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Analysis of virtual water flows related to crop transfer and its effects on local water resources in Hetao irrigation district, China, from 1960 to 2008

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Abstract

Together with the transfer of commodities, regions trade water that is needed for the production of commodities in virtual form. This is called virtual water flow or virtual water trade. Analysis of virtual water flows could supply a better understanding of water resources problems and provide some suggestions for the improvement of water resources management. The aim of the study was to determine the virtual water flows related to regional crop transfer and its effects on local water resources in Hetao irrigation district, China, from 1960 to 2008. Results indicate that: (1) virtual water export showed an increasing trend over the study period and the multi-year average value was 2.17×10^9 m³; (2) blue virtual water export accounted for 87.98% of virtual water export; (3) the export rate of water resources (the virtual water export related to crop transfer divided by the total water used in local area) increased from 38.51% in 1960s to 56.82% in 2000s. Results indicate that virtual water export put great pressure on local water resources and brought environmental issues to Hetao irrigation district. The government should take measures to improve both blue water (irrigation water) and green water (rain water) use efficiency to alleviate water crisis.

Key words: Virtual water flows, export rate of water resources, irrigation district, China.

Introduction

Natural resources are subject to increasing pressure from population growth, economic development and climate change, and the situation is more serious for water resources [1-3]. Currently, approximately one third of the world's population lives in countries suffering from water stress [4]. Over the next few decades, up to two-thirds of the world's population would experience water scarcity [5]. Now how to satisfy human's needs for water resources is an urgent problem. To solve this problem, new water evaluation and management methods from consumption and trade perspectives are needed [6].

Virtual water was introduced by Allan and it was originated from the concept of "materialization water" [7, 8].The virtual water content is defined as the water quantity needed in the production process of products and services [9]. Several authors have distinguished between the "green" (effective rainfall that is used directly by plants) and "blue" components (surface and ground water) of virtual water [10-12]. Green water is exclusively important for agricultural sectors while blue water has wider applications throughout the economy and especially high value added production activities [10, 12]. A number of studies have recognized the importance of the concept of virtual water for analyzing the rationality of production pattern and making potential contribution to saving water in the global scale [13-16].

Much attention has been devoted to the use of water in agriculture due to the fact that vast majority (90%) of global freshwater is used for food production [6]. Together with the transfer of commodities, regions trade water that is needed for the production of commodities. The water is not physically present in the products but in virtual form. This is called virtual water flows or virtual water trade. Currently, there is a growing body of literature that focuses on the virtual water flows related to crop transfer in global, regional (Middle-East, The Southern African Development Community, North-Africa and Sub-Sahara region) and national scale (China, India, Japan and Lebanese) [15-23].

There are a number of gaps lying in the previous studies of virtual water flows related to crop transfer. Firstly, most of the studies focus on large scale, thus concealing the spatial variability of large countries like China, the USA and Spain, all of which comprise a wide range of agro-climatic areas [24]. Secondly, the study period usually begins from 1990s while researches for long time sequence are still lacking.

The purpose of the present study was to come up with a comprehensive estimate of virtual water flows related to crop transfer at irrigation district scale in the period 1960-2008 and to analyze what the virtual water flows mean to local water resource. The results would contribute to a better understanding of water resources problems and provide some suggestions to improve water resource management in Hetao irrigation district.

Materials and Methods

Study area: Hetao irrigation district is located in the middle of the Yellow River Basin in the Bayan Nur City, Inner Mongolia, China. It is a drought region with scarce and erratically distributed rainfall (yearly average around 130-215 mm) and an average potential evapotranspiration of 2100-2300 mm [25]. Accumulated temperature ranges from 2700°C to about 3200°C, and sunshine time and frost-free days average are approximately 3150 hours and 135 days, respectively [26].

Hetao irrigation district is one of the three large irrigation areas in China [27]. It covers more than 5.74×10^5 hectares irrigation area [28]. The main crops of Hetao irrigation district are wheat, corn and sunflower[27].The water used for irrigation is mainly from the Yellow River. Water diverted from the Yellow River is request to reduce from 5×10^9 to 4×10^9 m^3/a by government since 2000s [25]. This undoubtedly puts high pressure on Hetao irrigation district's already scarce water resources.

