An improved method for calculating regional crop water footprint based on hydrological process analysis

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Abstract

Fresh water is consumed during agricultural production. With the shortage of water resources, assessing the water use efficiency is crucial to effectively manage agricultural water resources. The water footprint is an improved index for water use evaluation, and it can reflect the quantity and types of water usage during crop growth. This study aims to establish a method for calculating the regional scale water footprint of crop production based on hydrological processes, and the water footprint is quantified in terms of blue and green water. This method analyzes the water-use process during the growth of crops, which includes irrigation, precipitation, groundwater, evapotranspiration, and drainage, and it ensures a more credible evaluation of water use. As illustrated by the case of the Hetao Irrigation District (HID), China, the water footprint of wheat, corn and sunflower were calculated using this method. The results show that canal water loss and evapotranspiration were responsible for most of the water consumption and accounted for 47.9% and 41.8% of the total consumption, respectively. The total water footprint of wheat, sunflower and corn were 1380-2888 $m^3\ t^{-1}$, 942-1774 $m^3\ t^{-1}$, and 2095-4855 $m^3\ t^{-1}$, respectively, and the blue footprint accounts for more than 86%. The spatial distribution pattern of the green, blue and total water footprint for the three crops demonstrated that higher values occurred in the eastern part of the HID, which had more precipitation and was further away from the irrigating gate. This study offers a vital reference for improving the method used to calculate the crop water footprint.

Key words

SWAT model; Regional Scale; Water use process; Hetao Irrigation District

1 Introduction

Human activities and climate change have serious effects on the availability of water resources (Nijssen et al., 2001; Haddeland et al., 2014). Agricultural production is major consumer of global water resources and accounts for 85% of the global blue water (surface or groundwater) consumption (Shiklomanov, 2000; Vörösmarty et al., 2010). In China, 63% of all water is used for agricultural production each year, and the area of irrigated farmland is 39.6% of the total arable land. Irrigation is the key to ensure agricultural production (NBSC, 2016). With the rapid development of China's economy, the demand for water has increased in industrial production and in the lives of residents (Duh et al., 2008; Liu et al., 2008; Bao and Fang, 2012). Environmental pollution reduces water availability (Jiang, 2009; Schwarzenbach et al., 2010) and these changes place great pressure on regional water resources (Piao et al., 2010; Wang et al., 2014); meanwhile, climate change aggravates the situation (Elliott et al., 2014). With limited water resources, economic demand for water will inevitably and gradually take up the agricultural water use, which is a challenge for maintaining steady agricultural production (Chen, 2007; Khan et al., 2009), especially in the dry areas of northern China (Deng et al., 2006; Du et al., 2014). Strengthening agricultural water management and improving water use efficiency are significant aspects of handling water scarcity, and a reasonable evaluation of the water resource for crop production is the premise for developing an agricultural water management plan and implementing water saving measures. Therefore, how to precisely evaluate the effective utilization ratio of current agricultural water use, improve the utilization efficiency, and reduce the negative impact of the reduction of available agricultural water on agriculture production, are important issues that all countries need to address globally, which are also of vital importance for ensuring food production and reducing the pressure on water resources. The water footprint theory provides new insights and ideas to solve these problems

(Hoekstra, 2003). The water footprint is an indicator of freshwater use and can be used to quantify water consumption throughout the production supply chain. It reflects the amount of water, the green, blue and grey water that are consumed (Hoekstra et al., 2011). In the agricultural sector, it can also be used to evaluate whether a crop's water footprint is reasonable and whether it varies regionally. Since green water can be used in agricultural production, some measures can be taken to reduce the water footprint of crop production, especially to reduce the consumption of blue water, thereby easing the demand for blue water in agriculture. The accurate and precise quantification of crop production water footprint is the premise to achieving the above goals.

Currently, based on two mainly methods proposed by Hoekstra et al. (2011), many scholars have quantified various levels of crop production water footprint, such as a global level (Mekonnen and Hoekstra, 2011), a national level, such as Europe (Vanham and Bidoglio, 2013) and China (Zhao et al., 2009), and a regional level, such as Beijing (Sun et al., 2013a), Cremona province (Bocchiola, 2015) and Hetao (Luan et al., 2018). The first is the crop water requirement method (Cao et al., 2014; Sun et al., 2013c). This method simulates the actual evapotranspiration (ET) of crops under optimal conditions with the potential ET calculated by the Penman-Monteith Equation (Allen et al., 1998) and the effective precipitation calculation provided by the United States Department of Agriculture Soil Conservation Service (USDA SCS) (Doll and Siebert, 2002). The green water consumption is the smaller value of total crop actual ET and effective precipitation. The blue water consumption is obtained through the difference between the total crops actual ET and effective precipitation. Finally, when combined with crop yields, the crop blue and green water footprint (m^3 t^{-1}) can be calculated. The second is the irrigation schedule method. This method is based on an empirical formula model such as the CROPWAT model (FAO, 2010; Mekonnen and Hoekstra, 2011) CropSyst (Bocchiola et al., 2013), the EPIC model (Williams et al., 1989;

Shi et al., 2017), the GEPIC model (Liu et al., 2007), and the AQUACROP model (Pasquale et al., 2009; Chukalla et al., 2015; Zhuo et al., 2016). The detail calculation process of these two methods are listed in Supplementary material.

These methods can simulate actual ET throughout the crop growing period according to the soil water balance under optimal or suboptimal conditions. The blue water consumption is the smaller value of net irrigation water and the net irrigation water requirement. The green water consumption is equal to the total actual ET minus blue water. Both of the above methods are based on empirical formulas. A few scholars have attempted to calculate the regional scale water footprint, for example, Sun et al. (2013b) used the difference between diversion and drainage to calculate the water footprint of crop production in irrigated areas. However, these methods have certain shortages, which are as follows:

First, the applicability of the empirical method has not been determined, that is, whether the method is applicable to the field scale or regional scale of water footprint calculation needs further study. These methods calculated the field scale water footprint with net irrigation water considered as irrigation water, and without considering water loss during transport, which definitely serves for crop growth. Therefore, these methods are field scale methods, whereas a regional scale method should include the above two losses. At present, irrigation water mainly refers to the net irrigation water used by crops in the field. Current irrigation water analysis methods have not considered water loss during water delivery and drainage. Therefore, the calculation of the water footprint at the field scale cannot be accurately applied to irrigated agriculture. However, there are still few methods to calculate the water footprint on the regional scale.

