD, Kruse EE. Analysis of water footprint of potato production in the pampean region of Argentina. Journal of Cleaner Production 2015; 90: 91-96.

Rost S, Gerten D, Bondeau A, Lucht W, Rohwer J, Schaphoff S. Agricultural green and blue water consumption and its influence on the global water system. Water Resources Research 2008; 44(9): 137-148.

Schyns JF, Booij MJ, Hoekstra AY. The water footprint of wood for lumber, pulp, paper, fuel and firewood. Advances in Water Resources 2017; 107: 490-501.

Schyns JF, Hoekstra AY. 2014. The added value of water footprint assessment for national water policy: a case study for Morocco. PLoS One 2014; 9(6): 1-14.

Shi J, Liu J, Pinter L. Recent evolution of China's virtual water trade: analysis of selected crops and considerations for policy. Hydrology & Earth System Sciences Discussions 2014; 10: 11613-11641.

Skouteris G, Ouki S, Foo D, Saroj D, Altini M, Melidis P, et al. Water footprint and water pinch analysis techniques for sustainable water management in the brick-manufacturing industry. Journal of Cleaner Production 2018; 172: 786-794.

Symeonidou S, Vagiona D. The role of the water footprint in the context of green marketing. Environmental Science and Pollution Research 2018; 1-13.

Timmer MP, Dietzenbacher E, Los B, Stehrer R, Vries GJ. An Illustrated User Guide to the World Input–Output Database: the Case of Global Automotive Production. Review of International Economics 2015; 23: 575-605.

Tukker A, Bulavskaya T, Giljum S, Koning AD, Lutter S, Simas M, et al. Environmental and resource footprints in a global context: Europe’s structural deficit in resource endowments. Global Environmental Change 2016; 40: 171-181.

Tukker A, Dietzenbacher E. Global multiregional input-output frameworks: an introduction and outlook. Economic Systems Research 2013;25:1-19.

Vanham D, Mekonnen MM, Hoekstra AY. The water footprint of the EU for different diets. Ecological indicators 2013; 32:1-8.

Wang Z, Huang K, Yang S, Yu Y. An input-output approach to evaluate the water footprint and virtual water trade of Beijing, China. Journal of Cleaner Production 2013; 42: 172-179.

Yang H, Pfister S, Bhaduri A. Accounting for a scarce resource: virtual water and water footprint in the global water system. Current Opinion in Environmental Sustainability 2013; 5: 599-606.

Zhang C, Anadon LD. A multi-regional input-output analysis of domestic virtual water trade and provincial water footprint in China. Ecological Economics 2014; 100: 159-172.

Zhang Y, Zhang J, Tang G, Chen M, Wang L. Virtual water flows in the international trade of agricultural products of China. Science of the Total Environment 2016; 557-558: 1-11.

Zhang Y, Zhang J, Wang C, Cao J, Liu Z, Wang L. China and Trans-Pacific Partnership Agreement countries: Estimation of the virtual water trade of agricultural products. Journal of Cleaner Production 2017; 140: 1493-1503.

Zhang Y, Zhang JH, Tian Q, Liu ZH, Zhang HL. Virtual water trade of agricultural products: A new perspective to explore the Belt and Road. Science of the Total Environment 2018; 622-623: 988-996.

Zhang Z, Yang H, Shi M. Analyses of water footprint of Beijing in an interregional input-output framework. Ecological Economics 2011; 70: 2494-2502.

Zhuo L, Mekonnen MM, Hoekstra AY. Sensitivity and uncertainty in crop water footprint accounting: a case study for the Yellow River basin. Hydrology & Earth System Sciences 2014; 11: 2219-2234.

Zhuo L, Mekonnen MM, Hoekstra AY. The effect of inter-annual variability of consumption, production, trade and climate on crop-related green and blue water footprints and inter-regional virtual water trade: A study for China (1978-2008). Water research 2016; 94: 73-85.