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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 $\times$ 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 $\times$ 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 5.74×10^3 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

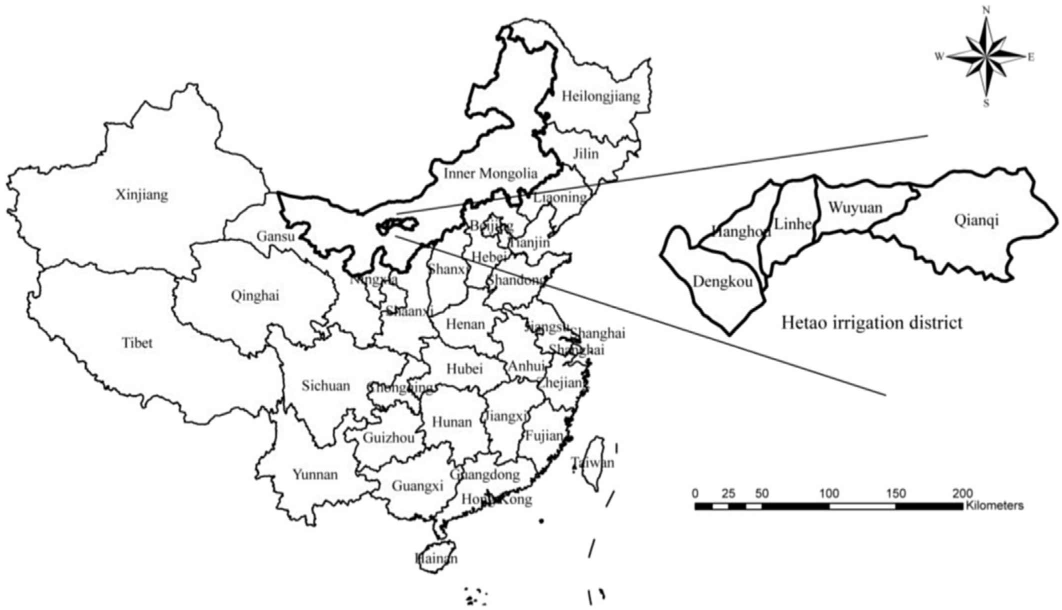

Fig. 1. Location of the Hetao irrigation district.

requirement (the difference between crop evapotranspiration and green water during the growing period) and the area of sown crops, which has been widely used in other studies (Cai et al., 2007; Kazbekov et al., 2009; Montesinos et al., 2011; Sun et al., 2013; Zhang et al., 2014).

2.3. Data sources

Monthly meteorological data (2001–2010), including temperature, relative humidity, wind speed, precipitation, and hours of sunshine, were obtained from the China Meteorological Data Sharing Service System (CMA, 2010). We used data from five meteorological stations (in Dengkou, Hanghou, Linhe, Wuyuan, and Qianqi).

Agricultural data, including crop yield, area sown, and water withdrawal and availability, were obtained from the Hetao irrigation district statistical data, agricultural statistical data for China, the Bayan Nur Water Resources Bulletin, and the China Water Resources Bulletin (MAC, 2001–2010; MWRC, 2001–2010).

Social and economic data, including annual population and crop consumption per capita, were obtained from the Bayan Nur Statistical Yearbook, the Inner Mongolia Statistical Yearbook, and the China Statistical Yearbook (NBSC, 2001–2010).

3. Results

3.1. WSI

The quantities of water withdrawal and availability for the counties in the Hetao irrigation district for 2001–2010 are presented in Table 1. Linhe was the largest water user, with an average water withdrawal of 1.12×10^9 m^3, accounting for about a quarter of the total water withdrawal in the Hetao irrigation district. Wuyuan was the second largest water user, with an average water withdrawal of 1.03×10^9 m^3. Dengkou used the least amount of water (642.14×10^6 m^3), accounting for 14.21% of the total water withdrawal for the Hetao irrigation district. Linhe (1.20×10^9 m^3) and Wuyuan (1.14×10^9 m^3) supplied nearly half of the water for the district. Qianqi had the lowest water availability of 764.55×10^6 m^3. The average water availabilities in Hanghou and Dengkou were 994.25×10^6 and 849.91×10^6 m^3, respectively, which were 30.04 and 11.16%, respectively, more than that in Qianqi.

Combining the variation of water withdrawal and availability, we could obtain the variation of WSI for the counties during 2001–2010. Dengkou had the lowest WSI (Fig. 2). It decreased from nearly 100% (99.80%) in 2001 to 67.79% in 2002 and then presented a slight increasing trend with an average growth rate of 0.90% per year until reaching 74.55% in 2010. The temporal variation of WSI in

Table 1
Water withdrawals and availabilities for the counties during 2001–2010.

Year	Water withdrawal (10^9 m^3)					Water availability (10^9 m^3)				
	Dengkou	Hanghou	Linhe	Wuyuan	Qianqi	Dengkou	Hanghou	Linhe	Wuyuan	Qianqi
2001	0.67	0.95	1.12	1.01	0.76	0.67	0.94	1.10	1.03	0.73
2002	0.64	0.93	1.16	1.03	0.77	0.94	1.03	1.27	1.15	0.83
2003	0.53	0.82	1.00	1.05	0.64	0.78	0.86	1.02	1.15	0.66
2004	0.60	0.86	1.13	1.00	0.72	0.84	0.92	1.20	1.10	0.74
2005	0.66	0.94	1.19	1.02	0.84	0.86	1.04	1.27	1.16	0.70
2006	0.66	0.91	1.13	1.06	0.87	0.86	1.01	1.24	1.18	0.79
2007	0.70	0.90	1.12	1.04	0.83	0.93	0.99	1.23	1.17	0.77
2008	0.64	0.92	1.13	1.01	0.80	0.88	0.95	1.15	1.08	0.77
2009	0.69	1.04	1.19	1.16	0.90	0.90	1.12	1.30	1.30	0.81
2010	0.64	0.96	1.07	0.97	0.81	0.85	1.07	1.18	1.13	0.84
Average	0.64	0.92	1.12	1.03	0.79	0.85	0.99	1.20	1.14	0.76