Virtual water flows related to crop transfer: The calculation was based on the methods provided by Ma *et al.* [19].

$$VWE = E \times WF \qquad (1)$$

VWE donates virtual water export related to crop transfer, m³; E is export volume of crop, kg and WF presents water footprint of crop in the producing region, m³/kg.

For the calculation of water footprint, the methodology described by Hoekstra *et al.* [29] has been used. The water footprint equals to the sum of water consumed over the growing period divided by the yield. The water used includes two parts: green water and blue water (grey water refers to the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards. It is a theoretical value that is not real consumed by the crop. Therefore, it is not included in water footprint in this paper). The green water is the minimum of the potential crop evapotranspiration and the effective rainfall. Potential crop evapotranspiration is equal to reference evapotranspiration times a crop parameter. The reference evapotranspiration is based on the FAO Penman-Monteith method and crop parameters are from CROPWAT [30, 31]. The effective rainfall is calculated according to a formula developed by the USDA Soil Conservation Service [32]. In irrigated areas, blue water is equal to the irrigation water requirement (the difference between potential crop evapotranspiration and green water). Blue water is assumed zero in non-irrigated areas.

Export rate of crop and water resources: The export rate of crop or water resources could present the share of crop or water resources consumed in other areas rather than in the study area. The analysis of export rates could help us quantify the distribution of crop or water resources.

$$ER = \frac{E}{O} \times 100\% \qquad (2)$$

ER is export rate of crop, %; O is output of crop, kg. We assumed export would happen when the output of crop exceeds the demand of local people. ER is 0 if all crops are consumed within the region. ER approaches 100% if nearly all crops are consumed in other regions.

$$ER_w = \frac{VWE}{TWU} \times 100\% \qquad (3)$$

ER_w donates export rate of water resources, %; TWU is total water use in local area, m³. ER_w is 0 if all water is used for the production of crops that are consumed by local habitats. ER_w approaches 100% if nearly all water is consumed to supply residents' needs in other areas.

Data sources: Meteorological data were taken from China meteorological science data sharing system [33]. Agricultural data, including crop yield, planting area and crop water use came from "Bayan Nur statistical yearbook" and "Hetao irrigation district statistical data"[28, 34]. Social and economic data, including population, consumption of crop per capita were taken from "Bayan Nur statistical yearbook", "Inner Mongolia statistical yearbook", "China agricultural statistical data " and " Hetao irrigation district statistical data"[28, 34-36].

Results

Output and export of crop: Fig. 1 shows the interannual variability of output and export of crop between 1960 and 2008. As one of thirteen major grain producing areas in China, Hetao irrigation district's crop output rose slowly with an average growth rate of 33.40×10^3 t/a before 1980 [26]. Then huge increase in crop demand for China has stimulated the farmers' enthusiasm in many areas including Hetao irrigation district [19]. Output of crop stepped into a rapid growth stage and the average growth rate was 206.29×10^3 t/a.

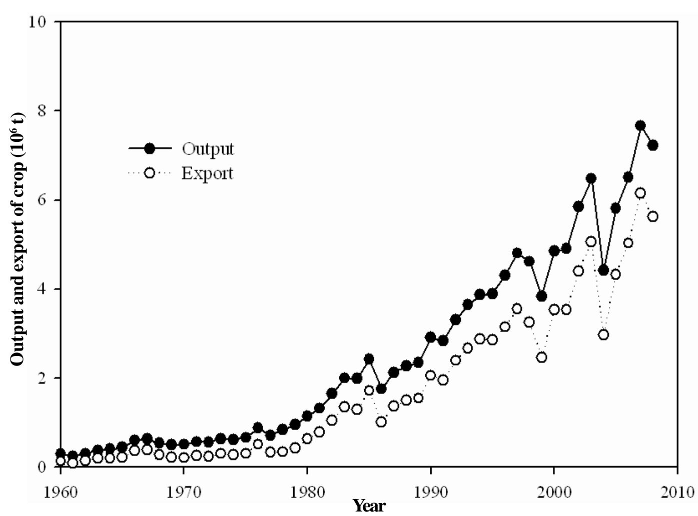

Figure 1. Output and export of crop in Hetao irrigation district from1960 to 2008.

