The Water Footprint of Uzbekistan’s Agricultural Products: 1980-2010

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Abstract. In this study, a Water-footprint Assessment Method (WAM) is proposed to assess agricultural water footprint and its flow in Uzbekistan’s agricultural sector. Several findings can be summarized: (i) the annual average water footprint of the agricultural sector is 33.3 billion cubic meters, which is in a downward trend, the main reason is the reduction of crop yield and the improvement of water use efficiency; (ii) the Green Water Footprint (GWF) and Blue Water Footprint (BWF) are 133 and 20 billion cubic meters respectively, cotton contributed most of the BWF, indicating that cotton consumed a lot of surface and groundwater, which indirectly led to the shrinking of the Aral Sea; (iii) an annual average of 3.23 billion m³ of total water footprint (TWF) flows to neighbouring countries such as Russia Federation, China and Bangladesh through agricultural products, accounting for 6.6% of the total water resources of Uzbekistan. These findings will provide theoretical and data support to policy makers for water resources optimization management.

1. Introduction

Global agricultural water use accounts for more than 70% of total water consumption [1]-[2]. Agricultural water use is the main disturbance factor for water resources management; therefore, a quantitative method of measuring agricultural water use is the basis for optimized allocation of regional water resources [3]. Water footprint provides a new method for agricultural water use measurement. The water footprint theory can reflect the real demand and occupation of water resources in a region or a country [4]-[5]. In recent years, several research works were conducted to assess water footprint of agricultural products [6]-[8]. Chapagain and Hoekstra (2011) calculated the global cotton water footprint from 1997 to 2001, the water consumption of cotton products worldwide is 2560×10⁸m³/yr. 84% of the water footprint of cotton products consumed by 25 European countries comes from outside Europe, mainly India and Uzbekistan [9]. Jackson and Konar (2015) calculated the water footprint of food aid in 2005, which is 10 km³. The United States is the largest contributor, accounting for 82% of the food aid water footprint, while Ethiopia, Sudan, North Korea, Bangladesh and Afghanistan receive the most water footprint embodied in food aid [10]. Novoa et al. (2019) provided a quantitative basis for assessing water consumption and degradation by analysing the Cachapoal River agricultural basin [11]. However, as an important agricultural production base in the world, Kazakhstan and Uzbekistan are the world’s major exporters of wheat and cotton, respectively. Central Asia located in arid and semi-arid areas has become an example of exporter of water-intensive agricultural products, making the agricultural water use account for more than 95% of the total water consumption for a long time. Moreover, since the beginning of this century, the scale of agricultural
irrigation has been expanding, agricultural water has increasingly occupied the water of ecological environment, seriously endangering the fragile ecological environment.

Therefore, exploring how much water resources are consumed in agricultural production activities and how they are distributed and evolved in time and space under the background of the increasing scale of agricultural production have become the core issue of this study. This study aims to develop a Water-footprint Assessment Method (WAM) for assessing state-level water footprint with a bottom-up approach. The proposed method is applied to integrated water resources management in Uzbekistan as a real case. WAM can (i) improve the accuracy to measure state-level WF; (ii) measure the WF through the agricultural products trade at the national level. Results will provide theoretical and data support to policy makers for water resources optimization management.

2. Study area and data
Uzbekistan is located in the middle of Asia, belonging to arid and semi-arid areas. The rainfall areas are unevenly distributed. The precipitation in winter is more than in summer. The rainfall in the plains in no more than 80 mm, and the precipitation in the mountains is up to 1000 mm. Agricultural growing area is 28.5 million hectares, accounting for 63% of the country’s land area. The total water consumption is [62, 65] km$^3$ per year, about 90% of which is used for irrigation. This study calculated the GWF and BWF of 10 major agricultural products (cotton, forage crops, grain crops, rice, corn, potatoes, sugar beet, vegetables, grapes and other fruits) in Uzbekistan, and the meteorological data such as precipitation, sunshine, humidity, temperature, and wind speed were obtained. The socioeconomic data was derived from the statistical yearbook of Uzbekistan and international organizations such as the United Nations Development Programme (UNDP) and the Food and Agriculture Organization of the United Nations (FAO).