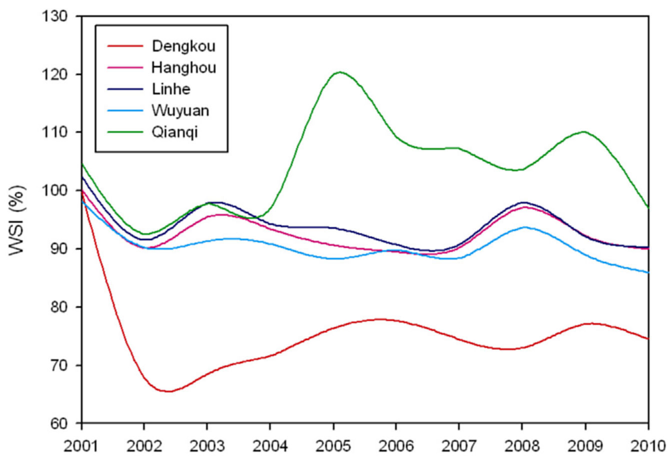

Fig. 2. Temporal variation of WSI for the counties during 2001–2010.

Hanghou was similar to those in Linhe and Wuyuan. The average WSI in Hanghou for 2001–2010 was 92.90%, and the WSIs in Linhe and Wuyuan were stable near 94.15% and 90.57%, respectively. The mean WSI in Qianqi was 97.98% for 2001–2004 and has exceeded 100% since 2005, indicating an over-appropriation of water resources.

3.2. Inter-county VWFs related to crop transfer

Crops transferred among the counties of the Hetao irrigation district included wheat, coarse cereals, sugar crops, and vegetables (Fig. 3). Linhe was the largest crop exporter (Fig. 3a), transferring 37.10 $\times$ 10^6 kg of crops (33.31 $\times$ 10^6 kg of vegetables, 3.77 $\times$ 10^6 kg of coarse cereals, and 22.29 $\times$ 10^3 kg of wheat) every year to meet the consumption needs of the other counties. Hanghou was the next largest exporter, with an export volume about 40% of that of Linhe. Qianqi had the lowest export volume (2.97 $\times$ 10^6 kg/y), which was less than 5% of the total volume of inter-county crop transfer. Qianqi was also the largest crop importer (Fig. 3b), importing 49.17 $\times$ 10^6 kg/y from other counties, which accounted for more than 60% of the total volume of crop transfer in the district. Wuyuan was the next largest crop importer, with an import volume of 10.97 $\times$ 10^6 kg/y. Only 1.23 $\times$ 10^6 kg/y of crops were exported to Dengkou, accounting for 1.67% of the total volume of crop transfer.

Vegetables were traded the most, with a transfer volume of 53.04 $\times$ 10^6 kg/y, representing 71.89% of the inter-county transfer volume (Fig. 3). The transfer volumes of sugar crops and coarse cereals were 11.20 $\times$ 10^6 and 9.48 $\times$ 10^6 kg/y, respectively. Nearly all wheat consumption could be met by local production. The trade volume of wheat was consequently only 68.28 $\times$ 10^3 kg/y, all of which was exported to Qianqi.

The inter-county green VWFs related to the transfer of the various crops are presented in Fig. 4. Green VWFs associated with wheat trade were all exported to Qianqi. The largest volume of green VWF (3.92 $\times$ 10^3 m^3/y) was from Hanghou. The trade of the other three types of crops was more complex. For coarse cereals, Wuyuan was the largest green VW exporter, with exports of 1.53 $\times$ 10^6 m^3/y, accounting for nearly half of the green VW trade of coarse cereals in the Hetao irrigation district. Qianqi was the largest green VW importer, through imports of coarse cereals. The volume of the green VWFs to Qianqi was 2.11 $\times$ 10^6 m^3/y, accounting for nearly two-thirds of the total inter-county green VWFs. The largest green VWF was from Wuyuan to Qianqi, totaling 950.33 $\times$ 10^3 m^3/y. The Linhe-Qianqi green VWF was the second largest, 73.63% of the volume of the Wuyuan-Qianqi VWF. The volumes of the green VWFs related to the trade of sugar crops and vegetables were much smaller than those for coarse cereals, 272.25 $\times$ 10^3 and 780.13 $\times$ 10^3 m^3/y, respectively. The largest flow due to the trade of sugar crops was from Wuyuan to Hanghou (82.26 $\times$ 10^3 m^3/y), and the largest flow due to the trade of vegetables was from Linhe to Qianqi (338.68 $\times$ 10^3 m^3/y).

Fig. 5 presents the inter-county blue VWFs related to the transfer of wheat, coarse cereals, sugar crops, and vegetables. Approximately 108.17 $\times$ 10^3 m^3 of water resources flowed to Qianqi from the other four regions in virtual form every year due to the trade of wheat. For coarse cereals, Dengkou was the largest blue VW exporter, with a volume of 13.93 $\times$ 10^6 m^3/y, accounting for 48.36% of the total inter-county blue VWFs. Qianqi was the largest blue VW importer for coarse cereals, importing 18.23 $\times$ 10^6 m^3/y of blue VW. The largest and smallest blue VWFs transferred for coarse cereals were from Dengkou to Qianqi (8.76 $\times$ 10^6 m^3/y) and from Hanghou to Qianqi (143.63 $\times$ 10^3 m^3/y), respectively. Wuyuan transferred 829.57 $\times$ 10^3 m^3/y of blue VW to Hanghou and 801.35 $\times$ 10^3 m^3/y to Linhe for sugar crops, accounting for approximately two-thirds of the inter-county blue VWFs associated with the trade of sugar crops. To meet the needs for vegetables, 3.20 $\times$ 10^6 m^3/y of blue water resources were transferred among

