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Modeling and assessing field irrigation water use in a canal system of Hetao, upper Yellow River basin: Application to maize, sunflower and watermelon

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SUMMARY

Water saving in irrigation is a key issue in the upper Yellow River basin. Excessive irrigation leads to water waste, water table rising and increased salinity. Land fragmentation associated with a large dispersion of crops adds to the agro-hydrological complexity of the irrigation system. The model HYDRUS-1D, coupled with the FAO-56 dual crop coefficient approach (dualKc), was applied to simulate the water and salt movement processes. Field experiments were conducted for maize, sunflower and watermelon crops in the command area of a typical irrigation canal system in Hetao Irrigation District during 2012 and 2013. The model was calibrated and validated in three crop fields using two-year experimental data. Simulations of soil moisture, salinity concentration and crop yield fitted well with the observations. The irrigation water use was then evaluated and results showed that large amounts of irrigation water percolated due to over-irrigation but their reuse through capillary rise was also quite large. That reuse was facilitated by the dispersion of crops throughout largely fragmented field, thus with fields reusing water percolated from nearby areas due to the rapid lateral migration of groundwater. Beneficial water use could be improved when taking this aspect into account, which was not considered in previous researches. The non-beneficial evaporation and salt accumulation into the root zone were found to significantly increase during non-growth periods due to the shallow water tables. It could be concluded that when applying water saving measures, close attention should be paid to cropping pattern distribution and groundwater control in association with irrigation scheduling and technique improvement.

1. Introduction

The Yellow River, the second longest river in China, plays a critical role in water supply in the Northwest and Northern China. Due to the arid and semi-arid climate conditions in the upper basin, irrigation plays a key role in the agricultural production, accounting for nearly 80% of the total water use in the Yellow River basin (Zhu et al., 2003). Water scarcity is severe, with average water availability smaller than 500 m^3 per capita (Wang et al., 2006). The basin holds only 3% of the country's water resources but occupies 13% of the country's cultivated area. Due to intensive water abstraction and frequent drought occurrence, the low reaches of the Yellow River have dried up many times since 1972 (Liu and Zheng, 2004). Water shortages have caused large losses and severe damages to both the economy and the environment, especially in the downstream areas. Nevertheless, excessive river water diversion occurs in the arid upstream irrigation districts, which exaggerates the river water shortage for irrigation in the downstream area.

Two anciently established and large irrigation districts, Qingtongxia Irrigation District (QID) and Hetao Irrigation District (Hetao), located respectively in Ningxia and Inner Mongolia provinces (Fig. 1), divert nearly 25% of the annual river flow (Chen et al., 2003). Hence, it is critical to improve agricultural water use and to reduce river water diversions, particularly in the upstream areas, while improving land and water productivity (Pereira et al., 2003). Since long time, in those upstream irrigation districts, excess water diversions coupled with poor irrigation and drainage practices have caused shallow water tables and severe water logging and salinity problems (Xu et al., 2011; Yu et al., 2010; Pereira et al., 2014). Large amounts of diversion water have been wasted through canal seepage and leakage, field deep

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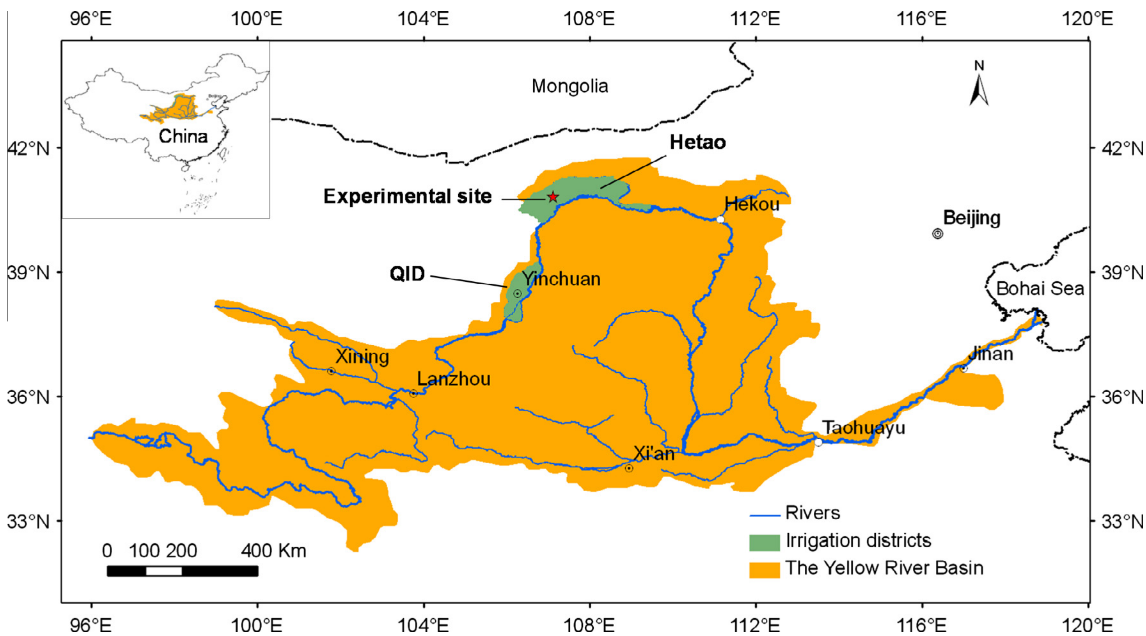

