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Hydrology and Earth System Sciences
Discussions

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

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https://doi.org/10.5194/hess-2018-125
Preprint. Discussion started: 27 March 2018

Hydrology and Earth System Sciences
Open Access
Discussions

Abstract

Fresh water is consumed during agricultural production. With the shortage of water resources, assessing the water use efficiency is crucial to effectively managing agricultural water resources. The water footprint is a new 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 region-scale water footprint of crop production based on hydrological processes. This method analyzes the water-use process during the growth of crops, which includes irrigation, precipitation, underground water, 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 footprints 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 footprints of wheat, sunflower and corn were 1380-2888 m^3/t, 942-1774 m^3/t, and 2095-4855 m^3/t, 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 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

https://doi.org/10.5194/hess-2018-125
Preprint. Discussion started: 27 March 2018

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 ensuring 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; Sun et al., 2018). 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 utilization of 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 is an important issue that all countries need to address Globally, this is 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

https://doi.org/10.5194/hess-2018-125
Preprint. Discussion started: 27 March 2018

Hydrology and Earth System Sciences
Discussions

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 and types of resources that are consumed (Hoekstra, 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. Because green water can be exploited, measures need to be taken to reduce the water footprints of crop production, especially to decrease the blue water consumption to mitigate the demand for blue water in agriculture. The accurate and precise quantification of crop water footprints is the premise to achieving the above goals.

Currently, many scholars have quantified various levels of crop water footprints and Hoekstra et al. (2011) put out two main methods for calculating the crop water footprint. The first method is the crop water requirement method. This method simulates the evapotranspiration (ET) of crops under optimal conditions with the 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) (USDA, 1994). The green water ET is the smaller value of total crop ET and effective precipitation. The blue water ET is obtained through the difference between the total crop ET and effective precipitation. Finally, when combined with crop yields, the crop blue and green water footprint can be calculated. The second method is the irrigation schedule method. This method is based on an empirical formula model such as the CROPWAT model (FAO, 2010) and the AQUACROP model (Pasquale et al., 2009). These methods can simulate crop ET throughout the growing period according to the soil water balance under optimal or suboptimal conditions. The blue water footprint is the smaller value of net irrigation water and the actual irrigation water requirement. The green water ET is equal to the total ET minus blue water. Both of the above methods are based on

https://doi.org/10.5194/hess-2018-125
Preprint. Discussion started: 27 March 2018

Hydrology and Earth System Sciences
Open Access
Discussions

empirical formulas. A few scholars have attempted to calculate the region-scale water footprints, 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 empirical methods have not determined the applicability; i.e., the method is applicable to a field-scale or region-scale water footprint calculation. These methods calculated the field-scale water footprint with net irrigation water considered as irrigation water, and without considering water loss during transport or drainage, which definitely serve for crop growth. Therefore, these methods are field-scale methods, whereas a region-scale method should include the above two losses. Presently, irrigation water is mainly consumed by irrigated agriculture, and the current methods have not included water loss during transport and drainage. Therefore, the field-scale water footprint calculation does not precisely apply to irrigated agriculture, but few region-scale methods of have been established.

Second, the irrigation data in these methods are simulation values and not based on the actual irrigation time and irrigation quota; therefore, these data cannot reflect the real situation of the local water usage due to the incorrect simulation data. At the same time, these methods cannot distinguish the source of the crop water, for instance, whether it is from precipitation, surface water or groundwater.

Third, the current region-scale method has not been appropriately established. The method that Sun et al. (2013b) used had certain limits. It included all of the water consumption, but it could not distinguish the specific source of blue water from canal loss, field 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.

https://doi.org/10.5194/hess-2018-125
Preprint. Discussion started: 27 March 2018

Hydrology and Earth System Sciences
Open Access
Discussions

Agricultural production water covers the diversion - transportation - irrigation - drainage and precise calculation of the above processes and the premise of quantifying crops' water footprints. 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 puts forward an improved region-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 based on physical hydrological model (SWAT), simulated the regional hydrologic cycle process, which obtained the water consumption and the field drainage, calculated the water loss during delivery using the water conveyance efficiency of the canal, and then quantified the region-scale crop water footprint using the yields of the crops. This method will provide comprehensive information for the water resource consumption process in the analysis of crop production links and improve the spatial resolution of quantifying the crops' water footprint.

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°C) and highest temperature in July (average 23°C). The annual average precipitation is 180 mm and annual potential evaporation is 220 mm. 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

https://doi.org/10.5194/hess-2018-125
Preprint. Discussion started: 27 March 2018

km) and 12 main ditches (total 523 km). The main crops include wheat, corn and sunflower (Fig. 1).

