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# Inter-county virtual water flows of the Hetao irrigation district, China: A new perspective for water scarcity

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ABSTRACT

The implementation of a virtual water trading policy at small and localized scales may potentially contribute to alleviating water scarcity and improving local water management. This study analyzed inter-county virtual water flows related to crop transfer and its relationship with water scarcity in the Hetao irrigation district during 2001–2010. The inter-county virtual water flows was 34.29 × $10^6$ $m^3$/y, and the largest exporter and importer were Dengkou and Qianqi counties, respectively. More than 90% of the virtual water flows originated from counties with lower water stress and was transferred to those with higher water stress. The water scarcity index (the ratio of water withdrawal to availability) was negatively correlated with virtual water balance (the difference between virtual water exports and imports). Counties with relatively high water stress benefited from the current pattern of virtual water flows, but the Hetao irrigation district lost 1.96 × $10^6$ $m^3$ of water annually. In the future, a more accurate evaluation of virtual water flows and a comprehensive understanding of the concept of water scarcity are needed for alleviating water scarcity and forming better production and trade strategies at the scale of irrigation districts.



## 1. Introduction

Freshwater is the most essential natural resource, but the inexorable rising water demands for growing food, supplying industries and sustaining urban and rural populations have led to a growing scarcity of freshwater in many parts of the world (Hoekstra et al., 2012; Vörösmarty et al., 2010). The issue of water scarcity has consequently received much attention from researchers in different disciplines (Hanasaki et al., 2013; Kummu et al., 2010; Návar-Cháidez, 2011; Návar, 2012, 2014; Zeng et al., 2013). In the early 1990s, Allan (1993) introduced the concept of virtual water (VW), defined as the volume of water resources required to produce commodities. As with traded commodities, countries trade water that is needed for production in virtual form, which is known as virtual water flow (VWF) or virtual water trade. VW adds a new dimension to international trade and shines a completely new light on water scarcity and the management of water resources (Novo et al., 2009; Hoekstra, 2010). An assessment of the relationship between current VW trade and water scarcity could provide an appropriate framework for finding solutions to water scarcity and could ultimately contribute to better production and trade strategies, especially for water-intensive commodities.

A growing body of literature focusing on the relationship between VWFs associated with crop trade and water scarcity is currently available. Kumar and Singh (2005) studied the relationship between the availability of renewable freshwater and net VW trade for 146 nations around the world. A country's VW trade was not determined by the state of its water resources, and VW often flowed from water-poor to water-rich countries. The relationship between water scarcity and a dependency on VW imports globally has also been studied (Chapagain and Hoekstra, 2008). A number of countries (e.g. Kuwait, Saudi Arabia, and Jordan) had both high

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water scarcity and a high dependency on VW imports, but various countries have high water scarcity but a low dependency on VW imports, mainly due to the lack of foreign currency, the pursuit of high national food self-sufficiency, a high efficiency of water use, or a fear of possible reduction in employment caused by the imports. Porkka et al. (2012) evaluated the role of VWFs in alleviating water scarcity by comparing two scenarios in central Asia, a baseline scenario that included VWFs and a scenario where international VWFs was eliminated. Over 80% of the population suffered from water stress, approximately 50% suffered from water shortage, and the removal of net VW exports considerably decreased water scarcity for approximately half the population. Novo et al. (2009) reported that Spain was a net VW importer through the international grain trade, and crop trade was apparently consistent with relative water scarcity, because net imports increased in dry years. The evolution of crop exports, expressed as a variation in quantity and volume, however, did not match the variations in the scarcity of water resources. In addition to the studies at global or national levels, some studies have tried to quantify the VWFs related to crop trade and to analyze its relationship with water scarcity at a more detailed level. Verma et al. (2009) calculated inter-state VWFs in India for a large inter-basin transfer plan. The analysis showed that the existing pattern of inter-state VW trade was exacerbating the scarcities in states already faced with water shortages. Bulsink et al. (2010) quantified Indonesian interprovincial VWFs related to trade in crop products and found that the largest VWF between provinces went to Java, the most water-poor island. The assessment of VWFs associated with crop transfer within a country was also included in the studies by Ma et al. (2006) and Kampman et al. (2008) that had shown that VW was exported from water-poor regions, putting extra pressure on their water resources.

