Research on water footprint of main crops production in Baoding, China

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Abstract: Based on the monthly meteorological data and basic agricultural data of Baoding Meteorological Station, this paper uses the Penman formula combined with CROPWAT software, and the gray water footprint calculation manual to calculate and analyze the production water consumption coefficient and production water of the main crops in Baoding in 2018. The results show that the water consumption coefficients of the main crops in Baoding city are cotton, peanut, rice, wheat, soybean, corn and vegetables. The water requirement of wheat in the whole growth period is mainly blue water, and the corn water requirement is mainly green water; the gray water footprint of all crops is greater than the blue water footprint. In 2018, the total production water footprint of major crops in Baoding was $65.31 \times 10^8$ m$^3$, of which the blue water footprint was $18.93 \times 10^8$ m$^3$, the green water footprint was $13.06 \times 10^8$ m$^3$, and the gray water footprint was $33.31 \times 10^8$ m$^3$. The sum of the blue water and gray water footprints is much larger than Baoding's average available water resources, and the regional water shortage is serious. Therefore, Baoding should further optimize the agricultural planting structure in order to protect the water resources and environment, and at the same time promote the reduction of pesticides and fertilizers to increase efficiency.

1. Introduction
Water shortage is a major resource and environmental problem facing the world in the 21st century. In 2018, the total amount of water resources in China was about 2.74 trillion m$^3$, and its per capita occupancy was less than 2000 m$^3$, which is less than 1/4 of the world's average. It is one of the 13 countries in the world with severe water shortages. Water shortage is generally considered to be one of the main factors restricting the further development of China's society and economy, and the agricultural sector is China's largest water consumption sector. In 2018, agricultural water consumption accounted for 61.4% of the total water consumption, especially in North China as an important agricultural grain production area in China. Its agricultural water consumption accounted for more than 75%, which is more than double the total of other industries and domestic water consumption. Therefore, water saving in agriculture is the key to water saving. With the increase of the economy and the expansion of the population, the water security situation has increased, and China's water security issues have risen to the strategic level of national security. Since 2012, China has issued "Instructions on the Implementation of the Most Strict Water Resources Management System" and the "Thirteenth Five-Year Plan for the Construction of a Water-Saving Society", which puts the emphasis on saving water and improving the efficiency of water resources utilization. Therefore, it is imperative to focus on reducing agricultural water use and improving the utilization rate of agricultural water resources.
In recent years, a number of scholars have conducted researches on agricultural water saving from different perspectives and different methods. Qin et al. [1] believe that a reasonable water rights and water price system is an effective way to enhance farmers' autonomy in water saving; Wei and Li [2] advocate that the government should take the lead and promote through system changes, capital investment and public services. Water-saving irrigation technology is the most direct way to improve agricultural water use efficiency. Zhang et al. [3] believes that by comprehensively considering the social, economic and ecological effects of agricultural water use and adjusting the agricultural planting structure, the best benefits can be achieved under the constraints of agricultural water resources. However, most studies have included irrigation water in their calculation, ignoring the use of soil water or green water during crop growth, and the effects of pesticides, fertilizers, and other substances on the water environment.

As a new concept, water footprint provides a novel perspective for understanding the relationship between physical water and virtual water in agricultural production. It is one of the hotspots in agricultural water management research. Water footprint is a water consumption index proposed by Hoekstra [4] and can be defined as the total amount of freshwater resources consumed during human production and consumption. According to the type of water use, water footprint can be divided into blue water footprint, green water footprint and gray water footprint [5]; where blue water refers to water stored in rivers, lakes and aquifers; green water refers to water that is derived from precipitation and stored on the surface of soil or plants and will be consumed by crop evapotranspiration; grey water refers to the amount of fresh water required to absorb and assimilate a certain pollution load based on the natural background concentration and existing water quality environmental standards. Crop virtual water represents blue water, green water and gray water that meet the needs of the crop growth process. It can not only quantitatively determine the true water demand of crops, analyze the causes of differences in crop water demand from the source, but also intuitively reflect the use of crop pesticides and fertilizers, in this case, the crop water and fertilizer can be allocated reasonably to achieve water saving in agriculture. The existing research about crop water footprint is mainly in the global, national, provincial or whole basin and other large-scale areas, and there are few studies in municipal areas; in addition, most of the researches is mainly focused on crop blue water footprint or green water footprints, there is not sufficient investigations on comprehensive evaluation of blue water, green water and gray water for crops[6-9].

In consideration of the above researches, this paper based on the theory of crop growth water footprint, takes Baoding, a municipal administrative district on the North China Plain, as the research object, conducts systematic calculation and analysis; tries to achieve agricultural water saving by adjusting the agricultural planting structure, with an expectation to providing a basis for regional water resources management and sustainable use.

