Science of the Total Environment 505 (2015) 1174–1181

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

# Evaluation of crop production, trade, and consumption from the perspective of water resources: A case study of the Hetao irrigation district, China, for 1960–2010

Jing Liu [a,c,d,1], Shikun Sun [b,c,d,1], Pute Wu [a,b,c,d,e,*], Yubao Wang [b,c,d], Xining Zhao [c,d,e]

[a] *Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi 712100, China*
[b] *College of Water Resources and Architectural Engineering, Northwest A&F University, Yangling, Shaanxi 712100, China*
[c] *Institute of Water Saving Agriculture in Arid Regions of China, Northwest A&F University, Yangling, Shaanxi 712100, China*
[d] *National Engineering Research Center for Water Saving Irrigation at Yangling, Yangling, Shaanxi 712100, China*
[e] *Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100, China*

## HIGHLIGHTS

- WF of production increased for 1960–2010 and WF of consumption declined after 1979.
- WF of production and VWE depended mainly on agricultural factors.
- WF of consumption and VWI depended mainly on socio-economic factors.
- Most of WF of production was exported and the share of import decreased after 1976.

## ARTICLE INFO

*Article history:*
Received 30 August 2014
Received in revised form 24 October 2014
Accepted 24 October 2014
Available online 14 November 2014

Editor: D. Barcelo

*Keywords:*
Water footprint
Virtual water flows
Influencing factors
Irrigation area
China

## ABSTRACT

The integration of water footprints and virtual water flows allows the mapping of the links between production, trade, and consumption and could potentially help to alleviate water scarcity and improve water management. We evaluated the water footprints and virtual water flows of crop production, consumption, and trade and their influencing factors in the Hetao irrigation district in China for 1960–2010. The water footprint of crop production and the export of virtual water fluctuated but tended to increase during this period and were influenced mainly by agricultural factors such as crop yield, irrigation efficiency, and area sown. The water footprint of crop consumption and the import of virtual water increased during 1960–1979 and decreased during 1980–2010 and were influenced by socio-economic factors such as total population, the retail-price index, and the proportion of the population in urban areas. Most of the water footprint of production was exported to other areas, which added to the pressure on local water systems. The import of virtual water led to a saving of water for the Hetao irrigation district, while its share of the water footprint of consumption has decreased significantly since 1977. An increase in irrigation efficiency can alleviate water scarcity, and its application should be coupled with measures that constrain the continued expansion of agriculture. Full-cost pricing of irrigation water was an effective policy tool for its management. Re-shaping regional water-production and water-trade nexuses by changing crop structures could provide alternative opportunities for addressing the problems of local water scarcity, but the trade-offs involved should first be assessed.

## 1. Introduction

Freshwater is the most essential natural resource, but the inexorable increasing water demands 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 in various disciplines (Hanasaki et al., 2013; Kummu et al., 2010; Zeng et al., 2013). The concept of the water footprint (WF), introduced by Hoekstra and Hung (2002) and subsequently elaborated by Hoekstra and Chapagain (2008), is a comprehensive indicator of the appropriation of freshwater and can provide a new perspective for water management (Hoekstra et al., 2011). The WF of production is the total volume of water used within an area, including the water used for making products consumed locally and for export (Ercin et al., 2013;

---

[*] Corresponding author at: Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100, China. Tel.: +86 29 87012411; fax: +86 29 87012210.
*E-mail address:* gjzwpt@vip.sina.com (P. Wu).

[1] Jing Liu and Shikun Sun contributed equally to this work.

http://dx.doi.org/10.1016/j.scitotenv.2014.10.088
0048-9697/© 2014 Elsevier B.V. All rights reserved.

Hoekstra et al., 2011). The WF of consumption is the total volume of water used to produce the goods and services consumed by the inhabitants of an area, and the production process could in local or outside the territory of this area (Ercin et al., 2013; Hoekstra et al., 2011). As with the trade of commodities, regions trade water in virtual form that is needed for production, which is known as virtual water flows (VWFs) or virtual water trade. The analysis of VWFs adds a new dimension to international trade and provides a completely new perspective on water scarcity (Hoekstra, 2010a; Novo et al., 2009).

A growing body of literature has focused on the quantification of the WF of agricultural production (Chapagain and Hoekstra, 2011; Mekonnen and Hoekstra, 2010; Zhang and Anadon, 2014), WF of agricultural consumption (Bulsink et al., 2010; Chapagain and Hoekstra, 2011; Ercin et al., 2013) and VWFs associated with the crop trade (Chapagain et al., 2006; Duarte et al., 2014; Lenzen et al., 2013). To explore the application of WFs and VWFs in more detail, some studies have investigated the relationships between WFs or VWFs and meteorological, agricultural, and socio-economic factors, including climate change (Hoekstra and Chapagain, 2007; Huang et al., 2013; Konar et al., 2013; Kummu et al., 2014), yield (Duarte et al., 2014; Ercin and Hoekstra, 2014; Vanham and Bidoglio, 2013), land endowment (Kumar and Singh, 2005; Rost et al., 2008; Verma et al., 2009), agricultural technology (Ercin and Hoekstra, 2014; Vanham and Bidoglio, 2013), population (Dalin et al., 2012; Hubacek et al., 2009; Suweis et al., 2011; Tamea et al., 2014; Zhao et al., 2014), and gross domestic product (Dalin et al., 2012; Duarte et al., 2014; Suweis et al., 2011; Tamea et al., 2014). A systematic analysis of the problems of regional water resources, however, requires the integration of WFs and VWFs, including their critical drivers, under a single and consistent framework. Few studies have attempted such an analysis.

Irrigation districts in China have produced more than 75% of the grain and have been serving an increasingly important function for ensuring the safety of China's food supply and socio-economic development (Cao et al., 2012). Studies on small and localized scales are more pertinent than global or national studies to specific regional problems (Zhang et al., 2011b). The aim of our study was to evaluate the WFs of crop production and crop consumption, the VWFs associated with the crop trade, and the factors influencing them in the Hetao irrigation district for 1960–2010. This study provides a new perspective for local water management and can help to alleviate local water scarcity.

## 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., 2011a). 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. Rainfall is scarce (130–215 mm y$^{-1}$) 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 approximately 135 frost-free days (Bai et al., 2011).

The Hetao irrigation district is an important area of agricultural production and trade. Irrigation depends mainly on water from the Yellow River. Allowable water diversions from the Yellow River to the Hetao irrigation district have decreased in recent years from 5 billion to 4 billion m$^3$ y$^{-1}$ (Ye et al., 2010). The development of the Hetao irrigation district has already been adversely affected by the combination of increasing water requirements and severely constrained resources of freshwater.

