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Embodied agricultural water use in China from 1997 to 2010

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ABSTRACT

Water is an important element in agricultural production. The recent population growth, rapid urbanization, and fast industrialization present increasing challenges for China's agricultural water use. Embodied water has been promoted as a substantial indicator for the assessment of water consumption induced by human activities. However, few studies have investigated the dynamic change in embodied agricultural water use by time-series data. The findings of such studies may facilitate the development of comprehensive sustainable water-usage strategies. Thus, this study quantifies the embodied agricultural water trade, as well as production- and consumption-based agricultural water footprints in China by using an input–output model during 1997–2010. According to the results, China's average embodied agricultural water intensity shows a declining trend from 43.33 m^3/thousand Yuan in 1997 to 32.66 m^3/thousand Yuan in 2010. The average embodied agricultural water intensity of the primary industry is larger than those of the secondary and tertiary industries. China has always been a net exporter of agricultural water. At the industrial level, the primary industry is a net importer because of the increasing food demand in China, the secondary industry has consistently been a net exporter, and the tertiary industry has maintained a trade balance. The production- and consumption-based embodied agricultural water uses demonstrate similar changing trends: both decrease from 1997 to 2007 and then significantly increase in 2010. The embodied agricultural water consumed by the primary industry shows a downward trend, whereas those consumed by the secondary and tertiary industries demonstrate an opposite trend. Therefore, in addition to the improvement of agricultural water efficiency, adjustments in consumption and trade structure are highly instrumental to the conservation of local agricultural water resources.

1. Introduction

China feeds 21% of the world's population with only 6.5% of the world's freshwater (UNOHCHR, 2010). The country's per capita natural freshwater availability is reduced to less than 2000 m^3/year and its available water resources are predicted to be fully exploited by 2030 (CWR, 2010). Owing to water scarcity, the effective use of water resources has significant importance in achieving sustainable development (Liu and Yang, 2010; Oki and Kanae, 2006). Water is a fundamental element in agricultural production. As the most water-intensive industry, agriculture accounts for 70% of the total freshwater consumption (Molden, 2007). Moreover, the agricultural water requirements of China will greatly increase with increasing food demand caused by the growing population, rapid urbanization, and fast industrialization. To protect China's agricultural water resources, the Chinese Government imposed in 2010 the "three red line" restriction policy to achieve efficient control of water quantity, efficiency, and quality. The irrigation water use efficiency of 60% is targeted by 2030 (State Council, 2012). The manner of implementing sustainable water use into the government's strategy to secure the future water supply of China has become a key scientific problem.

A comprehensive understanding of water use is the indispensable foundation for developing an effective water management strategy. Virtual water is a useful concept for understanding the total (including direct and indirect) water consumption (Allan, 1993). Interchangeable with "embodied water" and "exogenous water", this concept refers to the total water required for the whole production process of goods or services (Hoekstra and Hung, 2003; Wang et al., 2013). Input–output (IO) analysis (IOA), as a top-down method, has been widely applied in the field of virtual water accounting (Dietzenbacher and Velázquez, 2007; Wang et al., 2013). IOA provides a quantitative solution to represent the virtual water flows accompanied by monetary transactions for goods or services

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in an interconnected and interdependent economy (Costanza, 1980). Most studies on virtual water are related to food production due to its very large proportion of total water consumption (Spiess, 2014; Vanham, 2013; Wang et al., 2014a, 2014b; Wichelns, 2001). These findings provided a host of valuable policy recommendations to address issues of water scarcity and food security. Considering China's situation, virtual water studies have flourished recently and the research scope has been widely extended to various scales, that is, country (Guan and Hubacek, 2007; Zhang and Anadon, 2014), region (Wang et al., 2013), river (Chen et al., 2009; Feng et al., 2012), project (Meng et al., 2014; Shao and Chen, 2013) and product (Tian, 2013). As regards China's agricultural water utilization, the water footprints of various agricultural products in China, such as grain products (Huang et al., 2014) and milk products (Wang et al., 2014a), have been widely estimated. However, studies on the total embodied agricultural water use in China are still lacking. Few studies have investigated the dynamic changes in the embodied agricultural water use in China, an understanding of which may facilitate the development of a sustainable agricultural water-usage strategy in China. Regarding sustainable development strategy, the economy–resource interactions across time, space and organizations have attracted increasingly wide attentions (Liu et al., 2007, 2015; Mooney et al., 2013). It is necessary to consider the economic and water resources effects simultaneously, but not separately. However, there is still a lack of such framework to guide the fulfillment of shared values of Chinese economy and water resources.