Second, the irrigation data in these methods are simulation values and not based on the actual irrigation time and irrigation quota (the amount of water demanded for crop irrigation); therefore, these data cannot reflect the real situation of the local water usage due to the incomplete simulation data. At the same time, the traditional method does not completely analyze the water footprint components of water resources in the process of water diversion, water transfer, irrigation and drainage.

Third, the current regional scale method has not been appropriately established. The method that Sun et al. (2013b) used had these limitations which mentioned above. It included all of the water consumption, but it could not distinguish the specific source of blue water from canal loss, field actual ET or groundwater. Due to its low spatial resolution, only the water footprint of the entire irrigated area could be calculated instead of the difference inside this area.

Currently, most studies focus on the field scale and lack systematic evaluation on the whole process of water consumption during crop growth. To overcome this problem, this study put forward an improved regional scale calculation method of the crop water footprint based on hydrological process analysis and used it to quantify the crop water footprint in HID. This method simulated the hydrological cycle of the region based on a physical hydrological model (SWAT). Based on the method, this study analyzed the water input and output during crop production, and calculated the water consumption in crop growth, field drainage and water loss during canal water transport. Combined with crop yields, the water footprint of crop production at the regional scale was quantified. This method will provide comprehensive information for the analysis of water consumption during crop production process and improve the spatial resolution of the regional distribution of water footprint of crop production.

2 Materials and methods

2.1 Study site

The Hetao Irrigation District (HID) is located in the middle of the Yellow River basin in western Inner Mongolia (Fig. 1) and is one of the three largest irrigation districts in China. The HID has a continental monsoon climate with the lowest temperature in January (average -10℃) and highest temperature in July (average 23℃). The average monthly precipitation is 37.5 mm (May to September), 3.4 mm (October to next year April), and the average monthly potential evaporation is 290.6 mm (April to September), 77.2 mm (October to next year March). The area of the HID is 1.12×10^4 km^2.

Irrigation water is diverted from the Yellow River. The irrigation and drainage systems in the HID are composed of irrigation canals and drainage ditches; the irrigation system has a general main canal (228.9 km) and 12 main canals (total 755 km), and the drainage system has a general main ditch (227 km) and 12 main ditches (total 523 km). The main crops include wheat, corn and sunflower (Fig. 1).

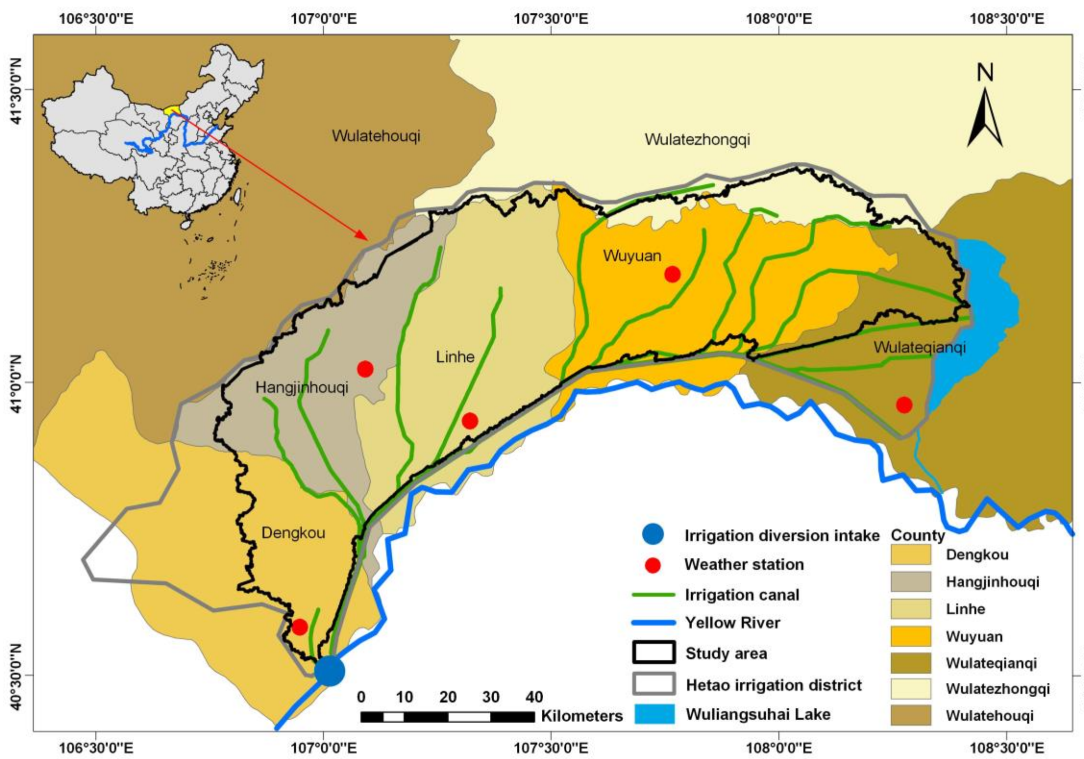

Fig. 1. Location of the Hetao Irrigation District (HID) in China

2.2 Model description

The SWAT (soil and water assessment tool) model is a semi-distributed physical hydrological model. The model was developed by USDA Agricultural Research Center and it used climate, soil, topography, plants and land management practices to simulate hydrologic, sediment, crop growth and nutrient cycle. The model partitions a watershed into sub-basins by topography and then partitions the sub-basins into hydrologic response units (HRU) based on soil type and land use to assess soil erosion, non-point pollution, and hydrologic processes (Haverkamp et al., 2002).The water balance equation governed by the hydrologic component of the SWAT model (Neitsch et al., 2011) is as follows:

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}\right) \quad (1)$$

where SW_t is the final soil water content (mm H_2O), SW_0 is the initial soil water content (mm H_2O), t is the time (days), R_{day} is the amount of precipitation on day i (mm H_2O), Q_{surf} is the amount of surface runoff on day i (mm H_2O), E_a is the amount of actual ET on day i (mm H_2O), W_{seep} is the amount of percolation and bypass flow exiting the bottom of the soil profile on day i (mm H_2O), and Q_{gw} is the amount of return flow on day i (mm H_2O).

2.3 Data collection

The data required by the SWAT model includes a digital elevation model (DEM), soil data, land use, and hydrological and climate data (Table 1). The climate data were obtained from five weather stations in the HID.

The water efficiency of the canal system in this model was obtained from local agricultural administrations (AHID, 2015). To divide the sub-basins, we defined the drainage ditch as the stream (AHID, 2015) and burn-in into the DEM, and the simulation results were verified by the discharge of the drainage ditch.

