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Comparison of volumetric and stress-weighted water footprint of grain products in China

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ABSTRACT

The water footprint (WF) concept links physical and virtual forms of water, which can be used for research on the impact on water resources imposed by human consumption or production activities. Debates remain on the calculation methods due to WF being applied for different research purposes, and the large amounts of data required for the calculation being hard to obtain. This paper calculated and compared two WFs called volumetric WF (the volumes of blue and green water are combined with the same weight) and stress-weighted WF (the volumes of blue and green water are combined with different weights) based on water use data to research crop water productivity of grain crops and its impact on water resources in each region of China. Results for volumetric WF and stress-weighted WF of grain products of each region in China differed greatly. In 2010, the average volumetric WF was 1.25 m^3/kg with the blue component 0.53 m^3/kg, and the average stress-weighted WF was 0.51 m^3/kg. In addition, there were significant differences of both kinds of WFs among regions in China. The results showed that volumetric WF could be used as a comprehensive indicator for evaluating crop water productivity, specified in space and time by source (green and blue WFs). Stress-weighted WF could offer a meaningful way of making quantitative comparisons between products, production systems and services in terms of their potential to contribute to water scarcity. The spatial distribution of these two WFs can help decision making to develop water-saving measures, relieve water stress and restore ecosystems for each region in China.

1. Introduction

China is the most populous country (1.3 billion) and the largest country in grain consumption (Hubacek et al., 2007). China's food security is of great significance not only to economic development and social stability in China, but also to peace, stability and development in the world (Huang and Li, 2010a; Wang et al., 2010; Wu et al., 2012). Food production is a high water consumption activity, but China's water resources are relatively scarce; the per capita water resource is only 1/4 of the global average level (Jiang, 2009; Khan et al., 2009; Wu et al., 2010a). Moreover, the spatial distribution of water resources is uneven; the cultivated land of northern China accounts for 60% of the total in China, but the share of water resources is only 17% (Cheng et al., 2009; MWRC (Ministry of Water Resources of China), 2011; Varis and Vakkilainen, 2001; Wang et al., 2012; Yang, 1998). Water shortage and its uneven distribution has been the biggest threat to China's grain security (Brown and Halweil, 1998; Cheng and Hu, 2012; Ge et al., 2011; Huang and Li, 2010b; Jin and Young, 2001; Martellaro, 1991; Peng, 2011; Wu et al., 2010b). Due to grain production being the largest sector of water consumption in China, the following problems are crucial to be resolved. How to properly evaluate Crop Water Productivity (CWP, expressing the amount of marketable product in relation to the amount of input water, kg/m^3) and is there any room to enhance it (Gao et al., 2014b)? What is the impact on water resources by grain production and how can water stress be relieved in water-scarce regions? And how can regional ecosystems be protected and ensure sustainable development? The WF concept helps to solve these problems.

The WF tool links physical and virtual forms of water together, which can be used for measuring direct water (water used in physical forms) and indirect water (water used in virtual forms, that is included in consumer goods or raw materials of production)

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together consumed by human consumption or production activities (Hoekstra et al., 2011). Therefore, the WF tool can extend and broaden the evaluation system of conventional water resources (Hoekstra, 2003; Hoekstra et al., 2011). The WF of a product is the volume of freshwater used to produce the product over the full supply chain. It shows water consumption volumes by source (green and blue WFs) and polluted volumes by type of pollution (gray WF), specified in space and time (Hoekstra et al., 2009, 2011).

WF was originally used primarily to study freshwater appropriation due to human consumption of goods and services (Bulsink et al., 2010; Chapagain and Orr, 2009; Fader et al., 2011; Hoekstra and Chapagain, 2007; Hoekstra and Mekonnen, 2012; Liu and Yang, 2010). Subsequently, with a wide application of WF in different research fields, it has been expanded and extended. Currently, WF is being used to study water consumption and pollution by human production or consumption, and it helps clarify how much green and blue water was used or polluted along the supply chain of a product, and indicate crop water productivity and water stress with spatial and temporal dimensions (Chapagain and Hoekstra, 2011; Ercin et al., 2013; Gao et al., 2014b; Steen-Olsen et al., 2012). Furthermore, applications of WF, together with virtual water trades (or flows), has proven that freshwater is a global resource, and wise water governance has a dimension that goes beyond the level of a river basin. Thus, traditional water management has evolved into an innovative approach breaking the boundaries of river basins and has been transformed to consider water globally (Aldaya et al., 2010; Hoekstra and Chapagain, 2008).

