Agricultural Water Management 199 (2018) 93–104

Contents lists available at ScienceDirect

Agricultural Water Management

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

Growth responses of crops and natural vegetation to irrigation and water table changes in an agro-ecosystem of Hetao, upper Yellow River basin: Scenario analysis on maize, sunflower, watermelon and tamarisk

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ARTICLE INFO

Article history:
Received 30 May 2017
Received in revised form
11 November 2017
Accepted 18 December 2017

Keywords:
Model simulation
Irrigation strategies
Optimum groundwater depth
Heterogeneous land covers
Agro-ecosystem
Salt accumulation

ABSTRACT

Due to water scarcity, water saving practices (WSPs) are being implemented in the irrigation districts of the upper Yellow River basin, causing a series of consequences, e.g. the reduction of field irrigation amount and groundwater depth (GWD) increase. The impacts of irrigation water reduction and GWD increase in canal systems with heterogeneous land covers is complex and remains unclear, thus the need to be elucidated to efficiently promote WSPs. Based on the two-year field observations in 2012 and 2013 and former studies, the HYDRUS-dualKc model, which has been well calibrated and validated in a typical canal system in Hetao, was used to predict the changes in transpiration, evaporation and salt accumulation considering scenarios with various GWDs and irrigation strategies. Results showed that under present irrigation scheduling, plant transpiration of maize, watermelon, tamarisk and sunflower had an initial slight increase, then reached a peak value, and finally decreased in the two years with GWD increase, while soil evaporation and salt accumulation both declined continuously. Based on integration results from the three crops and the natural vegetation simulation scenarios, an optimum GWD of between 1.7–2.3 m for the crop fields and 1.4–2.0 m for the natural land was recommended. With optimum GWD, 15%–30% of water diversion from the Yellow River during the growing season can be saved each year. When considering the irrigation strategies, salt accumulation increased and crop transpiration declined with irrigation reduction, yet the impact on soil evaporation was limited. It also showed that only sunflower had the potential to reduce irrigation amount (about 20%). Future water saving should pay more attention to the water delivery process and the optimization of irrigation during the non-growing season. An additional irrigation to watermelon during its development stage and a pre-season irrigation to tamarisk can largely improve their growth, and the recommended irrigation depths were 100 mm and 250 mm, respectively. These results can be reference criterion for the further implementation of WSPs.

1. Introduction

Improving irrigation management for water saving is a focus on world agricultural production. This is especially true for the Yellow River basin in China, which has suffered critical water shortages and resulting large losses and severe damage to both the economy and the environment (Ren et al., 2016). The Hetao Irrigation District (Hetao) is a typical arid irrigated region in the upper Yellow River basin. For a long time, excessive water diversions coupled with poor irrigation and drainage practices have caused shallow water tables and resulting severe water logging and secondary salinity problems. Large volumes of diverted water have been wasted through canal seepage and leakage, field deep percolation and runoff, as well as evaporation. Due to water scarcity and low water use efficiency, water-saving practices (WSPs) in Hetao have been and continue to be promoted by the government at both the irrigation district and farm levels. The application of WSPs causes a decline of groundwater table that favors the control of water logging and salinity (Xu

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https://doi.org/10.1016/j.agwat.2017.12.021
0378-3774/

et al., 2010). However, it also brings about new problems such as degradation of natural vegetation and increasing risk of drought.

Shallow groundwater exerts strong effects on vegetation that can maintain yield stability or even enhance productivity if it becomes a water source during water deficit periods (Nosetto et al., 2009). However, it can also hamper vegetation growth when it is too shallow due to waterlogging and root anoxia or may even cause severe soil salinization (Ayars et al., 2006; Kahlown et al., 2005). The appropriate irrigation for a given crop field is also closely related to the groundwater depth (GWD). Therefore, irrigation management strategies and adoption of WSPs should well consider the groundwater table management for arid areas with shallow water table. Note that this is a somewhat more complex issue for irrigated areas in the upper Yellow River basin. Because of the special "farmland use rights" (i.e. household contract responsibility system) (Tan et al., 2006) in China, the cropland has been divided into small farms, resulting in a fragmented crop distribution landscape (Wu et al., 2005; Ren et al., 2016). Various kinds of crops (e.g. wheat, maize, sunflower and melon) are planted in adjacent and small plots, and they may be rotated every one or two years (Fig. 1). At the same time, natural patches of grass, woods, shrub and marsh within and surrounding the croplands also play an important part in the landscape (Ren et al., 2017). All of the above factors make the land cover rather fragmented and heterogeneous. Various crops and plants have different phenological characteristics, and thus distinct irrigation and management strategies that may occur in adjacent areas. What is more, they are confronted with the same important external environment, i.e. the groundwater table in local agro-ecosystem. Understanding and quantifying the impact of groundwater influences on vegetation growth and searching for an optimum GWD and appropriate irrigation strategies are critical to minimize risks and maximize benefits in shallow groundwater areas.

