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Virtual Water Flows Related to Grain Crop Trade and Their Influencing Factors in Hetao Irrigation District, China

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ABSTRACT

Virtual water adds a new dimension to crop trades and provides a new way of thinking about water scarcity. A systematic analysis of virtual water flows requires integration of all critical drivers of virtual water flows under a single consistent framework. The aim of this study was to assess virtual water flows related to trades of grain crops (wheat, corn, rice, and coarse cereals) and their influencing factors in Hetao irrigation district, China during 1981-2010. Results indicated that: (1) volume of virtual water export decreased from 2.08×10^9 m^3 in 1981 to 1.27×10^9 m^3 in 2010. Volume of virtual water import fluctuated around 621.48×10^6 m^3 during study period; (2) Cultivated area per capita and total population were the major influencing factors for virtual water export in Hetao irrigation district. Volume of virtual water import was mainly influenced by consumption and retail price index of grain crops. Combination of large volume of virtual water export and severely constrained water resources confronted Hetao irrigation district with great challenges in its sustainable development. Decreasing virtual water export is a mean to alleviate regional water shortage pressure, and may be achieved by measures that constrain continued population expansion.

Keywords: Cereal crop, Embedded water, Irrigated area.

INTRODUCTION

Properly managing water resources is essential for achieving sustainable social and economic development, reducing poverty and promoting equity. The concept of virtual water content of a product, which is the amount of water used to generate a product, adds a new dimension to international trade and provides a new way of thinking about water scarcity and water resources management (Allan, 1993; Chapagain and Hoekstra, 2008). An inflow of virtual water generates water saving for importing regions, while an outflow of virtual water adds to the pressure on local water (Zhang *et al*., 2011).

Due to the large proportion of water withdrawn for crop production, significant works have been devoted to analyze the volumes of virtual water flows related to crop trade and its implication for water and food security (Zhao *et al*., 2010; Montesinos *et al*., 2011). It is plausible to assume that virtual water would transfer from water-rich regions to water-scarce regions, however, in many cases, flows of virtual water do not follow the spatial pattern of water

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availability (Kumar and Singh, 2005; Verma *et al*., 2009). The relationships between virtual water flows and other non-water related factors such as land endowment, urban population, and climate change have been explored (Verma *et al*., 2009; Zhao and Samson, 2012; Konar *et al*., 2013). However, a systematic analysis of virtual water flows requires integration of all critical drivers of virtual water flows under a single, consistent framework (Ercin and Hoekstra, 2014). In recent years, studies on the controls of global virtual water trades have been conducted (Suweis *et al*., 2011; Dalin *et al*., 2012; Tamea *et al*., 2014). However, there are few studies illustrating the determinants of virtual water flows on a regional scale.

Irrigation districts have produced more than 3/4 of grain crops, performing an increasingly important function in ensuring China's food security (MAC, 2011). Compared to a global scale, studies on smaller and more localized scales are more pertinent to specific regional problems (Zhang *et al*., 2011). Thus, the aim of this study was to analyze virtual water flows between Hetao irrigation district and the rest of China, and factors that influence them. This study focused on grain crops due to their significance in food security in China and could add a new dimension to crop trade and would be helpful in fostering better water management practices.

MATERIALS AND METHODS

Study Area

Hetao irrigation district is located in the west of Inner Mongolia, China (N 40°13′ to 42°28′, E 105°12′ to 109°53′) (Figure 1). It is the biggest gravity irrigation district in Asia with an irrigation area of 5.74×10^3 km^2 (Ye *et al*., 2010). It has a continental monsoon climate, and rainfall is scarce (yearly average around 130-215 mm) and erratically distributed (70% in July, August, and September); while annual evaporation is 2100-2300 mm (Ye *et al*., 2010).