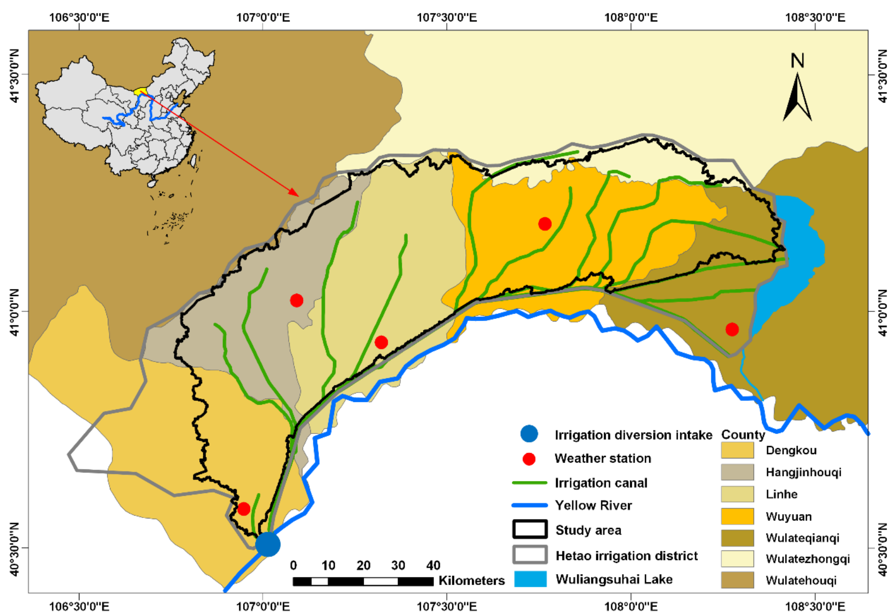

Fig. 1. Location of the Hetao Irrigation District (HID) in China

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),

https://doi.org/10.5194/hess-2018-125
Preprint. Discussion started: 27 March 2018

Hydrology and Earth System Sciences Discussions
Open Access
EGU

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 sub-basins, 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)

https://doi.org/10.5194/hess-2018-125
Preprint. Discussion started: 27 March 2018

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)

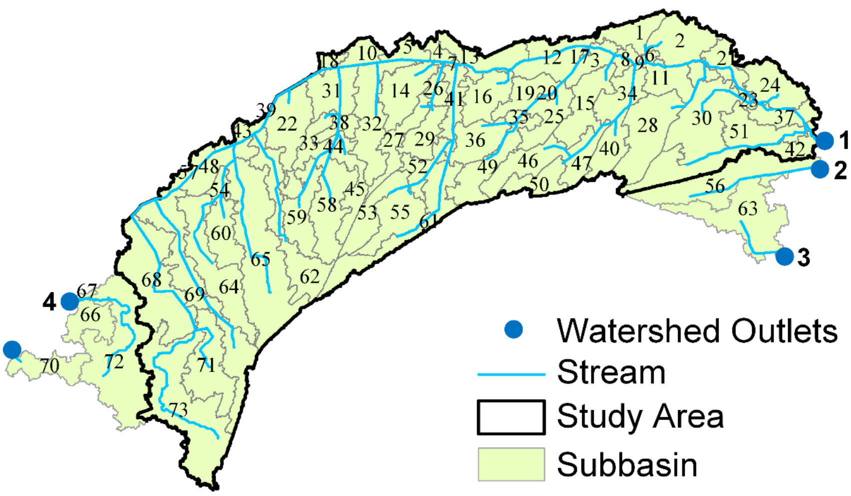

Fig. 2. Subbasins and study areas

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

https://doi.org/10.5194/hess-2018-125
Preprint. Discussion started: 27 March 2018

Hydrology and Earth System Sciences
Discussions

optimal simulation is 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.

For calibration and validation analyses, the monthly measured discharges were compared with the simulated discharge data and the model performance was evaluated using the coefficient of determination (R^2), Nash efficiency coefficient (NSE) (Nash and Sutcliffe, 1970; Moriasi et al., 2007) and percent deviation (PBIAS) (Gupta et al., 1999). The calculation formula is as follows:

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(Q_m - \overline{Q}_m\right)\left(Q_s - \overline{Q}_s\right)\right]^2}{\sum_{i=1}^{n}(Q_m - \overline{Q}_m)^2 \sum_{i=1}^{n}(Q_s - \overline{Q}_s)^2} \quad (2)$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_m - Q_s)^2}{\sum_{i=1}^{n}(Q_m - \overline{Q}_m)^2} \quad (3)$$

$$PBIAS = \frac{\sum_{i=1}^{n}(Q_m - Q_s)}{\sum_{i=1}^{n}Q_{m,i}} \times 100 \quad (4)$$

where Q_m is the measured data, $\overline{Q}_m$ is the mean of the measured data, Q_s is the model simulation data, and $\overline{Q}_s$ is the mean of the model simulation data.

