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A comprehensive analysis of blue water scarcity from the production, consumption, and water transfer perspectives

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ABSTRACT

The issue of growing water scarcity has been increasingly perceived as a global systemic risk. To solve it, an integrated approach considering different perspectives of water scarcity is at a premise. In this study, we developed an approach to calculate the blue water scarcity (BWS) and integrated the production, consumption, and water transfer perspectives into a single framework. The results are as follows: The average BWS in the Hetao irrigation district was 0.491 during the 2001–2010 year period, which was much larger than the threshold of 0.30, indicating a high water stress level. From the production perspective, the agricultural sector was the largest contributor to regional water scarcity and the average BWS was as high as 0.479. From the consumption perspective, BWS related to virtual water export was much larger than that related to water consumption for making products to be consumed locally and the values were 0.422 and 0.069, respectively. Under the influence of physical and virtual water transfer, BWS changed from 0.242 (medium to high water stress level) to 0.491 (high water stress level). Strategies for reducing agricultural water consumption, such as increasing crop water productivity, improving irrigation efficiency, and promoting more reasonable irrigation water price, could be adopted in the Hetao irrigation district to alleviate regional BWS. Compared with physical and virtual water import, the virtual water export played a more important role in influencing the regional water scarcity, and the increase in crop water productivity, decrease in crop export volume, or adjustment of trade pattern from water-intensive crops to water-extensive ones could be feasible measures to decrease virtual water export for lower water stress, while the trade-offs in the product-consuming regions should be considered.

1. Introduction

Water represents an essential element for humans, and it plays a significant role during the development of human society (Pedro-Monzonís et al., 2015; Vörösmarty et al., 2010). During the last few decades, water scarcity has been increasingly perceived as a global systemic risk, considering the increase in water demand and the limited water supply (Hoekstra et al., 2012; Mekonnen and Hoekstra, 2016). The issue of growing water scarcity has consequently received much attention from researchers worldwide (Hanasaki et al., 2013; Schewe et al., 2014; Veldkamp et al., 2015; Zhang et al., 2015). To solve this issue, an assessment of it is at a premise.

Thus far, many approaches including the water resource vulnerability index (Raskin et al., 1997), water stress index (Falkenmark et al., 1989), International Water Management Institute indicator (Seckler et al., 1998), critical ratio (Alcamo et al., 2000), and the water poverty index (Sullivan, 2002) were used to evaluate regional water scarcity, and many aspects such as water resources, access, and capacity were involved. In addition to these, other different perspectives should be considered to have more information about water scarcity. Vörösmarty et al. (2000) evaluated the global water scarcity from the perspective of production and showed the water scarcity for the domestic and industrial sectors (DI/Q), irrigated agriculture (A/Q), and their combination (DIA/Q) on a mean annual

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basis. Considering the large volume of water resources consumed, water scarcity related to food production was calculated (Kummu et al., 2014; Porkka et al., 2016; Schmitz et al., 2013). Besides the water consumption related to products consumed by local habitants, making the link between specific consumer products in a country to water problems elsewhere visible could help in setting priorities in either national or international context with respect to the most effective measures to reduce water consumption in the region where it is most needed (Ercin et al., 2013). Thus, the perspective of consumption should also be included in the assessment of water scarcity. With the development of the water transfer project and products trade, the transfer of both physical and virtual water has become increasingly common (Lenzen et al., 2013; Yang et al., 2013). Zhao et al. (2015) studied the water scarcity in China from the perspective of water transfer and the effects of virtual water transfer on regional water stress were also reported by Orlowsky et al. (2014) and Sun et al. (2016). Production, consumption, and water transfer could always be seen in the same area, and the complete picture of water scarcity could not be determined by any single perspective. Hence, there is a need for a water scarcity assessment approach that could simultaneously consider the production, consumption, and water transfer perspectives. Such a combined approach could provide more complete information on water scarcity in the world.

In China, irrigated areas have produced more than three-quarters of the grain production and have been serving an increasingly important function for ensuring China's food safety and socioeconomic development (Cao et al., 2012). However, there are few studies on water scarcity at the irrigation district scale (Liu et al., 2015a,b; Soto-García et al., 2013). Thus, the aim of this paper is to evaluate the water scarcity in the Hetao irrigation district, which is one of the most important irrigation districts in China. To accomplish this objective, we developed an approach to calculate the blue water scarcity (BWS) and integrated the production, consumption, and water transfer perspectives into a single framework. The value of BWS was estimated and analyzed from both the production and consumption perspectives. Finally, we compared the actual and hypothetical BWSs to show the effects of water transfer on regional water stress. This study could provide a comprehensive framework for studying water scarcity and ultimately contribute to better production, consumption, and trade strategies.

