Agricultural Water Management 178 (2016) 350–365

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Evaluation of crop water productivity under sprinkler irrigation regime using a distributed agro-hydrological model in an irrigation district of China

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ARTICLE INFO

Article history:
Received 25 December 2015
Received in revised form 17 August 2016
Accepted 5 October 2016

Keywords:
Sprinkler irrigation regime
Crop yield
Water productivity
Distributed SWAP-WOFOST model
Cropping pattern

ABSTRACT

Irrigation is essential for agriculture in the Hetao Irrigation District (HID), which is one of the important food production areas in China. Surface irrigation is main irrigation method, and the efficiency of irrigation water usage is very low. With the development of economics and the reduction of the water diversion from the Yellow River for agriculture, it is crucial to improve water productivity (WP) by trying to adopt modern irrigation method, such as sprinkler irrigation. In this study, a SWAP-WOFOST agro-hydrological model was calibrated and validated, and then used to simulate crop yields and WPs in the distributed manner under the scheduled sprinkler and surface irrigation regimes during 2000–2010 in the HID. The cropping pattern was adjusted further by quantitatively comparing the WPs of the three main crops. The results indicated that compared with the surface irrigation scenario, the annual average yields of spring wheat, spring maize, and sunflower were improved by 16.9%, 8.0%, and 11.4%, respectively, and the annual average WPs were increased by 7.9%, 5.0%, and 14.1%, respectively, after zoning in the sprinkler irrigation scenario. The corresponding multiyear (2000–2010) average required field irrigation amount for the whole cultivated lands would reduce about 4.09×10^8 m^3 per year. At the same time, the groundwater contribution to crop water consumption became more, which did not cause groundwater depth sustainable decline during 2000–2010. Therefore, the improvement of irrigation method and the adjustment of cropping pattern could contribute to more sustainable food production and saving agricultural water usage in the HID.

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1. Introduction

The Hetao Irrigation District (HID) is one of the main grain production regions in China (Xue et al., 2013; Yu et al., 2010). In this region, irrigated agriculture makes up 98% of HID's consumptive water usage due to arid and semi-arid climate (Ruan et al., 2008). To alleviate the serious water crisis of the Yellow River (Yang et al., 2010; Zhang et al., 2014), the annual average amount of irrigation water from the Yellow River will be reduced about 1.0 billion m^3 per year for HID in the future (Luo and Sophocleous, 2011; Xu et al., 2010; Yang et al., 2012). Reducing water diversion amount from the Yellow River and growing demand for water of industrial and domestic sectors are intensifying the pressure on agricultural water usage in the HID. However, the irrigation technology used in the HID is mainly surface irrigation, the coefficient of irrigation water usage is only 0.30–0.35, and the waste amount of water resource is serious (Ruan et al., 2008; Wang, 2012). Therefore, traditional irrigation agriculture in the HID is now facing a big challenge, which appeals people to develop modern water-saving irrigation technology for sustainable water usage. Sprinkler irrigation, as one of the earliest and most universal water-saving irrigation method, has been widely used all over the world (Dong et al., 2015; Wang et al., 2015). In China, the areas using sprinkler irrigation show a rapid increase during the last 20 years (Yu et al., 2009), which are approximately over an area of 3.3 million hectares by the end of 2012 (Cremades et al., 2015). In the Inner Mongolia Autonomous Region, with rapid economic development, farmers have been encouraged to shift from conventional surface irrigation to sprinkler irrigation to cope with the decreasing of water resources for agricultural irrigation (Wen et al., 2015). However, there is quite limited information available about the effect of sprinkler irrigation method on crop growth and water usage at the regional scale in arid and semi-

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http://dx.doi.org/10.1016/j.agwat.2016.10.003
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arid areas. Therefore, it is important to attempt to simulate the scheduled sprinkler irrigation regimes of different crops, and to evaluate the effect of sprinkler irrigation on crop yield and water productivity (WP = yield/evapotranspiration) quantitatively in the HID in Inner Mongolia.