Regional variations in water endowments and the impacts of VW trade on regional water scarcity might be overlooked at large scales (Liu et al., 2009; Zhang et al., 2011a). 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 social-economic development (Cao et al., 2012). Most regions, however, are facing serious water scarcity, mainly due to the consumption of water for agricultural production. The Hetao irrigation district has been treated as a whole to study the effects of VWFs on local water resources (Liu et al., 2013). The means by which water resources are transferred in virtual form within an irrigation district and the relationship with water scarcity are unknown. An analysis of regions within an irrigation district is of great significance for alleviating local water scarcity and forming better practices of water management.

The aim of this paper is to evaluate the inter-county VWFs related to crop transfer and its relationship with water scarcity in the Hetao irrigation district during 2001–2010. To accomplish this object, we estimated the water scarcity index (WSI, the ratio of water withdrawal to availability) for the five counties in this district and then analyzed the inter-county VWFs associated with crop transfer. At last, we evaluated the relationship between inter-county VWFs and water scarcity from the perspectives of direction and quantity.

## 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 $5.74 \times 10^3$ km$^2$ (Zhang et al., 2011b). It is located in western Inner Mongolia, China (40°13′–42°28′N, 105°12′–109°53′E), and includes five counties (Dengkou, Hanghou, Linhe, Wuyuan, and Qianqi) (Fig. 1). This area generally slopes toward the northeast at 0.125–0.2 m per km and has an average elevation of 1030 m a.s.l. (He, 2010).

The district has a continental monsoon climate with hot and dry summers and cold winters. Rainfall is scarce (130–215 mm/y) and erratically distributed (70% in July, August, and September), and the annual evaporation is 2100–2300 mm (Ye et al., 2010). The district annually has accumulated temperatures over 10 °C of 2700–3200 °C, 3150 h of sunshine, and about 135 frost-free days (Bai et al., 2011).

The Hetao irrigation district is an important area of agricultural production. The crops include rice, wheat, corn, coarse cereals, oil crops, sugar crops, vegetables, and fruits. Irrigation mainly depends on water from the Yellow River. A combination of increasing water requirements and severely constrained resources of freshwater in recent years has adversely affected development.

### 2.2. Methods

#### 2.2.1. Calculation of the WSI

The WSI is calculated as the ratio of water withdrawal to availability (Raskin et al., 1997). WSIs are categorized as follows (ECOSOC, 1997): below 10% (low water stress), 10–20% (low to medium water stress), 20–40% (medium to high water stress), 40–100% (high water stress), and above 100% (overexploited aquifers and/or desalination).

#### 2.2.2. Calculation of VWF

VWF is the result of regional trade. VWFs related to inter-county crop transfer in the Hetao irrigation district are calculated as the product of the crop transfer volume and the water footprint of the traded crops (Chapagain and Hoekstra, 2008). In our study, the virtual water balance (VWB) is defined as the difference between VW exports and imports during the study period. A positive VWB indicates net VW exports, and a negative value indicates net VW imports. Eight types of crops are included in this study: rice, wheat, corn, coarse cereals, oil crops, sugar crops, vegetables, and fruits.

We used the methodology described by Ma et al. (2006) for calculating the crop transfer volume among the five counties. This method is based on the crop surpluses and deficits of the counties. We assumed no changes in crop storage during the study period. A crop in a region had a surplus if production was higher than consumption and had a deficit if consumption was higher than production. Trade would occur from regions with surpluses to regions with deficits, and the distribution was proportionate to the deficits of the regions.

A water footprint is the volume of water consumed over the growing period per unit crop production, measured at the point of production (Hoekstra et al., 2011). Two types of water resources are included in this study: green water and blue water. Green water is equal to the minimum of crop evapotranspiration and effective rainfall (Hoekstra et al., 2011). We used the FAO Penman-Monteith method and the crop parameters from Allen et al. (1998) for calculating crop evapotranspiration. Effective rainfall was calculated based on a formula developed by the USDA Soil Conservation Service (FAO, 2012). Blue water is the volume of water withdrawn from supply sources minus return flows, allocated among the different crops (Flörke et al., 2013; Nakayama, 2011). The irrigation water requirement is one of the principal parameters for irrigation scheduling and a detailed knowledge of its magnitude and variability is of prime importance in formulating the policy for optimal allocation of water, as well as decision making in day-to-day operation and management of the irrigation system (Döll and Siebert, 2002; Joshi et al., 1995). Thus, the allocation of blue water in this study is proportionate to the irrigation water