Fig. 1. The Yellow River basin and location of the case study area (Hetao) and experimental site (YCA) (the river reach upstream to Hekou is upper Yellow River; the river reach between Hekou and Taohuayu is the middle Yellow River and the river downstream to the Taohuayu is the lower Yellow River. Hetao: Hetao Irrigation District; QID: Qingtongxia Irrigation District; YCA: Yangchang canal command area).

percolation and runoff, as well as evaporation. This has been largely studied and reported in literatures, and adequate water saving practices (WSPs) have been recommended (Miao et al., 2015; Hollanders et al., 2005; Pereira et al., 2007; Xu et al., 2010).

In the last decade, some of those WSPs have been implemented by the government at both the irrigation district and farm levels. They include: (1) improvement of water conveyance efficiency by lining canals and upgrading the hydraulic regulation and control; (2) increase of water use efficiency in the field by upgrading crop irrigation scheduling, adjusting the crop species, and adopting precise land leveling and water-saving irrigation technologies; and (3) optimization of water use policies and management schedules in some demonstration areas. Note that appropriate WSPs should not only save water without reducing crop yields, but also maintain ecological health. Those WSPs have been implemented in some parts of the canal system, and the efficiency of canal water conveyance has been increased to a certain degree (SWRH-BWB, 2005). However, the complexity of the field hydrological processes in Hetao has led to many difficulties in the definition of field WSPs and their coordination with the canal conveyance (Pereira et al., 2007, 2012; Jiang et al., 2015).

Agro-hydrological complexity in the upstream irrigated areas of the river basin is caused by shallow water tables and high land fragmentation (Xu et al., 2007, 2012a). The land has been divided into small farms due to the special "farmland use rights" (i.e. household contract responsibility system) (Tan et al., 2006). This forms a small-scale, household-based individual production, resulting in a fragmented crop distribution landscape (Wu et al., 2005; Tan et al., 2006). Namely, many different crops are planted in adjacent and small plots where diverse irrigation schedules are followed. Thus, under shallow water table conditions, when some of the crops are irrigated, the groundwater system provides the pathway for the movement of the excess water from the irrigated plots to the adjacent non-irrigated lands. As a result, the excess water can be re-consumed by soil evaporation and vegetation uptake through capillary rise (Konukcu et al., 2006), which can also lead to salinity buildup in non-irrigated areas. In the last several decades, the effects of shallow water tables on water use and crop growth have been extensively researched worldwide. It has been well known that the fate of water and solute and the plant growth has close relationships with the groundwater depth (Kang et al., 2001; Zhu et al., 2009), the nature of vadose zone (Grismer and Gates, 1988), planted crops (Kahlown et al., 2005), irrigation management (Askri et al., 2014) and salinity conditions (Ghamarnia and Jalili, 2014). These studies were generally carried out with the lysimeter or field experiments, while the simulation model is often adopted for analysis and prediction as well. When reviewing the previous studies, it is presented that many studies are focus on a single crop (Soppe and Ayars, 2003; Xu et al., 2013; Askri et al., 2014), and some studies also researched on several different crops while most either in different periods or in different individual fields (Ayars et al., 2006; Pereira et al., 2007; Jiménez-Martínez et al., 2009; Wang et al., 2011). While on a larger regional scale, the distributed modeling has become the dominant approach, which could synthetically consider the spatial variability of soil, crop, water level and climate. Many previous studies have applied this approach to evaluate the system behaviors and water productivity in different areas worldwide (Kite, 2000; Wesseling and feddes, 2006; Singh et al., 2006; Jiang et al., 2015). It also should be note that the distributed modeling primarily focuses on the regional problems, and thus tends to ignore or simplified some agro-hydrological processes among fields that may be very important such as in Hetao (Singh et al., 2006; Bormann and Diekkrüger, 2003; Hao et al., 2015). To our knowledge, there are few reported studies that simultaneously consider the factors of fragmented crops, different irrigation schedules and the lateral groundwater exchange in an irrigation system, particularly for the researches in the upper Yellow River basin (Wang et al., 2004; Pereira et al., 2007; Xu et al., 2013). Yet, these factors are essential to be considered for reflecting the actual field conditions and water use in the canal irrigation systems in Hetao. In order to accurately understand agro-hydrological processes at