R^2 measures the simulated and measured values of goodness. The closer the value is to 1, the higher the agreement is between the simulated and measured discharge. The NSE is widely applied in hydrologic models that range from negative infinity to 1 with 1 being the ideal value. The PBIAS assesses the average deviation of the simulated values from observed values with 0 as the ideal value, and a positive (negative) PBIAS value shows an underestimation (overestimation) bias of the simulated variable compared to the measured variable. The monthly model data simulation results can be classified as satisfactory if $R^2 > 0.6$, $NSE > 0.5$ and $PBIAS < \pm 25$ and can then be used for further

https://doi.org/10.5194/hess-2018-125
Preprint. Discussion started: 27 March 2018

Hydrology and Earth System Sciences
Discussions
Open Access

analysis (Moriasi et al., 2007).

The SWAT-CUP parameter sensitivity analysis procedure showed that the CN2, ESCO, GW_REVAP and ALPHA_BF parameters were more sensitive. In this study, the R2, NSE, and BIAS for the measured and calibration period were 0.77, 0.65 and 17, respectively; and the R2, NSE, and PBIAS for the validation period were 0.68, 0.61 and 21, respectively(Luan et al., 2018). The model simulation result can be classified as satisfactory (Moriasi et al., 2007). Therefore, the results demonstrated that the SWAT model was applicable in HID for future hydrologic process assessments.

2.5 The region-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 region-scale water footprint of crop production (Fig. 3).

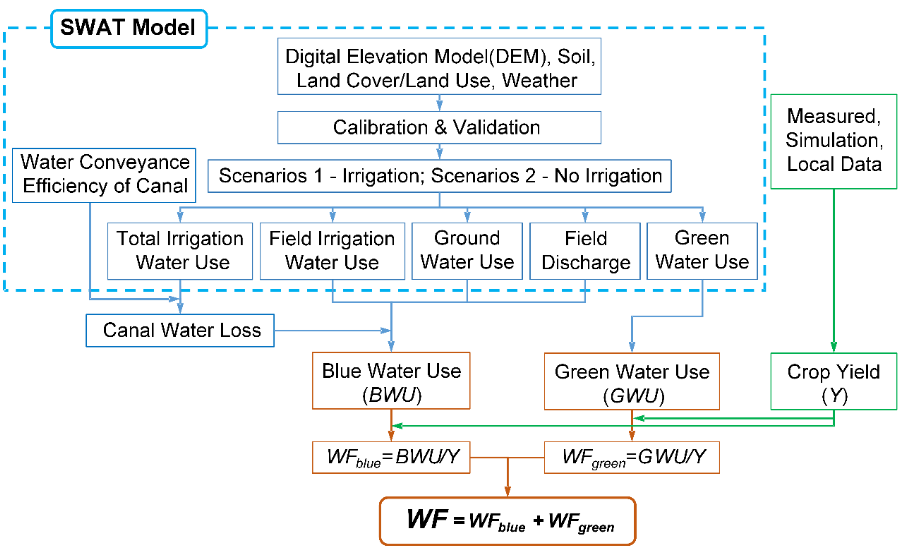

Fig. 3. The flowchart for calculating the region-scale water footprint

In this study, green water consumption is the ET produced by the consumption of precipitation during crop growth. 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

https://doi.org/10.5194/hess-2018-125
Preprint. Discussion started: 27 March 2018

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 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), water consumption was derived from precipitation and irrigation water in the fields (irrigation systems and irrigation quotas are based on local irrigation methods), i.e., the actual situation of crop water use. In scenario 2 (S2), water consumption was only derived from precipitation without irrigation. In S1, after calibration and validation of the model, and by modifying the crop water management data, removing irrigation water, and simulating again, the results in S2 could be obtained. Then, the results were calculated using two simulations, specifically, modifying the single variable to observe the corresponding result. The calculation formula is as follows.

$$WF = WF_g + WF_b = \frac{W_g}{Y} + \frac{W_b}{Y} \quad (5)$$

$$W_g = ET_{s2} - Q_g \quad (6)$$

$$W_b = Q_c + Q_f + Q_g + Q_d \quad (7)$$

$$Q_c = I_t - I_f \quad (8)$$

$$Q_f = ET_{s1} - W_g \quad (9)$$

where WF is the water footprint of crop production (m^3/t), WF_g is the green footprint (m^3/t), WF_b is the blue water footprint (m^3/t), 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), ET_{s1} is the crop actual ET during the crop growth period in Scenario 1 (m^3), ET_{s2} is the crop actual ET

https://doi.org/10.5194/hess-2018-125
Preprint. Discussion started: 27 March 2018