Hetao irrigation district has been an important agricultural producing area where about 1/10 of grain crops of Inner Mongolia was produced in the 2000s (NBSC, 2011). The most commonly cultivated grain crops

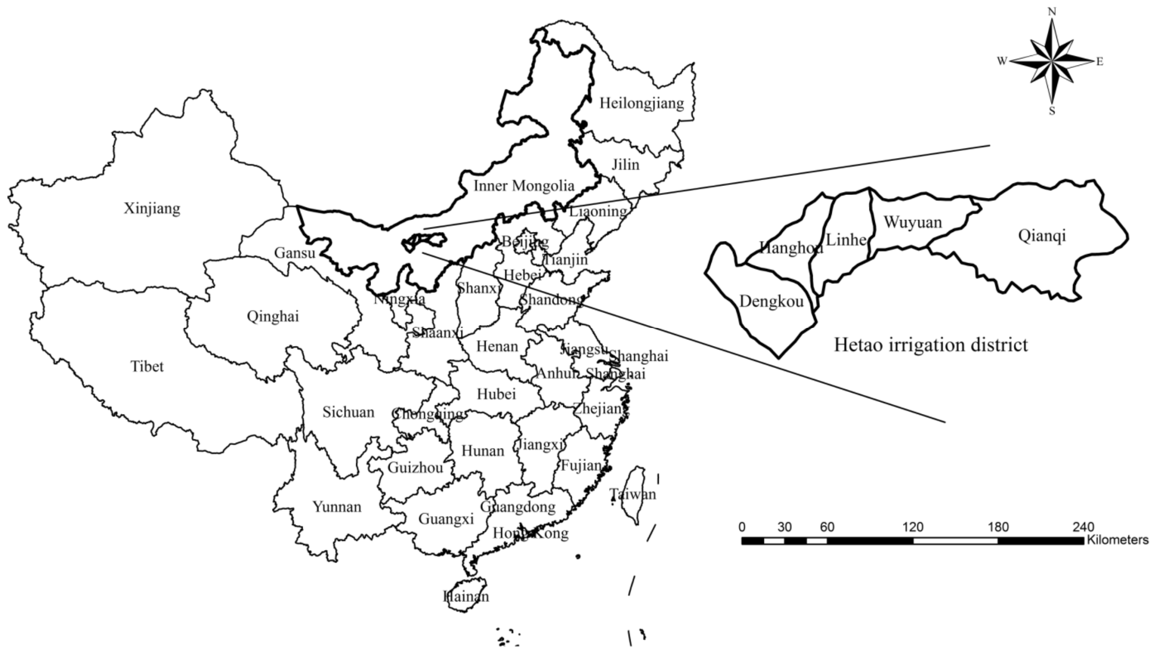

Figure 1. Location of Hetao irrigation district.

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in this region have been wheat and corn, accounting for more than 80% of grain crops sown areas during 1981-2010 (wheat 63.16%, corn 20.92%) (MAC, 2011). Average yields per unit area were 4.47×10^3 kg ha^{-1} for wheat and 9.17×10^3 kg ha^{-1} for corn (MAC, 2011). Irrigation in this region mainly depends on water from the Yellow River. In the 2000s, about 7.75×10^3 m^3 ha^{-1} water diverted from the Yellow River was used for irrigation and average efficiency was 0.41 (MAC, 2011). Water obtained from the Yellow River has decreased from 5×10^9 to 4×10^9 m^3 a^{-1} in the past years, which has put high pressure on water resources (Ye *et al*., 2010).

Model and Data

CROPWAT 8.0 Model is a decision support tool developed by the Land and Water Development Division of FAO (FAO, 2012a). It has been widely used for the calculation of crop evapotranspiration and effective precipitation based on soil, climate, and crop data (Chapagain and Hoekstra, 2008; Ercin and Hoekstra, 2014). Calculation of crop evapotranspiration with CROPWAT 8.0 Model is based on the Penman-Monteith method, and four alternative methods are provided for the estimation of effective precipitation (Allen *et al*., 1998; FAO, 2012a).

Meteorological data, including air temperature, relative humidity, wind speed, hours of sunshine and precipitation were obtained from China Meteorological Data Sharing Service System (CMA, 2010). Agricultural data including crop yield, cultivated area, and irrigation water withdrawal were collected from "Hetao Irrigation District Statistical Data" and “China Agricultural Statistical Data” (MAC, 2011). Social and economic data including population, grain consumption, gross domestic product, and retail price index were taken from "Bayan Nur Statistical Yearbook" and "China Statistical Yearbook" (NBSC, 2011).