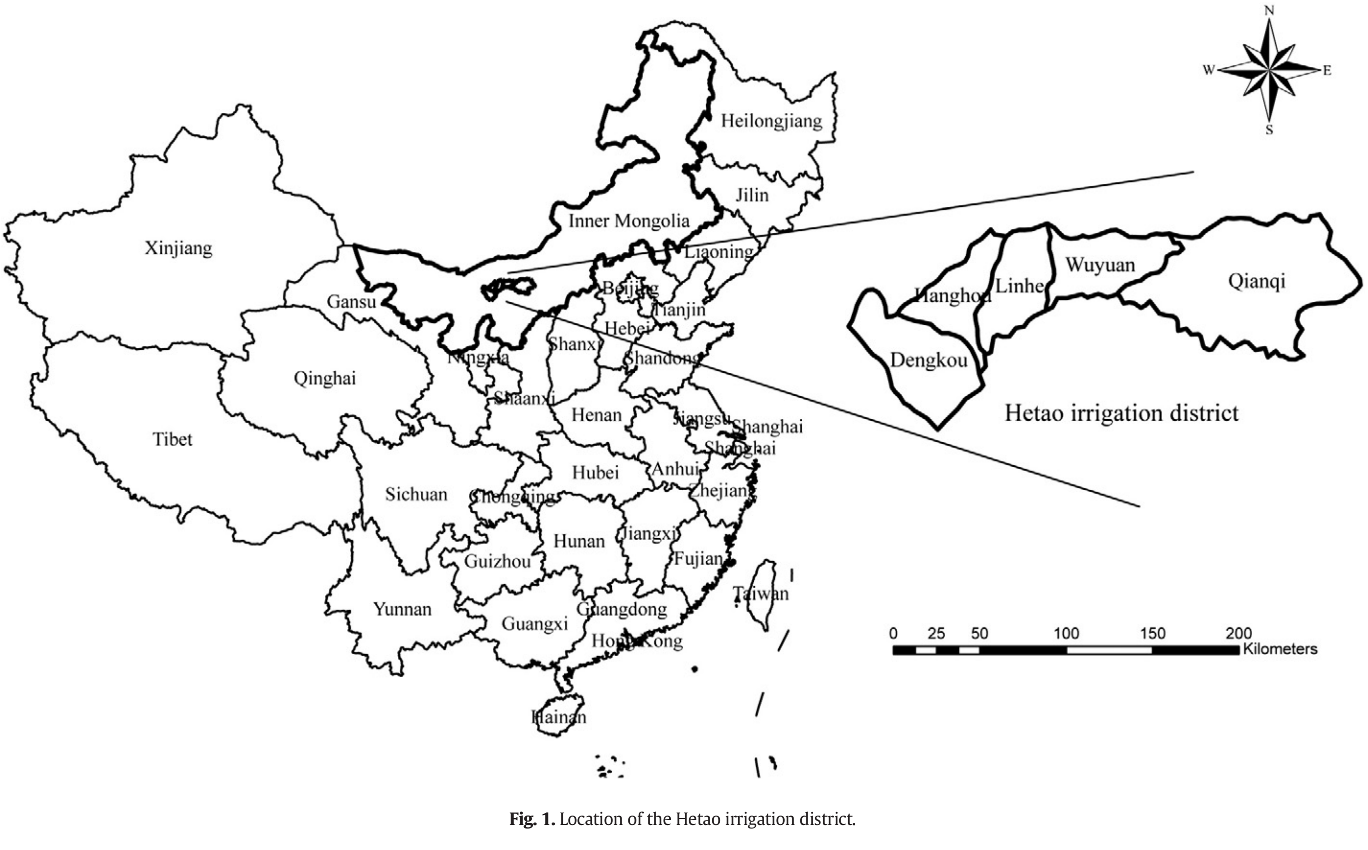

**Fig. 1.** Location of the Hetao irrigation district.

### 2.2. Calculation of WFs and VWFs

The WF of crop production in the Hetao irrigation district was calculated as the product of the volume of crop production and the crop virtual water content (VWC). The WF of crop consumption was calculated as the product of the volume of crop consumption and the crop VWC. The VWF was calculated as the product of the volume of crop trade and the crop VWC (Chapagain and Hoekstra, 2008; Ma et al., 2006; Hoekstra et al., 2011). Ten types of crops were included in this study: rice, wheat, corn, coarse cereals, sunflowers, melons, vegetables, tomatoes, oilseed crops, and sugar beets.

We used the methodology described by Bulsink et al. (2010) for calculating the volumes of crop transfers. This method was based on crop surpluses and deficits. A surplus occurred when the volume of production of a crop was larger than its consumption. A deficit occurred when the volume of consumption of a crop was larger than its production. We assumed that all crop surpluses in the Hetao irrigation district were exported to other areas and that all crop deficits could be met by importing.

The VWC is the volume of water consumed per unit of crop production over the growing period, measured at the point of production. Due to the absence of data, we assumed that the VWC of imported crops equaled the VWC of exported crops. Two types of water resources are consumed during the crop growing period: 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 Penman–Monteith method of the Food and Agriculture Organization for calculating crop evapotranspiration (Allen et al., 1998). Effective rainfall was calculated based on the method used by the Soil Conservation Service of the United States Department of Agriculture (FAO, 2012). Blue water is the volume of water withdrawn from supply sources minus the return flows and then allocated among the various crops (Flörke et al., 2013). Return flows in the Hetao irrigation district were 25% of the water withdrawn (Nakayama, 2011). The allocations among the crops were proportionate to their requirements for irrigation water (Montesinos et al., 2011), calculated as the difference between the volumes of crop evapotranspiration and green water during the growing period (Hoekstra et al., 2011).

### 2.3. Analysis of influencing factors

The values of the WFs and VWFs were determined by crop VWC and crop production, consumption, and trade patterns (Chapagain and Hoekstra, 2008; Ma et al., 2006; Hoekstra et al., 2011). Ten factors that can affect these parameters were first chosen, based on the literature and data availability (Table 1), to explore the factors influencing WFs and VWFs in the Hetao irrigation district during 1960–2010. The contribution rates of the factors were then calculated to determine the share of the dependent-variable variation caused by the independent-variable variation (Yang et al., 2000).

The contribution rates of the influencing factors were calculated by Yang et al. (2000):

$$\delta_i = \alpha_i \times \frac{\Delta x_i}{x_i} \Big/ \frac{\Delta y}{y} \times 100\% \qquad (1)$$

where $\delta_i$ is the contribution rate of influencing factor $x_i$, $\alpha_i$ is the elastic coefficient of influencing factor $x_i$ obtained by multiple linear regression analysis (Yang et al., 2000), $\Delta x_i$ is the variation of $x_i$, $\Delta y$ is the variation of $y$, and $y$ is the volume of the WF or VWF.