The model generated 5 outlets and 73 subbasins, and the measured data of the first outlet in the study area was obtained. Therefore, this study chose the area controlled by this outlet as the study area. The crops' yields (wheat, corn and sunflower) required for the calculation of the water footprint was obtained from the Statistical Yearbook of the local agricultural administrations (AHID, 2015).

Table 1 Data used in the study and the resources

Dataset	Data description	Resolution	Data sources
DEM	—	30×30 m	Geospatial Data Cloud (CAS, 2009a)
Soil	Soil type map, Soil physical and chemical properties	1:1000000	China Soil Scientific Database (CAS, 2009b)
Land use	—	1:100000 (2010)	Data Center for Resources and Environmental Sciences (CAS, 2010)
Weather	Precipitation, Wind speed, Solar radiation, Maximum temperature, Minimum temperature, Relative humidity	Daily (1980-2012)	China Meteorological Data Network (NMIC, 2015) The Administration of Hetao Irrigation District (AHID, 2015)
Hydrologic	Stream map, Discharge	Monthly (2003-2012)	The Administration of Hetao Irrigation District (AHID, 2015)
Crop parameter data	Dates of plant and harvest, Dates of irrigation, Irrigation quota	—	The Administration of Hetao Irrigation District (AHID, 2015)

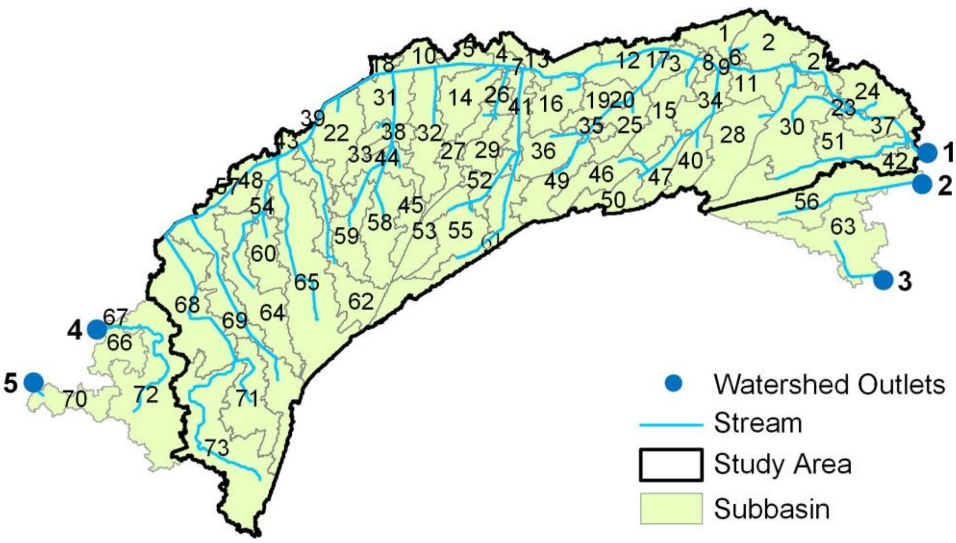

Fig. 2. Subbasins and study areas

2.4 Calibration and validation

The Sequential Uncertainty Fitting (SUFI-2) algorithm in SWAT-CUP was applied for calibration and validation (Abbaspour et al., 2007; Abbaspour, 2012) by comparing the simulated stream discharge from the model with the measured discharge data. The global sensitivity analysis integrated within SUFI-2 was used to evaluate the hydrologic parameters for the discharge simulation and then the optimal simulation was established by adjusting the sensitivity parameters and through multiple iterations. The calibration period was from 2006-2009, and the validation period was from 2010-2012. The result of the SWAT calibration and validation process is satisfactory, the detailed process is available in Supplementary material.

2.5 The regional scale water footprint calculation method

Based on the water footprint theory framework provide by Hoekstra et al. (2011), this study suggests a new way of quantifying the regional scale water footprint of crop production (Fig. 3).

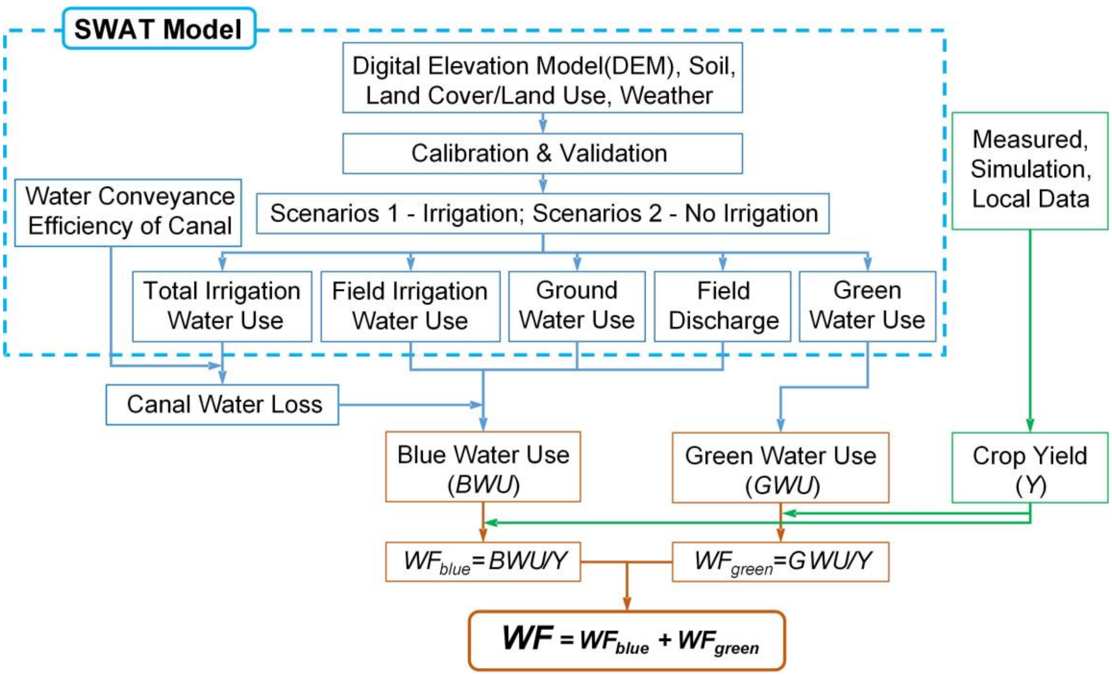

Fig. 3. The flowchart for calculating the regional scale water footprint

In this study, green water consumption is the effective precipitation during crop growth process.