Calculation of Virtual Water Flows

Virtual water flows between Hetao irrigation district and the rest of China, due to transfer of grain crops, were calculated by multiplying trade volumes of grain crops by water footprint of the traded grain crops (Chapagain and Hoekstra, 2008). Four kinds of grain crops, namely, wheat, corn, rice, and coarse cereals were analyzed in this study.

Grain transfer volume was calculated based on surpluses and deficits, as described in Bulsink *et al*. (2010). A surplus took place when the production of a grain crop in Hetao irrigation district was larger than its consumption. A deficit occurred when consumption of a grain crop was larger than its production. It was assumed that all grain surpluses in Hetao irrigation district were exported to other areas of China and all grain deficits were met by importing them from the rest of China.

Water footprint refers to water consumption per unit of crop production over their growing period, measured at the point of production (Hoekstra *et al*., 2011). Because of the absence of data, water footprint of imported crop was assumed equal to that of exported crop in this study. Two kinds of water resources were consumed during crop growing period: green water and blue water.

Green water was calculated for each 10-day period as the lower value of crop evapotranspiration and effective precipitation, and added up for the length of growing period using CROPWAT 8.0 Model (Mubako and Lant, 2008). Calculation of crop evapotranspiration was based on the Penman-Monteith method (Allen *et al*., 1998). Effective precipitation was estimated using the USDA Soil Conservation Service method, due to its wide use in water management (Jensen *et al*., 1990).

Total blue water consumption was determined by the difference between irrigation water withdrawal and return flows (Mubako and Lant, 2008; Flörke *et al*.,

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2013). Based on the study of Nakayama (2011), return flows were 25% of water withdrawal in Hetao irrigation district. Total blue water was distributed proportionally among different crops according to their theoretical irrigation water requirements (Montesinos *et al*., 2011). If crop evapotranspiration was larger than the effective precipitation, the difference between them was used as theoretical irrigation water requirements, otherwise the theoretical irrigation water requirements was zero (Hoekstra *et al*., 2011).

Multiple Linear Regression Analysis

Multiple linear regression analysis has been widely used to explore the relationship between a dependent variable and several independent variables (Mousanejad *et al*., 2010; Um *et al*., 2011). In order to analyze the influencing factors of virtual water flows, multiple linear regression models were built with SPSS 16.0 at a significance level of 5% (α= 0.05). Before regression analysis was performed, a normality test was done using the Shapiro-Wilk test, and natural logarithm transformation was applied to variables whose distributions were not normal. In the regression analysis, independent variables were entered into the regression model when the significance of *F* value was less than 0.05, one after the other in successive steps, until no other independent variables could be entered. At each step, independent variables already entered into the model were checked, and removed from the model if the significance of *F* value was more than 0.10.

For constructed models, several criteria were used for regression diagnostics (Um *et al*., 2011). Goodness-of-fit of model was verified by R^2, and *F*-test and *t*-test were used to verify statistical significance. Variance inflation factor (VIF) was used to identify multicollinearity among variables, where values greater than 5–10 indicated a multicollinearity problem. The Durbin-Watson test was applied to evaluate independence of residuals, where values between 1 and 3 indicated no autocorrelations.

Selection of Independent Variables

Based on the literature on virtual water flows and data availability, independent variables chosen in this study were listed as follows, and the statistical description is presented in Table 1:

Climate

According to the study of Konar *et al.* (2013), a decrease of global virtual water flows related to crop trade could be seen under climate change. In this study, mean annual temperature and annual precipitation were selected as proxies for climate change.

Table 1. Statistical description of independent variables used in multiple regression analysis.

Independent variable	Symbol	Unit	Maximum	Minimum	Mean	Standard deviation
Mean annual temperature	tem	°C	10.26	7.63	9.00	0.66
Annual precipitation	pre	mm a^{-1}	242.84	77.00	163.25	42.83
Sown area of grain crops per capita	area	ha cap^{-1}	0.25	0.11	0.19	0.04
Total population	Tpop	10^6 cap	1.60	1.19	1.43	0.13
Urban population	Upop	10^6 cap	0.69	0.27	0.47	0.14
Yield per unit area	yie	10^3 kg ha^{-1}	7.82	2.41	5.28	1.72
Agricultural water use efficiency	AWUE	-	0.42	0.30	0.34	0.04
Retail price index of grain crops	RPI	100	9.54	1.02	4.35	2.75
Gross domestic product per capita	GDP	10^3 yuan cap^{-1}	3.23	0.34	1.44	0.94
Consumption of grain crops per capita	con	10^3 kg cap^{-1} a^{-1}	0.32	0.19	0.25	0.04