To determine the relative proper sprinkler irrigation regimes for different crops, a number of studies have been conducted to analyze irrigation water amount, irrigation water productivity, crop yield, crop WP, and water management response indicators under the sprinkler irrigation practice by the field experiments or modeling (Djaman et al., 2013; Liu et al., 2011; Sezen et al., 2011; Singh and Singh, 1996; Wang et al., 2015; Wen et al., 2015). Their results provided suggestions for the application of sprinkler irrigation regime at site-specific. Moreover, several researches quantitatively compared the crop yield, consumption water amount, and WP under the sprinkler and the other irrigation methods. For example, the certain research had failed to show any significant difference in terms of maize yield between the flooding and sprinkler irrigation methods (Adamsen, 1992; O'Neill et al., 2008; Wang et al., 2012). However, according to the research carried out by Greenwood et al. (2008), the sprinkler irrigation resulted in lower water consumption of maize than traditional irrigation method, thus it was benefit for maize to improve WP. O'Neill et al. (2008) also found that compared with the furrow irrigation, there was only a small yield increase with similar total water usage and WP for maize under the sprinkler irrigation. For wheat, Ren et al. (1996) reported that spring wheat yield under the sprinkler irrigation was 20%–30% higher than those under the flooding irrigation, and water saving 50%–60%. Yang et al. (2000) pointed out that the water use efficiency (WUE) of winter wheat under the sprinkler irrigation was higher than those under the flooding irrigation. Liu et al. (2003) compared crop yields and WUEs of winter wheat under the sprinkler and surface irrigation, and found that the yield of winter wheat for sprinkler irrigation was increased 274 kg ha^{-1} and 291 kg ha^{-1}, and the WUE of winter wheat was increased by 63.3% and 35.7% for two years, compared to the surface irrigation. Kahlown et al. (2007) pointed out that the water savings, wheat yield, and WP of the sprinkler irrigated treatment were higher than those of the basin irrigation, without respect to application of irrigation water above or below actual crop water requirement in Pakistan. Liu et al. (2011) also found that the sprinkler irrigation could save 50−150 mm irrigation water for winter wheat, compared to the surface irrigation in Beijing area. Their results all showed that the sprinkler irrigation was a potential measure to improve the crop growth and to develop water-saving agriculture at site-specific. However, because of extreme variability in soil and eco-hydrological conditions, site-specific results could not be generalized and applied to the entire region. To promote the sprinkler irrigation method at the regional scale, it was significant to study the sprinkler irrigation regimes of different crops by synthetically considering the spatial variability of climate, crop, and soil. Although the usage of field experiments was the credible technique for studying the effect of the sprinkler irrigation, large-scale field experiments were time consuming and very costly to conduct. The distributed models were the useful tools for assessing the irrigation management quantitatively at the regional scale (Droogers et al., 2000; van Dam et al., 2006).

So far, the Soil-Water-Atmosphere-Plant (SWAP) model in the distributed manner had been widely used for evaluating irrigation system water-saving potential by the appropriate allocation of river water and the reduction of deep percolation at a regional scale (Jiang et al., 2015; Noory et al., 2011; Singh et al., 2006), few studies focused on saving irrigation water through the conversion of irrigation method. Khan and Abbas (2007) indicated that the scheduled irrigation module of the SWAP model combined with the Geographic Information System (GIS) method could support decision that making for increasing WP from the farm to regional levels, and help to establish an improved irrigation method for sprinkler irrigation with certain water-saving potential. However, we have noticed that few studies have been devoted to simulate scheduled sprinkler irrigation regimes for different crops by the calibrated and validated distributed SWAP-WOFOST model at the regional scale, and then quantitatively evaluated the effect of the converting irrigation methods on crop yield and WP.

The objectives of this study are: (i) to validate and apply the distributed SWAP-WOFOST model to simulate the scheduled sprinkler irrigation regimes of the main crops in the HID, and (ii) to evaluate the crop yields and WPs under the surface and sprinkler irrigation methods, and (iii) to adjust cropping pattern so as to increase crop WP through improving irrigation technology and proper selection of crops matching with soils.

2. Materials and methods

2.1. Study area

The HID is one of the three largest irrigation districts in China, with an irrigated area of 5.74×10^3 km^2 (Liu et al., 2015; Yu et al., 2010). It is located in the west of Inner Mongolia, China (106°20′–109°19′E, 40°19′–41°18′N), and includes five counties: Dengkou (DK), Hangjinhouqi (HH), Linhe (LH), Wuyuan (WY), and Wulateqianqi (WQQ) (Fig. 1). The district is an important area of agricultural production, and spring wheat, spring maize, and sunflower are the major crops (Wang, 2012).

The region is characterized as continental arid and semi-arid climate. Rainfall is scarce (130–215 mm), and mainly occurring from June to August, and the annual evaporation is 2100–2300 mm (Liu et al., 2015; Xue et al., 2013). The precipitation is not sufficient to meet crop water demand, so irrigation is very important for crop growth in the HID. Irrigation water is mainly diverted from the Yellow River, and then it is transmitted to the field by irrigational channel. There are intricate drainage ditches, which consist of a main drain ditch, 12 trunk, 49 sub-trunk, 183 tributary, 56 lateral, 1533 sub-lateral, and more than 9200 furrow ditches in this region (Wang et al., 1993). Under the joint action of rainfall, evaporation, irrigation, drainage et al., the annual average groundwater depth is about 1.5 m during April to October in the HID. Since the improper irrigation management, there is a large volume of irrigation water loss and the water usage is inefficient (Wang, 2012).

2.2. Description about SWAP-WOFOST model

SWAP model is used to simulate soil water movement, solute and heat transport, and crop growth (Kroes et al., 2008). In the model, the Richards' equation, which includes root water extraction, is used to compute transient soil water flow. The soil hydraulic properties are described using the Mualem (1976) and van Genuchten (1980) functions. The upper boundary conditions are determined by the potential evapotranspiration (ET_P), irrigation, and precipitation. The ET_p is estimated using the Penman-Monteith method (Allen et al., 1998). Interception of irrigation water may occur in case of sprinkler irrigation. The lateral drainage is computed using the equation of Hooghoudt or Ernst, which assumes that it is extracted laterally in the saturate zone of the soil profile. The solute transport is described by considering the processed of the convection and dispersion. The convection-dispersion equation used was derived from the van Genuchten and Cleary (1979) and Boesten and van der Linden (1991) in this study. Simulation of crop growth used the detail sub-model WOrld FOod STudies (WOFOST), which can simulate the actual and potential yield of crop dry matter under the water and salt stress conditions. A detail model description of WOFOST is available in the literatures (Spitters et al., 1989;

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