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Modeling and assessing agro-hydrological processes and irrigation water saving in the middle Heihe River basin

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ABSTRACT

Water use conflicts between agriculture and ecosystem have become a more severe and acute problem in the Heihe River basin (HRB). Excessive irrigation water use in the middle oasis of the HRB has caused gradual deterioration of water quality and eco-environment both in middle and lower HRB. The urgent issue is to make a quantitative analysis and an improvement of irrigation water use in middle oasis. In this paper, distributed agro-hydrological modeling was conducted to access the irrigation water use and potential water-saving in the major irrigation system of middle HRB (MOIS), using the GIS-based SWAP-EPIC model. The modeling work was based on the abundant data from field experiments, remote sensing, surveys and statistics, and previous eco-hydrological studies. The reliability of the distributed simulation was evaluated using the remote sensing data of actual evapotranspiration (ET_a). Then, spatial distribution of irrigation water depth, ET_a, deep percolation and crop yield and the related impact factors were systematically analyzed in MOIS. Results indicated that only 53% of total applied water was efficiently used through ET_a, whereas deep percolation loss and canal conveyance loss accounted for 22% and 25% of the total applied water, respectively. The beneficial water use fraction was still low in MOIS, averaging only 0.70 on field scale and 0.52 on district scale. Water-saving analysis predicted that 15% of irrigation amount could be saved efficiently, with especial emphasis on the rational water allocation and distribution. In addition, our results related to agro-hydrological processes could provide very valuable information for improving the existing watershed hydrological modeling in the HRB.

1. Introduction

Water scarcity and water use conflicts are extremely serious in many inland river basins with heavily irrigated agriculture and fragile ecosystems (Ji et al., 2006; White et al., 2014; Cheng et al., 2014). Efficient use of agricultural water is a priority for local social-economic development and ecological security (Thevs et al., 2015). The Heihe River basin (HRB), the second largest inland river basin in China, is such a typical region located in the arid northwest China. The main river (i.e. Heihe River) originates in Qilian Mountain, and enters the middle artificial oasis through Yingluo Gorge, and finally discharges into the downstream area of Gobi Desert after Zhengyi Gorge (Fig. 1). Both the agricultural irrigation in middle oasis and the fragile ecosystems in downstream basin strongly depend on the Heihe River water. However, the irrigation water diversion of the middle oasis accounts for more than 80% of the river runoff at Yingluo Gorge (Zhao et al., 2010). The river runoff is thus usually inadequate to maintain the health of ecosystems in downstream HRB. Continuous deterioration of the water and eco-environment quality have occurred since 1950s (Cheng et al., 2014), typically due to groundwater level decline, natural vegetation degradation, soil desertification, and terminal lake shrinkage (Qi and Luo, 2005; Guo et al., 2009; Cheng et al., 2014).

Since 2002, the Ecological Water Diversion Project (EWDP) has been applied aiming to restore the ecosystems in downstream HRB (Ma et al., 2015). According to the EWDP, the river water allocated to middle oasis is to be significantly reduced for increasing runoff discharge. The downstream ecosystems are being gradually restored after 12 years of water reallocation (Cheng et al., 2014). Meanwhile, for adapting the reduction of river water allocation, various water-saving practices have been implemented in middle oasis. Yet, the total water use is actually not reduced in middle oasis (Shi et al., 2010), due to inappropriate land and water use and management (Jiang et al., 2015; Wu et al., 2015). More groundwater is exploited to supplement irrigation. This has resulted in a declining trend in groundwater levels (Wen

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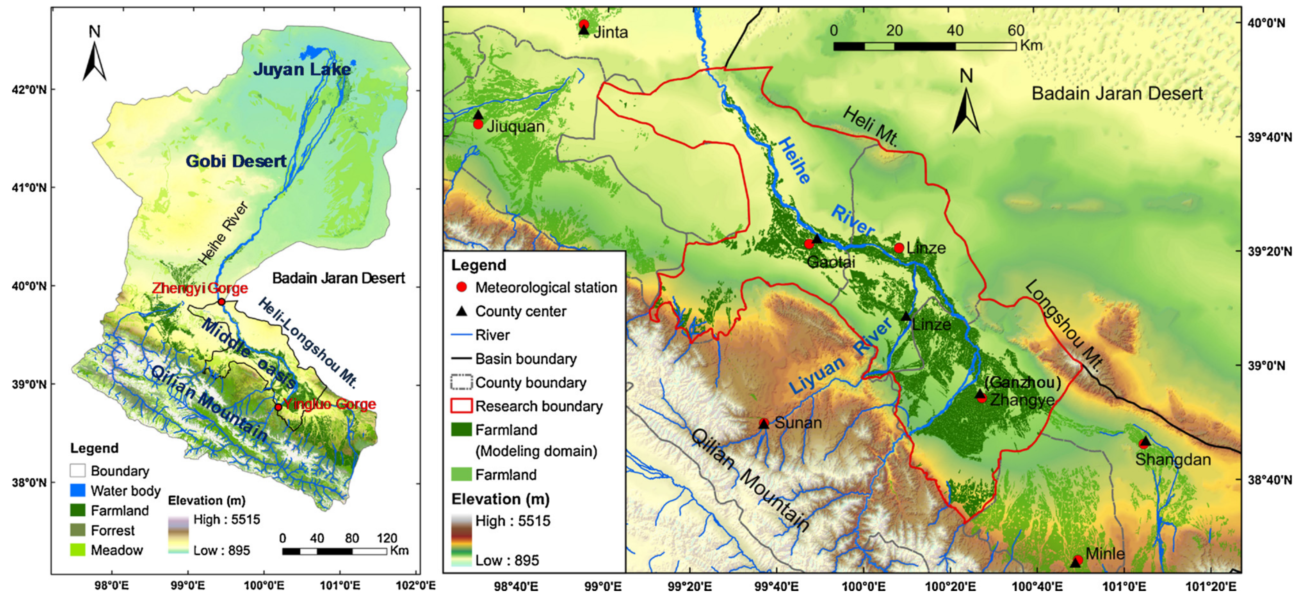