Blue water consumption includes canal water loss during delivery, the ET produced by consumption of irrigation water and groundwater for crops growth, and the drainage in the fields. To calculate the canal water loss, an extra model needs to be established according to the HID situation, and the other can be simulated and obtained by the SWAT model.

2.5.1 Calculation of water consumption factors in the fields

Water consumption in the fields consists of 4 parts including the actual ET of precipitation, irrigation water, groundwater utilized by crops, and field drainage. This study set up two scenarios and calculated the above water consumption by changing the sources of water in the SWAT model. In scenario 1 (S1), crop water consumption was derived from precipitation and irrigation water (irrigation systems and irrigation quotas are based on local irrigation methods), i.e., the actual situation of crop water use. In scenario 2 (S2), crop water consumption was only derived from precipitation without irrigation. The S2 was used to calculate the consumption of green water. In this study area (HID), because of less rainfall, the effective precipitation formed by precipitation is all used for crop growth. Therefore, the consumption of green water for crops is equal to the effective precipitation, which means that green water is reflected by calculating the effective precipitation stored in soil by SWAT model. The calculation formula is as follows.

$$WF = WF_g + WF_b = \frac{W_g}{Y} + \frac{W_b}{Y} \tag{2}$$

$$W_g = PRECIP_{s2} - SUPQ_{s2} - LATQ_{s2} \tag{3}$$

$$W_b = Q_c + Q_f + Q_d \tag{4}$$

$$Q_c = I_{t,s1} - I_{f,s1} = \frac{I_{f,s1}}{k_{s1}} - I_{f,s1} \tag{5}$$

$$Q_f = ET_{s1} - W_{\mathrm{g}} \tag{6}$$

$$Q_d = WYLD_{s1} \tag{7}$$

where WF is the water footprint of crop production (m^3 t^{-1}), WF_g is the green footprint (m^3 t^{-1}), WF_b is the blue water footprint (m^3 t^{-1}), W_g is the green water consumption during the crop growth period (m^3), W_b is the blue water consumption during the crop growth period (m^3), Y is the crop yield (t), $PRECIP_{s2}$ is the precipitation during the crop growth period in Scenario 2 (m^3), $SUPQ_{s2}$ is the surface runoff during the crop growth period in Scenario 2 (m^3), $LATQ_{s2}$ is the soil lateral flow during the crop growth period in Scenario 2 (m^3), Q_c is the amount of water loss in the canal system (m^3), Q_f is the actual ET of field irrigation water (m^3), Q_d is the field discharge (m^3), $I_{t,s1}$ is the total amount of irrigation water diversion in Scenario 1 (m^3), and $I_{f,s1}$ is the actual amount of water irrigated in the field in Scenario 1 (m^3). k_{s1} is the effective utilization coefficient of canal water in Scenario 1(Obtained from the local Water resources management department), ET_{s1} is the crop actual ET during the crop growth period in Scenario 1 (m^3), $WYLD_{s1}$ is the total amount of water leaving the HRU in Scenario 1 (m^3). The data of parameters $PRECIP_{s2}$, $SUPQ_{s2}$, $LATQ_{s2}$, $I_{t,s1}$, ET_{s1}, $WYLD_{s1}$ were obtained from the SWAT model.

2.5.2 Calculation of water loss during delivery

Water transfer loss is a kind of water loss in the process of channel water delivery, and it is an important part of blue water consumption in crop production. For a piece of cultivated land, the water loss during the process of the crop production includes the loss of water from the water source to the field flowing through the canal system. In the Hetao Irrigation District, irrigation canal is composed of seven grades (general main canal, main canal, sub-main canal, branch canals, lateral canals, field canals, and sub-lateral canals). Because of the complex distribution of canal system and the lack of hydrological data in irrigation districts (the lack of effective utilization coefficient of canal water below the main canal). Therefore, in calculating the water loss of canal system during crop production process, we generalized Hetao Irrigation District into a model similar to the histogram (Fig. 4).

We divide the total water loss of canal system into two parts. Part A is the loss of the main canal and canal, and Part B is the loss of the remaining canal system (the water loss of the sub-main canal and its sub-channels at all levels). The calculation of water loss in part A is as follows: first, the water loss of each section is calculated by dividing the main canal into equal distances (10 km). Then the water transfer loss of each section of the canal is allocated to each field downstream [Equation 10], thereby obtaining the water transfer loss in the crop production process on the field block. Therefore, the actual water loss caused by irrigation in a field is the sum of the water loss of the transfer canal and the canal in the upstream. We assign the actual water loss of the field by irrigation (Q_{ji}, equation 11) to the midpoint of each section, and use Kriging interpolation in ArcGIS to obtain the water loss distribution map of the figure a (Part A).

Due to the lack of the effective utilization coefficient of canal water and the distribution map of the canals at all levels and below, the calculation process of the water loss in Part B is as follows: the remaining canal loss in each irrigation canal is divided by the main canal irrigation and the unit area loss of the canal control area is obtained. Then, the amount of water loss per unit area within the control range of each main canal in the irrigation area (Q_j, equation 15) is obtained, and the data is brought into ArcGIS for the water loss distribution map of figure b (Part B). Finally, the figure a and the figure b are superimposed and calculated in the ArcGIS using the map algebra module of the spatial analysis tool to obtain the water loss distribution map of the canal system in HID. The formulas are as follows:

$$Q_{ji} = W_{jn} \times \left(\frac{1}{n} + \frac{1}{n-1} + \cdots + \frac{1}{n-(i-1)} \right) \quad j \in (1,2,3,\cdots,m) \quad i \in (1,2,3,\cdots,n) \tag{8}$$

$$W_{jn} = \frac{W_A \times k_j}{n \times S_{jn}} \tag{9}$$

$$W_A = I_{t,s1} \times \left(1 - k_{gc} \times k_{mc}\right) \tag{10}$$

$$S_{jn} = \frac{S_j}{n} \tag{11}$$

$$Q_j = \frac{W_B \times k_j}{S_j} \tag{12}$$

$$W_B = Q_c - W_A \tag{13}$$

where Q_{ji} is the actual amount of water loss per unit area of the i section of the jth main canal in Part A(m^3 ha^{-1}), W_{jn} is the water loss per unit area of the section of the jth main canal in Part A (m^3 ha^{-1}), j is the number of the main canal, i is the number of the equidistance sections in the jth main canal, n is the total number of the sections in the jth main canal, m is the total number of the main canals, W_A is the amount of water loss in Part A (m^3), k_j is the coefficient of the water distribution from the general main canal to the jth main canal, S_{jn} is the area of each sections in the jth main canal (ha), $I_{t,s1}$ is the amount of total irrigation water diversion in Scenario 1(m^3), k_{gc} is the water conveyance efficiency of the general main canal, k_{mc} is the water conveyance efficiency of the main canal, S_j is the area controlled by the jth main canal (ha), Q_j is the water loss per unit area of the jth main canal in Part B (m^3 ha^{-1}), W_B is the amount of water loss in Part B (m^3), and Q_c is the amount of water loss in the canal system (m^3).