### 2.4. Data sources

Monthly meteorological data (1960–2010) for temperature, relative humidity, wind speed, precipitation, and hours of sunshine were from the China Meteorological Data Sharing Service System (CMA, 2010). The data were collected at meteorological stations in the five counties (Dengkou, Hanghou, Linhe, Wuyuan, and Qianqi). Agricultural data for crop yield, area sown, price of water for agricultural production, and irrigation efficiency were obtained from Hetao Irrigation District Statistical Data and China Agricultural Statistical Data (MAC, 1960–2010). Social and economic data for annual population, annual urban population, crop consumption per capita, gross domestic product, and the retail-price index were obtained from the Bayan Nur Statistical Yearbook, the Inner Mongolia Statistical Yearbook, and the China Statistical Yearbook (NBSC, 1960–2010).

**Table 1**
Factors chosen for the analysis of influencing factors.

| Category | Factor | Description | Literature on relationships between specific factors and WFs or VWFs |
|---|---|---|---|
| Meteorological | Annual average temperature | The average of 12 monthly average temperatures during a year (°C). | Hoekstra and Chapagain (2007), Huang et al. (2013), Kummu et al. (2014), Konar et al. (2013) |
| | Annual precipitation | The sum of 12 monthly precipitations during a year (mm). | Hoekstra and Chapagain (2007), Huang et al. (2013), Kummu et al. (2014), Konar et al. (2013) |
| Agricultural | Yield | The crop output per unit area sown ($10^3$ kg/ha$^{-1}$). | Duarte et al. (2014), Ercin and Hoekstra (2014), Vanham and Bidoglio (2013) |
| | Area sown | The area of land sown with crops ($10^3$ ha). | Kumar and Singh (2005), Rost et al. (2008), Verma et al. (2009) |
| | Irrigation efficiency | The value of irrigation water used in the field divided by total irrigation water withdrawn from the source (–). | Ercin and Hoekstra (2014), Vanham and Bidoglio (2013) |
| | Water price for agricultural production[a] | The price of a cubic meter of water used for agricultural production ($10^{-3}$ Yuan m$^{-3}$). | Arouna and Dabbert (2010), Hoekstra et al. (2011) |
| Socio-economic | Total population | The total number of people alive at a certain time within a given area ($10^6$). | Dalin et al. (2012), Tamea et al. (2014), Zhao et al. (2014) |
| | Proportion of population in urban areas | The proportion of people residing in cities or towns of the total number of people at a certain time within a given area (%). | Hubacek et al. (2009), Zhao et al. (2014) |
| | Gross domestic product per capita[a] | The sum of the value added by all resident producers plus any product taxes not included in the valuation of output divided by the population ($10^3$ Yuan person$^{-1}$). | Dalin et al. (2012), Duarte et al. (2014), Suweis et al. (2011), Tamea et al. (2014), Zhao et al. (2014) |
| | Retail-price index of crops[a] | A reflection of changes in the retail prices of commodities. Changes of it could affect the purchasing power of residents, market equilibrium, and ratio of consumption to accumulation (100). | Djanibekov et al. (2013), Jansen and Schulz (2006) |

[a] Water price for agricultural production, gross domestic product per capita, and the retail-price index in this study were presented on a constant-price base period (1960).

## 3. Results

### 3.1. WF of crop production

Fig. 2a shows the variation of the WF of crop production in the Hetao irrigation district from 1960 to 2010. The WF of production was $2.78 \times 10^9$ m$^3$ in 1960. It then fluctuated but with an increasing trend at an average growth rate of $18.04 \times 10^6$ m$^3$ y$^{-1}$ to $3.66 \times 10^9$ m$^3$ by 2010, 1.32-fold higher than in 1960. The production of coarse cereals constituted the largest share (40.52%) in the 1960s (Fig. 2b), followed by wheat (36.85%) and rice (12.08%). The production of wheat (41.97%), coarse cereals (38.52%) and corn (10.33%) accounted for more than 90% of the WF in the 1970s. The proportion of sunflowers of the total WF has increased significantly since the 1980s, while the share of coarse cereals declined rapidly. The proportion of sunflowers was the largest among all crops in the 2000s at 29.77%, and sunflowers, wheat (28.70%), corn (15.71%), and melons (8.31%) together accounted for more than 80% of the total WF of production.

The rates of contribution of the various factors to the WF of crop production are presented in Table 2. The volume of the WF of crop production was mainly influenced by crop yield, irrigation efficiency, and area sown, with contribution rates of 88.33, −12.68, and 8.53%, indicating that the improvement of yield was responsible for 88.33% of the increase in the WF, and the increase in the area sown contributed 8.53% of the increase of the WF. The increase in irrigation efficiency led to a 12.68% decrease in the WF.

### 3.2. WF of crop consumption

Fig. 3 shows the variation of the WF of crop consumption from 1960 to 2010 and the contributions of the crops in each period. The WF of crop consumption increased from $1.02 \times 10^9$ m$^3$ in 1960 to $2.15 \times 10^9$ m$^3$ in 1979 at an average growth rate of $55.51 \times 10^6$ m$^3$ y$^{-1}$ (Fig. 3a), mainly due to the increasing volume of consumption. The WF then decreased, with fluctuations, mainly due to the relatively large impact of a decreasing VWC relative to the increasing volume of consumption. The WF of crop consumption in 2010 was $699.72 \times 10^6$ m$^3$, approximately 33% of that in 1979.

The consumption of rice constituted the largest share (61.82%) of the WF of crop consumption in the 1960s (Fig. 3b), followed by wheat (14.83%) and coarse cereals (11.93%). More than 90% of the WF in the 1970s was due to the consumption of rice (70.16%), wheat (16.37%), and coarse cereals (7.36%). The proportion of sunflowers to the total WF has increased significantly since the 1980s, while the share of rice has decreased. More than 40% of the WF in the 2000s was due to the consumption of rice, followed by wheat (19.18%), sunflowers (13.02%), and coarse cereals (12.77%).

**Table 2**
Contribution rates of the factors influencing the WF of crop production.

| Influencing factor | Elasticity coefficient | Factor variation ratio (%) | Contribution rate (%) |
|---|---|---|---|
| Yield | 0.169 | 4.39 | 88.33 |
| Irrigation efficiency | −0.310 | 0.34 | −12.68 |
| Area sown | 0.364 | 0.20 | 8.53 |
| Sum | | | 84.18 |
| Other factors | | | 15.82 |

Due to the temporal variation (Fig. 3a), we analyzed the contribution rates for the WF of crop consumption for two periods: 1960–1979 and 1980–2010 (Table 3). For 1960–1979, 93.15% of the increase in the WF in the study area could be accounted for the increases in total population (84.15%) and annual precipitation (9.00%). The change in the WF for 1980–2010 was mainly dominated by changes in the retail-price index and the total population, whose contribution rates were 93.15 and −12.78%, respectively.