2. Material and methods

2.1. Study area

The Hetao irrigation district is the largest gravity-fed irrigation district in Asia, with an irrigated area of 5.74×10^3 km^2 (Zhang et al., 2011b). It is located in western Inner Mongolia, China (40°13′–42°28′ N, 105°12′–109°53′E) (Fig. 1(a)), and includes five counties (Dengkou, Hanghou, Linhe, Wuyuan, and Qianqi) (Fig. 1(b)). The district has a continental monsoon climate. Rainfall is scarce (130–215 mm per year) and erratically distributed (70% in July, August, and September), and the annual evaporation is 2100–2300 mm (Ye et al., 2010). The Hetao irrigation district is an important area of agricultural production, and about one-third of the land in this area is occupied by crops (Fig. 1(c)).

In the Hetao irrigation district, about 14% of groundwater is exploited (Yue et al., 2013). Because of the poor quality of wastewater and high cost of wastewater treatment technology, the volume of wastewater reuse in this area is small (about 2 million m^3 per year for the industrial sector and 0.1 million m^3 per year for the agricultural sector) (Liu, 2012; Ren et al., 2014). Besides the local water resources, the water used in this region depends mainly on the water from the Yellow River. The volume of allowable water diversions from the Yellow River to the Hetao irrigation district presents a fluctuating trend during the 2001–2010 year period, and the value in 2010 was 4.61×10^9 m^3, which was 436.70×10^6 m^3 less than that in 2009 (Fig. 1(d)). On the other hand, as much as 4.39×10^9 m^3 of water resources were used in the Hetao irrigation district in 2010 (MWRC, 2010). With rapid socioeconomic development, conflicts between the increasing water demand and the limited water supply have become more severe, which have affected the development in the Hetao irrigation district.

Table 1
The category of BWS.

Category	Value of BWS
Low water stress	<0.1α
Low to medium water stress	0.1α–0.2α
Medium to high water stress	0.2α–0.4α
High water stress	>0.4α

α is the water consumption ratio.

2.2. Methods

In this study, the BWS at the Hetao irrigation district was calculated on the basis of the value of the blue water footprint and blue water resources, and the BWSs were then analyzed from the production, consumption, and water transfer perspectives. The integrated framework for the evaluation of BWS is presented in Fig. 2.

2.2.1. BWS

In this study, the BWS at the irrigation district was calculated using the following equation:

$$BWS = BWF/BWR = BWF/(LWR + PWI + VWI) \quad ,(1)$$

where BWF is the blue water footprint (m^3), which means the consumptive use of surface and groundwater (Hoekstra et al., 2011). Large volumes of water withdrawals typically return to the local water system and become available for reuse; the volume of water consumed consequently provides a more accurate basis for estimating water scarcity than the volume of water withdrawn (Hoekstra et al., 2012); BWR is the regional blue water resources (m^3), and three types of water resources are included for an irrigation district: LWR local water resources (m^3), PWI physical water import (m^3), and VWIvirtual water import (m^3). LWR is estimated by adding the volumes of surface water and groundwater and then subtracting the repeated part of them. PWI means water diversion from the Yellow River to the Hetao irrigation district in this study. With the import of commodities, regions import water in virtual form that is needed for the production of commodities; this is known as virtual water import.

According to the study of ECOSOC (1997), the water stress of an area is low if the ratio of water withdrawal to availability is below 0.1. The water stress is medium if the ratio is 0.2 and is high if the ratio is above 0.4. The value of blue water footprint could be obtained by multiplying the water withdrawal by a water consumption ratio (the proportion of water consumption to water withdrawal) (Cai et al., 2003; Hoekstra et al., 2012; Liu et al., 2016). Consequently, the BWS was categorized as follows in this study (Table 1):

For an irrigation district, not only the value of BWS but also the components of it are of great significance for alleviating regional water scarcity. From the perspective of production, regional water stress could be caused by water consumption in the agricultural, industrial, or domestic sector. The BWSs of different sectors could be calculated as follows:

$$BWS_a = BWF_a/BWR \quad (2)$$