3. Methodology
This study used the Cropwat model of the United Nations Food and Agriculture Organization (FAO) to calculate blue water footprint and green water footprint (the amount of grey water footprint is too small, so it is not in the scope of this study).

The formula for calculating the green water footprint of crops is:

\[
WF_{green} = \frac{CWU_{green}}{Y} \quad (1)
\]

\[
CWU_{green} = 10 \times \sum_{t=1}^{lgp} ET_{green} \quad (2)
\]

\[
ET_{green} = \min(ETc, P_{eff}) \quad (3)
\]

\[
ETc = ET0 \times Kc \quad (4)
\]

$WF_{green}$ represents the green water footprint (m$^3$·t$^{-1}$); $CWU_{green}$ (Crop Water Usage) is green water consumption of crops (m$^3$·ha$^{-1}$); $Y$ (Yield) is crop yield per ha (t·ha$^{-1}$); $ET_{green}$ is green water requirement of crops; 10 is constant factor which is a conversion coefficient that converts the depth of water (mm) into the amount of water per unit area (m$^3$·ha$^{-1}$); the sum $\sum$ is the accumulation from the planting date (first day) to the harvest date (lgp-length of growth process indicates the length of the growing season, measured in days); $ETc$ is the crop evapotranspiration (mm); $ET0$ is the crop reference evapotranspiration (mm), calculated by Cropwat 8.0 software [12], the value of $Kc$ is also obtained from FAO.; $P_{eff}$ effective rainfall.

The formula for calculating the blue water footprint of crops is:

\[
WF_{blue} = \frac{CWU_{blue}}{Y} \quad (5)
\]

\[
CWU_{blue} = 10 \times \sum_{t=1}^{lgp} ET_{blue} \quad (6)
\]

\[
ET_{blue} = \max(0, ETc - P_{eff}) \quad (7)
\]

$WF_{blue}$ represents the blue water footprint (m$^3$·t$^{-1}$); $CWU_{blue}$ is blue water consumption of crops (m$^3$·ha$^{-1}$); $ET_{blue}$ is green water requirement of crops; the other parameters are the same as above. After
calculating the green and blue water footprint of crops in Uzbekistan, the sum of which is the total water footprint of crops.

\[ TWF = \sum_{i=1}^{n} (WF_{i,\text{blue}} + WF_{i,\text{green}}) \times Y_i \]  

(8)

TWF represents the total water footprint of crops; i is the type of crops.

4. Results and discussion

In this study, ten types of agricultural products (cotton, forage crops, grain crops, rice, corn, potatoes, sugar beet, vegetables, grapes and other fruits) are considered. These 10 agricultural products account for more than 90% of the output of the entire agricultural sector in Uzbekistan [12]. From 1980 to 2010, the average annual WF of selected products was 33.28 billion m³/yr, of which the GWF was 13.33 billion m³/yr and the BWF was 19.95 billion m³/yr, indicating the agricultural sector requires a large amount of artificial irrigation. The TWF is dominated by cotton, accounting for 46.35% of the total (Figure 1), with forage crops and cotton being the main contributors to the GWF and BWF, respectively. This is in line with Uzbekistan’s status as the world’s leading cotton exporter, the results also show that cotton consumes most of the water resources of the agricultural sector. Therefore, improving the water use efficiency of cotton (such as improving cotton varieties and increasing its use of effective precipitation) and appropriately reducing the cotton growing areas will effectively alleviate the pressure on water resources in Uzbekistan.

From the perspective of inter-annual changes, the TWF decreased from 43.98 billion m³ in 1980 to 32.58 billion m³ in 2010, of which the lowest point was 26.41 billion m³ in 2001 (Figure 2(a)). The main reason is that the output of agricultural products in Uzbekistan dropped significantly after the collapse of the Soviet Union. The sharp decline has only slowly recovered after 2001. The GWF decreased from 15.3 billion to 13.9 billion during 1980-2010, accounting for about 40% of the TWF. The results indicate that although the amount of GWF shows a decreasing trend, its proportion shows an insignificant upward trend. There are two main reasons for the decline of GWF. One is the decrease of growing areas, the other is the decrease of precipitation. The reduction of growing areas makes the area of crops withstand precipitation decrease; the decrease of precipitation makes the utilization of effective precipitation decrease accordingly. The BWF showed a significant downward trend (from 28.67 to 18.66 billion m³), which was related to the decline of agricultural production and the shortage of local water resources.