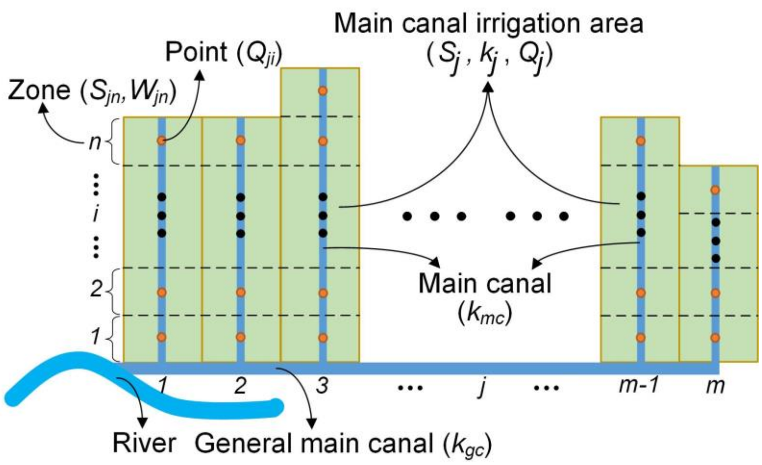

Fig. 4. Model for calculation of water loss in canal system

Note: S_{jn} is the area of each sections in the jth main canal, W_{jn} is the water loss per unit area of the section of the jth main canal in Part A, Q_{ji} is the actual amount of water loss per unit area of the i section of the jth main canal, S_j is the area controlled by the jth main canal, k_j is the coefficient of the water distribution from the general main canal to the jth main canal, Q_j is the water loss per unit area of the jth main canal in Part B, k_{gc} is the water conveyance efficiency of the general main canal, k_{mc} is the water conveyance efficiency of the main canal, j is the number of the main canal, i is the number of the equidistance sections in the jth main canal.

3 Results

3.1 Analysis of the process of crop production and the quantification of hydrological elements in each link

Fig. 5 shows the average water input and consumption of the study area in the process of water diversion, transportation, irrigation and drainage from 2006 to 2012. In HID, the water input for irrigation for the three crops in the study area was 3177×10^6 m^3, water loss during transportation in the canals was 1652×10^6 m^3, the actual field irrigation water was 1525×10^6 m^3, precipitation in the farmland was 510 $\times10^6$ m^3, the actual ET of the farmland was 1442×10^6 m^3, the field discharge was 352×10^6 m^3, and the groundwater was not considered because the consumption was small. Precipitation and irrigation are the water input items in the process of crop production, and the canal water loss, field actual ET and field drainage are the water output items. For water input, precipitation and irrigation accounted for 25.1% and 74.9%, respectively. For water output, channel water loss, field actual ET and field drainage accounted for 47.9%, 41.8% and 10.3%, respectively. Irrigation is the main water source in the irrigated district, and the water loss in the canals and actual ET are the main water output in the irrigated district.

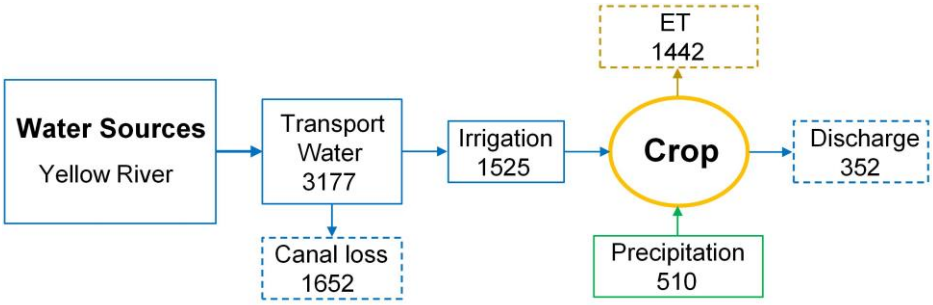

Fig. 5. The amount of water during crop growth ($\times 10^6$ m^3)

Green water is the precipitation used for crop growth; therefore, the green water footprint is highly correlated with precipitation in its growth period. Wheat's growth period is from April to July, whereas that of corn and sunflower is from May to September. During the growth period of wheat, the mean precipitation from 2006 to 2012 was 108.9 mm, and for corn and sunflower, the corresponding mean precipitation was 176.1 mm. The green footprint of wheat during the growth period was lower than that of corn and sunflower because of the lower mean precipitation in the wheat growth period. The green water consumption of corn was close to the value of sunflower. The average green water consumption of wheat, corn and sunflower were 895 m^3 ha^{-1}, 1441 m^3 ha^{-1} and 1419 m^3 ha^{-1} (Fig. 6 a1, b1, c1), respectively. Meanwhile, green water consumption in the high precipitation area was larger, for instance, the precipitation during the wheat growth period in Wuyuan reached 116.3 mm, and the green water consumption in this region was the largest (up to 995 m^3 ha^{-1}). In the growth period of corn and sunflower, the precipitation in Wulateqianqi reached 199.4 mm, and the green water consumption in this area was again the largest, reaching 1785 m^3 ha^{-1} and 1765 m^3 ha^{-1}, respectively.