### 3.3. VWFs

The variation of virtual water export (VWE) associated with the crop trade from 1960 to 2010, and the contributions of the crops in each period, are presented in Fig. 4. The VWE associated with the crop trade increased, with fluctuations, from $2.09 \times 10^9$ m$^3$ in 1960 to $3.27 \times 10^9$ m$^3$ in 2010 (Fig. 4a). The average growth rate during the study period was $23.53 \times 10^6$ m$^3$ y$^{-1}$.

Nearly half (47.04%) of the VWE associated with the crop trade in the 1960s was due to the trade of coarse cereals (Fig. 4b). The trade of coarse cereals and wheat (41.01%) accounted for approximately 90% of the VWE. The volume of the VWE in the 1970s was dominated by coarse cereals (42.16%), wheat (40.05%), and corn (12.16%). The proportion of sunflowers of the VWE has increased significantly since the 1980s, while the share of coarse cereals rapidly decreased. Wheat was the largest contributor to the VWE in the 1980s (41.70%) and 1990s (48.72%). The proportion of sunflowers (30.72%) was the largest of all crops in the 2000s, followed by wheat (28.00%) and corn (17.61%).

The virtual water import (VWI) associated with the crop trade was $340.00 \times 10^6$ m$^3$ in 1960 (Fig. 5a). The VWI increased significantly as the volume of imports increased, with an average growth rate of $67.84 \times 10^6$ m$^3$ y$^{-1}$, to a maximum VWI of $1.58 \times 10^9$ m$^3$ in 1979. The influence of the decreasing VWC then exceeded that of the increasing import volume, and the VWI consequently decreased rapidly to $315.95 \times 10^6$ m$^3$ by 2010 at a mean rate of $22.63 \times 10^6$ m$^3$ y$^{-1}$.

Fig. 5b shows the contributions of the crops to the VWI in different periods. The volume of the VWI was mainly due to the import of rice (Fig. 5b) whose cultivation was not suitable in the Hetao irrigation district. Only 0.15% of the VWI in the 1960s was associated with the import

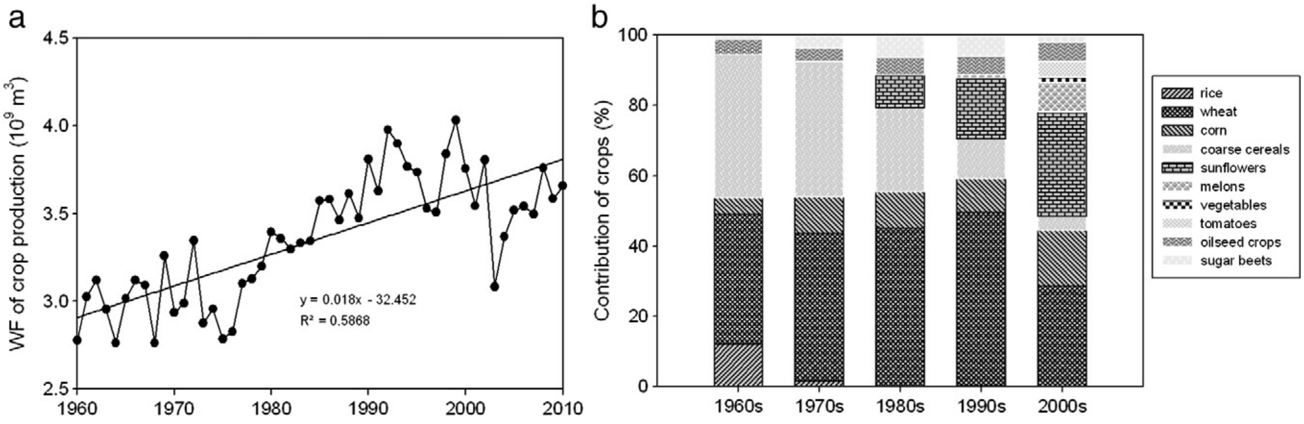

**Fig. 2.** Temporal variation of the WF of crop production in the Hetao irrigation district during 1960–2010 (a) and the contributions of the various crops in each period (b).

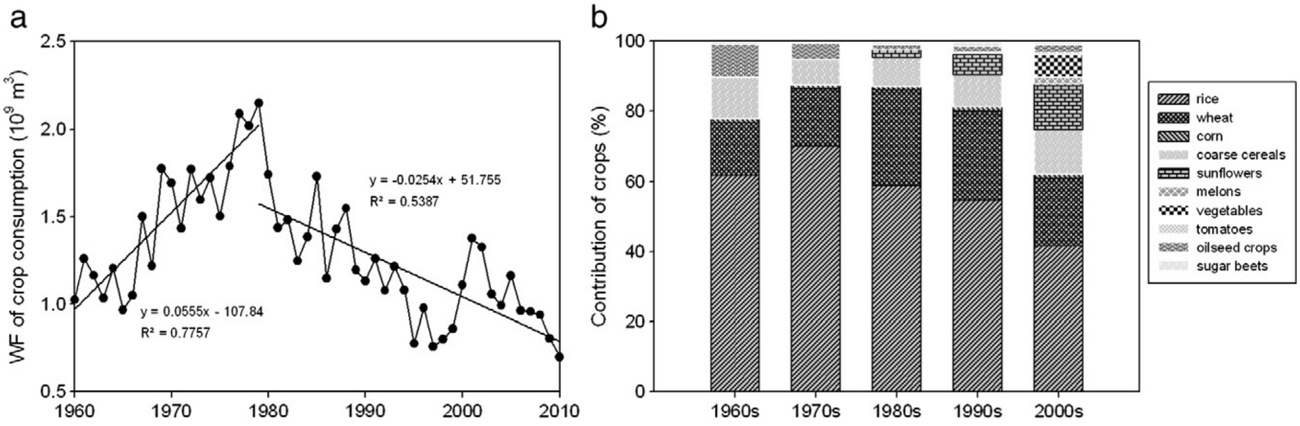

**Fig. 3.** Temporal variation of the WF of crop consumption in the Hetao irrigation district during 1960–2010 (a) and the contributions of the various crops in each period (b).

of sugar beets. The shares of rice and oilseed crops of the total VWI in the 1970s were 99.70 and 0.30%, respectively. Rice was the only contributor to the VWI in the 1980s and 1990s. The trade of coarse cereals and vegetables in the 2000s accounted for 2.13 and 1.46% of the total VWI, respectively, with the remainder due to the import of rice.