Hydrology and Earth System Sciences
Open Access
EGU
Discussions

during the crop growth period in Scenario 2 (m^3), Q_g is the amount of groundwater that rises to the soil plow layer (m^3), Q_c is the amount of water loss in the canal system (m^3), Q_f is the ET of field irrigation water (m^3), Q_d is the field discharge (m^3), I_t is the amount of total irrigation water diversion (m^3), and I_f is the actual amount of water irrigated in the field (m^3).

2.5.2 Calculation of water loss during delivery

Water loss during transportation occurs in the canal and is an important part of blue water consumption of the crops growth. Because of the complexity of the irrigation canal system and the lack of hydrological data (lack of water conveyance efficiency of the branch canal and lower canal), we generalized the irrigation area into a similar rectangle model (Fig. 4). Each rectangle is the area controlled by each main canal, which is represented by the central line. The natural canal system is divided into two parts when calculating the water loss of the canal system. Part A is the loss of the general main canal and the main canals, and the part B is the loss of the rest of the canal system including the branch canals, lateral canals, field canals, and sub-lateral canals.

The water loss in part A could be calculated as follows: divide the main canal by equidistance (10 km) and then calculate the water loss of each section, which was produced by local and downstream water of which local water accounted for a small amount and the rest belonged to the downstream. Therefore, the local accurate water loss should include this section and upstream sections. We assumed local water loss to the midpoint of each canal. In ArcGIS, we used a Kriging interpolation to obtain the water loss figure of part A.

Water loss in part B could be calculated as follows: the water loss of the other canals below the main canal divided by the area controlled by each main canal and the water loss per unit area controlled by the corresponding canal could be obtained. Then, the water loss per unit area controlled by each

https://doi.org/10.5194/hess-2018-125
Preprint. Discussion started: 27 March 2018

main canal could be obtained. The data of parts A and B are calculated using the Space analysis tool in ArcGIS 10.1 software to obtain the distribution map of the water loss in the drainage system.

The formulas are as follows:

$$W_A = I_t \times \left(1 - k_g \times k_m\right) \quad (10)$$

$$S_{ji} = \frac{S_j}{i} \quad (11)$$

$$W = \frac{W_A \times k_j}{i \times S_{ji}} \quad (12)$$

$$Q_n = W \times \left(\frac{1}{i} + \frac{1}{i-1} + \frac{1}{i-2} + \cdots + \frac{1}{i-(n-1)}\right) \quad \mathrm{n} \in (1, 2, 3, \cdots, i) \quad (13)$$

$$W_B = Q_c - W_A \quad (14)$$

$$Q_j = \frac{W_B \times k_j}{S_j} \quad (15)$$

where W_A is the amount of water loss in part A (m^3), I_t is the amount of total irrigation water diversion (m^3), k_g is the water conveyance efficiency of the general main canal, k_m is the water conveyance efficiency of the main canal, S_j is the area controlled by the jth main canal (ha), i is the number of the equidistance section of the jth main canal, S_{ji} is the area per section controlled by the jth main canal (ha), k_j is the ratio of the diversion volume of the jth main canal to the total diversion, W is the water loss per unit area of the section of the jth main canal in part A (m^3/ha), Q_n is actual the amount of water loss per unit area of the section of the jth main canal (m^3/ha), W_B is the amount of water loss in part B (m^3), and Q_j is the water loss per unit area of the jth main canal (m^3/ha).

https://doi.org/10.5194/hess-2018-125
Preprint. Discussion started: 27 March 2018