Gray water is the freshwater volume required to assimilate the load of pollutants from agricultural nonpoint source pollution, an issue on which significant research such as agricultural nitrogen, phosphorus loss and water pollution has been conducted (Gao et al., 2012, 2013,2014a; Li et al., 2013; Wan et al., 2013), but not water consumption for crop use. This paper neglected the gray WF and focused only on green and blue components of WF in the calculation. Thus, WF includes blue water footprint (BWF, volume of blue water appropriated from surface and groundwater resources), and green water footprint (GWF, volume of green water which is the precipitation stored in the soil and eventually evaporated, transpired or incorporated into plants) (Hoekstra et al., 2011; Ridoutt et al., 2009; Ridoutt and Pfister, 2010).

Some scholars propose that WFs include the actual volume of blue and green water that are the crude summation of more than one form of water consumption (Ridoutt and Pfister, 2010, 2013; Pfister et al., 2009). Pfister and Hellweg (2009) and Ridoutt and Pfister (2010) argued that product WF shares few characteristics compared with product carbon footprint. The carbon footprints of different products can be meaningfully compared, and the greenhouse gases emissions arising from different forms of consumption are additive by weighting various greenhouse gases according to global warming potential. Unfortunately, WFs can't do this because the ratios of blue and green WFs are different for different products and the importance of blue and green components differs greatly. In addition, there is no clear relationship between a WF and potential social and environmental harm: a product with a lower WF could be more damaging to the environment than one with a higher WF if the former was produced in a watershed with more serious water scarcity than the latter. Therefore, Ridoutt and Pfister (2010) proposed a revised approach for water footprint calculation which is to multiply each BWF component by a water-stress index and neglect GWF, because green water use in agriculture does not contribute to water scarcity. Ridoutt and Pfister named this WF stress-weighted WF, and the prior WF with actual volumes of green and blue water volumetric WF (Yang et al., 2013).

Hoekstra et al. (2009, 2011) suggested that the primary and established role of the WF devised as a comprehensive indicator of freshwater appropriation was for water resources management. From a water resources management perspective, it is of great significance that spatially and temporally explicit information on WFs is in actual volumes and impacts in real terms. Data on WFs of products inform the discourse about sustainable, equitable, and efficient freshwater use and allocation (Hoekstra and Chapagain, 2008). Moreover, WF helps to estimate local environmental, social, and economic impacts. Environmental impact assessment should include a comparison of each WF component to available water at relevant locations and time. Volumetric WFs contain highly relevant information, which disappears when translating volumes into stress-weighted impact indices (Hoekstra et al., 2011; Poff et al., 2010).

Both the volumetric WF and stress-weighted WF are significant from their own perspective. There are few research efforts on volumetric WF of grain products in China, and none is on stress-weighted WF. Mekonnen and Hoekstra (2010, 2011) estimated volumetric WF at a 5 by 5 arcmin grid based on a field Evapo-Transpiration (ET) method. Sun et al. (2013) calculated volumetric WF at the scale of provinces based on a field ET method. Therefore, the current research is mainly based on the calculation of ET by an empirical formula as suggested by FAO with average meteorology data for 5–10 years (Hoekstra et al., 2011). The use of average meteorology and crop yield data makes it hard to reflect the temporal change of WF of grain products, a point noted by Hoekstra et al. (2012). This method is a modeling of crop production and water consumption at the field scale, and it does not take into account the loss of irrigation water during the transmission and distribution process from the water sources to the field. Thus, the calculated value of BWF is smaller than the actual value. Hence, when research regions such as a country, a region or a watershed have data on water use, BWF should be calculated based on the actual water use. Thus, the BWF calculated with data on water use could reflect the level of agricultural water use and water stress. Then, the GWF can be calculated with effective precipitation data. The WF calculated with actual water use can evaluate crop water productivity and water stress more precisely, and this will help identify measures to promote crop water productivity and relieve water stress.

This paper provides volumetric and stress-weighted WFs accounting based on water use in China's grain production. It analyses crop water productivity and water stress in different regions by comparing the spatial differences of the two kinds of WFs across different regions in China in 2010. The research using volumetric WF to evaluate crop water productivity and stress-weighted WF to analyze water stress can help decision making to develop water-saving measures, relieve water stress and restore ecosystems for each region in China.

2. Methods and data

2.1. Methods

2.1.1. Study area

The research area of this study is China Mainland excluding Taiwan Province, Hong Kong and Macao (Fig. 1). It consists of 31 Provinces, Autonomous regions and Municipal cities (PAMs). We classified these PAMs into eight regions: North-central (NC), Northeast (NE), Huang-huai-hai (HHH), Northwest (NW), Southeast (SE), Yangtze (YT), South-central (SC) and Southwest (SW) according to their geographic location and conditions of weather, water resources and food production (Wu et al., 2012; Ma et al., 2006). Then NC, NE, HHH and NW were classified as the north, except for the Anhui province which belongs to the HHH region, and the other four regions and Anhui province were considered the south.