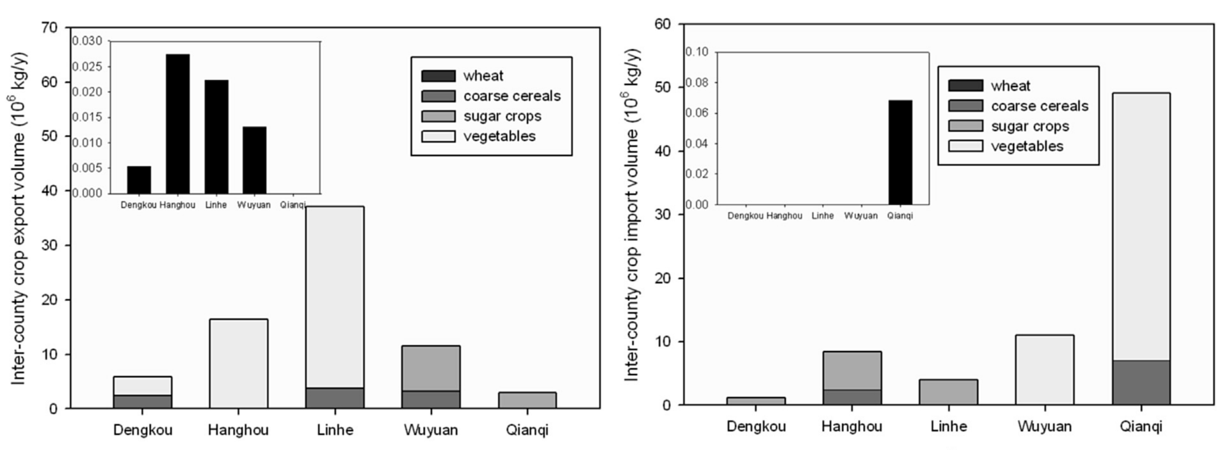

Fig. 3. Inter-county crop export (a) and import (b) volumes during 2001–2010. Note: The inter-county transfer volumes for wheat were much smaller than for the other crops. The insets for wheat-transfer volumes consequently have a different scale for the y-axis.

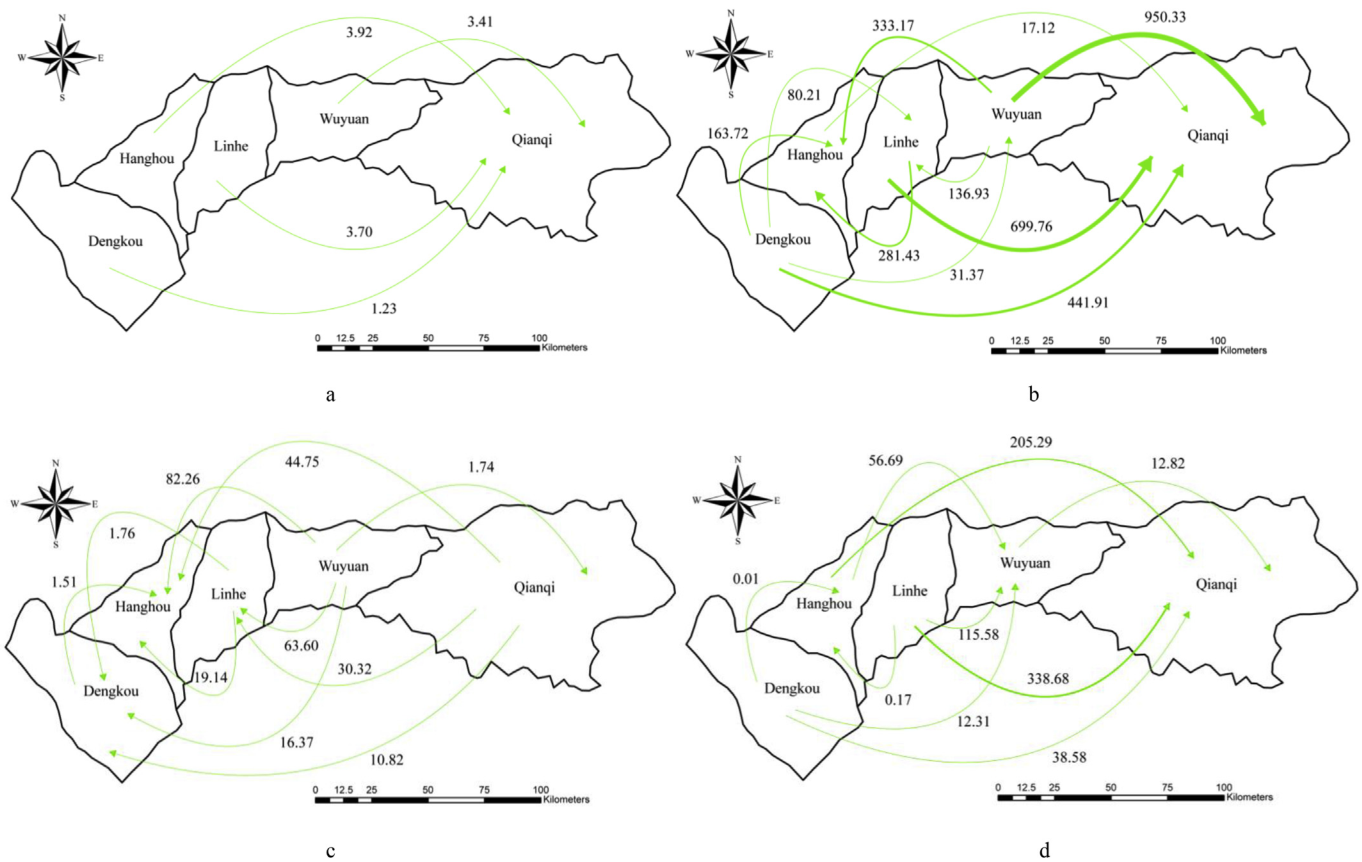

Fig. 4. Inter-county green VWFs during 2001–2010 (10^3 m^3/y) for (a) wheat, (b) coarse cereals, (c) sugar crops, and (d) vegetables. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the counties. The largest blue VWF due to the trade of vegetables was from Linhe to Qianqi, with a volume of 1.35×10^6 m^3/y. The second largest flow was from Hanghou to Qianqi, with a volume of 1.00×10^6 m^3/y. The volume of the blue VWF from Dengkou to Hanghou was the smallest, at 16.76 m^3/y.