Hydrology and Earth System Sciences
Discussions

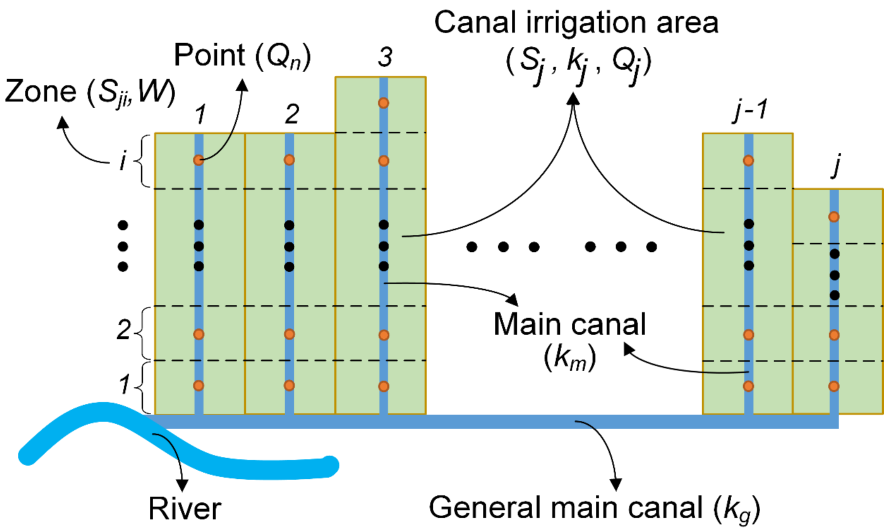

Fig. 4. Generalized model of the irrigation area

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 Mm^3, water loss during transportation in the canals was 1652 Mm^3, the actual field irrigation water was 1525 Mm^3, precipitation in the farmland was 510 Mm^3, the actual ET of the farmland was 1442 Mm^3, the discharge was 352 Mm^3, and the groundwater was not considered because the consumption was less than 5%. When inputting water into the farmland, irrigation and precipitation accounted for 74.9% and 25.1%, respectively; however, when consuming water, the discharge took up 47.9%, 41.8% and 10.3%, respectively. Irrigation was the main water source in the irrigated district, and the water loss in the canals and actual ET were the main water output in the irrigated district.

https://doi.org/10.5194/hess-2018-125
Preprint. Discussion started: 27 March 2018

Hydrology and Earth System Sciences
Discussions

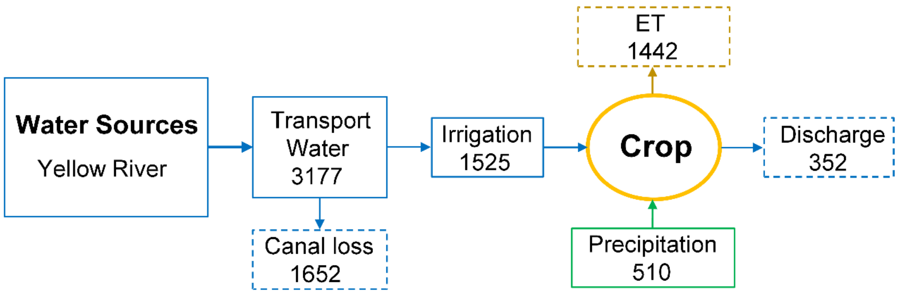

Fig. 5. The amount of water during crop growth (Mm^3)

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 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.

https://doi.org/10.5194/hess-2018-125
Preprint. Discussion started: 27 March 2018

Hydrology and Earth System Sciences
Discussions

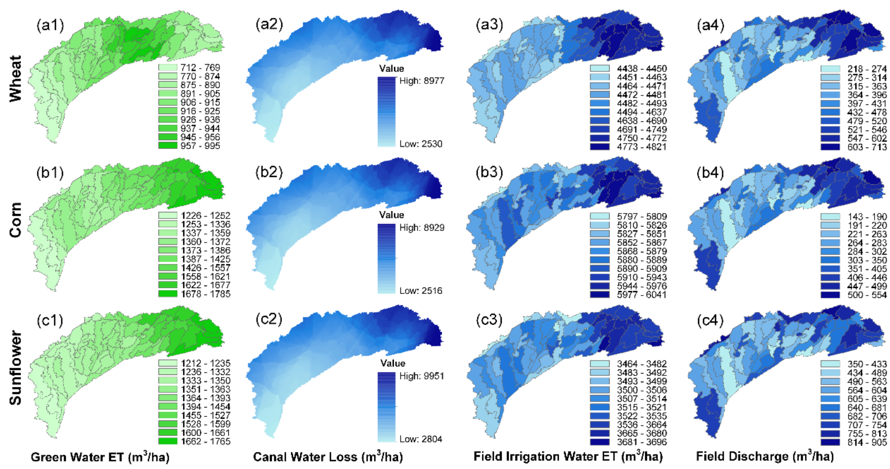

Fig. 6. Spatial distribution of the different water consumption of three crops (m^3 ha^{-1})

Blue water is surface water and groundwater used for crop growth. 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 different amount of canal water loss was caused by the difference of water loss in the unit area, at 4778 m^3 ha^{-1}, 4753 m^3 ha^{-1} and 5297 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 green water footprint of the crops is produced by precipitation during crop growth. The spatial difference of the green water footprints of wheat, corn and sunflower in HID was obvious (Fig. 7). It

https://doi.org/10.5194/hess-2018-125
Preprint. Discussion started: 27 March 2018

Hydrology and Earth System Sciences
Open Access
Discussions

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 footprints 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. Sunflower had the largest green water footprint in Wulateqianqi (538 m^3 t^{-1}) and the lowest in Linhe (325 m^3 t^{-1}). The green water footprint of crop production also varied across crops. The largest average green water footprint in HID was sunflower, followed by wheat and corn.