The export of crop showed a similar increasing trend with output of crop over the study period (Fig. 1). The annual growth rates were 15.78×10^3 and 166.12×10^3 t/a during 1960-1980 and 1980-2008 respectively.

Fig. 2 shows that ER presented a fluctuating rising trend with an average rate of 0.76%/a. ER was affected by two factors: output and export of crop. The value of export in 2000s was almost 20 times of that in 1960s while it was less than 14 times for output of crop (Fig. 1). The influence of export was larger than that of output in the study period so ER showed an increasing trend.

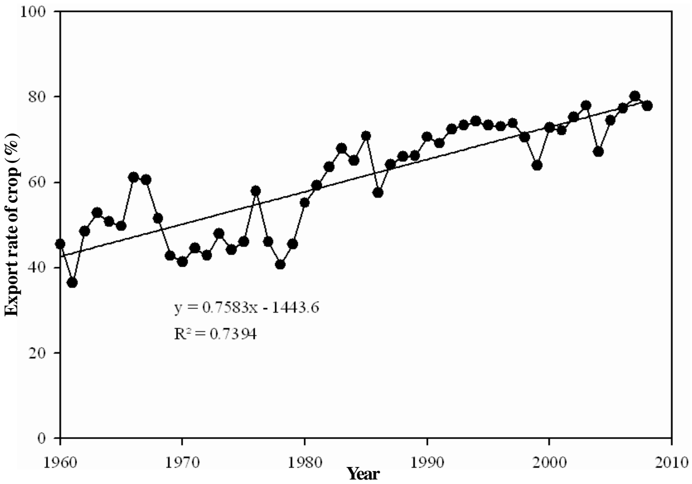

Figure 2. Export rate of crop in Hetao irrigation district from1960 to 2008.

ER was 45.51% in 1960 which shows that about half of the crop produced in Hetao irrigation district were consumed by the residents in other areas rather than the local habitants. It reached 77.93% in 2008.The high ER demonstrates only 1/5 of the crop produced in the area were used to supply local habitants' needs.

Virtual water export: As can be seen from Fig. 3 the virtual water export of crop showed a fluctuating rising trend with an average of 2.17×10^9 m^3. The influencing factors of virtual water export were export volume of crop and its water footprint. The export increased (Fig. 1) while the water footprint of crop decreased mainly due to rapid increase of yield in 1960-1980. Under the combined influence of the two factors, virtual water export fluctuated around the average level of 1.66×10^9 m^3. The period from 1980 to 1993 was the rapidly growing stage of virtual water export and the average growth rate was 83×10^6 m^3/a. After the maximum value of 3.11×10^9 m^3 in 2003, virtual water export decreased to 2.59×10^9 m^3 in 2008.

The blue virtual water export accounted for 87.98% of virtual water export during the study period. It is consistent with the agricultural production characterizes of Hetao irrigation district - production of crop mainly relies on blue water resources (irrigation water).The value

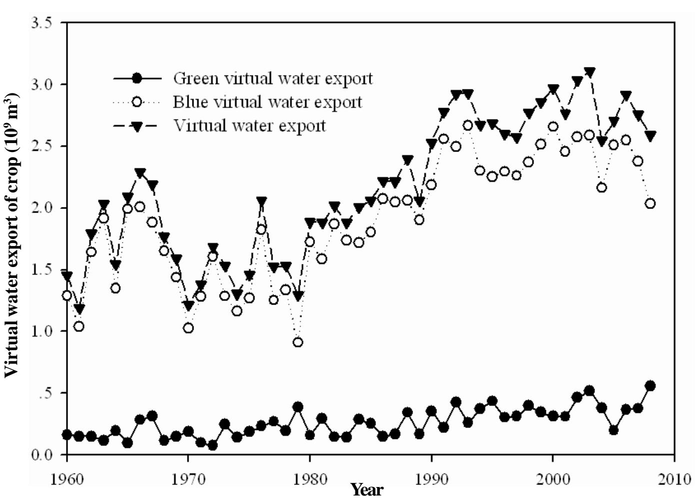

Figure 3. The virtual water export related to crop transfer of Hetao irrigation district from1960 to 2008.

of green virtual water export was much smaller compared with blue virtual water export. The green virtual water export fluctuated between 76.46×10^6 and 559.29×10^6 m^3 from 1960 to 2008. The changes of green virtual water export were mainly caused by export volume and the uneven distribution of rainfall during the study period.