The inter-county crop trade accounted for a VWF of 9.24×10^6 m^3/y from Dengkou to Qianqi (Fig. 6), representing more than a quarter of the total VWFs in the Hetao irrigation district. The volume of VWF between Wuyuan and Qianqi was the second largest, at 6.67×10^6 m^3/y. The VWF from Dengkou to Wuyuan was less than 10^6 m^3/y. Dengkou was the largest VW exporter through crop trade (14.54×10^6 m^3/y). The VW export volumes from Dengkou, Wuyuan, and Linhe represented 42.40, 31.34, and 22.84% of the total transfer volume, respectively. Qianqi was the largest VW importer, with an import volume of 23.02×10^6 m^3/y, accounting for 67.13% of the total VWFs. The VW import volume for Hanghou (8.04×10^6 m^3/y) was smaller than that for Qianqi. The net volumes of VW exported by Dengkou, Wuyuan, and Linhe were 14.54×10^6, 10.40×10^6, and 4.94×10^6 m^3/y, respectively. The net volumes of VW imported by Qianqi and Hanghou for crop transfer were 23.02×10^6 and 6.86×10^6 m^3/y, respectively.

3.3. Relationship between inter-county VWFs and water scarcity

All inter-county VWFs related to the trade of wheat were transferred from counties with lower WSIs to counties with higher WSIs (Table 2). For coarse cereals, the average volume of VWFs from areas with relatively low water stress to those with relatively high water stress was 29.00×10^6 m^3/y, accounting for more than 90% of the total inter-county VWFs related to the trade of coarse cereals. For sugar crops, the average values of the VWFs from counties with higher WSIs to counties with lower WSIs and of those in the opposite direction were 865.54×10^3 and 1.84×10^6 m^3/y, respectively. For vegetables, 916.55×10^3 m^3/y of water resources were transferred from counties with higher WSIs to counties with lower WSIs, and the volume in the opposite direction was about four times higher.

In 2001, 5.89×10^6 m^3 of water resources were transferred from counties with higher WSIs to those with lower WSIs (Fig. 7), and the volume of VWFs in the opposite direction was more than five times higher. In 2005 and 2007, the volume of VWFs from areas with relatively high water stress to those with relatively low water stress was less than 1×10^6 m^3, representing less than 1% of the total inter-county VWFs. All VWFs related to crop transfer originated from counties with lower WSIs in 2008 and 2009, relieving the water scarcity of the counties with higher WSIs.

The relationship between inter-county VWFs and water scarcity was analyzed from the viewpoints of both direction and quantity. The green, blue, and total VWBs, from the largest to the smallest, due to the crop transfer of the five counties during 2001–2010 are presented in Fig. 8. The corresponding WSIs are also depicted. The WSI tended to increase as the total VWB related to crop transfer decreased from 48.99×10^6 m^3 (Dengkou in 2002) to -56.09×10^6 m^3 (Qianqi in 2002) (Fig. 8c). The Pearson correlation coefficient indicated that WSI was negatively correlated with the total VWB, and the correlation was significant at the 0.01 level (Table 3). WSI was also negatively correlated with the blue VWB, and the correction was significant at the 0.01 level with a