2. Materials and methods

2.1. Location

Baoding is located in the central and western part of the North China Plain, which is severely water-scarce and has a three-legged momentum with Beijing and Tianjin. It has an area of 22,122km²and a permanent population of 10.349 million at the end of 2018 [10], ranking first place in Hebei Province. As one of the most serious water-scarce cities in the country, Baoding's per capita water resource was as low as 233m³in 2018. Water shortage has become the biggest obstacle to Baoding's agricultural production and social and economic development. As a typical agricultural city with the most cultivated land in Hebei Province, in 2018 Baoding agricultural irrigation water accounted for 92% of the direct water consumption of the entire economic sector [11], so the agricultural sector is a key breakthrough point in Baoding's water-saving work. With Baoding being included in the core functional zone of central Beijing-Tianjin-Hebei in the "Outline of Beijing-Tianjin-Hebei Coordinated Development", it has become an important carrier of regional central cities and non-capital city functions. Also because of the national new district in Xiong'an, the establishment and protection of sufficient water resources
and a good water environment are the first issues that Baoding needs to solve. In view of the above, this study chose Baoding for empirical research.

2.2. Method

2.2.1. Blue Water Footprint and Green Water Footprint Calculation

This paper uses the CROPWAT model to simulate the blue water demand intensity and green water demand intensity of crops in Baoding. The CROPWAT accounting model developed by the Land and Water Development Division of the Food and Agriculture Organization of the United Nations (FAO). This model takes the crop growth mechanism as the core and calculates the blue and green water requirements of crops by inputting regional meteorological parameters, crop parameters and soil parameters. It can not only accurately calculate the total crop water footprint under different climatic conditions, but also provide a basis for improving the regional crop planting structure.

In this model, the Crop Evapotranspiration (ETc) under standard conditions, i.e., the blue water and green water evapotranspiration requirements, is defined as the product of the crop coefficient and the reference crop evapotranspiration (ETO) [12]:

\[ ET_c = E_T_0 \times K_c \]

Where, ETc is the total crop evapotranspiration (mm), Kc is the crop coefficient, and ETo is the reference crop evapotranspiration (mm), which can be calculated by the CROPWAT model based on the Penman formula (Smith, 1992; Allen et al., 1998).

\[ E_T_0 = \frac{0.408\Delta(R_n - G) + r \times \frac{900}{T + 273} V_2(P_a - P_d)}{\Delta + r(1 + 0.34V_2)} \]  

(1)

where, \( \Delta \) is the slope of the correlation curve between saturated water vapor pressure and temperature (KPa•℃⁻¹); \( R_n \) is the net radiation on the crop surface (MJ•m⁻²•d⁻¹); \( G \) is the soil heat flux (MJ•m⁻²•d⁻¹); \( r \) is the hygrometer constant (KPa•℃⁻¹); \( T \) is the average air temperature (℃); \( V_2 \) is the wind speed (m•s⁻¹) at a height of 2 meters above the ground; \( P_a \) and \( P_d \) are saturated water vapor Pressure (KPa) and measured water vapor pressure (KPa) respectively;

The total crop evapotranspiration ETc refers to the water demand CWR(m³·hm⁻²) of the growing area of crop c. Due to the unit difference, the conversion formula is as follows:

\[ CWR = 10 \times ET_c \]  

(2)

The water required for crop growth includes blue water and green water. The effective precipitation per unit area during the crop growth period ER is calculated using the empirical formula of effective rainfall embedded in CROWAPT. The irrigation water requirement is the difference between the crop water requirement and the effective rainfall. When the crop water requirement is less than the effective rainfall, the irrigation water requirement is 0:

\[ IR = \max(0, CWR - ER) \]  

(3)

Where, IR represents the blue water demand, and ER represents the effective rainfall.

The total growth water footprint can be estimated by the product of crop planting area and water consumption per unit area.

\[ WF_{Blue} = IR \times Ac \]  

(4)

\[ WF_{Green} = ER \times Ac \]  

(5)

In the formula, \( WF_{Blue} \) and \( WF_{Green} \) respectively represent the blue water footprint and green water footprint of the crop; \( Ac \) represents the planting area of crop c.

2.2.2. Grey Water Footprint Calculation

The gray water footprint is based on the existing water quality standard and natural background concentration, and dilutes certain pollutants to the freshwater volume required by the maximum concentration allowed by the standard [13], that is to reflect the degree and scale of water pollution by diluting the amount of fresh water contaminated to harmless fresh water. This article defines the crop gray water footprint as the amount of fresh water required to dilute the water pollution caused by the
part of the leaching fertilizer that has penetrated into the ground or into the surface water body to a standard amount.

