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Virtual water flows of grain within China and its impact on water resource and grain security in 2010

Y.B. Wang[a,b,c,d], P.T. Wu[a,b,c,*], X.N. Zhao[b,c], B.A. Engel[d]

[a] Key Laboratory for Agricultural Soil and Water Engineering in Arid Area of Ministry of Education, Northwest A&F University, Yangling, Shaanxi 712100, PR China
[b] Institute of Water Saving Agriculture in Arid Regions of China, Northwest A&F University, Yangling, Shaanxi 712100, PR China
[c] Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100, PR China
[d] Department of Agricultural and Biological Engineering, Purdue University, West Lafayette, IN 47906, USA

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ABSTRACT

Virtual water (VW) is a useful tool to help solve water crises, ecological degradation and grain production issues. Research on virtual water flow (VWF) of grain is conducive to quantifying the spatial distribution of grain production and consumption, and highlighting water use, consumption and transfer paths in the process of production and consumption. Based on the analyses of water use and grain yield, consumption, allocation and transfer, this paper calculated VWFs of 31 provincial level administrative units, and compared VWFs among eastern, central and western China, as well as between southern and northern China. The results showed the total amount of VWFs related to grain among the 31 provincial level administrative regions was 113.8 Gm^3 (green water and blue water; green water: soil water originating from rainfall; blue water: irrigated water abstracted from ground or surface water systems) in 2010, and 45.0 Gm^3 for blue water. The relatively developed eastern China imported 83.5 Gm^3 VW from the undeveloped mid-west, and 33.2 Gm^3 for blue water. Southern China, a water abundant region, imported 77.5 Gm^3 VW from water-short northern China, and 30.7 Gm^3 for blue water. VW usually flows from water-poor regions to water-rich regions and from regions with high water use efficiency for grain production to regions with low water use efficiency within China. For the nation, VWFs saved about 57.9 Gm^3 water in 2010, and 47.9 Gm^3 for blue water, which means that higher-opportunity-cost blue water was saved more than green water. However, because grain production is a water-intensive and low-income endeavor, VWFs related to grain have placed tremendous pressures on water resources and ecosystems in virtual-water exporting areas, and resulted in negative impacts on development of industry and other sectors. Further, VWFs related to grain have set off a serious threat to food security. Therefore, we suggest charging fees to beneficiaries of VWFs related to grain, and making some economic compensation to exporting areas, thereby promoting the recovery and development of grain production in virtual-water importing areas, and improving the enthusiasm for growing grain and ability for investment in agricultural water-saving technologies in virtual-water exporting areas.

1. Introduction

With the world's largest population (1.3 billion) and the second-largest national economy, water shortages in China could shake world food security and threaten global prosperity (Brown, 1995; Cheng et al., 2009; Shalizi, 2006; Wang et al., 2012). Therefore, the issues of water supply and grain production have always been a crucially important concern for the Chinese government and people (Liu et al., 2008; Yang, 1998). Furthermore, these issues have drawn more and more international attention because China and the rest of the world are increasingly connected, both economically and environmentally (Blanke et al., 2007; Brown and Halweil, 1998; Cai and Ringler, 2007; Khan et al., 2009; Nickum, 1998; Smil, 1995; Tso, 2004).

In China, traditional grain producing areas are mainly located in the middle-east where the land is relatively flat, especially the

* Corresponding author at: College of Water Resources and Architectural Engineering, Northwest A&F University, Yangling 712100, PR China.
Tel.: +86 29 87082802; fax: +86 29 87082802.
E-mail addresses: wyb0406@sina.com (Y.B. Wang), gjzwpt@vip.sina.com (P.T. Wu).

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southern portion of the middle-east because of the relatively adequate water resources. There was a saying 'After harvest both in Hunan and Hubei, the whole country will have sufficient', which indicates the grain production of two provinces in the southern portion of the middle-east was crucial for China's food safety in the past (Ma et al., 2006; Wu et al., 2010). However, since the economic reform, began in 1978, eastern China, which is close to the sea, especially the southeast, has experienced rapid economic development due to its geographical advantages. The changing structure of the economy, i.e., industrialization and urbanization, creates a situation where land is the focus of intense competition. The rare agricultural land in these regions is under pressure of being used for building or road construction (Chen, 2007; Jin and Young, 2001; Lin and Ho, 2003; Varis and Vakkilainen, 2001; Yang and Li, 2000). Therefore, the center of China's grain production has experienced a gradual westward, northward shift. As a result, the north of the middle-west has become a major production and export area of grain, and the south of the eastern region has become a major importing area (Yang, 1998).

Grain production is a water-intensive and low-income endeavor, and as its center transfers geographically, what impacts would be brought on regional water resources, ecosystem, grain security and economic development in China (Yu et al., 2011)? Furthermore, what measures can be taken to relieve the negative impacts? There is great significance to answer these questions for alleviating China's water resources pressure and supporting food security.