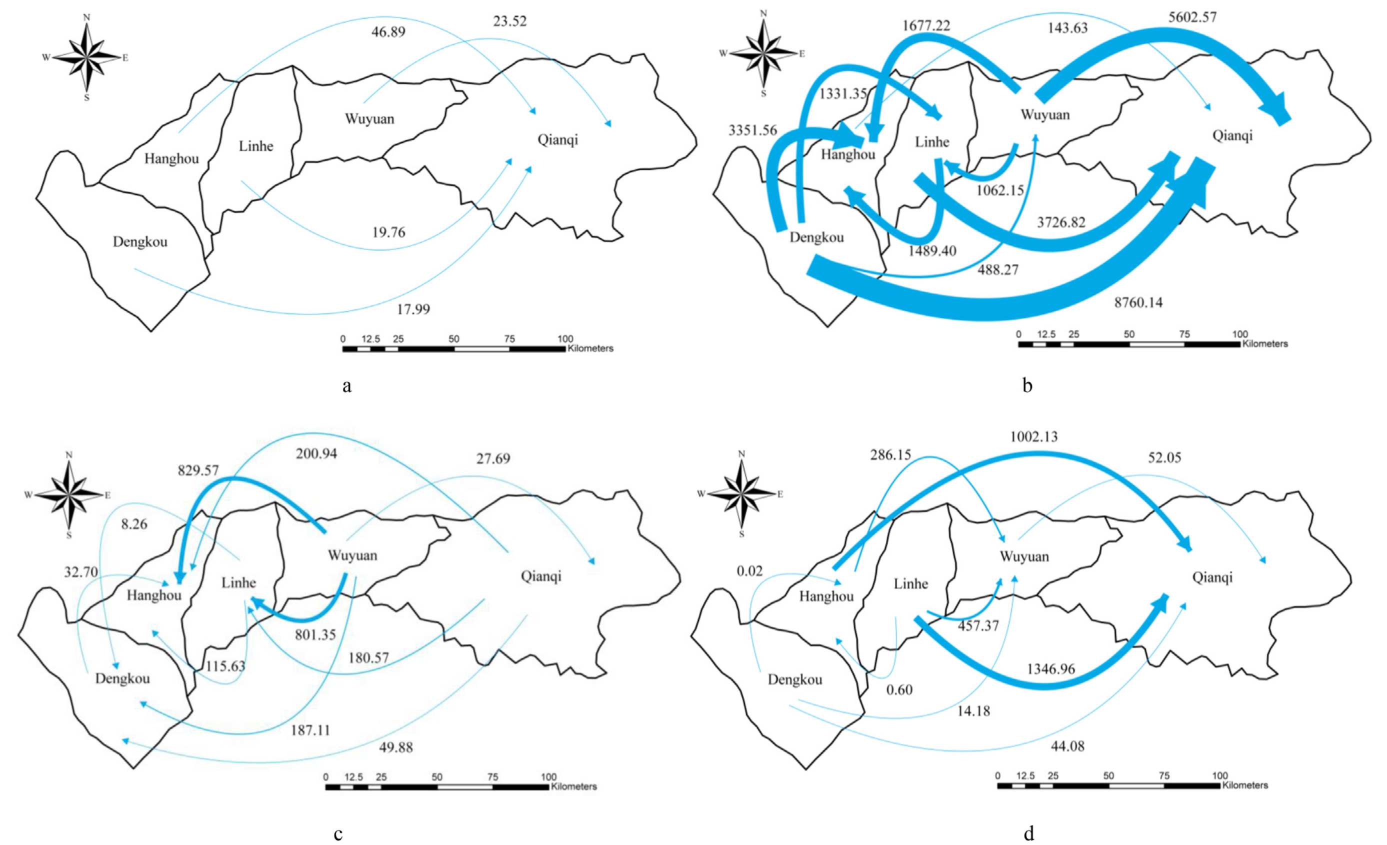

Fig. 5. Inter-county blue VWFs during 2001–2010 (10^3 m^3/y) for (a) wheat, (b) coarse cereals, (c) sugar crops, and (d) vegetables. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

correlation coefficient of −0.463 (Table 3). The WSI tended to increase as the green VWB decreased from 7.04 × 10^6 m^3 (Wuyuan in 2008) to −6.00 × 10^6 m^3 (Qianqi in 2004) (Fig. 8a). The Pearson correlation coefficient indicated that WSI was negatively correlated with the green VWB, but the correlation was not significant at the 0.01 level (Table 3), mainly due to larger influences of factors other than water scarcity.

4. Discussion

The average WSIs for the counties of the Hetao irrigation district were 76.10% (Dengkou), 92.90% (Hanghou), 94.15% (Linhe), 90.57% (Wuyuan), and 103.93% (Qianqi) during 2001–2010, indicating that the district was highly water stressed. The WSIs in these five

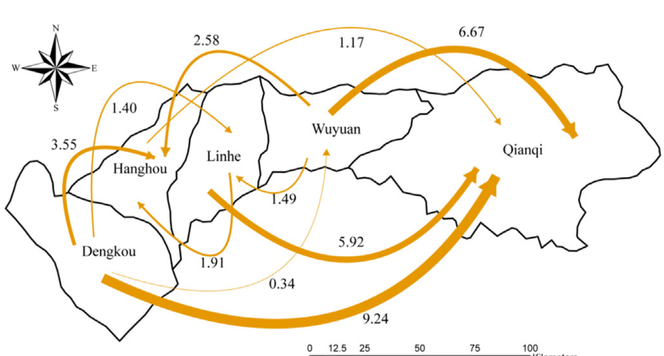

Fig. 6. Inter-county total VWFs during 2001–2010 (10^6 m^3/y).

counties were much higher than the WSI of 48.30% reported for northern China (Jiang, 2009), mainly due to the combination of a large volume of water withdrawn and the limited water availability in this area. In the Hetao irrigation district, where fertile land and abundant sunshine and heat provided good conditions for growing crops, as much as 4.39 × 10^9 m^3 of water resources were used annually for agricultural production (MWRC, 2001–2010). Combined with water withdrawn for other purposes (126.58 × 10^6 m^3), the total water withdrawal in the district was 4.52 × 10^9 m^3/y (MWRC, 2001–2010). Streamflow of the Yellow River, the source of more than 90% of the water for the district, has significantly decreased since the 1950s due to both climate change and human activities (Wang et al., 2006; Zhang et al., 2009). As a result, only 4.50 × 10^9 m^3/y of water resources was diverted from the Yellow River to the Hetao irrigation district during the study period (MWRC, 2001–2010). The total water availability in the district was 4.95 × 10^9 m^3, less than 2% of the total for northern China, while water withdrawal in the district accounted for 3.61% of that for northern China (Jiang, 2009; MWRC, 2001–2010). The Hetao irrigation district has thus experienced a much severer water scarcity than average for northern China.

Approximately 34.29 × 10^6 m^3/y of water resources were transferred in virtual form among the counties of the Hetao irrigation district due to crop transfer during 2001–2010. VW adds a new dimension to the inter-county crop trade (Novo et al., 2009). We should point out, however, that VWF is scale-dependent. At the county scale, VW trade represents a saving of water for the importing counties and relieves the pressure on the regional water resources; it also represents water "losses" for the exporting counties (in the sense that the water cannot be used again for other

Table 2
Inter-county VWFs in different directions for the various crop types during 2001–2010.

