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Original Articles

Changes and driving mechanism of water footprint scarcity in crop production: A study of Jiangsu Province, China

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ABSTRACT

The mitigation of water stress in crop production is important for relieving the growing global water shortage. The water footprint scarcity (WFS) for regional water stress evaluation integrating blue and green water resources and the water footprint of the crop production industry were developed in this paper. Three subregions in China, industry-based southern Jiangsu (SJS), agriculture-based northern Jiangsu (NJS) and middle-type central Jiangsu (CJS), were selected to study the spatiotemporal pattern and driving mechanism of WFS. The results show that green water accounts for 56.6% and 71.8% of agricultural water resources available (AWA) and crop water footprint (CWF) of Jiangsu Province. The WFS of Jiangsu was calculated to be 2.26, and almost all prefectures for every year from 1996 to 2015 faced very high water stress (WFS > 1.20). The WFS value increased in NJS and CJS and decreased in SJS over time; meteorological and social factors affected the WFS at the same time. Land irrigation was the main factor to explain the growing water stress in the agriculture-based NJS. The WFS revealed the water shortage more clearly, especially in the water-poor agriculture-based areas, than the results of the conventional water stress index. The strategies for environmental change adaptation suggested by this study are to use WFS for agricultural water suitability evaluation and water resource management policy formulation; to reduce WFS through irrigation efficiency and crop variety promotion worldwide; and to implement compensation measures for agricultural products and virtual water trade to help underdeveloped agricultural production areas improve their agricultural production technology and control irrigation expansion.

1. Introduction

Water is the essential element for human survival, ecology maintenance and society development (Bakker, 2012; Loo et al., 2012; Pedro-Monzonís et al., 2015). The increased water scarcity caused by human activity and environmental changes has been perceived as a global systemic risk due to the increase in direct and indirect water consumption and the limited water supply during the past decades (Vörösmarty et al., 2000; Schewe et al., 2014; Mekonnen and Hoekstra, 2016). More than 90% of water consumption worldwide is due to the demand of agricultural products (Hoekstra and Mekonnen, 2012). Approximately 69% of freshwater (blue) resources are withdrawn for irrigation in the agricultural sector (FAO 2016), and irrigation demands continue to increase. Furthermore, environmental changes and urbanization will further affect the utilization of water resources in agricultural production systems (Cao et al., 2018a,b). It is of great significance to alleviate the water resource scarcity caused by crop production (Hoekstra et al., 2011).

An evaluation indicator that identifies the relationship between water availability and utilization establishment is a feasible way to understand the impact of human activity on water resources. Falkenmark et al. (1989) proposed a water resource vulnerability index

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and delimited 1700 m^3 per capita as a blue water resource shortage threshold. Raskin et al. (1997) defined water scarcity as the ratio of water use to total water resources available and established the water stress index (WSI). WSI is one of the most commonly used indicators for current water scarcity evaluation (Falkenmark, 2001; Li et al., 2017; Munia et al., 2016; Moe et al., 2014; Nilsalab et al., 2016; Strzepek et al., 2015). Other indicators include the International Water Management Institute indicator, criticality ratio (Alcamo et al., 2000; Alcamo and Henrichs, 2002), water poverty index (Sullivan, 2002), and water exploitation index (Lallana and Marcuello, 2004). Regulations have established environmental reserves of water to be maintained in rivers, implying that rivers are often involved in regional (blue) water scarcity assessment (Hoekstra et al., 2011, Brown and Matlock, 2011; Cazcarro et al., 2016). Green water scarcity is also a concern for scholars (Wanders et al., 2010; Woli et al., 2012; Mu et al., 2013; Schyns et al., 2015). Water footprint (WF), which is a measure of humanity's appropriation of fresh water in volumes of water consumed and/or polluted and is divided into blue, green and gray WFs (Hoekstra and Mekonnen, 2012; Cao et al., 2014; Zhuo et al., 2016a; Gil et al., 2017), can reflect the shortage of blue-green water in terms of quantity and quality. WF can be used to quantify the effect of inhabitant activity in two dimensions: production and consumption (Hoekstra and Mekonnen, 2012; Vanham and Bidoglio, 2013; Zhou et al., 2017). The consumption WF is inseparable from inter-regional virtual water flows (Chen and Chen, 2013; Dong et al., 2014). Water scarcity assessments based on blue-green water, water footprint and virtual water flow have been made in the last decade (Hoekstra et al., 2011, 2012; Cao et al., 2017; Liu et al., 2017). Population growth and changes in inhabitants' dietary structure are the direct cause of regional water footprint and stress (Liu and Savenije, 2008; Wong et al., 2016; Cao et al., 2018b). Increased population and the popularity of meat consumption increase local water stress and increase water scarcity in other areas in the form of virtual water imports. Therefore, the basis of water scarcity caused by virtual water flow is water scarcity caused by production (Zhuo et al., 2016b). Current regional water shortage assessments are rarely premeditated by water availability, especially the green water resource availability (Cao et al., 2017). The literature has presented fertile achievements in the sustainability of blue and green water assessment. However, the conclusion may be one-sided due to the joint action of the two resources being isolated. The scope of water resources considered in scarcity evaluation should be extended, especially for crop production.