The main fertilizers used in agriculture include nitrogen fertilizers, phosphate fertilizers, potash fertilizers and compound fertilizers, of which nitrogen fertilizers and compound fertilizers account for about 50% and 30% of the total fertilizer application in Baoding [10], while the reasonable proportion of nitrogen in compound fertilizer exceeds 50%. Nitrogen in agricultural soil mainly migrates in the form of nitrate nitrogen and other compounds, and the weak adsorption capacity of soil colloids makes it easy to be leached to the lower layer of the soil, becoming the main source of pollution of shallow groundwater. The flowability of phosphorus is poor; the water-soluble potassium of potassium accounts for a relatively small amount, so it is considered that the pollution of soil and water quality by phosphate fertilizer and potassium fertilizer is limited [14]. Considering the above factors, this paper takes the research object of nitrogen fertilizer crop pollution and uses the nitrate nitrogen leaching rate as a parameter to calculate the crop grey water footprint. According to the Water Footprint Evaluation Manual, the gray water footprint calculation formula is as follows:

\[
WF_{grey} = \frac{Appl \times \phi}{C_{max} - C_{nat}}
\]

Where, \(Appl\) refers to the amount of nitrogen fertilizer application; \(\phi\) refers to the leaching rate, which is the proportion of the pollutants finally entering the water body; \(C_{max}\) is the maximum nitrogen concentration allowed by environmental water quality standards; \(C_{nat}\) is the initial concentration of nitrogen in natural water bodies, because the data is difficult to obtain, and it is generally very small and is usually assumed to be calculated as zero [8].

In order to calculate the fertilization data of different crops, this article refers to the "Chinese Handbook of Fertilization and Fertilization for Agricultural Services", and distributes the total amount of nitrogen fertilizer application provided in the "Baoding Economic Statistical Yearbook" by the following formula [15-16]:

\[
S_{Ne} = \frac{S_{NT} \cdot m_cS_c}{\sum_{c=1}^{6} m_cS_c}
\]

\[
AR_c = \frac{S_{Ne}}{A_c}
\]

Where, \(S_{Ne}\) refers to the nitrogen fertilizer application rate of each crop in Baoding, \(S_{NT}\) refers to the sum of the fertilizer application rates of all crops; \(m_c\) refers to the proportion of the planting area of each crop to the total area; \(S_c\) refers to the ratio between the fertilization rates of each crop; \(AR_c\) refers to the nitrogen fertilizer application rate per unit area of crop c.

2.3. Data Sources
The research objects of crop in this paper include Baoding's major food crops, including wheat and corn, major oil crops, including soybeans and peanuts, and major economic crops, including cotton and vegetables. The planting area, yield and fertilizer amount of major crops are from the "Statistical Yearbook of Baoding 2018". In the CROPWAT simulation, the reference crop evapotranspiration ET0 is calculated with the month as the time step. The meteorological data involved comes from the Chinese meteorological data sharing platform; the crop coefficients data comes from the internal database of the Cropwat system. In the calculation formula of grey water footprint, the leaching rate of nitrogen fertilizer is the proportion of the nitrogen finally entering the water body to the net amount of nitrogen fertilizer application. The leaching rate of nitrogen fertilizer is 7.4% according to the existing studies [17].

3. Results and discussion

3.1. Water consumption coefficient of main crop growth
The demand for blue and green water of crops depends on the weather, soil and other conditions, and
the consumption of gray water depends on the amount of fertilization. The total water consumption intensity of crops is the sum of the consumption coefficients of blue water, green water and gray water. The results of water consumption per unit area of major crops in Baoding in 2018 are shown in the figure 1.

From Figure 1, the highest water footprint per unit area of Baoding crops is 12276 m³/hm² of cotton, and the lowest is 2814 m³/hm² of vegetables; between which are peanuts (9031 m³/hm²) and rice (8760 m³/hm²), wheat (7536 m³/hm²), soybean (6402 m³/hm²) and corn (5716 m³/hm²). From the perspective of the structure of blue water and green water, corn, soybeans and peanuts mainly rely on rain-fed, green water accounts for more than 50%, while wheat and rice growth mainly depends on irrigation water, blue water accounts for more than 50%; the proportion of blue-green water demand for peanuts and vegetables is not much different. From the perspective of gray water consumption intensity, the gray water coefficient of all crops is greater than the blue water coefficient and green water coefficient; among them, cotton has the highest fertilization during the growing period, so the gray water footprint is much higher than that of other crops. The gray water footprint of wheat, rice and peanut is also relatively high.

