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Modeling crop water consumption and water productivity in the middle reaches of Heihe River Basin

Jiang Li[a], Ting Zhu[a], Xiaomin Mao[a,*], Adebayo J. Adeloye[b]

[a] Center for Agricultural Water Research in China, China Agricultural University, Beijing 100083, China
[b] Institute for Infrastructure and Environment, Heriot-Watt University, Edinburgh EH14 4AS, UK

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ABSTRACT

Heihe River Basin is located in the arid inland area of northwest China and is facing serious water shortage problems. Since irrigation is the largest water consumer in the middle reaches of the Basin, it is crucial to study the crop yields and water consumption in order to improve the agricultural water productivity and to support sustainable economic development in this region. Based on field experiments in 2012 on typical crops, AquaCrop model was calibrated for seed maize, field maize and spring wheat; the models were validated using monitored data in 2013. Then considering the spatial distribution of soil types, groundwater depth, agricultural management and cropping patterns, ArcGIS was applied for the pre/post processing of the AquaCrop to quantify the spatial distribution of water consumption and water use efficiency (WUE) in a typical irrigation district and the whole middle reaches. Results indicate that the AquaCrop model can reasonably simulate the canopy cover development, biomass accumulation and crops yield, as well as the evolution of soil moisture in this area. For example, the Nash–Sutcliffe efficiency index for seed maize canopy cover was at least 0.91 during calibration and 0.96 during validation. Spatial analysis of simulated water consumption showed that total water consumption decreased from east to west due to the nature of the crops and the area cultivated. WUE for all the crops was above unity, with the vegetables recording the highest in 2012 and 2013 of 2.74 kg m^{-3} and 3.19 kg m^{-3} respectively. The least WUE was recorded for spring wheat, i.e. 1.19 kg m^{-3} and 1.67 kg m^{-3} in 2012 and 2013 respectively. Further simulations under future possible climate change scenarios showed that WUE of seed maize and field maize might rise to some extent, while WUE for spring wheat might decrease by 0.39% in 2030 but increase by 14.63% in 2050 under climate change scenario SRES B2.

1. Introduction

The middle reaches of Heihe River Basin, located in the arid region of northwest China, is facing serious water shortage problems due to the strong evaporation potential, little precipitation, limited upstream water inflow, and the mandatory water discharge to downstream areas since 2000 (Ministry of Water Resources, 2001). The continued development of the local economy requires even more water resources, while the evidence provided by the deteriorating natural vegetation in this region indicates that the available water resources was over-utilized (Chen et al., 2005). Water consumption in agriculture accounts for more than half of the total water abstraction (Xu and Cheng, 2000), and currently considerable amounts of water diverted for irrigation are not effectively used for crop production (Smith, 2000). Therefore quantification of the crop water consumption and the water productivity in this area is an essential step toward the development of more efficient systems for allocating of the limited water resources for the overall benefit of the local economy while preserving the integrity of the natural environment.

Evapotranspiration (ET) is the consumptive use of water for crop growth. Thus, water productivity evaluation requires an understanding of the relationship between crop growth and ET, for various types of crops. ET can be obtained by direct measuring or indirect calculation. Weighing lysimeters, eddy covariance systems and Bowen ratio systems are often-used tools for the direct, *in situ* measurement of ET (Wegehenkel and Gerke, 2013; Holland et al., 2013; Liu et al., 2013). However, because such measurements are expensive, time consuming and site specific, the indirect (or calculation) methods are often preferred. The indirect or calculation methods for ET (or evaporation) include the Penman model (Penman, 1948), Penman–Monteith (PM) model (Monteith,

* Corresponding author. Tel.: +86 (10) 6273 8498; fax: +86 (10) 6273 6533.
E-mail addresses: lj397947820@163.com (J. Li), tingzi311@qq.com (T. Zhu), maoxiaomin@cau.edu.cn (X. Mao), a.j.adeloye@hw.ac.uk (A.J. Adeloye).

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1965), or reference ET methods such as FAO56 Penman–Monteith (FAO-PM) method (Allen et al., 1998) and KSOM-based method (Adeloye et al., 2011).

Crop models were developed in the last few decades for understanding the relationship between dynamic crop growth indices and their main controlling factors (Bouman et al., 1996). There are mainly three types of crop growth models according to their key driving factors, i.e., carbon-driven models, radiation-driven models and water-driven models (Abedinpour et al., 2012). Carbon-driven models describe the crop growth based on carbon assimilation and one of the representative models is WOFOST (van Diepen et al., 1989). Radiation-driven models derive the crop biomass directly from the intercepted solar radiation through a single conversion coefficient, known as the radiation use efficiency (Monteith and Moss, 1977). Examples are EPIC (Jones et al., 1991; Cabelguenne et al., 1999) and CERES model (Ritchie and Otter, 1984). The latter is a model based on crop growth controlled by phonological development processes, and has been widely used to simulate the responses of yields and water use efficiencies of wheat and maize to climate change scenarios (Guo et al., 2010).