The VWE associated with the crop trade was mainly influenced by crop yield, irrigation efficiency, area sown, and mean annual temperature (Table 4). The increase in yield, area sown, and temperature accounted for 84.22, 9.21, and 4.35% of the increase in the VWE, respectively. In contrast, the increase in irrigation efficiency accounted for 14.68% of the decrease in the VWE.

Due to the temporal variation of VWI (Fig. 5a), we analyzed the rates of contribution for two periods: 1960–1979 and 1980–2010 (Table 4). For 1960–1979, 93.57% of the increase in the VWI associated with the crop trade was due to the increase in the total population (84.39%) and the proportion of the population living in urban areas (9.18%). The variation of VWI for 1980 to 2010 was mainly influenced by the retail-price index (89.52%) and the total population (−2.01%).

## 4. Discussions and policy

WFs and VWFs are two powerful accounting tools that can map the links between agricultural production, the behavior of human consumption, and trade activities (Zhang and Anadon, 2014). From the perspective of production, the WF of the Hetao irrigation district could be exported to other areas in virtual form or be used for local consumption. From the perspective of consumption, the WF could be supplied by the VWI from other regions or by local production. Comparing the volumes of the WF of crop production and the VWE, more than 75% of the WF of production in 1960 was exported to other areas rather than consumed by local habitants, and the share increased significantly to 89.51% by 2010 (Fig. 6a). A large percentage of the VWE represents water "losses" (in the sense that the water cannot be used again for other purposes in an area), thereby adding to the pressure on the local water systems (Bulsink et al., 2010; Chapagain et al., 2006; Zhang et al., 2011b). From the perspective of consumption, approximately 33% of the WF in 1960 was supplied by imports from other areas through the crop trade (Fig. 6b), which can conserve water and relieve the pressure on regional water resources (Bulsink et al., 2010; Chapagain et al., 2006; Zhang et al., 2011b). The share of the WF of consumption from imports of the total volume, however, decreased significantly after 1976 to less than 50% by 2010 (Fig. 6b).

Since 2000, many policy tools for the management of water resources have been promoted by the central government to alleviate the severe water scarcity, and the improvement of irrigation efficiency in the agricultural sector, the largest water consumer, has been one of the most important policies (Liu and Orr, 2010; Liu and Yang, 2012; Liu et al., 2013). Traditional surface-flooding irrigation is still common in the Hetao irrigation district. The irrigation efficiency in this area was 0.42 in 2010, which was much lower than the national average (Bai et al., 2011; Liu and Orr, 2010). An increase in irrigation efficiency from the current level to the average target by the application of more advanced techniques is thus a feasible measure for relieving the current water scarcity in the Hetao irrigation district. Jevons' paradox (or a rebound effect) suggests that a more efficient use of water may increase the aggregate demand for water (Alcott, 2005; Ward and Pulido-Velazquez, 2008). Consequently, an improvement of irrigation efficiency in the Hetao irrigation district should be coupled with measures that constrain the continued expansion of agriculture. As water becomes an increasingly scarce resource, a full-cost pricing of water is recognized as another effective policy tool for its management, and the need for such pricing has received worldwide acknowledgment (ICWE, 1992). The price for irrigation water in the Hetao irrigation district was only 0.053 Yuan $m^{-3}$ in 2010, which was much lower than its real value (Wang, 2012). The implementation of full-cost pricing for irrigation water, including all cost components, such as operation and maintenance costs, capital costs, opportunity costs, scarcity rents, and external costs of water use, would encourage local farmers to adjust their behavior of water use and to contribute to the sustainable use of water (Hoekstra, 2013; Rogers et al., 2002).

The allowable diversion of water from the Yellow River to the Hetao irrigation district should be decreased from 5 billion to 4 billion $m^3$ $y^{-1}$

**Table 3**
Contribution rates of the factors influencing the WF of crop consumption.

| Period | Influencing factor | Elasticity coefficient | Factor variation ratio (%) | Contribution rate (%) |
|---|---|---|---|---|
| 1960–1979 | Total population | 1.073 | 3.12 | 84.15 |
| | Annual precipitation | 0.198 | 1.81 | 9.00 |
| | Sum | | | 93.15 |
| | Other factors | | | 6.85 |
| 1980–2010 | Retail-price index | −0.687 | 4.82 | 93.15 |
| | Total population | 1.420 | 0.32 | −12.78 |
| | Sum | | | 80.37 |
| | Other factors | | | 19.63 |

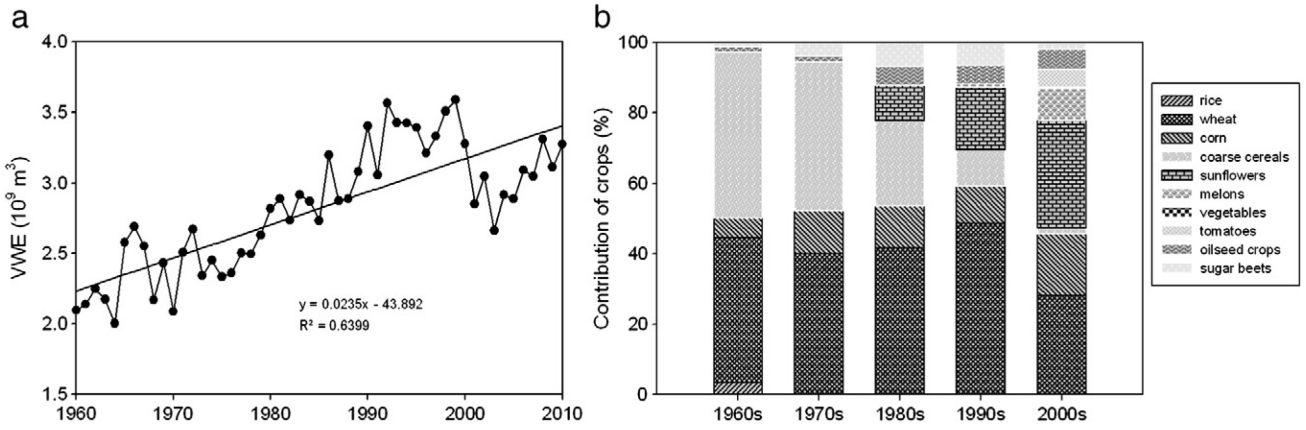

**Fig. 4.** Temporal variation of the VWE in the Hetao irrigation district during 1960–2010 (a) and the contributions of the various crops in each period (b).