Year	From counties with higher WSIs to counties with lower WSIs (10^6 m^3)				From counties with lower WSIs to counties with higher WSIs (10^6 m^3)			
	Wheat	Coarse cereals	Sugar crops	Vegetables	Wheat	Coarse cereals	Sugar crops	Vegetables
2001	0.00	5.89	0.00	0.00	0.00	33.36	0.00	0.00
2002	0.00	6.90	0.00	1.94	0.00	65.12	0.00	5.49
2003	0.00	12.52	0.00	4.11	0.00	39.90	0.00	11.67
2004	0.00	1.36	2.32	3.12	0.00	25.80	1.81	13.99
2005	0.00	0.00	2.02	0.00	0.00	41.70	4.19	5.53
2006	0.00	0.01	3.33	0.00	0.00	10.98	0.11	0.00
2007	0.00	0.00	0.19	0.00	0.00	22.69	0.53	0.00
2008	0.00	0.00	0.54	0.00	1.20	51.88	2.34	0.00
2009	0.00	0.00	0.16	0.00	0.00	3.53	2.46	0.00
2010	0.00	0.00	2.20	0.00	0.00	0.00	5.02	0.00
Average	0.00	1.77	0.87	0.92	0.12	29.00	1.84	3.67

Note: In the calculation of the averages, the origins and destinations of the VWFs were considered. For equal VWFs, but with opposite origins and destinations, the total was zero.

purposes in the exporting counties), thereby adding to the pressure on the local water systems (Bulsink et al., 2010; Chapagain et al., 2006; Zhang et al., 2011a). More than 90% of the inter-county VWFs related to crop trade in the Hetao irrigation district flowed from counties with relatively low water stress to those with relatively high water stress during the study period. Counties with relatively high water stress consequently benefited from the existing trade pattern from the perspective of water resources, while counties with relatively low water stress did not. At the scale of the irrigation district, the net effect of inter-county VWFs would depend on the actual water volumes used for crop production in the exporting counties in comparison to the volumes that would have been required to produce these traded crops in the importing counties (Chapagain et al., 2006; Konar and Caylor, 2013). A net water saving will arise, indicating a more efficient use of the irrigation district's water resources, if the trade is from counties with relatively high water productivity to counties with lower water productivity, otherwise a net water losing or a less efficient use of the irrigation district's water resources will occur (Chapagain et al., 2006; Konar and Caylor, 2013). As can be seen from Table 4, the Hetao irrigation district is clearly not a beneficiary of the current trade strategy from the perspective of water resources: 1.96×10^6 m^3/y of water was lost during the study period.

With water becoming scarcer, the VW trade is increasingly important in regional negotiations and is often advocated as one of a set of feasible policy options for alleviating regional water scarcity (Lenzen et al., 2013). From the perspective of water resources, a given county in the district could substantially benefit from reducing the export of water-intensive products while importing these highly water-intensive products from other counties. Before concrete policy implications can be drawn, however, we must determine if these VWFs are coming from counties with relatively high water productivity, which could thus contribute to establishing a more efficient water use or a water saving at the scale of the irrigation district. At the same time, however, the feasibility of implementing such a VW trading policy must be assessed against other alternatives and factors of the natural, socioeconomic, environmental, and political conditions and other regional and national objectives (Yang and Zehnder, 2007; Yang et al., 2013). We must emphasize that the VW trading policy can be implemented in conjunction with other alternatives, rather than being exclusive to them (Yang and Zehnder, 2007; Yang et al., 2013).

Water scarcity can be the driving force behind inter-regional trade in water-intensive products such as crops, but more often other factors play a decisive role (Wichelns, 2010; Yang et al., 2003). In our study, only 26.2% of the changes in the green VWB could be explained by the WSI. The analysis by Kumar and Singh (2005) of 131 countries showed that access to arable land can be a key driver of VW trade. Verma et al. (2009) tested this hypothesis using per capita data for gross cropped area for Indian states and found that the per capita gross cropped area was negatively correlated with net VW imports. In the Hetao irrigation district, the wheat transfer volume was less than 1% of the total inter-county crops trade volume. We consequently used the total area sown per capita of coarse cereals, sugar crops, and vegetables to test this hypothesis of access to arable land. The area sown per capita significantly decreased with the decrease in the green VWB from 7.04×10^6 m^3 (Wuyuan in 2008) to -6.00×10^6 m^3 (Qianqi in 2004) (Fig. 9a). The change in area sown per capita was positively correlated with the green VWB, at a significance level of 0.01 and with a correlation coefficient of 0.649 (Table 5). A positively correlated relationship could also be derived from the analysis of the blue and total VWBs (Table 5). A comparison of the correlation coefficients in Tables 3 and 5 indicates that the change in area sown per capita contributed more to the change in the green, blue, and total VWBs than did the WSI.

An accurate determination of the necessary trade data in a small area such as the Hetao irrigation district for a ten-year period is currently difficult, and the assumption of changes in crop stocks could introduce uncertainties for the estimation of inter-county VWFs. Also, many factors influencing the allocation of blue water were not included in this stage of the study, mainly due to the absence of data. We should also note that a universally accepted

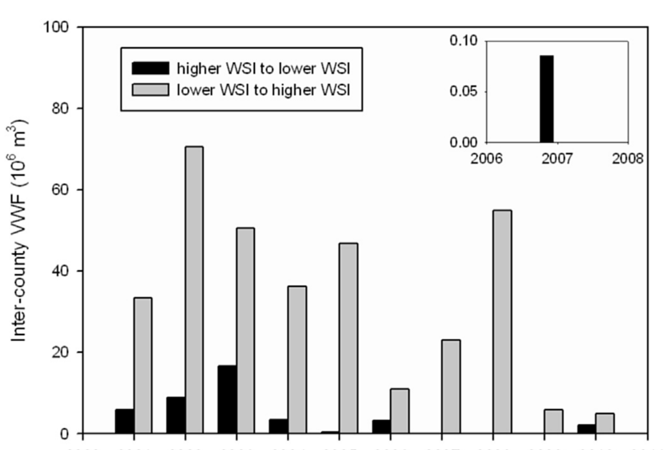

Fig. 7. Inter-county VWFs in different directions during 2001–2010. Note: The volume of the inter-county VWFs from higher-to lower-WSI counties in 2007 was very small. The inset for 2007 consequently has a different scale.