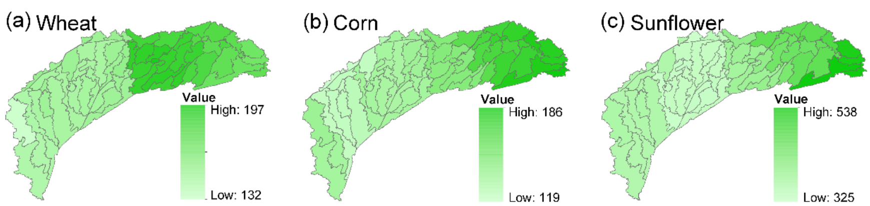

Fig. 7. The spatial distribution of the green water footprint of crop production in the HID (m^3 t^{-1})

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, 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 (4317 m^3 t^{-1}). The

https://doi.org/10.5194/hess-2018-125
Preprint. Discussion started: 27 March 2018

blue water footprint of crop production also varied across crops. The largest of the average blue water footprint in the HID was sunflower, followed by wheat and corn.

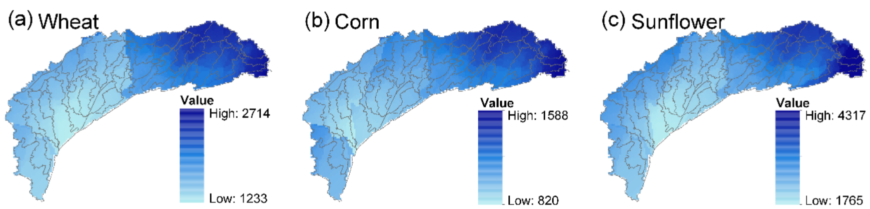

Fig. 8. The spatial distribution of the blue water footprint of crop production in the HID ($m^3 t^{-1}$)

3.4 The regional total water footprint of crop production

The total water footprint of crop production consists of both blue and green water footprints during the crop growth period. Fig. 8 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, 4885 $m^3 t^{-1}$) 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.

https://doi.org/10.5194/hess-2018-125
Preprint. Discussion started: 27 March 2018

Hydrology and Earth System Sciences
Discussions
Open Access

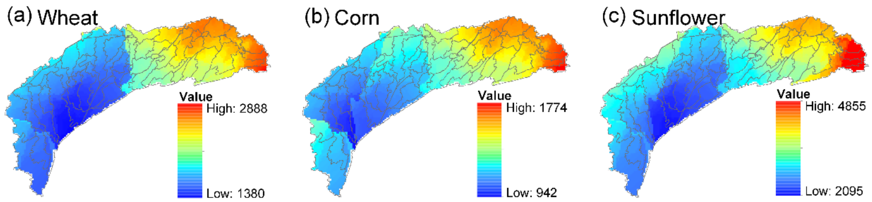

Fig. 9. The spatial distribution of the total water footprint of crop production in the HID (m^3/t)

4 Discussion

4.1 Methods of calculating crop production water footprints——region scale and field scale

In this paper, the calculation method of calculating crop production water footprints is divided into the field and region scales, according to the calculation boundary of water consumption in crop growth.

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. Current studies had different geographical scales, such as a global scale (Mekonnen and Hoekstra, 2011), a national scale, such as Europe (Vanham and Bidoglio, 2013) and China (Zhao, 2009), and a regional scale, such as Beijing (Sun, 2013a), Cremona province (Bocchiola, 2015) and Hetao (Luan et al., 2018); however, they all calculated the crop production water footprint of the field scale. These studies were based on empirical formulas, which could be divided into two methods. The first method is the irrigation schedule method, such as CROPWAT (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 (Chukalla, 2015; Zhuo 2016). The other method is the crop water requirement method (Cao et al., 2014; Sun et al., 2013c). The calculation of crop ET in these methods was based on the full satisfaction of the crop water requirement, there is no water deficit, and the actual soil water content was not taken into consideration. Therefore, the results did not reflect the actual water consumption of the crops, and the water footprint of the crop production in the field scale cannot

https://doi.org/10.5194/hess-2018-125
Preprint. Discussion started: 27 March 2018

Hydrology and Earth System Sciences
Open Access
Discussions

distinguish the source of blue water consumption from the surface water or groundwater.