to ensure national water security (Ye et al., 2010). Reshaping the regional water-production and water-trade nexuses by changing crop structures from water-intensive grain crops (rice, wheat, corn, and coarse cereals) to less water-intensive non-grain crops could provide alternative opportunities for addressing the problems of water scarcity and could decrease the total water withdrawal in this area. Nevertheless, optimizing the water-production or water-trade nexus by changing crop structures may have more widespread socio-economic consequences than the measures for the direct conservation of water (Konar et al., 2013; Zhang and Anadon, 2014; Zoumides et al., 2014). A reduction in the production of grain crops in the Hetao irrigation district, as an important area of agricultural production in China, could have an adverse effect on national food supply. If other irrigation districts similarly change their cropping patterns, China might risk moving away from food self-sufficiency and become vulnerable to potential threats, such as war or national disasters (Hoekstra, 2010b; Roth and Warner, 2007). The current cultivation of non-grain crops in the Hetao irrigation district, such as vegetables, requires more advanced technologies and less labor than do traditional grain crops (Zhou et al., 2000). Employment in the agricultural sector may thus decrease. In addition, an increase in grain import caused by a decrease in local production may reduce the incomes of farmers who cultivate grain crops, mainly due to the competition between the imported grain crops and those produced locally (Hoekstra, 2013). The trade-offs involved in the adjustment of cropping patterns should thus first be assessed before the adjustment could be used as a tool to alleviate regional water problems (Konar et al., 2013; Zhang and Anadon, 2014; Zoumides et al., 2014). Other policy tools, such as the control of population growth, increasing awareness, and reducing food waste, have great potential for relieving the current water scarcity (Liu and Yang, 2012; Vanham and Bidoglio, 2013).

An accurate determination of the necessary long-term trade data for a small area such as the Hetao irrigation district is currently difficult, and the assumption that trade volume is based on surpluses and deficits could introduce uncertainties for the estimation of the WFs and VWFs. We assumed that exported and imported crops had the same VWC; within this context the calculation of VWI could thus demonstrate how much water could be saved by importing rather than producing crops locally (Zhao et al., 2010). In addition, some variables were not included in our analysis of influencing factors, mainly due to the lack of data. Nevertheless, this study provides an initial attempt to determine WFs and VWFs and their influencing factors on an irrigation scale. This attempt could potentially help to alleviate water scarcity and to formulate better practices of water management.

## 5. Conclusions

The WF of production and the VWE in the Hetao irrigation district increased, with fluctuations, during 1960–2010. Two tendencies of variation were observed for the WF of consumption and the VWI: an increasing trend during 1960–1979 and a decreasing trend during 1980–2010. The WF of production and the VWE were mainly influenced by agricultural factors such as crop yield, irrigation efficiency, and area sown. Socio-economic factors, such as total population, the retail-price index, and the proportion of the population living in urban areas, played a more important role in the WF of consumption and the VWI.

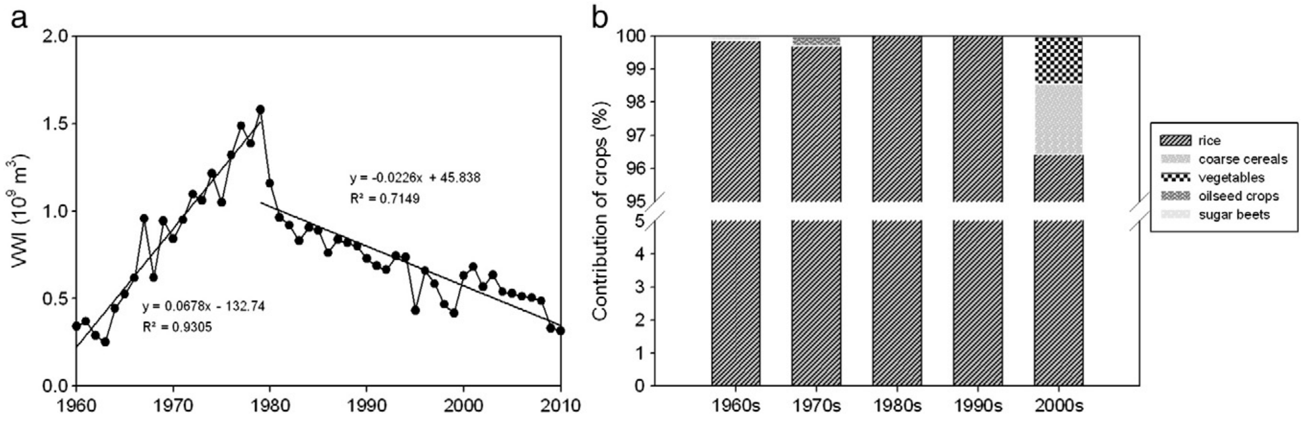

**Fig. 5.** Temporal variation of the VWI in the Hetao irrigation district during 1960–2010 (a) and the contributions of the various crops in each period (b).

**Table 4**
Contribution rates of the factors influencing the VWFs.

| Variable | Influencing factor | Elasticity coefficient | Factor variation ratio (%) | Contribution rate (%) |
|---|---|---|---|---|
| VWE | Yield | 0.303 | 4.39 | 84.22 |
| | Irrigation efficiency | −0.675 | 0.34 | −14.68 |
| | Area sown | 0.739 | 0.20 | 9.21 |
| | Mean annual temperature | 0.234 | 0.29 | 4.35 |
| | Sum | | | 83.10 |
| | Other factors | | | 16.90 |
| VWI (1960–1979) | Total population | 2.276 | 3.12 | 84.39 |
| | Proportion of population in urban areas | 1.324 | 0.58 | 9.18 |
| | Sum | | | 93.57 |
| | Other factors | | | 6.43 |
| VWI (1980–2010) | Retail-price index | −0.611 | 4.82 | 89.52 |
| | Total population | 0.207 | 0.32 | −2.01 |
| | Sum | | | 87.51 |
| | Other factors | | | 12.49 |

Most of the WF of production was used to export to other areas, which added to the pressure on the local water systems. The VWI represented a saving of water for the Hetao irrigation district and could relieve the pressure on regional water resources, while its share of the total WF of consumption decreased significantly after 1976. An increase in irrigation efficiency is one of the feasible policy tools that could alleviate water scarcity, but its application should be coupled with measures for constraining the continued expansion of agriculture. As water becomes an increasingly scarce resource, full-cost pricing of irrigation water would be another effective policy tool for its management. Reshaping the regional water-production and water-trade nexuses by changing crop structures could provide alternative opportunities for addressing the problems of local water scarcity, but the trade-offs involved should first be assessed.

## Acknowledgments

This work was jointly supported by the Special Foundation of the National Natural Science Foundation of China (51409218), the National Science & Technology Supporting Plan (2011BAD29B09), the 111 Project (B12007), the Supporting Plan of Basic Operational Cost of Research from Northwest A&F University (QN2011130), and the Fundamental Research Funds for the Central Universities (Z109021425).

