Environment International 121 (2018) 178–188

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Evolution of China's water footprint and virtual water trade: A global trade assessment

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ARTICLE INFO

Handling Editor: Yong Guan Zhu

Keywords:
Water footprint
Global supply chain
Cluster analysis
Virtual water trade
China

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.

1. 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

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https://doi.org/10.1016/j.envint.2018.09.011
Received 5 July 2018; Received in revised form 22 August 2018; Accepted 6 September 2018

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., 2017). 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; Z. Liu et al., 2015; J. 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., 2018; 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., 2017; 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, 2017, 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 was 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., 2018). 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 among 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.