**Figure 1.** The composition of the water footprint in Uzbekistan’s agricultural sector (1980-2010)
Figure 2. (a) Inter-annual changes of the water footprint, (b) Water footprint of agricultural products in the states of Uzbekistan (billion m$^3$, 1980-2010)

Due to differences in crop planting structure, economic development level and climate conditions, the differences of the GWF and BWF among the states are also large (Figure 2(b)). From 1980 to 2010, the states with a WF of more than 3 million m$^3$/yr were Ferghana, Tashkent, Samarkand, Surhan and Andijan. From the perspective of the average annual change of 13 states, except for Navoi and Andijan with the average annual growth of 8.57 and 1.48 million m$^3$, respectively, the rest of the states were in a decreasing trend, among which the highest decreases were Tashkent, Fergana, Surkhandarya and Bukhara, reduced by 59.84, 58.95, 51.36 and 45.13 million m$^3$/yr, respectively; Jizzakh and Kashkadarya had the smallest reduction, at 8.45 million m$^3$/yr each. The reason is that Tashkent, Fergana, Surkhandarya and Bukhara are states with relatively abundant water resources and high crop yields in the 1980s, resulting in significant inter-annual changes over the last 30 years.
Figure 3 shows the inter-annual variation of water footprint trade, the value fluctuated between [3.36, 6.42] billion m$^3$, and the value rose at the beginning, then reduced, reaching the maximum value of 6.42 billion m$^3$ in 2007. This is because the trade volume of water-intensive cotton reached a maximum of 1.13 million tons in 2007. Among the TWF, the trade volume of BWF accounts for 73%, with an annual average of 3.50 billion m$^3$ and a net export of 3.36 billion m$^3$. Cotton accounts for 72% of the net export trade volume of BWF. The TWF flows to neighbouring countries such as Russia Federation, China and Bangladesh, and imports mainly come from Kazakhstan because of the import of wheat. Because cotton consumes large amounts of BWF, and the export of cotton brings a mass of net water export from Uzbekistan, this makes the agricultural water use tense. Therefore, the government has gradually reduced cotton-growing area, exports and increased the growing area of high value-added crops such as fruits and vegetables since 2006. The cotton growing area is expected to decrease from 1.44 million hectares in 2005 to 1 million in 2021, the export of cotton will be stopped in 2025, and all cotton will be converted to domestic consumption.

Figure 3. Exports, imports and trade balance of agricultural-products-related water footprint from 1980-2010 (million m$^3$)

5. Conclusions
In the study, a Water-footprint Assessment Method (WAM) is proposed for analysing agricultural water footprint and its flow in Uzbekistan’s agricultural sector. Several findings have been revealed as follows: (i) the annual average water footprint of the agricultural sector is 33.3 billion m$^3$, which is in a downward trend, from 44 billion cubic meters in 1980 to 32.6 billion m$^3$ in 2010, the value in 2001 is
the least, only 26.4 billion m$^3$. The main reason is the reduction of crop yield and the improvement of water use efficiency; (ii) the GWF and BWF are 133 and 20 billion m$^3$ respectively, and the proportion of forage crops is the largest in the GWF (55.06%), and the largest proportion of cotton in the BWF (69.7%). In the TWF, cotton and forage crops account for 46.35% and 23.52% respectively. Cotton contributed most of the BWF, indicating that cotton consumed a lot of surface and groundwater, which indirectly led to the shrinking of the Aral Sea; (iii) an annual average of 3.23 billion m$^3$ of TWF flows to neighbouring countries such as Russia Federation, China and Bangladesh through agricultural products, accounting for 6.6% of the total water resources of Uzbekistan. These findings can be useful for an in-depth analysis of the relationship between agricultural growth and water consumption, and the spatial and temporal evolution between agricultural production and the ecosystem in Central Asia.

Acknowledgments
This research was supported by the Strategic Priority Research Program of Chinese Academy of Sciences (Grant No. XDA2006030202).

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