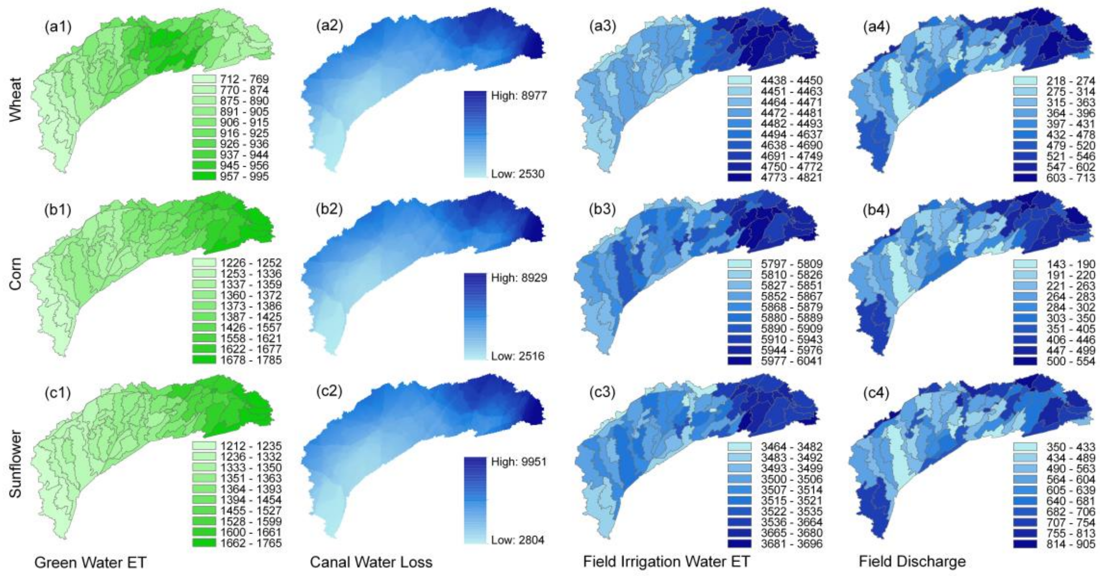

Fig. 6. Spatial distribution of the different water consumption of three crops (m^3 ha^{-1})

Blue water is the surface water used for crop growth in this study. In blue water consumption, the farther away from the watershed inlets the longer the canal was and the larger the water loss of the three crops. Northeast of the irrigation area (parts of Wuyuan and Wulateqianqi) and due to the far distance from watershed inlets, canal water loss in these places was much higher than that in other areas, and the maximum canal water loss of wheat, corn and sunflower reached 8977 m^3 ha^{-1}, 8929 m^3 ha^{-1} and 9951 m^3 ha^{-1}, respectively.

The actual ET and the discharge of the three crops was higher in the east than in the west, which was due to the higher evaporation in the east than in the west. Meanwhile, Fig. 6 shows that the actual ET in the field was complementary with discharge. The higher the actual ET, the smaller the discharge and vice versa.

3.2 The regional green water footprint of crop production

The spatial difference of the green water footprint of wheat, corn and sunflower in HID was obvious (Fig. 7). It can be seen from the figure that the overall distribution of the green water footprint of the three crops was higher in the east than it was in the west. However, the distribution of green water footprint was somewhat different for each crop. Wheat had the largest green water footprint in Wuyuan (197 m^3 t^{-1}) and the lowest in Dengkou (132 m^3 t^{-1}). Corn had the largest green water footprint in Wulateqianqi (186 m^3 t^{-1}) and the lowest in Hangjinhouqi (119 m^3 t^{-1}), but in Dengkou, it was approximate to that in Linhe, ranging from 133 to 139 m^3 t^{-1}. Sunflower had the largest green water footprint in Wulateqianqi (538 m^3 t^{-1}) and the lowest in Linhe (325 m^3 t^{-1}).

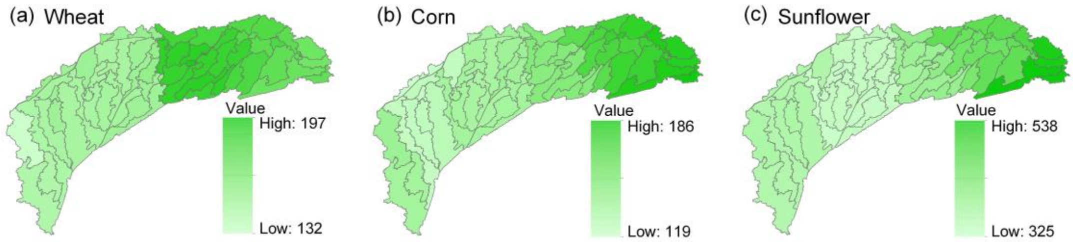

Fig. 7. The spatial distribution of the green water footprint of crop production in the HID (m^3 t^{-1})

3.3 The regional blue water footprint of crop production

The blue water footprint of the crops is produced by blue water that is consumed during crop growth. The blue water consumption during crop growth mainly includes the loss during transportation, actual ET and field drainage. Fig. 8 shows the spatial variability of wheat, corn, and sunflower in HID. The overall distribution of the total water footprint of the three crops was higher in the east than in the west and higher in the north than in the south. However, the specific distribution was somewhat different for each crop. Wheat had the largest blue water footprint in Wulateqianqi (2714 m^3 t^{-1}) and the lowest in southern Linhe (1233 m^3 t^{-1}). Corn had the largest blue water footprint in northern Wulateqianqi (1588 m^3 t^{-1}) and the lowest in southern Hangjinhouqi (820 m^3 t^{-1}). Sunflower had the largest blue water footprint in northern Wulateqianqi (4317 m^3 t^{-1}) and the lowest in southern Linhe (1765 m^3 t^{-1}).

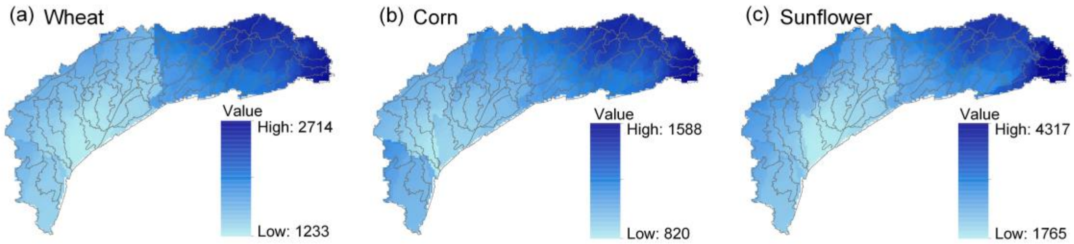

Fig. 8. The spatial distribution of the blue water footprint of crop production in the HID (m^3 t^{-1})

3.4 The regional total water footprint of crop production

The total water footprint of crop production consists of both blue and green water footprint during the crop growth period. Fig. 9 shows the total water footprint of crop production and spatial variability of wheat, corn, and sunflower in HID. The overall distribution of the total water footprint of the three crops was higher in the east (Wulateqianqi and Wuyuan) than it was in the west (Dengkou), followed by the central region (Hangjinhouqi and Linhe) and was higher in the north than in the south. However, the specific distribution was somewhat different for each crop. Wheat had the largest total water footprint in the east (Wulateqianqi, 2888 m^3 t^{-1}) and the lowest in southern Linhe (1380 m^3 t^{-1}). Corn had the largest total water footprint in the east (Wulateqianqi, 1774 m^3 t^{-1}) and the lowest in southern Hangjinhouqi (942 m^3 t^{-1}). Sunflower had the largest total water footprint in the east (Wulateqianqi, 4855 m^3 t^{-1}) and the lowest value was in southern Linhe (2095 m^3 t^{-1}). The total water footprint of crop production also varied across crops. The largest of the average total water footprint in the HID was sunflower, followed by wheat and corn. The blue water footprint of wheat, corn and sunflower accounted for 89%, 87% and 86% of the total water footprint, respectively.