VW as a tool provides methods and ideas to solve such problems. VW is an important concept, which is the amount of embedded freshwater used to produce agricultural and industrial goods proposed by Tony Allan in 1993 (Allan, 1993, 1994, 2003). The proposed VW are changing the traditional idea of water management that only focuses on the use and distribution of the entity water. We must also consider the important role of VW in the form of regional production, consumption and redistribution (Hoekstra and Chapagain, 2007; Oki and Kanae, 2004). To assess water scarcity, there are three ameliorating processes using VW tools. First, the global role of VW in water-shortage regions, then, the impact of socio-economic development on water management options, and finally, the cultural specificity of water demand management policies. All three processes have the characteristics of being economically invisible and politically silent in the easily politicized management of water (Allan, 2007).

VWFs can help water-scarce regions solve water problems by importing water-intensive commodities which are usually agricultural products, and it can achieve water savings at a global scale (Aldaya et al., 2010; Chapagain et al., 2006). The global volume of crop-related international VWFs between nations was 695 Gm^3/yr on average for the period 1995–1999, and this means that 13% of the water used for crop production in the world is not used for domestic consumption but for export (in virtual form) (Hoekstra and Chapagain, 2008; Hoekstra and Hung, 2002, 2005; Liu and Yang, 2010; Rockström and Gordon, 2001). To the regions that import products, these regions' water savings are equal to the import product amount multiplied by the product water footprint (the amount of water consumed per unit of product, which contains blue water and green water, m^3/kg; green water: soil water originating from rainfall; blue water: irrigated water abstracted from ground or surface water systems) of the domestic commodity. VFWs are beneficial to solving local water deficits such as water-poor areas importing water-intensive products from water-rich regions. For instance, the Middle East's water saving is 30.3 Gm^3/yr by importing crop products, and it is 16.0 Gm^3/yr for Egypt (Allan, 2006; Hoekstra and Hung, 2005). The whole country net effect of VWF between two regions will depend on the actual water volume used in the exporting region in comparison to the water volume that would have been required to produce a commodity in the importing region. There will be net water savings, if the flow is from a region with relatively high water productivity. There can be net additional consumption of water if the transfer is from low to high production sites (Hoekstra and Chapagain, 2008; Chapagain et al., 2006).

However, VWFs not only generate water savings for importing regions but also mean water losses for the exporting regions. Western Europe imported 76 Gm^3/yr VW creating an additional pressure on exporting nations' water resources (Chapagain et al., 2006; Chapagain and Hoekstra, 2007; Hoekstra and Hung, 2005). VWFs will give commodity-exporting areas, especially water-scarce exporting areas, enormous pressure on water resources. VWFs make water competition more prominent between low effective use grain production and other high effective use industries, and may lead to negative impacts on grain production (Chapagain and Orr, 2009; Huang et al., 2009; Jiang, Y., 2009; Novo et al., 2009; Pfister et al., 2009; Ridoutt and Pfister, 2010). Moreover, VW output will impose huge impacts on fragile ecosystems in northern China where ecological degradation has been quite severe, and it will also make ecological restoration more difficult (Ma et al., 2013; Wu et al., 2011; Zhang et al., 2012).

Little is known about regional VWFs of grain within China because previous studies mostly focused on VWFs among countries (Ma et al., 2006; Wu et al., 2010). There are several studies on north-to-south VW transfer. Wu et al. (2010) found that China's traditional southern food transported to the north had been substituted for north-to-south transportation since 1990. They also calculated the blue-water amount of VWF related to grain from 1990 to 2008, and the result showed that the amount was increasing. Ma et al. (2006) calculated and obtained the amount of VWF related agricultural products from the north to the south (52.0 Gm^3) in 1999. Guan and Hubacek (2007) found that it was 4.5 Gm^3 of fresh water virtually flowing out of North China to South China excluding rainwater in agricultural production in 2000. Sun et al. (2013) obtained a result that VWFs only related to wheat, maize and rice reached 30.1 Gm^3 from the north to south within China in 2009. To date, we have found no studies on VWFs between the east, the middle, and the west of China, while the net VWFs can impose large water stress to hinder economic development in the undeveloped middle and west regions.

There are a number of limitations in the previous studies of VWFs within China. One is these studies always calculate evapotranspiration to obtain water footprint (WF) of agricultural products which is the volume of freshwater used to produce products over the full supply chain (Hoekstra et al., 2011), but this method does not take the loss of irrigated water into account. China's irrigated water use efficiency was only 0.5, which means only half of the irrigated water could be transported to the farmland for crop use, in 2010. Therefore, the calculated values of VWF (WF of grain products multiplied by the amount of grain imported or exported) would be lower than the actual values without considering the loss of irrigation water. Secondly, most studies only paid attention to the pressures on water resources in water-scarce north regions which were caused by the export of VW; no analysis of water-saving effects of VWF for the whole country was conducted. Finally, previous studies did not consider the linkages between regional economic development and the VWFs of grain.

This paper aims to calculate the amount of grain reallocation and transfer, agricultural water use efficiency and the VWFs in different regions, and to assess the impacts on water resources, grain security and sustainable development caused by VWFs related to grain. This study has focused on the analysis of VWFs within China. VWFs between China and other countries have not been taken