The region-scale water footprint calculation method considered all of the water consumption related to crop growth from the water source to the field. It not only included 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. The blue water was consumed for crop growth and thus had to be included in the calculation of the water footprint. This was also the definition of crop water consumption in the crop production water footprint concept, which included all of the processes related to crop production, such as storage and transportation (the water that ran to other basins or seas such as the discharge out of the region instead of running back to the former basin) (Hoekstra, et al., 2011). The water footprints of the whole area irrigated by the canal system could be calculated by the region-scale method. To date, few studies have examined a region-scale water footprint. Sun et al. (2013b) calculated the regional water footprint in HID; however, the calculation was merely based on the principle of water balance and calculated the blue water consumption of the whole region based on the difference of water diversion and discharge in the region without distinguishing the specific parts of blue water loss.

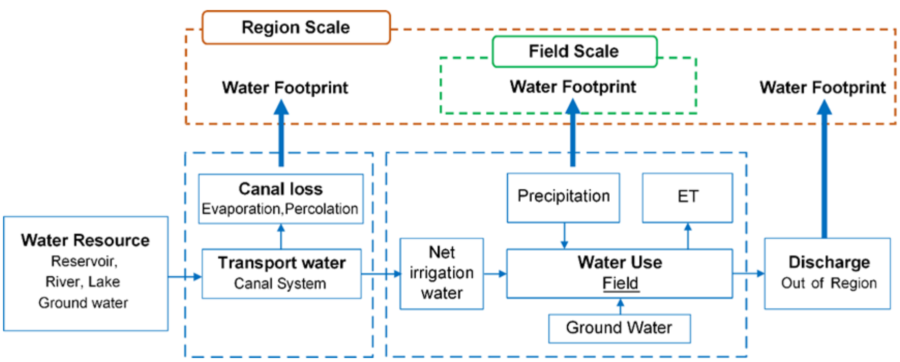

Fig. 10. The different scales of calculating water footprints

4.2 Comparison of the applicability of two methods

https://doi.org/10.5194/hess-2018-125
Preprint. Discussion started: 27 March 2018

Hydrology and Earth System Sciences
Open Access
Discussions

The applicable conditions of the two methods of calculating water footprints are different. In terms of the calculation boundary, the calculation of the green water footprint is the same, whereas the calculations of the blue water footprint are different. Fig. 11 illustrates the water sources and use conditions of two types of agriculture. The rainfed agriculture depends on precipitation (green water) and groundwater (blue water), and the water consumption mainly includes ET. While irrigation agriculture relies on surface water, groundwater and precipitation, water consumption includes ET, transport loss and discharge. Therefore, the field-scale method is suitable for calculating the water footprint of rainfed agriculture, whereas the region-scale method applies to the calculation of the irrigation agriculture water footprint.

Currently, irrigated farmland occupies 39.6% of the total arable land in China (NBSC, 2016). Globally, irrigated area accounts for 20.6% of all arable land (FAO, 2016). Overall, the yields of irrigation agriculture are much higher than that of rainfed agriculture. If the water footprints of irrigation agriculture are calculated by the field-scale method without considering water loss during transportation or discharge, the calculated values are smaller than the actual values, and the actual water footprints of irrigation agriculture cannot be precisely assessed. This is also the deficiency of the current crop production water footprint studies because most studies have adopted the field-scale method. Therefore, using the region-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.

https://doi.org/10.5194/hess-2018-125
Preprint. Discussion started: 27 March 2018