In croplands, many studies have addressed the effects of GWDs on soils and crops growth in different regions of the world (e.g., Benz et al., 1981; Kang et al., 2001; Ayars et al., 2006). Some studies also discussed optimum GWDs and irrigation strategies for crop growth (Zipper et al., 2015; Kahlown et al., 2005; Xu et al., 2013). Williamson and Kriz (1970) demonstrated that it is necessary to know at least the crop species, soil characteristics and watering procedure to specify an optimum water table depth. Among crop attributes, root growth and distribution and tolerance to waterlogging and salinity are of key importance in regulating groundwater influences (Nosetto et al., 2009). In natural ecosystems, much of the research on vegetation water use from shallow ground water as well as the ecological water table depth has been done as well (Feng et al., 2012; Li et al., 2015; Cui and Shao, 2005). These studies provide knowledge of the interaction between shallow groundwater and vegetation water uptake. Appropriate GWD and irrigation management strategies for a certain crop or certain natural vegetation were proposed. However, it is difficult to extend and generalize the results because of different soil types, irrigation regimes, plant rooting patterns and salinity tolerances, depth and fluctuations of water tables, and climatic conditions. Moreover, due to heterogeneous land cover patterns and the regional effect of the groundwater table, results of the former studies focusing on a certain land cover may be unsuitable for irrigation districts in the upper Yellow River basin. Appropriate groundwater management in an agro-ecosystem should consider the growth of different crops and the sustainability of natural vegetation simultaneously.

When it comes to the control of GWD, drainage engineers are generally concerned with removing excess soil water and lowering the water table as rapidly as economically feasible, irrespective of the type of crops. Plant scientists, on the other hand, have generally studied the water and aeration requirements of specific crops under laboratory or field experimental conditions, neglecting its applicability in the field with heterogeneous land covers. To our knowledge, there are few reported studies that determine optimal GWD and irrigation management strategies with comprehensive consideration of fragmented crops, natural vegetation and the lateral groundwater exchange at the scale of canal irrigation system, particularly for research in the upper Yellow River basin (Wang et al., 2004; Pereira et al., 2007; Xu et al., 2013). Research based on a canal system can provide a more realistic view on water table and irrigation management, because the whole agro-ecosystem in a district is more comparable to a representative irrigation canal system which contains various kinds of land cover, not a single crop. Thus, the results can be of practical significance in real agro-ecosystems.

In arid irrigated areas with shallow water tables, the optimum GWD should achieve the following objectives: (1) reducing salt accumulation as much as possible to improve soil conditions; (2) reducing non-beneficial bare soil evaporation to increase water use efficiency; (3) favoring crop growth combined with appropriate irrigation to increase yields, or at least no reduction; and (4) maintain the sustainability of natural patches within and surrounding the croplands. Consequently, the determination of optimum GWD and irrigation strategies for an agro-ecosystem involves ground water quality, vegetation salt tolerance, canal delivery management, irrigation frequency and the nature of the vadose zone. This level of complexity makes it impossible to conduct field experiments that can fully consider all the factors at once (Ayars et al., 2006). Moreover, the control of the groundwater level in the field is difficult and costly in field experiments.

In this study, a simulation model which has been calibrated and validated in a typical agro-ecosystem of Hetao (Ren et al., 2016, 2017) was adopted to explore series of simulation scenarios. In order to obtain optimum groundwater and irrigation management strategies, systematic comparison and analysis of the simulation results were conducted. Therefore, the objectives of this paper were: (1) to simulate water and salt dynamics and to assess irrigation water use under various groundwater table and irrigation scenarios in an irrigation canal system of Hetao, upper Yellow River basin; and (2) to further propose an optimum groundwater and irrigation management strategy for Hetao and other arid irrigation districts of the upper Yellow River basin, which could provide comprehensive consideration of the cultivation of various crops and the sustainability of natural lands for the whole agro-ecosystem.

2. Materials and methods

2.1. Field site and experiment

2.1.1. Location, land cover and irrigation water use in hetao

The Hetao covers an area of 1.12 Mha and is located upstream of the Yellow River, North China. The plain elevation in Hetao varies from 1007 to 1050 m above mean sea level (MSL), and exhibits a small slope in the direction of southwest to northeast. The groundwater table is shallow with depth ranging between 0.5–3.0 m during the year, and it has a very small hydraulic gradient of 0.10–0.25‰ regionally. Soil is mainly formed from alluvial deposits with a silt loam texture. Hetao has an arid to semi-arid continental climate. The average annual precipitation is 160 mm, while 20 cm pan evaporation averages 2240 mm annually. The mean annual temperature is 8.2 °C, and there are 135–150 frost-free days and 3100–3300 h of sunshine per year (Feng et al., 2005).

The Hetao includes 0.57 Mha of agricultural area irrigated by the Yellow River. The predominant crops grown are sunflower, maize, wheat and some vegetables. Their distribution is highly fragmented because of smallholder land use rights. Another important land use type in Hetao is natural land which covers an area about half as large as that of the agricultural land. The natural