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Land endowment

Kumar and Singh (2005) showed that "access to arable land" could be a key driver for virtual water trades. The same hypothesis was tested for Indian states, and a similar conclusion was obtained (Verma *et al.*, 2009). In this study, grain sown area per capita was chosen as an independent variable for regression analysis.

Population

A study conducted by Dalin *et al.*, (2012) and Tamea *et al.*, (2014) indicated that total population played a major role in determining international virtual water fluxes, while Zhao and Samson (2012) stated that urban population was more appropriate than total population in estimating virtual water flows for developing countries. In this study, both total population and urban population were selected as independent variables for regression analysis.

Technology

Changes in agricultural production technology could modify international trade pattern and international flows of virtual water (Sivapalan *et al.*, 2012). In this study, technology changes were addressed in terms of crop yield and agricultural water use efficiency, similar to other studies (Ercin and Hoekstra, 2014).

Retail price index (RPI)

RPI is a reflection of changes in retail prices of commodities, and its calculation is shown in Equation (1) (NBSC, 2011). Changes of *RPI* could affect the purchasing power of residents, market equilibrium, and ratio of consumption to accumulation (NBSC, 2011). Thus, changes of *RPI* for grain crops were expected to have an influence on grain transfer, which in return would generate variation in virtual water trade. In this study, *RPI* for grain crops calculated on a constant-price base period (1980) was chosen as an independent variable.

$$RPI = \frac{\sum_{i=1}^{n} p_{i-t} s_{i-b}}{\sum_{i=1}^{n} p_{i-b} s_{i-b}} \times 100 \qquad (1)$$

Where, p_{i-t} and p_{i-b} are retail prices of commodity i in period t and base period (Yuan kg^{-1}); s_{i-b} is sale volume of commodity i in base period (kg) and n is number of types of commodity.

Gross domestic product per capita (GDP per capita)

GDP is the sum of value added by all resident producers plus any product taxes (without accounting for subsidies) not included in the valuation of output, and *GDP* per capita is *GDP* divided by population (NBSC, 2011). *GDP* per capita is closely related to regional trade activity and has an influence on virtual water trades (Suweis *et al.*, 2011; Dalin *et al.*, 2012; Tamea *et al.*, 2014). In this study, *GDP* per capita calculated on a constant-price base period (1980) was selected as an independent variable for regression analysis.

Consumption

Transfer volume of grain crops is a function of production, consumption and stock change (FAO, 2012b). Volume of virtual water flows was determined by transfer volume of grain crops and their water footprint (Chapagain and Hoekstra, 2008). Consequently, grain crops consumption per capita was expected to be a possible influencing factor of virtual water flows.

RESULTS

Transfer Volume and Water Footprint of Grain Crops

As shown in Figure 2-a, the exported volume of grain crops increased from 577.02×10^6 kg in 1981 to 1.59×10^9 kg in