## References

Alcott B. Jevons' paradox. Ecol Econ 2005;54(1):9–21.
Allen RG, Pereira LS, Raes D, Smith M. Crop evapotranspiration, Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper, 56Rome, Italy. : Food and Agricultural Organization; 1998.
Arouna A, Dabbert S. Determinants of domestic water Use by rural households without access to private improved water sources in Benin: a seemingly unrelated Tobit approach. Water Resour Manag 2010;24(7):1381–98.
Bai GS, Zhang R, Geng RJ. Integrating agricultural water-saving technologies in Hetao irrigation district. Bull Soil Water Conserv 2011;31:149–54.
Bulsink F, Hoekstra AY, Booij MJ. The water footprint of Indonesian provinces related to the consumption of crop products. Hydrol Earth Syst Sci 2010;14(1):119–28.
Cao XC, Wu PT, Wang YB, Zhao XN, Liu J. Analysis on temporal and spatial differences of water productivity in irrigation districts in China. Trans Chin Soc Agric Eng 2012;28(13):1–7.
Chapagain AK, Hoekstra AY. The global component of freshwater demand and supply: an assessment of virtual water flows between nations as a result of trade in agricultural and industrial products. Water Int 2008;33(1):19–32.
Chapagain AK, Hoekstra AY. The blue, green and grey water footprint of rice from production and consumption perspectives. Ecol Econ 2011;70(4):749–58.
Chapagain AK, Hoekstra AY, Savenije HHG. Water saving through international trade of agricultural products. Hydrol Earth Syst Sci 2006;10(3):455–68.
CMA. China Meteorological Data Sharing Service System. Beijing: China Meteorological Administration; 2010 (Available in http://cdc.cma.gov.cn).
Dalin C, Suweis S, Konar M, Hanasaki N, Rodriguez-Iturbe I. Modeling past and future structure of the global virtual water trade network. Geophys Res Lett 2012;39(24).
Djanibekov N, Frohberg K, Djanibekov U. Income-based projections of water footprint of food consumption in Uzbekistan. Glob Planet Chang 2013;110:130–42.
Duarte R, Pinilla V, Serrano A. The effect of globalization on water consumption: a case study of the Spanish virtual water trade, 1849–1935. Ecol Econ 2014;100:96–105.
Ercin AE, Hoekstra AY. Water footprint scenarios for 2050: a global analysis. Environ Int 2014;64(3):71–82.
Ercin AE, Mekonnen MM, Hoekstra AY. Sustainability of national consumption from a water resources perspective: the case study for France. Ecol Econ 2013;88:133–47.
FAO. CROPWAT 8.0 Model. Rome: Food and Agriculture Organization; 2012 [Available, www.fao.org/nr/water/infores_databases_cropwat.html [22 January 2012]].
Flörke M, Kynast E, Bärlund I, Eisner S, Wimmer F, Alcamo J. Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: a global simulation study. Glob Environ Chang 2013;23(1):144–56.
Hanasaki N, Fujimori S, Yamamoto T, Yoshikawa S, Masaki Y, Hijioka Y, et al. A global water scarcity assessment under Shared Socio-economic Pathways—part 2: water availability and scarcity. Hydrol Earth Syst Sci 2013;17(7):2393–413.
He YJ. Research of water utilization and management in Hetao irrigation district, Inner Mongolia. Inn Mong Water Conservancy 2010;3:14–5.
Hoekstra AY. The relation between international trade and freshwater scarcity (No. 2010-05). Staff working paper ERSD. Geneva: World Trade Organization; 2010a.
Hoekstra AY. The water footprint of animal products. In: D'Silva J, Webster J, editors. The meat crisis: developing more sustainable production and consumption. London, UK: Earthscan; 2010b. p. 22–33.
Hoekstra AY. The water footprint of modern consumer society. Routledge; 2013.
Hoekstra AY, Chapagain AK. Water footprints of nations: water use by people as a function of their consumption pattern. Water Resour Manag 2007;21(1):35–48.
Hoekstra AY, Chapagain AK. Globalization of water: sharing the planet's freshwater resources. Oxford, UK: Blackwell Publishing; 2008.
Hoekstra AY, Hung PQ. Virtual water trade—a quantification of virtual water flows between nations in relation to international crop trade. Value of Water Research Report Series, no. 11Delft. : UNESCO-IHE; 2002.
Hoekstra AY, Chapagain AK, Aldaya MM, Mekonnen MM. The water footprint assessment manual: setting the global standard. London, UK: Earthscan; 2011.

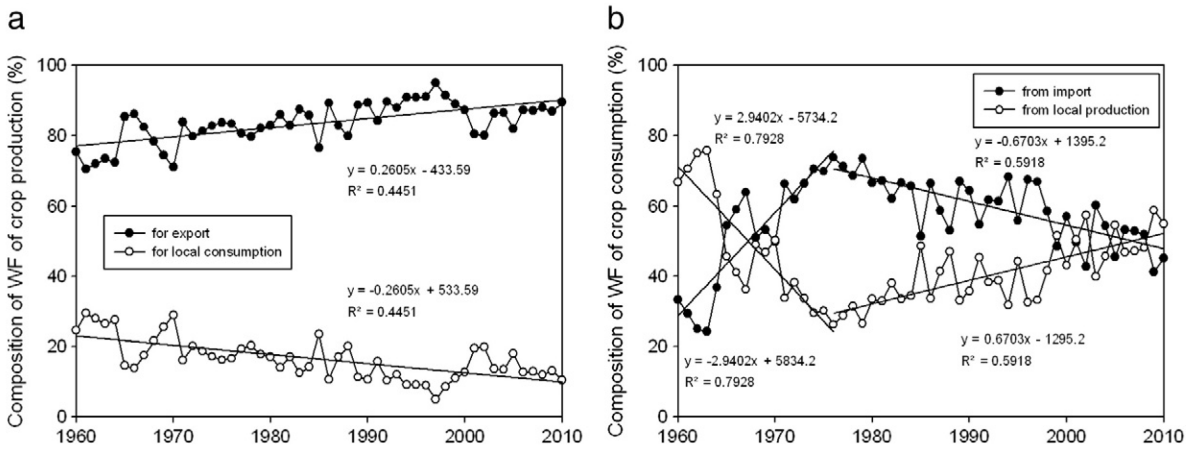

**Fig. 6.** Composition of the WF in the Hetao irrigation district during 1960–2010 from the perspectives of production (a) and consumption (b).

Hoekstra AY, Mekonnen MM, Chapagain AK, Mathews RE, Richter BD. Global monthly water scarcity: blue water footprints versus blue water availability. PLoS One 2012;7(2):e32688.

Huang CL, Vause J, Ma HW, Yu CP. Urban water metabolism efficiency assessment: integrated analysis of available and virtual water. Sci Total Environ 2013;452–453:19–27.