Virtual water flow is determined by interregional socioeconomic attributes and the difference in product capacity (willingness). Different measures should be used to relieve water shortages caused by agricultural production in different areas. The driving mechanism of water scarcity must be identified for different types of regions. Analysis of the driving mechanism of water scarcity indicators based on WF has not been reported. The purposes of the current paper are as follows: establishing the water footprint scarcity (WFS) index based on the blue and green water resource framework; analyzing the temporal-spatial patterns of WFS in the Jiangsu Province, China, and identifying the driving factors of WFS in different types of regions to discuss the applicability and mitigation measures of WFS. The results of this study may provide reference for water resource management in different types of regions under the changing environment.

2. Methods and materials

2.1. Study area

Jiangsu Province, located in eastern China (116.30°–121.95° E, 30.75°–35.33° N), is one of the 13 major food producing areas in the country. Jiangsu comprises 13 prefectures (Fig. 1), has an area of 107.2×10^3 km^2 and had a population of 79.8 million in 2015 (Jiangsu Bureau of Statistics, 2016). The per capita water resource available in Jiangsu is only approximately 700 m^3, although China's two main rivers, the Yangtze River and the Huaihe River, flow across the province from west to east. The prefectures are partitioned into three subregions, southern Jiangsu (SJS), Central Jiangsu (CJS) and Northern Jiangsu (NJS), according to geographical location, water resources and economic and agricultural conditions. SJS is located south of the Yangtze River and includes Suzhou, Wuxi, Changzhou, Zhenjiang and Nanjing; CJS is located between the Yangtze River and the Huaihe River and includes Nantong, Yangzhou and Taizhou; NJS is located north of the Huaihe River and includes Xuzhou, Huai'an, Yancheng, Lianyungang and Suqian (Fig. 1). The water resource, economic and agricultural production conditions for the three subregions of Jiangsu in 2015 are listed in Table 1.

2.2. Water footprint scarcity (WFS)

The recognized method for calculating the conventional water stress index (WSI) is the ratio of water use (WU) to the amount of water

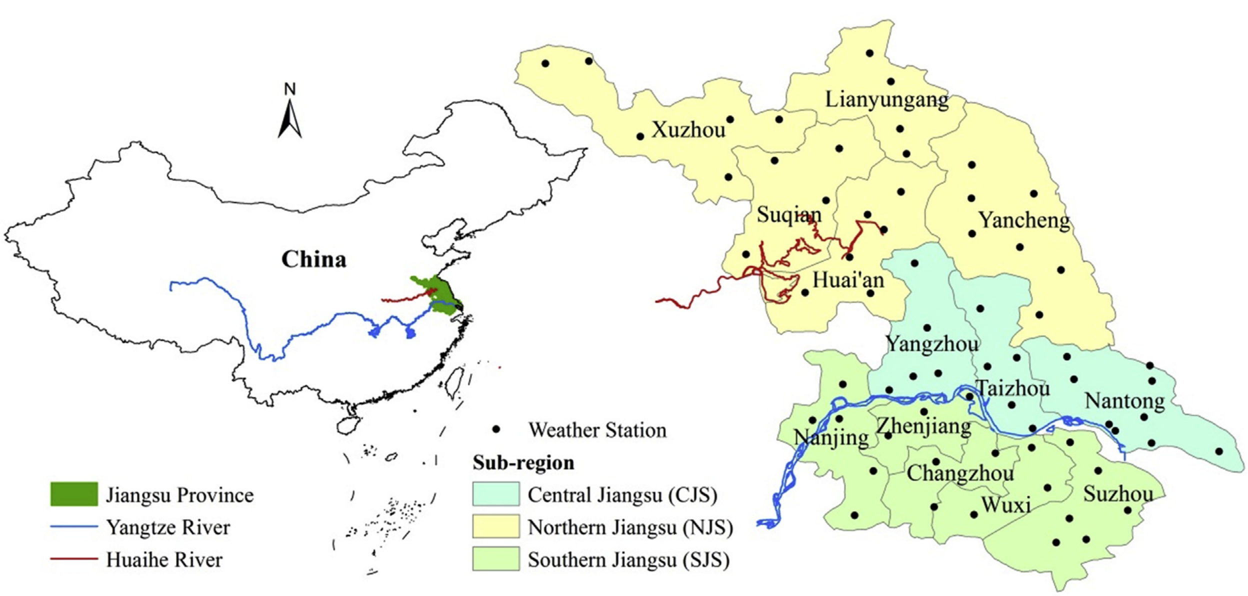

Fig. 1. Location and regional division of Jiangsu Province.