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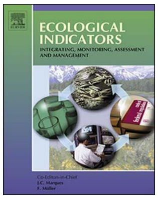

Quantitative study of the crop production water footprint using the SWAT model

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ABSTRACT

Assessment of the water use efficiency is the key to effectively manage agricultural water resource. The water footprint is a new index for water use evaluation, and its quantification is a precondition for assessment of the agricultural water use efficiency. Due to the shortage of water footprint calculation methods and computational module defects, this study aims to establish a method for calculating the water footprint of crop production based on hydrological processes. In this study, the field-scale water footprints of wheat, corn and sunflower were calculated using the SWAT model in the Hetao irrigation district (HID), China. The results showed that the average total water footprints of wheat, corn and sunflower were 1.036 m^3/kg, 0.774 m^3/kg and 1.510 m^3/kg, respectively. Additionally, the proportions of green water footprints in wheat, corn and sunflower were 22.3%, 26.1% and 29.4%, respectively. Water footprint calculations based on the SWAT model can reflect the spatial differences of water footprints during the process of crop production. The overall distribution pattern of the green, blue and total water footprints for the three crops demonstrated that high values were in the east part of the HID, followed by the west and the central areas. The SWAT-based water footprint offers high spatial resolution and is effective in exploring the spatial heterogeneity of crop water footprints.

1. Introduction

Global consumption of freshwater resources has grown more than sixfold in the past century (Gleick, 2000). Local water consumption has accumulated as a global problem (Vörösmarty et al., 2015). With the growth of the population and people's changing lifestyles, future demand for freshwater resources will continue to increase (Rosegrant and Ringler, 2000; Liu et al., 2008). The need for effective evaluations of water use efficiency has become an important global problem as the demand for water resources increases (Perry, 2007; Vörösmarty et al., 2010). Agricultural production is a water-intensive and low-return industry; the agricultural sector accounts for 85% of global blue water (surface or groundwater) consumption (Shiklomanov, 2000). In China, more than 60% of annual water resources are used for agricultural production and irrigation is the most important way of agricultural fresh water consumption (NBSC, 2014). The rapid development of China's economy, industrial production and urban areas will cause enormous pressure on regional water resources (Yu et al., 2011; Wang et al., 2014; Sun et al., 2016). Industrial economic development will pressure limited water resources, which will have a significant negative impact on agricultural production. Therefore, it is crucial to develop quantitative assessments and improve the utilization efficiency of agricultural water use to reduce the adverse effects of reduced water availability. It is important to study these problems to safeguard food security in China.

The water footprint theory provides methods and ideas to solve such problems (Hoekstra, 2009; Aldaya et al., 2010; Hoekstra and Mekonnen, 2012; Galli et al., 2012; Jackson et al., 2015). The water footprint is an indicator of freshwater use and can be used to quantify water consumption throughout the entire production supply chain. It reflects the amount of water and types of resources that are consumed and identifies contamination and pollution in the system. The water footprint of crop production is the ratio of water consumed per unit area during the growth period and its yield (Hoekstra and Mekonnen, 2012). In the agricultural sector, the crop production water footprint shows whether water consumption in crop growth period water is from green water (rainfall) or blue water (surface or groundwater), along with their respective volumes and proportions (Hoekstra and Chapagain, 2008; Hoekstra et al., 2011). It can also evaluate whether the crop's water footprint is reasonable and whether it varies regionally.

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These results can help inform whether measures can be taken to reduce the crop production water footprint and limit the proportion of blue water consumption. Accurate and precise quantification of crop water footprints is beneficial in assessing crop water use, these would improve the agricultural water use efficiency and decrease the volume of agricultural water consumption (Hoekstra and Hung, 2002; Hoekstra, 2003).