Water-driven models normally assume that crop growth rate is linearly proportional to transpiration through a constant of proportionality known as the water productivity (WP) parameter (Steduto and Albrizio, 2005). They are particularly suitable for conditions such as those in northwest China where water is the key limiting factor for crop production. Compared with carbon-driven models and radiation-driven models, water-driven models are the least complex and most parsimonious (Steduto et al., 2007, 2009). There are mainly two water-driven models in common use – CropSyst (Stockle et al., 2003) and AquaCrop (Steduto et al., 2009). Of these, AquaCrop, developed by the Food and Agricultural Organization (FAO) of the United Nations, has seen the most use because of its simplicity and the fact that for most commonly grown crops, further calibration is often not required (Vanuytrecht et al., 2014). It has been widely used and applied successfully to different crops, like barley (Nazari et al., 2013), wheat (Salemi et al., 2011; Lorite et al., 2013), maize (Kim and Kaluarachchi, 2015), cabbage (Kiptum et al., 2013), seed cotton (Voloudakis et al., 2015) and some others (Vanuytrecht et al., 2014; Paredes et al., 2015). For these reasons, AquaCrop was adopted for the current study.

Most of the crop models including AquaCrop are point-scale models based on plot or field experiments and are unable to consider spatial heterogeneity in such factors as crop types, soil characteristics and irrigation practices and scheduling. However, unless such point scale evaluations can be up-scaled to the much more useful regional scale, the full impacts/benefits of this kind of analysis cannot be realized. Geographic Information Systems (GIS) can be used to extend their applications to regional scale through loose, close or embedded coupling (Ines et al., 2002; Mo et al., 2009; Fortes et al., 2005). For example, Lorite et al. (2013) manipulated the AquaCrop input and project files in a GIS platform and developed two tools (AquaData and AquaGIS) to manage the programs, which not only saved operating time but also enabled the simulation of the regional impacts of climate change on wheat yields in Andalusia, Spain. Jiang et al. (2015) adopted a similar analysis to characterize water consumption and yield using SWAP-EPIC and ArcGIS for an irrigation district in China. In the current study, however, we have extended the work by Jiang et al. (2015) to cover the entire middle reaches of Heihe River Basin, thereby providing for the first time useful information that will aid irrigation water management in this main agricultural region of northwest China.

The aim of this study therefore is to evaluate the spatial pattern of crop water consumption and water use efficiency (WUE) in the middle reaches of Heihe River Basin, a basin characterized by heterogeneous soil textures, various types of crops, and with limited water resources, using AquaCrop loosely coupled with ArcGIS for the pre/post processing. The objectives are to:

(1) Evaluate the performance of AquaCrop for predicting local soil water balance and crop yield based on the field experiment data from 2012 to 2013.
(2) Quantify the total water consumption and WUE, and their spatial distribution in the typical irrigation districts and in the whole middle reaches of Heihe River Basin.
(3) Predict the response of regional crop growth and water consumption under future possible climate change scenarios.

In the next section, the methodology adopted for the study and the materials are described. Then, the results and discussions are presented, after which follows the main conclusions of the study.

2. Materials and methods

Fig. 1 depicted the method for calculating the water consumption and WUE in the middle reaches of Heihe River Basin. The water consumption was analyzed in three scales, the spot scale with typical crops, the regional scale in a typical district (i.e., Yingke Irrigation District) and the large regional scale in the middle reaches of Heihe River Basin (including 17 main irrigation districts). Seed maize, field maize, spring wheat and vegetable were selected as the typical crops to be investigated because of their popularity in this area. The water consumption and yield of these crops was simulated by AquaCrop model, which was calibrated and validated by the observed field data from year 2012 to 2013. Then ArcGIS was applied for the pre/post processing of the AquaCrop to quantify the spatial distribution of water consumption and WUE in the regional scales, based on the spatial distribution of soil types, groundwater depth, agricultural management and cropping patterns.

2.1. Study site

Heihe River Basin (37°–43°N, 97°–103°E) is located in northwest China and is a typical arid region. The middle reaches, covering an area of 13,942 km^2 with 2379 km^2 of irrigated farmland, is to be studied in this research (Fig. 2). It has a temperate climate with the mean annual temperature varying from 0 °C to 5 °C, annual average precipitation of 129.6 mm and annual potential evaporation of 1400 mm. Soil moisture stresses are therefore common without irrigation. Typical crops in this region include the main food crops, i.e., field maize and spring wheat, the main cash food, i.e., seed maize, and some vegetables, e.g., cabbage. Due to the limited precipitation in the area, irrigation is required during the entire crop growing season (from April to October), with water diverted from either the Heihe River or pumped from the aquifer.

2.2. Field experiment and data collection

2.2.1. Field experiment

The field observation was carried out in the farmland of field maize, seed maize and spring wheat in Yingke Irrigation District, which is one of the 17 main irrigation districts in Heihe middle reaches (Fig. 2) during the year 2012–2013 (Jiang et al., 2015). Leaf area index (LAI), and above ground biomass were recorded at intervals of about 10 days during the crop growing period. Soil moisture was also sampled at 20 cm intervals down to the 140 cm below ground surface using the gravimetric sampling method, every 10 days during the growing period, with three replicates (see Fig. 2 for the location of the observation points). Irrigation was applied according to the schedule in Table 1. Soil moisture at field