Hubacek K, Guan D, Barrett J, Wiedmann T. Environmental implications of urbanization and lifestyle change in China: ecological and water footprints. J Clean Prod 2009;17(14):1241–8.

ICWE. The Dublin statement on water and sustainable development. International Conference on Water and the Environment, Dublin, Ireland; 1992.

Jansen A, Schulz C. Water demand and the urban poor: a study of the factors influencing water consumption among households in Cape Town, South Africa. S Afr J Econ 2006;74(3):593–609.

Konar M, Hussein Z, Hanasaki N, Mauzerall DL, Rodriguez-Iturbe I. Virtual water trade flows and savings under climate change. Hydrol Earth Syst Sci 2013;17(8):3219–34.

Kumar MD, Singh OP. Virtual water in global food and water policy making: is there a need for rethinking? Water Resour Manag 2005;19:759–89.

Kummu M, Ward PJ, de Moel H, Varis O. Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia. Environ Res Lett 2010;5(3):034006.

Kummu M, Gerten D, Heinke J, Konzmann M, Varis O. Climate-driven interannual variability of water scarcity in food production potential: a global analysis. Hydrol Earth Syst Sci 2014;18(2):447–61.

Lenzen M, Moran D, Bhaduri A, Kanemoto K, Bekchanov M, Geschke A, et al. International trade of scarce water. Ecol Econ 2013;94:78–85.

Liu J, Orr S. Water footprint overview in the governmental, public policy, and corporate contexts. Water Front 2010:73–9.

Liu J, Yang W. Water sustainability for China and beyond. Science 2012;337:649–50.

Liu J, Zang C, Tian S, Liu J, Yang H, Jia S, et al. Water conservancy projects in China: achievements, challenges and way forward. Glob Environ Chang 2013;23:633–43.

Ma J, Hoekstra AY, Wang H, Chapagain AK, Wang D. Virtual versus real water transfers within China. Philos Trans R Soc Lond B 2006;361:835–42.

MAC. Hetao irrigation district agricultural statistical data and Chinese agricultural statistical data. Ministry of Agriculture of the People's Republic of China. Beijing: Chinese Agricultural Press; 1960-2010.

Mekonnen MM, Hoekstra AY. A global and high-resolution assessment of the green, blue and grey water footprint of wheat. Hydrol Earth Syst Sci 2010;14(7):1259–76.

Montesinos P, Camacho E, Campos B, Rodríguez-Díaz JA. Analysis of virtual irrigation water. Application to water resources management in a Mediterranean River Basin. Water Resour Manag 2011;25(6):1635–51.

Nakayama T. Simulation of the effect of irrigation on the hydrologic cycle in the highly cultivated Yellow River Basin. Agric For Meteorol 2011;151(3):314–27.

NBSC. Bayan Nur statistical yearbook, Inner Mongolia statistical yearbook and China statistical yearbook. Beijing: National Bureau of Statistics of China, China Statistical Press; 1960–2010.

Novo P, Garrido A, Varela-Ortega C. Are virtual water “flows” in Spanish grain trade consistent with relative water scarcity? Ecol Econ 2009;68(5):1454–64.

Rogers P, De Silva R, Bhatia R. Water is an economic good: how to use prices to promote equity, efficiency, and sustainability. Water Policy 2002;4(1):1–17.

Rost S, Gerten D, Bondeau A, Lucht W, Rohwer J, Schaphoff S. Agricultural green and blue water consumption and its influence on the global water system. Water Resour Res 2008;44(9).

Roth D, Warner J. Virtual water: virtuous impact? The unsteady state of virtual water. Agric Hum Values 2007;25(2):257–70.

Suweis S, Konar M, Dalin C, Hanasaki N, Rinaldo A, Rodriguez-Iturbe I. Structure and controls of the global virtual water trade network. Geophys Res Lett 2011;38(10).

Tamea S, Carr JA, Laio F, Ridolfi L. Drivers of the virtual water trade. Water Resour Res 2014;50(1):17–28.

Vanham D, Bidoglio G. A review on the indicator water footprint for the EU28. Ecol Indic 2013;26:61–75.

Verma S, Kampman DA, Van der Zaag P, Hoekstra AY. Going against the flow: a critical analysis of inter-state virtual water trade in the context of India's national river linking programme. Phys Chem Earth 2009;34:261–9.

Vörösmarty CJ, McIntyre PB, Gessner MO, Dudgeon D, Prusevich A, Green P, et al. Global threats to human water security and river biodiversity. Nature 2010;467(7315):555–61.

Wang JP. Study on irrigation water price in Inner Mongolia Autonomous Region [Doctoral dissertation] Chinese Academy of Agricultural Sciences; 2012.

Ward FA, Pulido-Velazquez M. Water conservation in irrigation can increase water use. Proc Natl Acad Sci U S A 2008;105(47):18215–20.

Yang Q, Zhu RX, Zhang J, Han WT. Mechanization profit portion estimation in plant products industry in Shaanxi Province. Trans Chin Soc Agric Eng 2000;16:64–7.

Ye ZY, Guo KZ, Zhao SY, Xu B. The current development and focal points in short-term water-saving agriculture in Hetao irrigation district. China Rural Water Conservancy Hydropower 2010;6:81–4.

Zeng Z, Liu J, Savenije HHG. A simple approach to assess water scarcity integrating water quantity and quality. Ecol Indic 2013;34:441–9.

Zhang C, Anadon LD. A multi-regional input–output analysis of domestic virtual water trade and provincial water footprint in China. Ecol Econ 2014;100:159–72.

Zhang X, Hao FH, Wang X. Assessment of phosphorus loss under different tillage methods in Hetao agricultural irrigation areas. Trans Chin Soc Agric Eng 2011a;27:59–65.

Zhang ZY, Yang H, Shi MJ, Zehnder AJB, Abbaspour KC. Analyses of impacts of China's international trade on its water resources and uses. Hydrol Earth Syst Sci 2011b;15(9):2871–80.

Zhao X, Yang H, Yang Z, Chen B, QIN Y. Applying the input–output method to account for water footprint and virtual water trade in the Haihe River Basin in China. Environ Sci Technol 2010;44:9150–6.

Zhao C, Chen B, Hayat T, Alsaedi A, Ahmad B. Driving force analysis of water footprint change based on extended STIRPAT model: evidence from the Chinese agricultural sector. Ecol Indic 2014. http://dx.doi.org/10.1016/j.ecolind.2014.04.048.

Zhou FS, Wang QR, Tang YP, Ren YS. Study on agricultural modernization in the Hetao irrigation district. Forw Position 2000;11:50–60.

Zoumides C, Bruggeman A, Hadjikakou M, Zachariadis T. Policy-relevant indicators for semi-arid nations: the water footprint of crop production and supply utilization of Cyprus. Ecol Indic 2014;43:205–14.