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Analysis

A multi-regional input–output analysis of domestic virtual water trade and provincial water footprint in China

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ABSTRACT

China's booming economy has brought increasing pressures on its water resources. The water scarcity problem in China is characterized by a mismatch between the spatial distributions of water resources, economic development and other primary factors of production, which leads to the separation of production and consumption of water-intensive products. In this paper, we quantify the scale and structure of virtual water trade and consumption-based water footprints at the provincial level in China based on a multi-regional input–output model. We found that virtual water withdrawals and consumption embodied in domestic trade amounts to 184 billion m^3 and 101 billion m^3 in 2007, respectively, which is equivalent to 38% and 39% of national total fresh water withdrawals and consumption, respectively. Virtual water trade embodied in domestic trade is about two times as much as virtual water embodied in China's international exports. Water footprint in all four municipalities, i.e., Beijing, Tianjin, Shanghai and Chongqing, depends heavily on virtual water inflow from other provinces. China has a north-to-south net VWT pattern which is roughly the opposite of the distribution of its water resources. In addition to water efficiency improvement measures, re-shaping the water-trade nexus can be a significant complementary tool to address local water scarcity problems.

1. Introduction

China is facing serious water resources shortages as a result of the dual-stresses of decreasing availability of water resources (both in terms of quantity and quality) and of its ever-increasing water demand driven by its rapid industrialization and urbanization (Cheng et al., 2009; Jiang, 2009; Liu and Yang, 2012; Zhu et al., 2001). The overexploitation of some major river basins has already resulted in rivers being cutoff and the depletion of underground aquifers. For example, in China's Haihe river basin (its most water deficient basin), all 21 major trunk tributaries have experienced long periods of cutoff of more than 200 days per year on average since the 1980s (Li et al., 2006). Cumulatively, the overdraft of groundwater in the Haihe River Plain amounted to 130 billion m^3 since the 1950s, which led to up to 100 m in the drawdown of groundwater level (Werner et al., 2013). On the other hand, the competition for limited water resources among agriculture, industry and domestic water use is expected to become even more intensive in the future. Water shortage is a major challenge to China's food security in the 21st century as increasing income and changing diets are expected to contribute to a growing food demand in China (Gao and Hu, 2011). China's rapidly expanding energy sector is also thirsty for water. The availability of water resources is regarded as the biggest limitation to the construction of additional large-scale coal mines and coal-fired electricity plants in the arid northern China as proposed in the national energy development plans (Green Peace, 2012; NDRC, 2012).

Water scarcity in China is characterized by two prominent spatial features. First, there is a huge discrepancy between the spatial distribution of water resources and the spatial distribution of population and economic development. For example, the North, Northeast and Northwest parts of China account for 57% of land area, but only 15% fresh water resources. The East, Central & South areas, with 43% of fresh water resources, have 57% of China's population and contribute to 64% of GDP (See Appendix A for region classification). Second, there is a mismatch between the location of water resources and other primary factors of production, such as arable land and fossil fuel resources. For example, more than half of the wheat output in China is produced in the North China Plain (e.g., Hebei, Shanxi, Shandong and Henan account for 57% of the total wheat output in China in 2010), which is heavily dependent on groundwater irrigation in winter (MOA, 2011). The over-exploitation of groundwater for irrigation has become a major challenge to sustainable social-economic development in the arid North region,

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causing severe adverse impacts on the environment and ecosystems through rivers drying up, land subsidence, and sea water intrusion (Foster et al, 2004; Zheng et al, 2010). Both of these features contribute to the fact that production and consumption of water-intensive products are to a large extent separated, and water-intensive products are not always produced in water abundant regions. Therefore, interpreting the water scarcity problem from the perspective of the water-trade nexus (Allan, 2003) is helpful for understanding the driving forces behind local water use in China. Virtual water trade (VWT) and water footprint (WF) are two powerful accounting tools mapping the linkages between consumption behavior, trade activities, and anthropogenic water use.

The aim of this research is to investigate how domestic inter-provincial trade shapes China's virtual water trade pattern and to reveal the spatial and structural characteristics of the provincial water footprint by final use category and by product in China. Section 2 gives a brief review of studies on VWT and WF with a special focus on China. Section 3 introduces the basic methodology of the MRIO model used in this study, and the sources of water withdrawal and consumption data. The results are presented in Section 4 in three aspects: (1) a comparison of the magnitude and composition of China's inter-provincial and export-embodied virtual water flows; (2) the water footprint by province and its relationship to regional water resource availability and economic development; and (3) the spatial pattern of virtual water trade within China. Finally, Section 4 discusses policy implications and suggestions for future research.

2. A Review of Studies on Virtual Water Trade and Water Footprint

The term “virtual water” was introduced by Allan in the 1990s (Allan, 1998) and referred to water used to produce agriculture products that are internationally traded. The traditional approach to assessing VWT embedded in one product is to multiply the trade volume of the product by the product's water intensity. Both water withdrawal and water consumption embedded in VWT can be analyzed within this framework by using different water withdrawal or consumption coefficient per unit output. Significant work has been devoted to estimating the virtual water content of different crops in different countries (Chapagain and Hoekstra, 2003), to quantify VWT between nations and regions via international trade (Hoekstra and Chapagain, 2007; Hoekstra and Hung, 2002; Dalin et al., 2012; Oki and Kanae, 2004), and to investigate the water savings realized through VWT (Chapagain et al., 2006).