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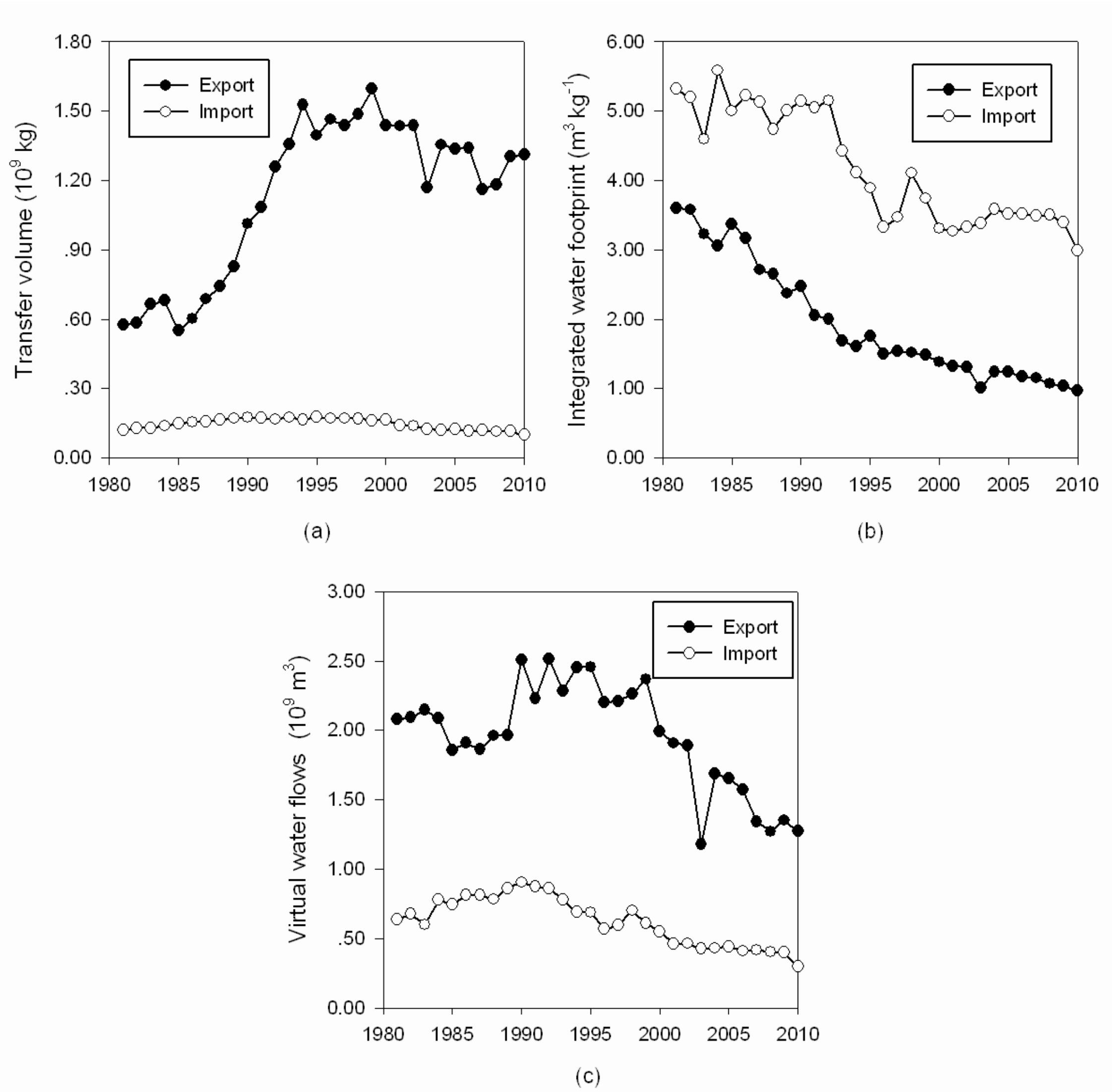

Figure 2. Variation of transfer volume (a), integrated water footprint (b) and virtual water flows (c) for exported/imported grain crops in Hetao irrigation district during 1981-2010.

1999, with an average growth rate of 66.15×10^6 kg per year. Since 2000, the exported volume had been fluctuating, with a decreasing trend towards 1.31×10^9 kg in 2010. In the 1980s, the import of grain crops increased from 119.71×10^6 kg to 171.80×10^6 kg. The value of imported volume was stable in the 1990s and showed a falling trend in the 2000s until reaching 98.84×10^6 kg in 2010.

Integrated water footprint was calculated according to the weighted average of water footprint and transfer volume of each crop. The value of integrated water footprint for exported grain crops decreased from 3.60 m^3 kg^{-1} in 1981 to 0.97 m^3 kg^{-1} in 2010 and the average falling rate was 0.09 m^3 kg^{-1} per year (Figure 2-b). A significantly decreasing trend could also be seen for integrated water footprint of imported grain crops, which was 1.71 m^3 kg^{-1} larger than that of exported grain crops in 1981 and 2.02 m^3 kg^{-1} larger in 2010.