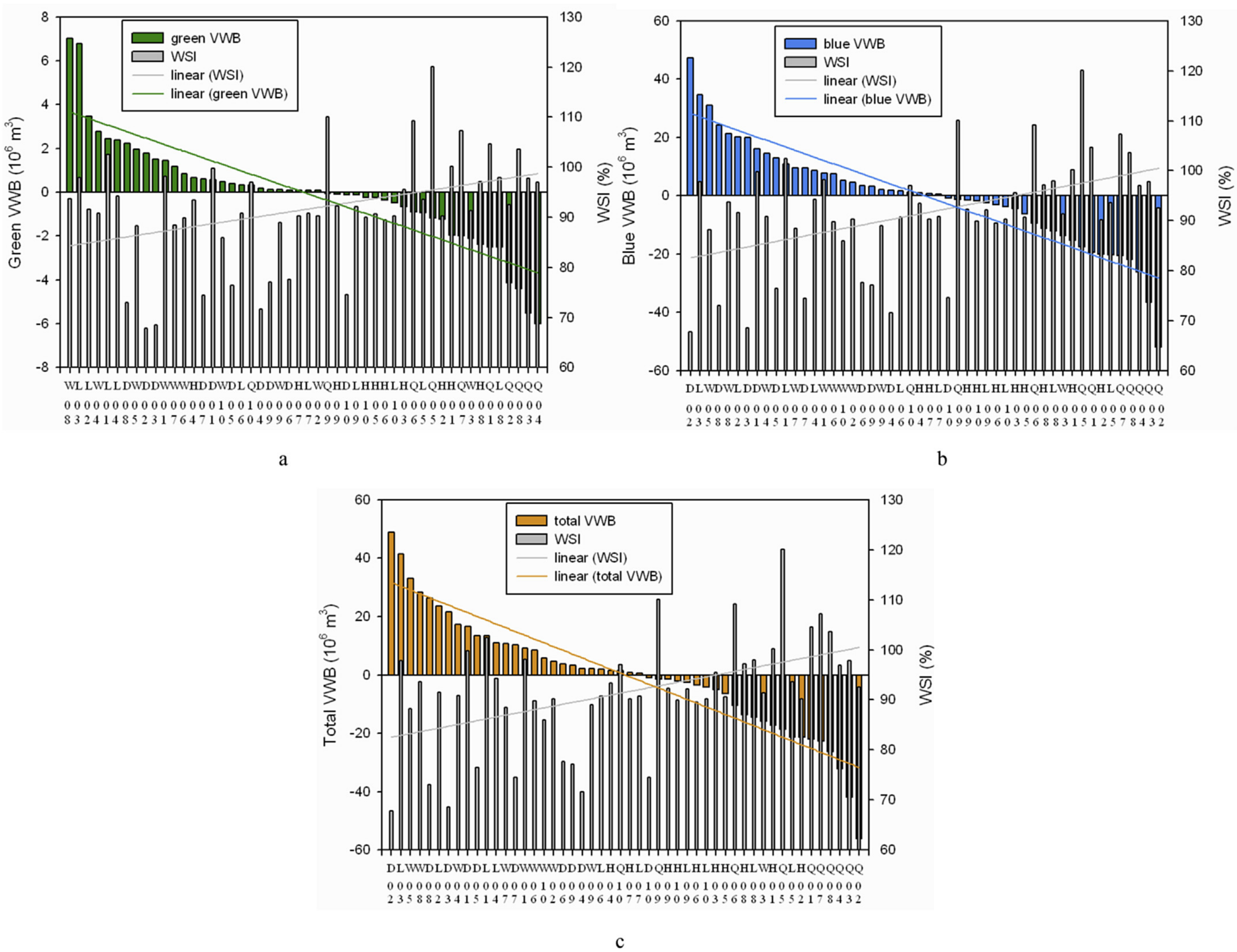

Fig. 8. Relationships between VWB, from largest to smallest, and WSI for green (a), blue (b), and total (c) VWBs. Note: Letters and numbers on the x-axes: D, Dengkou; H, Hanghou; L, Linhe; W, Wuyuan; Q, Qianqi; 01-10, 2001–2010. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Pearson correlation coefficients for VWB and WSI.

	Green VWB (10^6 m^3)	Blue VWB (10^6 m^3)	Total VWB (10^6 m^3)
WSI (%)	−0.262	−0.463**	−0.446**

Note: ** Significant at the 0.01 level.

definition for water scarcity does not yet exist, and water scarcity could be more complex than is indicated by the WSI. This study, though, does provide a broad overview of inter-county VWFs related to crop transfer and its relationship with water scarcity from the perspectives of direction and quantity. This overview can potentially help to alleviate water scarcity and to form better practices of water management for counties in an irrigation district.

Table 4
Water savings for the Hetao irrigation district due to inter-county VWFs for the various crop types during 2001–2010.

Year	Wheat (10^6 m^3)	Coarse cereals (10^6 m^3)	Sugar crops (10^6 m^3)	Vegetables (10^6 m^3)	Total (10^6 m^3)
2001	0.00	2.08	0.00	0.00	2.08
2002	0.00	−20.34	0.00	8.29	−12.06
2003	0.00	18.53	0.00	13.12	31.65
2004	0.00	2.17	4.75	−1.07	5.85
2005	0.00	−18.27	0.70	−1.77	−19.34
2006	0.00	−3.06	0.99	0.00	−2.07
2007	0.00	−9.03	0.10	0.00	−8.93
2008	−0.43	−20.14	−0.02	0.00	−20.59
2009	0.00	0.10	0.41	0.00	0.51
2010	0.00	0.00	3.34	0.00	3.34
Average	−0.04	−4.80	1.03	1.86	−1.96

Note: Negative values indicate water losing.