To fill the research gap, this study presents an embodiment analysis of China's virtual agricultural water use through time-series IO data during the period of 1997–2010. Temporal changes in agricultural water use efficiency, agricultural water trade pattern, and production-versus consumption-based agricultural water use are specifically calculated and analyzed in this study. The rest of the paper is organized as follows. Section 2 elaborates on the IOA method and the latest available economic and environmental data sources. Section 3 presents the analysis results on China's embodied agricultural water use during 1997–2010. Section 4 discusses some key issues associated with China's virtual agricultural water use. Finally, Section 5 concludes.

2. Method and data sources

Economic globalization has rendered international trade an important way to balance water resource deficit and surplus through resource transfer accompanied by the flows of commodities or services. IOA is a useful method to integrate agricultural water resources into the economic network to reveal water resource flows in/out the concerned economy (Costanza, 1980; Guo et al., 2014). Depending on the research scope, relevant studies can be categorized as single regional IOA (SRIO) and multi-regional IOA (MRIO). SRIO not only clarifies how water resources are assigned to final consumption but also determines the sources and destinations of virtual water flows. Currently, SRIO has been widely employed at national and regional levels (Chen and Chen, 2015; Duarte et al., 2002; Guo et al., 2012; Lenzen and Foran, 2001; Mubako et al., 2013). MRIO provides an analysis of virtual water flows not only in different sectors but also in various regions (Guo and Shen, 2014; Wiedmann, 2009). Studies focusing on interregional virtual water flows have been conducted by many researchers (Ewing et al., 2012; Wang et al., 2009; Zhang and Anadon, 2014; Zhang et al., 2011a). In the time-series analysis of virtual water flows within a targeted region, SRIO is applicable for discussing the changing trend of virtual water flows. In this study, China's embodied agricultural water flows during 1997–2010 are estimated by using SRIO. The detailed algorithm and data sources are described in this section.

2.1. Algorithm

To calculate and compare the virtual water flows accompanied by various economic activities, such as production, consumption, and trade activities, an ecological IO table (Table 1) whose origin dates back to Odum's ecological and general systems theory (Odum, 1983, 2000) is established. This table is composed of two parts, namely, the traditional economic IO table and the direct sectoral agricultural water use table.

On the basis of the sectoral biophysical balance and IO model, the virtual water flow process within the economic network can be described as follows: water resources are directly incorporated into agricultural production activities and are then entered into the interconnected and interdependent economy in the form of virtual water flows hidden in agricultural products. To quantify virtual water flows in various economic activities, embodied agricultural water intensity is first proposed and defined as the sum of direct and indirect agricultural water use in the whole supply chain to produce the per unit monetary value of targeted commodities or services (Yang et al., 2013). Embodied agricultural water flows in economic activities are obtained as the product of economic values and corresponding embodied agricultural water intensities.

2.1.1. Embodied agricultural water intensity

The sectoral biophysical balance for the embodied agricultural water flows can be formulated as follows:

$$\varepsilon_j x_j = \sum_{i=1}^{n} \varepsilon_j z_{ij} + w_j, \tag{1}$$

where

ε_j is the embodied agricultural water intensity of commodities or services from Sector j,
x_j represents the economic value of total output from Sector j,
z_{ij} is the economic value of intermediate inputs from Sector i to Sector j, and

Table 1
Basic structure of the ecological IO table for agricultural water (revised from Chen et al. (2010)).

Input		Output						
		Intermediate use				Final consumption	Export	Total output
		Sector 1	Sector 2	⋮	Sector n			
Intermediate input	Sector 1	z_{11}	…		z_{1n}	f_1	e_{x1}	x_1
	Sector 2	⋮	…		⋮	⋮	⋮	⋮
	…							
	Sector n	z_{n1}	…		z_{nn}	f_n	e_{xn}	x_n
Direct agricultural water use		w_1	…		w_n			