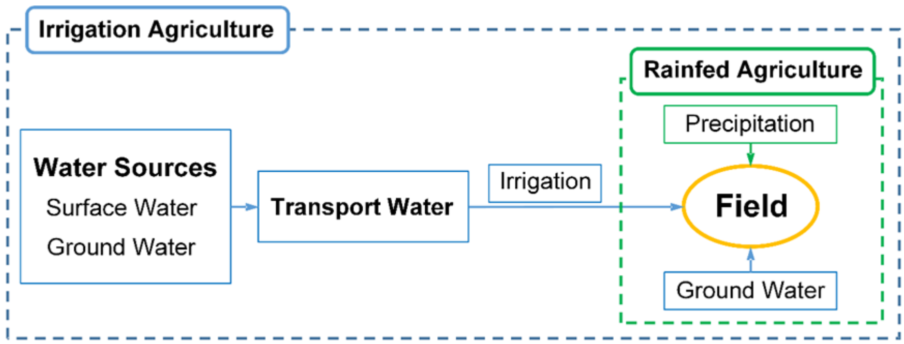

Fig. 11. Irrigation agriculture and rainfed agriculture

4.3 The methods of calculating region-scale crop production water footprints

In this study, we proposed an improved calculation method of the region-scale crop production water footprint. The method based on the hydrological model (SWAT model), which used the irrigation canal water use coefficient, calculated all of the water consumption in the process of crop growth by area (Hetao irrigation area) such as green water consumption, blue water in conveying process consumption, and irrigation and drainage in the field. The SWAT model could be used to simulate the regional hydrologic cycle and its simulation results could calculate the water use process during the crop growth period such as irrigation, precipitation, groundwater, ET and drainage. Then, combined with the water conveyance efficiency of the canal, the water canal loss during transportation could be calculated. In addition, this method could calculate the use of groundwater during the crop growth period, and therefore, blue water could be divided into surface water and groundwater for an additional accurate analysis of water sources for crop growth. To date, many scholars have conducted a few corresponding studies (Mekonnen and Hoekstra, 2010). Therefore, this method can calculate water use during the crop growth period and then more precisely calculate the blue, green and total crop water footprints.

In HID, the canal water loss accounted for 47.9% of all water consumption, which is one of the

https://doi.org/10.5194/hess-2018-125
Preprint. Discussion started: 27 March 2018

Hydrology and Earth System Sciences
Open Access
Discussions

main water consumption components during the crop growth period. Therefore, it is necessary to calculate the crop water footprints in irrigated areas using the regional scale. The water footprints of three crops (wheat, corn and sunflower) in HID and calculated by this method are 1380-2888 m^3 t^{-1}, 942-1774 m^3 t^{-1}, and 2095-4855 m^3 t^{-1}, respectively. These values are higher than the results calculated by the field-scale method. Cao et al. (2014) calculated the mean crop water footprints of China irrigation agriculture from 1998 to 2010 in which the mean total water footprint of many crops in the Inner Mongolia autonomous region (including HID) was 1556 m^3 t^{-1}. Sun et al. (2013b) used the region-scale method and the water balance principle to calculate the average water footprint of HID and it was 3.91 m^3 kg^{-1} in which blue water accounted for 90.9% and green water accounted for 9.1%. This result was the average water footprint of many crops, and the value was approximate to our results for the blue water of wheat, corn and sunflower and accounted for 89%, 87% and 86%, respectively. However, Sun et al. (2013b) could not distinguish each crop or illustrate the difference of spatial distribution.

The region-scale method proposed in this paper not only applies to water footprints of irrigation agriculture but also applies to the calculation of rainfed agriculture. If there is only natural precipitation without irrigation in the study area, irrigation can be excluded in the SWAT model to simulate the water circle in the field with rainfed conditions to calculate the field-scale water footprints of crop production. Therefore, this study method is suitable for two scales.

There are limitations to this approach. The method needs more data types (for instance, DEM, land use, soil and climate data, hydrological data, and crop management), and high-precision data is required, which are difficult to obtain. This method does not apply to areas without the above data.

5 Conclusions

https://doi.org/10.5194/hess-2018-125
Preprint. Discussion started: 27 March 2018

Hydrology and Earth System Sciences
Discussions

In this study, we proposed an improved region-scale method for calculating crop water footprints. This method is 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 footprints.

The method can analyze the process of water use during the crop growth period, including irrigation precipitation, groundwater, ET and drainage, for a more comprehensive calculation of water consumption during the crop growth period and more precisely quantify crop production water footprints. The method can be applied to calculate the crop production water footprint at both the field and region scale. In HID, the main water consumption occurs during the crop growth period; the canal water loss was 1652 Mm^3 and ET in the field was 1442 Mm^3, which accounted for 47.9% and 41.8% of the total consumption, respectively.

Based on this method, the total water footprints of three crops (wheat, corn and sunflower) in HID were 1380-2888 m^3 t^{-1}, 942-1774 m^3 t^{-1}, and 2095-4855 m^3 t^{-1}. In terms of spatial distribution, the values were higher in the east than they were in the west. The spatial distributions of blue and green water footprints were similar, and the blue water footprint accounted for more than 86% of the total water footprint.

Green water consumption was directly related to precipitation in the crop growth period. Less precipitation in the growth period of wheat led to less green water consumption and blue water consumption accounted for 93.1%. For corn and sunflower, blue water consumption accounted for 89.7% and 90.1%, respectively. For blue water consumption, 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.

https://doi.org/10.5194/hess-2018-125
Preprint. Discussion started: 27 March 2018

Hydrology and Earth System Sciences
Open Access
Discussions

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

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