Many scholars have quantified various levels of crop water footprints and there are two main methods for crop water footprint calculation. The first method is based on an empirical formula model, such as CROPWAT model (Mekonnen and Hoekstra, 2011; Sun et al., 2013a) and CropSyst model (Bocchiola, 2015). The second method is statistical method which is based on regional water balance (Zhao et al., 2009; Sun et al., 2013b). But these methods have following shortcomings: first, the evapotranspiration (ET) calculated by these two methods is a theoretical value (Allen et al., 1998). The ET was calculated under the optimal conditions (Mekonnen and Hoekstra, 2011; Sun et al., 2013a,c; Bocchiola, 2015), but the obtained results may not be in accord with facts. Therefore, the quantification method needs to be refined. Second, both of these methods do not consider the influence of actual soil moisture condition, terrain and farmland management practices on crop water consumption. Third, the low spatial resolution in these studies is not conducive to the actual operational management of agricultural water since it is at the regional or district level, such as in Europe (Vanham and Bidoglio, 2014), Spain (Duarte et al., 2014; Castellanos et al., 2016), the Yellow River basin (Zhao et al., 2010), the Haihe river basin (Zhuo et al., 2015) and the entire Hetao irrigation district (Sun et al., 2013b,c). Further, the accurate calculations of field scale water footprints are needed by the administration to effectively manage water resource, but few studies have focused on the spatial variation of crop production water footprints within an administrative region or river basin. Here, distributed hydrological models (SWAT model) can contribute to meeting these requirements.

Based on the water footprint computation framework, the aim of this study is to provide a new way for calculating the water footprint of crop production in the Hetao irrigation district based on a hydrological model.

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 area of HID is $1.12 \times 10^4\,\text{km}^2$, and the average elevation is 1005–1060 m. The HID has a continental monsoon climate, with the lowest temperature in January (average −10 °C, the lowest −32 °C) and highest temperature in July (average 23 °C, the highest 35 °C). The annual precipitation is 145–216 mm and annual potential evaporation is 1987–2375 mm. The major crops are spring wheat, corn and sunflower. The growth period of wheat is between April and July, while the corn and sunflower is between May and October. Irrigation water is diverted from the Yellow River, and the primary irrigation technology used in HID is surface irrigation (Sun et al., 2013b). The irrigation and drainage system in HID are constituted by irrigation canals and drainage ditches. The irrigation system has a primary canal (228.9 km) and 12 supplementary canals (total 755 km). The drainage system has a primary main ditch (227 km) and 12 supplementary ditches (total 523 km) (AHID, 2015).

2.2. Model description

The SWAT (soil and water assessment tool) model is at the scale of a small watershed to river basin and evaluates the physical hydrological distribution to simulate the quality and quantity of both surface and ground water as well as to predict the environmental impact of land use, land management practices, and climate change (Arnold et al., 1998; SWAT, http://swat.tamu.edu/). It also incorporates the effects of water, evapotranspiration, run off, topography, and agricultural management practices. The model partitions a watershed into subbasins by topography and then partitions the subbasins into hydrologic response units (HRU) based on soil type and land use to assess soil erosion, nonpoint pollution, and hydrologic processes (Haverkamp et al., 2002). HUR is the basic unit of model computation. Because each HRU hydrological simulation process is independent, the data obtained from the simulation results were different, causing the ET in output data to be different. The water balance equation governed by the hydrologic component of the SWAT model (Neitsch et al., 2011) is as follow:

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

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 evapotranspiration 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 topography, soil, land use, discharge and climate. The global digital elevation model (GDEM) (30 × 30 m resolution) was provided by the Geospatial Data Cloud site (CAS, 2009a). Soil data (1:1,000,000) were obtained from the China Soil Scientific Database (CAS, 2009b). Land use data (1:100,000) of 2010 were obtained from the Data Center for Resources and Environmental Sciences (CAS, 2010).

The discharge data (AHID, 2015) included monthly data from 2003 to 2012. Due to the gentle slope, low levels of precipitation and strong evaporation, the drainage network based on the DEM was not consistent with the actual water system. Therefore, to divide the subbasin, 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 climate data during 2003 and 2012 were obtained from the China meteorological data network (NMIC, 2015), which included daily data of precipitation, solar radiation, maximum and minimum temperature, wind speed and relative humidity for five weather stations in the HID (Fig. 1). The average precipitation (2006–2012) of five counties in the HID are shown in Fig. 2.

The crop yield (wheat, corn and sunflower) required for the calculation of the water footprint was obtained from the Statistical Yearbook of local agricultural administrations (AHID, 2015), the three crops yield and spatial distribution are shown in Fig. 3. The irrigation parameters (irrigation time, irrigation quota) of different crops (wheat, corn and sunflower) were obtained from the local farmers in the HID, and then these parameters are entered to the model for simulation.

2.4. Calibration, validation, and sensitivity analysis

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 land use data from 2010 were used to represent the land use patterns of the 2010s (2003–2012). The calibration period was from 2006 to 2009, and the validation period was from 2010 to 2012. The global sensitivity analysis integrated within SUFI-2 was used to evaluate the hydrologic parameters for the discharge simulation.

For calibration and validation analyses, the monthly measured