The effects of virtual water export on local water resources: There were three kinds of water resources used in Hetao irrigation district: water diverted from the Yellow River, other surface water and ground water (Fig. 4). The annual water diverted from the Yellow River from 1960 to 2008 was 4.36×10^9 m^3, accounting for 86.86% of the total water resources used in the area. It showed a decreasing trend from 1991 to 2008. The share of other surface water resources in total water uses in the study area was less than 1% and it was mainly from rainfall. Compared to surface water resources, ground water resources were more stable, with smaller annual changes. The ground water resources are mainly used for citizen living and industry development rather than farming irrigation due to the high saline and alkaline concentration[37].

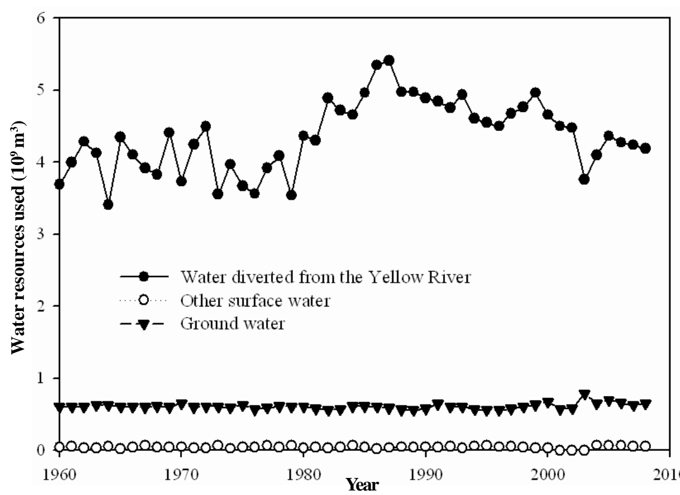

Figure 4. Water resources used in Hetao irrigation district.

Given that more than 90% of the water in this region is used in agriculture, learning the effects of virtual water flows related to crop transfer on local water resources is of great meaning to the regional water resources management [34].

ER_w was 33.52% in 1960 showing that about 1/3 of water resources consumed in Hetao irrigation district were transported to other areas in the form of crop (Fig. 5). The value increased at an average rate of 0.57%/a. ER_w reached its maximum (68.38%) in 2003 which means 3.11×10^9 m^3 water resources (irrigation water plus rain water) flowed out from the study area. From 2003 to 2008 both virtual water flows and total water resources used in the area presented a fluctuating decreasing trend (Figs 3 and 4). Under the combined influence of the two factors, ER_w decreased from 68.38% in 2003 to 52.97% in 2008. The high export rate put high pressure on the limited water resources in the study area.

Discussion

During the study period, 2.17×10^9 m^3 water resources were exported due to the transfer of crop per year and the export rate of water resources rose with an average growth rate of 0.57%/a (Figs 3 and 5). The combination of increasing virtual water export and severely

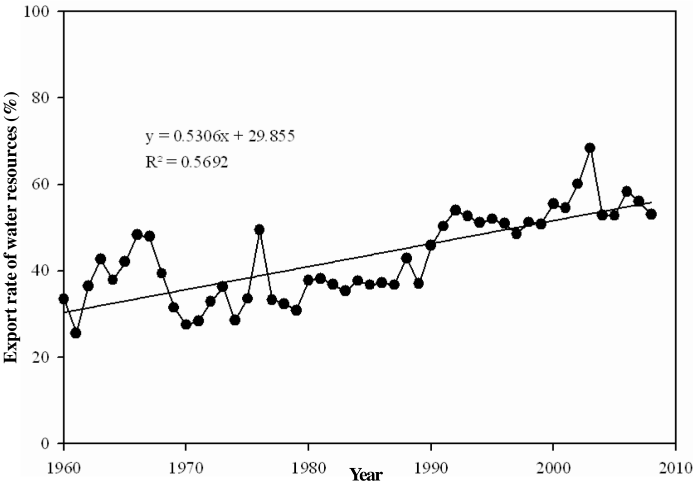

Figure 5. The export rate of water resources.

constrained fresh water resources confronts Hetao irrigation district with great challenges in its water resources distribution among different sectors. Environmental water requirement is hard to be met. Wuliangsuhai lake, located in Hetao irrigation district, is one of thirteen large freshwater lakes in China. The water supply for Wuliangsuhai lake in 2000s was less than 80% of that in 1990s [34]. As a result, Wuliangsuhai lake begins to dry up and the water area decreases to about 300 hectares in 2008 [34].