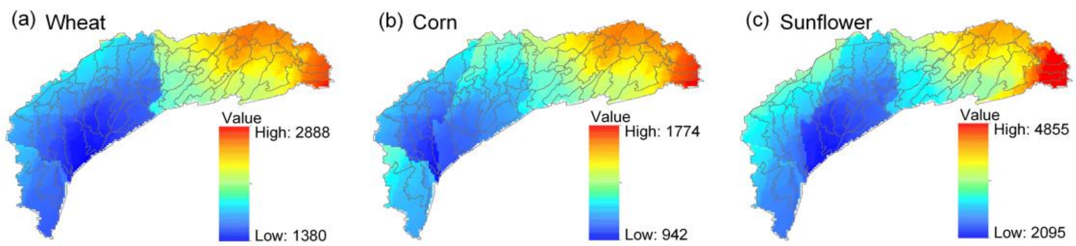

Fig. 9. The spatial distribution of the total water footprint of crop production in the HID (m^3 t^{-1})

4 Discussion

4.1 The regional scale and field scale methods for calculating crop production water footprint

In this paper, the calculation method for calculating crop production water footprint is divided into the field scale and regional scale method, according to the calculation boundary of water consumption in crop growth process. The field scale water footprint is composed of the transpiration of crops and the evaporation of soil, and the water loss during transportation is not included. The regional scale water footprint calculation method considers all of the water consumption related to crop growth from the water source to the field. It not only includes the ET from the field but also the water loss during transportation in the canal system and the water loss discharged out of the region.

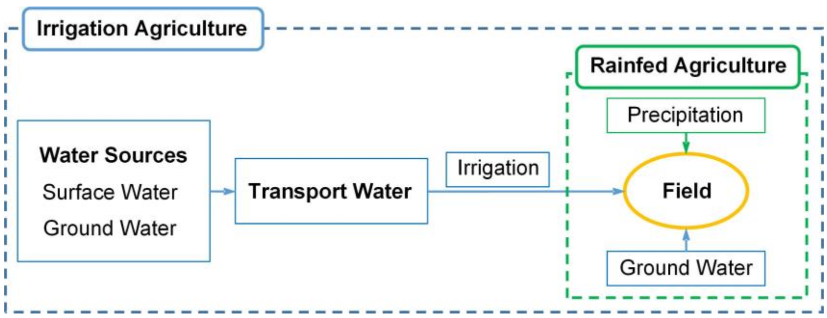

Fig. 10. Irrigation agriculture and rainfed agriculture

Currently, irrigated farmland occupied 39.6% of the total arable land in China (NBSC, 2016). Globally, irrigated area accounted for 20.6% of all arable land (FAO, 2016). Overall, the yields of irrigation agriculture are much higher than that of rainfed agriculture. Fig. 10 illustrates the water sources and use conditions of two types of agriculture. In irrigated agriculture, water (blue water) goes through the following processes from water source to field: water diversion, water transportation (canal system or pipeline), different methods (surface irrigation, sprinkler irrigation, drip irrigation, etc.) to irrigate crops, and excess water discharged from the field. In irrigated agricultural production, especially in areas where water is transported through channels for irrigation, a large amount of water is lost (canal leakage or water evaporation) during the transportation process, which is indirectly used for crop production. The transportation process generates a large amount of cost (energy, machinery, facilities, management, etc. for water diversion). Therefore, this water loss is also a part of the crop production water footprint. In China, the irrigation water consumption was 360×10^9 m^3, and the effective utilization coefficient of irrigation water was 0.53 (MWR, 2015), which indicated that about 169.2×10^9 m^3 of water resources were lost in the process of transportation and irrigation. It is necessary to include the amount of blue water loss during irrigation into the crop production water footprint. Fig. 11 is the calculation range of the regional scale and field scale method of crop production water footprint. Consequently, the calculation method on regional scale can comprehensively calculate all the water consumption in the crop production process, and the calculated results of water footprint are more accurate, while the field scale method only calculates part of the water consumption in the process (Zhao et al., 2009; Bocchiola et al., 2015). At the same time, the calculation method on regional scale proposed in this study improves the resolution of the water footprint results. It can also reflect the variation of the water footprint within the region, and more effectively discover the water footprint hotspots, and avoid the shortcomings that can only reflect the mean value of the regional results due to low resolution (Vanham and Bidoglio, 2013; Zhuo et al., 2016). These two advantages of the regional scale approach can help local authorities to develop more rational water allocation and management policies.

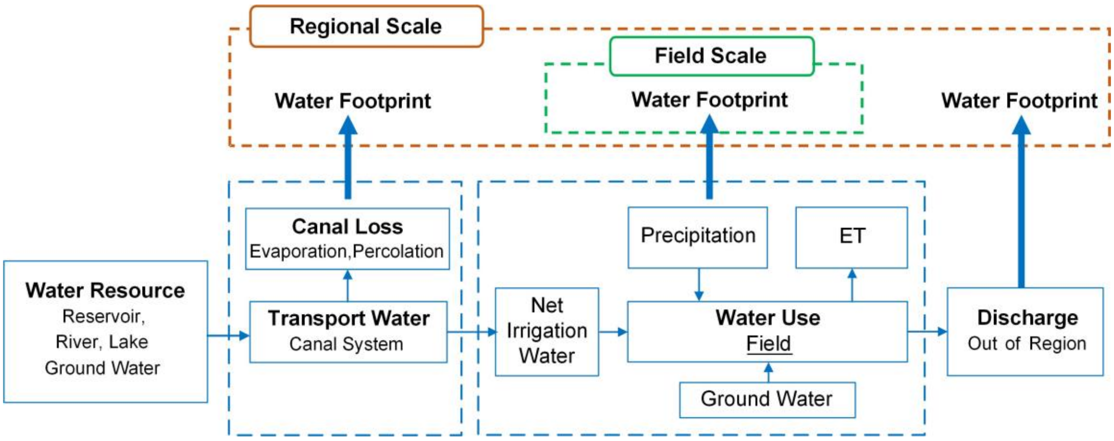

Fig. 11. The different scales of calculating water footprint

4.2 Comparison of the results of two methods

For the field scale method, the calculated value was less than the actual value because it did not consider the loss of water during transportation or discharge, and the actual water footprint of irrigation agriculture cannot be precisely assessed. At present, most studies use field scale method (e.g. CROPWAT model) (Lovarelli et al., 2016), so these studies mainly focus on agricultural water use at field scale, lacking an analysis of the entire process of agricultural production water use, which is also the shortcomings of the current research on the crop production water footprint. Therefore, using the regional scale method to calculate the crop water footprint, especially in irrigation agriculture, is the basis for a comprehensive and accurate evaluation of a crop production water footprint in China and other regions or countries.