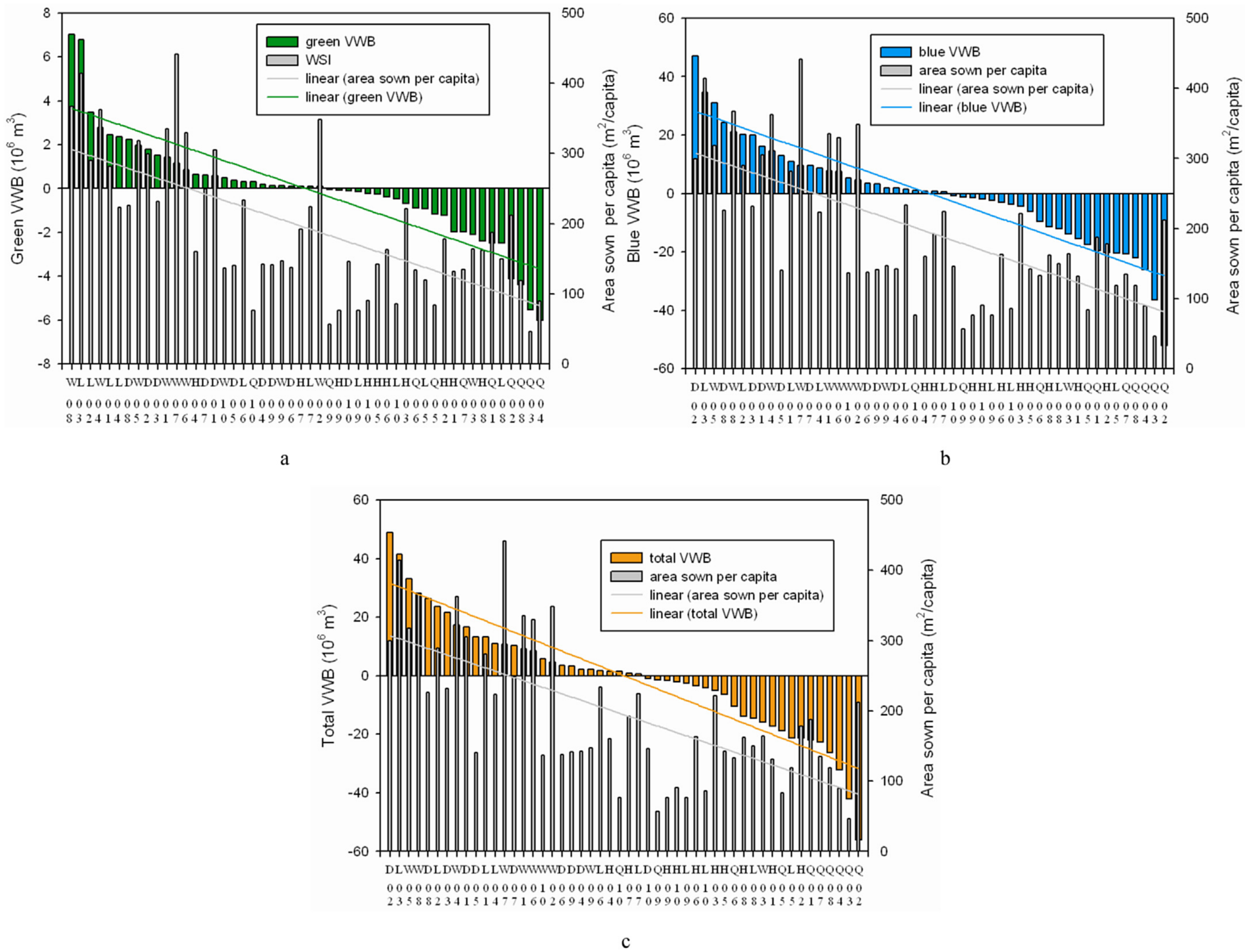

Fig. 9. Relationships between VWB, from largest to smallest, and area sown per capita for green (a), blue (b), and total (c) VWBs. Note: Letters and numbers on the x-axes: D, Dengkou; H, Hanghou; L, Linhe; W, Wuyuan; Q, Qianqi; 01-10, 2001–2010. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In the future, a more accurate evaluation of VWFs and a more comprehensive understanding of the concept of water scarcity are needed for a better analysis of the relationship between VWFs and water scarcity.

5. Conclusion

The concept of VW adds a new dimension to regional trade, and the analysis of the relationship between the inter-county transfer of VW and water scarcity is of great significance for alleviating water scarcity and improving the practices of water management. This study found that the inter-county VWFs associated with crop transfer in the Hetao irrigation district was 34.29 × 10^6 m^3/y during the study period and that more than 90% originated from counties with lower WSIs and was destined to those with higher WSIs. WSI was negatively correlated with VWB.

Counties with relatively high water stress benefited from the current pattern of inter-county VWFs, while the Hetao irrigation district as a whole suffered a water losing of 1.96 × 10^6 m^3/y. The change in area sown per capita contributed more to the change in the VWB than did the WSI. The various objectives and factors of the natural, socioeconomic, environmental, and political conditions should be taken into account for implementing a VW trading policy. In the future, a more accurate evaluation of VWFs and a more comprehensive understanding of the concept of water scarcity are needed to alleviate water scarcity and to design better production and trade strategies at the scale of irrigation districts.

Table 5
Pearson correlation coefficients for VWB and area sown per capita.

	Green VWB (10^6 m^3)	Blue VWB (10^6 m^3)	Total VWB (10^6 m^3)
Area sown per capita (m^2/capita)	0.649**	0.602**	0.618**

Note: ** Significant at the 0.01 level.

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