The potential impacts of a large volume of virtual water export on local water resources are also demonstrated in agricultural production. Grain crops usually need more water in the production than economic crops in the study area [28, 33, 34]. Under the huge water resources press more farmers are willing to choose economic crops rather than grain crops. The ratio of grain crop planting area and economic crop planting area had changed from 7:3 in 1990s to 5:5 in 2000s [28], but a new question rises. The output of grain presented a drop trend since 2003, and the value in 2008 was less than 80% of that in 2003 [28, 34]. National food policy (keeping food self-sufficiency at a high level) could not be guaranteed if other major grain producing areas decrease the planting area of grain crops just like Hetao irrigation district.

From an economic point of view it makes sense to produce and export crop in a place like Hetao irrigation district where the sunshine and heat provide good conditions for agricultural production [30]. Water extracted by Hetao irrigation district from the Yellow River was 1×10^9 m^3 more than the amount government set since 1990 [25]. Looking at the big picture, the phenomenon of agricultural virtual water export and distribution policy for the Yellow River will not change in the long run. How to use the water not only economically but also environmentally is the key topic of the study area in future.

It is an urgent task for Hetao irrigation district to alleviate its water resources pressure with both traditional measures and "softer" methods [38, 39]. Traditional measures should be taken based on the water source. The flooding irrigation is very common in Hetao irrigation district. The irrigation water use coefficient was only 0.42 in 2010 which was much lower than that in the developed countries [25, 26]. Aged and damaged irrigation facilities accounted for 53% of the total facilities [26]. The cut of leaks in water supply systems by lining and introduction efficient irrigation techniques such as drip irrigation could make a significant contribution to the alleviation of irrigation water stress. The share of green virtual water export in virtual water export was 86.36% for China in 1996-2005 while it was only 12.64% in the study area [40] (Fig. 3). The vast difference demonstrates the potential of green water use and provides new thoughts for water resources management in Hetao irrigation district. In future, government should pay more attention to the cultivation of drought tolerant crops and the construction of rainwater use facilities, which could increase green water use efficiency and save blue water, which has greater opportunity cost [41, 42].

The "softer" methods include for example water pricing and agricultural subsidies. In most parts of Hetao irrigation district, irrigation cost is based on the irrigation area, not the volume of water used which leads to a great waste of water resources [43]. If this kind of charging mode could be changed, more efficient water use would be achieved. In future we also require detailed analysis of the opportunity costs of production and comparative advantages in regions engaging in virtual water flows, which can guide both areas towards strategies that benefit each [42].

Due to data constraint, the assessment does not fully differentiate the regional discrepancy in water use efficiency which would not affect the major points to be addressed because of the similarity of natural and irrigation conditions in different parts of the study area. Furthermore, in the process of quantifying blue water footprint, the irrigation is assumed to be sufficient to cover the irrigation water requirements, but in reality, the crop may suffer water stress where water is scarce[44]. Meanwhile, because of the lack of export data, we assumed export would happen when the output of crop exceeds the demand of local people. Consequently, these would bring some uncertainties to the assessment of virtual water flows related to crop transfer. Improved calculation method should be addressed in future studies for more accurate results.

Conclusions

The virtual water perspective and the discussion of export rate of water resources have brought much needed attention to important water issues in Hetao irrigation district. The analysis of virtual water flows related to crop transfer has provided chances to informed policies to improve water use efficiency and alleviate water resources pressure.

The results of our study show that virtual water export related crop trade rose with a multi-year average value of 2.17×10^9 m^3. Agricultural production in the area mainly relies on blue water (irrigation water) and the proportion of blue virtual water export in virtual water export was 87.98%. More than half of the water resource withdrawal is exported in virtual form during the study period.

Environmental issues arose accompanying with the large volume of virtual water export. There is a real need for both traditional and softer measures to reduce the adverse effects of such a great ER_w for the water resources management in the long run.

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