In HID, the water footprint of three crops (wheat, corn and sunflower) calculated by regional scale method were 1380-2888 m^3 t^{-1}, 942-1774 m^3 t^{-1}, and 2095-4855 m^3 t^{-1}, respectively. These values were higher than the results calculated by the field scale method. Cao et al. (2014) calculated the average crop water footprint of irrigation agriculture in China from 1998 to 2010 and the average value of many crops in the Inner Mongolia autonomous region (including HID) was 1556 m^3 t^{-1}. Sun et al. (2013b) calculated the average water footprint of HID by using regional scale method and water balance principle and the result was 3910 m^3 t^{-1}. The proportion of blue water and green water was 90.9% and 9.1% respectively. This result was the average water footprint of many crops, and the value was approximate to our results. Qin et al. (2016) calculated the water footprint of sunflower in Jilin province by using field scale method and found that the water footprint of sunflower in this area from 2006 to 2008 were 1280 m^3 t^{-1}, 1684 m^3 t^{-1} and 1726 m^3 t^{-1}, respectively, which was smaller than this study. This is because Jilin's water footprint is mainly composed of green water footprint, which reached 95%, and its blue water footprint is smaller. In addition, these studies all showed the water footprint of the region, which cannot distinguish the spatial distribution of the crop production water footprint within the region, and has a limited impact on the improvement of local water resources management.

This method also has limitations. The method requires more data types (e.g. DEM, land use, soil data, climate data, hydrological data, and crop management data), and higher data resolution. Therefore, the method is not applicable to areas where the above data are lacking.

4.3 Strategies for adjusting the crop production water footprint

The water footprint of crop production is affected by crop species. Different crops have different water use characteristics and different growth periods. Therefore, adjusting the crop planting structure can change the water supply in the region (Fasakhodi et al., 2010), which in turn affects the water footprint of crop production. At the same time, changing the crop pattern, planting crops which growth periods are consistent with the precipitation period can increase the utilization of green water, reduce the consumption of blue water, and reduce the pressure on local water resources (Liu et al., 2018). This study found that in the HID, the growth period of sunflower is basically the same as the precipitation period. Consequently, expanding the planting area of sunflower can make better use of local precipitation resources and reduce the use of blue water.

Crop yield is an important factor affecting the water footprint of crop production. Selecting crop varieties with high yields and improving agricultural management measures play an important role in increasing crop yields. Sun et al. (2013b) found that improving agricultural management measures is an important factor to increase crop yield and reduce water footprint of crop production. Liu et al. (2014, 2015) discussed the water use situation and virtual water flow in Hetao Irrigation District and found that crop yield had an important impact on the water footprint of crop production, and with the increasing of crop yield per unit area, the water footprint of crop production had declined.

The efficiency of irrigation system is affected by the way of water transportation, the condition of canal system, the irrigation technology and so on. Therefore, the water use efficiency of the regional irrigation system can be improved by changing the water delivery method (from the channel to the pipeline) and the irrigation method (such as dropper, sprinkler and other advanced irrigation technologies). For the study area, the results show that more than half of the water resources were lost during the process of canal water transport and irrigation. Therefore, adopting anti-seepage measures to reduce the leakage of canal system, and adopting advanced irrigation technology to reduce the amount of irrigation water will help to reduce the water footprint of crop production in this region.

5 Conclusions

In this study, we proposed an improved regional scale method for calculating crop production water footprint. This method was based on the hydrological model (SWAT model), combined the irrigation parameters of the irrigation area (water conveyance efficiency of canal), and calculated the crop production water footprint.

The method provided whole hydrological processes analysis for water use during crop production, including water diversion, irrigation/precipitation, field evapotranspiration and drainage, Therefore, the method contributed to establish a more comprehensive calculation of water consumption during the crop growth period and more precisely quantify crop production water footprint. The method can be applied to calculate the crop production water footprint at both the field and regional scale. In HID, the main water consumption occurs during the crop growth period; the canal water loss was 1652×10^6 m^3, and actual ET in the field was 1442×10^6 m^3, which accounted for 47.9% and 41.8% of the total used, respectively.

The regional climate, the condition of irrigation system and the crop yield are the main factors that affect the water footprint of crop production. The area with higher crop yield per unit area, higher efficiency of irrigation water use, less irrigation water loss and closer to source of water has lower crop production water footprint. Water loss during transportation increased with the increasing distance of the canals, and the farther away from the watershed inlets they were, the more water was lost, the values were higher in the east than they were in the west in the study area.

Due to special climatic conditions, crops in Hetao Irrigation District mainly depend on irrigation water in the production process. Overall, in the composition of water footprint in Hetao Irrigation District, blue water footprint accounts for more than 86%. Therefore, applying water-saving irrigation technology, increasing channel lining rate and reducing the loss of irrigation water are the main ways to adjust and control the water footprint of crop production in this area.

Based on the SWAT model, this paper analyzed the utilization and consumption of water resources during crop production in irrigated areas, which provided a hydrological mechanism for quantifying the water footprint of crop production. However, the SWAT model does not consider the relation of groundwater flow between different subbasins. At the same time, the shallow groundwater evaporation is based on the soil as a medium and directly into the atmosphere, the model cannot accurately quantify the recharge of shallow groundwater to soil water. Consequently, the SWAT model cannot accurately simulate the shallow groundwater consumption of crops. Therefore, combining the groundwater model, analyzing the flow of water in the process of regional agricultural production, and then quantifying the water footprint of crop production is the direction of further research.

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Author Contributions: Pute Wu, Shikun Sun and Yubao Wang designed the study. Xiaobo Luan, Yali Yin, Xuerui Gao and Jing Liu did the literature search and data collection. Xiaobo Luan, Shikun Sun and Yali Yin managed and analyzed the data. Xiaobo Luan and Suikun Sun drew the figures and wrote the paper. All authors discussed and commented on the manuscript.

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