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Virtual Water Flows Associated with Transfer of Grain Crops

Figure 2-c presents the inter-annual variability of virtual water flows related to transfer of grain crops during 1981-2010. In the 1980s, the value of virtual water export fluctuated around 2.05×10^9 m^3, which then decreased from 2.23×10^9 m^3 in 1991 to 1.27×10^9 m^3 in 2010 with an average falling rate of 69.73×10^6 m^3 per year. Before achieving its maximum (903.76×10^6 m^3) in 1990, the value of virtual water import increased at an average rate of 29.01×10^6 m^3 per year, then decreasing at an average rate of 27.47×10^6 m^3 per year, until reaching 295.54×10^6 m^3 in 2010.

Influencing Factors of Virtual Water Flows

The goodness-of-fit of the constructed regression models for virtual water export (R^2= 0.941) and virtual water import (R^2= 0.932) were well, and standards for statistical significant level were satisfied as per the results of *F*-test and *t*-test (Table 2). The *VIFs* were 2.607 (virtual water export model) and 1.395 (virtual water import model), indicating no multicollinearity among variables. The Durbin-Watson test for both models showed no autocorrelations between residuals.

Sown area of grain crops per capita and total population were the major influencing factors for virtual water export. An increase of 1 ha cap^{-1} for grain sown area could result in 15.407×10^9 m^3 more virtual water export as long as the total population remained constant. About 2.463×10^9 m^3 more virtual water would flow out from Hetao irrigation district if the total population increased by 1×10^6 cap and the grain sown area per capita remained constant. The regression model for virtual water export could be expressed as: *VWE* (10^9 m^3) = *-4.410+15.407area (ha cap^{-1}) +2.463Tpop (10^6 cap)*

The volume of virtual water import was mainly influenced by grain crop consumption and *RPI*. An increase of grain crop consumption would generate a rise of virtual water import, while the opposite relationship could be observed between RPI and virtual water import. The regression model for virtual water import could be expressed as: *VWI* (10^9 m^3) = *0.069+2.801con (10^3 kg cap^{-1} a^{-1})-0.037RPI (100)*

DISCUSSION

Knowledge of virtual water flows entering and leaving a region can put a new light on actual water scarcity (Chapagain and

Table 2. Regression models for virtual water export and import.

Model summary				
Regression model	R^2	Std. error of the estimate	F-test (Sig)	Durbin-Watson
Virtual water export	0.941	0.100	0.000	1.744
Virtual water import	0.932	0.051	0.000	1.515

Regression model		Unstandardized coefficient B	Unstandardized coefficient Std. error	Standardized coefficient Beta	t-test (Sig)	VIF
Virtual water export	(Constant)	-4.410	0.452		0.000	
	area	15.407	0.794	1.468	0.000	2.607
	Tpop	2.463	0.228	0.816	0.000	2.607
Virtual water import	(Constant)	0.069	0.084		0.016	
	con	2.801	0.291	0.568	0.000	1.395
	RPI	-0.037	0.004	-0.535	0.000	1.395

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Hoekstra, 2008). About 2.05×10^9 m^3 of water flowed out from Hetao irrigation district due to export of grain crops in the 1980s, accounting for 40% of available water resources in this region. A large volume of virtual water export means loss of water in the exporting region, in the sense that the water cannot be used anymore for producing high-value commodities or serving domestic needs (Zhang *et al*., 2011). In the 2000s, virtual water export decreased to 1.51×10^9 m^3, still accounting for one third of available water resources in Hetao irrigation district. The import of virtual water could contribute to alleviating the existing water resources pressure, while it was relatively small, it amounted to about 30% of virtual water export during 1981-2010.

The results of this study show that virtual water export related to transfer of grain crops was mainly influenced by grain crops area per capita and total population. This was mainly due to the fact that, as an important agricultural production and export area, grain crops export in Hetao irrigation district would increase with respect to the enhancement of agricultural production capacity caused by the increase of grain crops area per capita and total population. For virtual water import, a decrease of grain crop consumption might lessen the demand of grain crop import from other areas, consequently, leading to a relatively small volume of virtual water import. A rise of RPI could result in less grain crops consumption, which would also lead to a smaller virtual water import.