Hoekstra and Hung (2002) introduced the concept of water footprint, defined as the sum of domestic water use and net VWT imported into a country. According to this widely accepted concept, water footprint refers in particular to consumptive water use (Hoekstra et al, 2011). This indicator includes water consumption both inside and outside a country, but associated with final consumption of products and services in that country. Many studies have revealed the relationship between the structure of local consumption, trade patterns and the resulting water footprint of specific sectors in specific countries, e.g., the Netherlands (Oel et al., 2009), France (Ercin et al., 2013), and the United Kingdom (Yu et al., 2010). Other studies have established a more comprehensive picture of water footprint by nations at the global scale (Dalin et al., 2012; Hoekstra and Chapagain, 2007; Mekonnen and Hoekstra, 2011; Ridoutt and Pfister, 2010). Studies on VWT and WF have catalyzed the need to re-think a country's water demand from the perspective of consumption rather than production.

The combination of environmental extended input–output analysis (EIOA) with traditional WF analysis has enabled recent progress in water footprint research (Ewing et al., 2012; Turner et al., 2007; Wiedmann et al., 2007). In contrast to the bottom-up WF accounting, which only considers direct water use in production, water footprints calculated using input–output models include both direct and indirect water use along the complex supply chain of producing a specific product for final consumption (Lenzen et al, 2013).

An important conclusion from studies on VWT is that international VWT in many cases does not follow the spatial pattern of fresh water resource availability. Kumar and Singh (2005) compared the VWT of 146 countries and found that some water abundant countries are net importers of food with high water intensities while some water-scarce countries are net exporters. Dabrowski et al. (2009) concluded that the trade of agriculture products is more likely to be driven by crop productivity rather than water scarcity in a country. At a national level, in a study of inter-state VWT in India, Verma et al. (2009) also concluded that interstate virtual water flows moved from water scarce to water rich regions in India, which is exacerbating scarcity in water scarce regions.

In terms of China, some previous studies have focused on VWT embodied in agriculture products using bottom-up crop-by-crop accounting frameworks, e.g., Liu et al. (2007); Ma et al. (2006); Liu and Savenije (2008) and Zeng et al. (2012). Quite a lot EIOA-based studies with different spatial resolutions have emerged in recent years. Most studies focus on the water footprint of cities (see e.g., Wang et al. (2013) and Zhang et al. (2012) for the study on the water footprint of Beijing), provinces (see e.g., Dong et al. (2013) for Liaoning province), river basins (see e.g., Zhao et al. (2010) for a study of the Haihe river basin), sub-national regions (see e.g., Guan and Hubacek (2007) for VWT between north and south China) or the entire nation (see e.g., Hubacek et al. (2009); Zhao et al. (2009) and Zhang et al. (2011a)). Only a few studies have used multi-regional input–output (MRIO) tables and considered domestic trade. For example, Zhang et al. (2011b) quantified the WF of Beijing using a 30-region 33-sector MRIO table of China for 2002. In the study of VWT of the Yellow river basin, Feng et al. (2012) constructed a 4-region 48-sector MRIO table comprising of the upper, middle and lower sections of Yellow river basin and the rest of China.

Existing studies on China have two main limitations: 1) studies based on single region input–output (SRIO) tables fail to include the full supply chain of China's domestic inter-regional trade, therefore they are not able to fully reveal the spatial differences of economic development, water resource availability and water footprint in China; and 2) studies based on MRIO tables either have coarse spatial resolution or are incomplete in the water use inventory. For example, Zhang et al. (2011b) used the sectoral water withdrawal quotas of Beijing for all other provinces, and do not calculate actual water withdrawals or consumption by province. Therefore, the full picture of inter-provincial VWT in China is still missing. This study overcomes these two limitations by incorporating China's latest MRIO table, which includes a detailed dataset of water withdrawals and consumptive water use by sector and by province.

3. Methodology and Data

3.1. Mathematic Form of MRIO Model

Multi-regional input–output models are an extension of single region IO models in that they reflect the inter-regional trade of commodities and services. The corresponding resource and environmental impacts resulting from consumption activities in one region can be traced to specific production sectors in other regions through the inter-regional supply chain (Wiedmann, 2009; Wiedmann et al., 2007). We now turn to describing the implementation of the MRIO methodology in this application.

Assume that there are R regions and each region is divided into N sectors (each sector produces a homogenous product). The balance of production activities in region r can be expressed as Eq. (1), i.e., the total output in each sector equals the output used as intermediate input plus the output used as final consumption:

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

where, x^r is an $N \times 1$ column vector of output in region r; A^{rr} is an $N \times N$ local direct requirement matrix of region r; each element in matrix A^{rr},