According to the calculation results of the crop water consumption coefficient, when adjusting the crop planting structure, the planting area is compressed in the order of wheat, rice, cotton, peanut, soybean, corn and vegetable with the order of high to low of blue water consumption coefficient, and it is easy to obtain better effect of water-saving in irrigation; and in accordance with the order of gray water consumption coefficient from high to low, the planting area shall be compressed in the order of cotton, peanut, rice, wheat, soybean, corn, vegetable, compress the planting area, in order to achieve better effect of fertilizer saving and emissions reducing.

3.2. Footprint of Crop Water Consumption

The water consumption coefficient of the crop and the planting area jointly determine the crop water footprint. The water footprint of the main crop production in Baoding in 2018 is shown in Figure 2.

In 2018, the total water footprint of the major crops in Baoding was 65.31×10⁸ m³, of which the blue...
water footprint was $18.93 \times 10^8 \text{m}^3$, the green water footprint was $13.06 \times 10^8 \text{m}^3$, and the gray water footprint was $33.31 \times 10^8 \text{m}^3$. Affected by the gray water consumption coefficient of the crops, the gray water footprint of all crops exceeds the blue water footprint, indicating that the water pollution caused by the growth of Baoding crops requires more fresh water to dilute it to usable status. Therefore, special attention needs to be paid to crops to save fertilizer. The sum of the blue water footprint and the gray water footprint of Baoding is much larger than the amount of available water resources in Baoding that year, which verifies the importance of reducing the production water footprint of crops to realize that Baoding water resources can carry sustainable agricultural development. At the same time, the shortage of water quantity and water quality in Baoding is very serious. In the future social and economic development process of Baoding, how to more effectively develop, use and manage water resources has become a core issue.

From the perspective of crop classification, although cotton, peanuts, and rice are the top three crops with the highest water consumption coefficients, the planting area is less than 10% of the wheat and corn planting area, it does not dominate the water consumption of the planting industry, which means there is limited space for saving water and reducing emissions by compressing the planting area of cotton and peanuts. Although the water consumption coefficient of wheat ranks fourth place, it is the crop with the largest water consumption in Baoding, accounting for 56% of the total water consumption of the crop, and it is dominated by the blue water footprint (52% of the total blue water footprint). Corn is the crop whose total water footprint is second only to wheat, and its water consumption accounts for 24.5% of the total water footprint of the crop, of which the green water footprint accounts for 48%, which is the largest among all crops. The water footprint of peanuts, soybeans and vegetables is relatively small. Therefore, wheat and corn are the key points for Baoding to realize water saving by adjusting the crop planting structure.

4. Conclusion
This paper reveals the actual consumption of water resources in the production process of the major crops by calculating the blue water footprint, green water footprint and gray water footprint of the main crops in Baoding in 2018. Cotton and rice are the crops that consume the most water in Baoding, but due to the small planting area of cotton and rice, they have not dominated the agricultural production process. Wheat and corn are the crops with the largest water consumption in Baoding. Among them, wheat's blue water consumption and gray water consumption account for the largest proportion of the total water footprint, and corn's green water footprint accounts for the largest proportion of their total water footprint.

Because green water has a lower opportunity cost than blue water, and because the growth of crops causes the transpiration of green water to be the same as that of natural vegetation systems, the negative impact on the environment is minimal [4][18], therefore it is recommended that Baoding to reduce or to control the cultivation of high water-consuming crops such as wheat under the premise of ensuring food security, moderately promote the cultivation of crops with low irrigation water requirements such as corn and soybeans, and promote the transformation of irrigated agriculture to rain-fed agriculture, further to optimize the planting structure of crops; at the same time improve irrigation conditions and shift to water-saving agriculture. Considering that the gray water consumption of crops in Baoding is the largest, and the root cause is the increase in the amount of fertilization, therefore, the government of Baoding should formulate and implement a comprehensive remediation plan for agricultural non-point source pollution, promote the reduction and efficiency of pesticides and fertilizers, and the comprehensive utilization of organic fertilizer.

This paper still has the following limitations: firstly, this study only calculated the blue water footprint, green water footprint and gray water footprint of Baoding's main crops, but did not account for the water footprint of the entire agricultural sector; secondly, gray water calculation only considers the water pollution caused by nitrogen fertilizer application, ignoring the impact of farming methods and climate types. The calculated fertilizer application rate is lower than the actual application rate. In addition, the impact of pesticides upon water quality is also ignored. Therefore, the gray water
calculation results of this study are relatively conservative.

Acknowledgment
This research was supported by the Central Geological Exploration Fund Center of the Ministry of Natural Resources of the People’s Republic of China (Grant no. 121114000000180007).

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