In the long run, Hetao irrigation district could not obtain more water resources from the Yellow River (Ye *et al*., 2010). To meet the growing regional water consumption needs, a change in virtual water trade is needed. Taking the relatively small volume of virtual water import into account, decreasing virtual water export is one feasible mean for alleviating the existing water shortage pressure in Hetao irrigation district. Compared with decreasing grain crops area per capita, which could have an adverse effect on food supply for other regions, measures that constrain continued population expansion are more practical.

Some assumptions that have been made in this study could bring some uncertainties to the assessment of virtual water flows. In this study, transfer volume was calculated based on surpluses and deficits. However, farmers may prefer to increase storage rather than export surpluses in years with natural disaster. Furthermore, imported volume might be larger than deficits when habitants could afford that. Due to differences in climate, soil, agricultural management and other items, water footprint of grain crops produced in different regions may vary greatly (Hoekstra *et al*., 2011). No differences were assumed for water footprint between exported and imported grain crops in this study. If imported grain crops were from areas with better growing condition and higher agricultural production level, which means a smaller water footprint than that in Hetao irrigation district, then the estimation for virtual water import would be higher. In opposite cases, calculated virtual water import might be smaller than actual value. While similar assumptions have been made in other studies, within this context, calculation of virtual water import could 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 the regression analysis mainly due to the lack of data availability, such as agricultural subsidies and the price of water for irrigation. Nevertheless, more than 90% of variation of virtual water trades could be explained at a significance level of 5%. Overall, the results of this study provide some insight into the potential for improving water resources management in irrigation districts by showing the temporal variations and influencing factors of virtual water trade.

CONCLUSIONS

Virtual water export decreased from 2.08×10^9 m^3 in 1981 to 1.27×10^9 m^3 in 2010, and virtual water import fluctuated around

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621.48×10^6 m^3 during 1981-2010. Grain sown area per capita and total population were major influencing factors for virtual water export in Hetao irrigation district. Volume of virtual water import was mainly influenced by grain crop consumption and *RPI*. More than 90% of variation of virtual water trades could be explained at a significance level of 5%.

Combination of the large volume of virtual water export and severely constrained water resources has confronted Hetao irrigation district with great challenges in sustainable development. Decreasing virtual water export is one of the possible means for alleviating regional water shortage pressure, and may be achieved by measures that constrain continued population expansion.

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جریان های آب مجازی مربوط به تجارت غلات و عوامل موثر بر آنها در ناحیه آبیاری هتائو در چین

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چکیده

آب مجازی بُعد جدیدی به تجارت محصولات کشاورزی می افزاید و راه جدیدی برای چاره جویی در مسله کمبود آب باز می کند. تحلیلی سامانه ای از جریانات آب مجازی نیازمند آن است که همه

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عوامل اصلی جریان های آب مجازی در یک چارچوب منسجم تلفیق شوند. هدف پژوهش حاضر ارزیابی جریان های آب مجازی مربوط به تجارت غلات (گندم، ذرت، برنج و دیگر غلات) و عوامل موثر در آن ها درناحیه آبیاری هتائو در چین طی سال های ۱۹۸۱تا ۲۰۱۰ بود. نتایج بررسی حاکی از آن بود که (۱) حجم آب مجازی صادر شده از مقدار $2/08\ x10^9\ m^3$ در سال ۱۹۸۱ به $1/27\times10^9$ m^3در سال ۲۰۱۰ کاهش یافت.در طی همین مدت، حجم آب مجازی وارد شده در حدود $621/48\ x10^6\ m^3$ در نوسان بود، (۲) سطح زیر کشت به ازای هر نفر و جمعیت کل، اصلی ترین عوامل موثر در صدور آب مجازی در ناحیه آبیاری هتائو بودند. اما، حجم آب مجازی وارداتی بیشتر تحت تاثیر مقدار مصرف و نیز قیمت شاخص خرده فروشی غلات بود. ترکیب حجم زیاد آب مجازی صادراتی و محدودیت شدید منابع آب، ناحیه آبیاری هتائو را با چالش های بزرگی از نظر توسعه پایدار رو در رو ساخته است. به این ترتیب، کاهش صادرات آب مجازی چاره ای است برای کاهش فشار ناشی از کمبود آب که برای این منظور می توان از روش هایی که افزایش مداوم جمعیت را محدود می کند بهره جست.