Fig. 1. The Heihe River basin and study area covering the major irrigation systems of the middle oasis (MOIS) (note: the meteorological station has the same name as the country except Zhangye).

et al., 2007; Zhou et al., 2011) and the shrinkage of wetland and grassland areas (Hu et al., 2015) in middle oasis. Therefore, how to optimize the water allocation ratio to middle oasis and increase the agricultural water use efficiency becomes the challenge to the HRB (Cheng et al., 2014). Comprehensive research concerning hydrology, ecology and economy is accordingly conducted for revealing and coordinating the complex relationship of water-ecosystem-economy in the HRB.

The ecological and hydrological studies are most extensively conducted in the HRB. For the middle oasis where surface water and groundwater interacts frequently, the quantitative research on evapotranspiration, river-runoff and groundwater dynamics are the core topics. Large improvements have been achieved during the last decade, with both the implementation of more observation networks and the adoption of advanced new techniques and innovative models. Traditional hydrological or hydrogeological models (e.g. MODFLOW, FEFLOW and SWAT) and some integrated surface water-groundwater models (e.g. GSFLOW) are both applied for simulating and analyzing surface runoff, soil water balance and groundwater dynamics (Hu et al., 2007; Zhou et al., 2011; Tian et al., 2015; Li et al., 2017; Zang et al., 2012). On the other hand, the systematic experiments and data production at different scales are carried out for better understanding the eco-hydrological processes and improving the modeling accuracy (Li et al., 2013a). These studies include: (1) various remote sensing techniques are applied for detecting the ground geographic features (e.g. land use, crop pattern, leaf area index, etc.) (Zhong et al., 2014; Zhao et al., 2015; Chen et al., 2015; Fan et al., 2015); (2) evapotranspiration data and products in different scales are obtained with eddy covariance, large-aperture scintillometer and satellite image (Liu et al., 2011; Hu and Jia, 2015; Xiong et al., 2015; Lian and Huang, 2015); (3) isotope tracing is used to quantify the sources and composition of river-runoff (Zhang et al., 2009); (4) sampling analysis related to soils, plants and waters are widely carried out as well. Overall, the integrated eco-hydrological studies related to the interaction of water, soil, vegetation and atmosphere have become a hot spot at present (Li et al., 2013b; Yang et al., 2015; Gao et al., 2016; Ma et al., 2015). However, with further research, it is increasingly recognized that the agricultural water use in middle oasis is still not well understood, although it is so significant for water cycle and water management both in middle oasis and the HRB. Some previous research, referring to agricultural water issues (Su et al., 2007; Jiang et al., 2015, 2016; Ge et al., 2013), is mostly implemented on a farmland or a local regional scale while rarely on an oasis scale. This may be primarily due to the difficulties in availability of large datasets for considering the spatial variance of soil, irrigation, crop pattern, etc. Also, the previous hydrological modeling generally adopts a simplified manner to conceptualize the irrigation effects in middle oasis (e.g. Tian et al., 2015; Zhou et al., 2011; Zang et al., 2012). However, massive important spatial distributed data and observed data of middle HRB have become available due to the supports of above-mentioned extensive research in recent years. This makes it practicable to simulate the complicated agro-hydrological processes on an oasis scale.

In addition, the efficiency analysis related to multiple scales and users is the prerequisite to realize reasonable water use (van Halsema and Vincent, 2012; Nair et al., 2013). For irrigation systems, it is commonly applied to each irrigation sub-system of storage, conveyance, off- and on farm distribution, and on-farm application (Bos and Nugteren, 1990). Different terms have been proposed and used since 1950s, such as the classical *irrigation efficiency* (IE) (Israelson, 1950), three efficiency terms (i.e. conveyance efficiency, distribution efficiency and field application efficiency) formulated by the ICID/ILRI (Bos and Nugteren, 1990), and some adapted IE (e.g. *effective irrigation efficiency* and *irrigation sagacity*) (Keller and Keller, 1995; Solomon and Burt, 1999). Moreover, the improvement of local efficiencies generally cannot represent a reduction of water losses and an increase of efficiency within a larger system or in river basins, since the waste or non-consumed water could be reused somewhere (Molden et al., 2007; van Halsema and Vincent, 2012). Recently, some irrigation scientists point out that the term efficiency often leads to misconceptions and misuse, owing to its various and confused definitions (Perry, 2007; Jensen, 2007; Pereira et al., 2012). Hence, the present trend is to apply some new indicators that use a ratio or fraction to replace the traditional efficiency terminology, which make definitions more directly refer to different water use component (e.g. consumptive and non-consumptive use, beneficial and non-beneficial use) (Foster and Perry, 2010; Pereira et al., 2012). An expected advantage of these indicators is that irrigation managers and farmers could understand them better than efficiency terms.

Therefore, the purpose of this study was to conduct a distributed agro-hydrological modeling and to assess the irrigation water use and water-saving for the major irrigation systems in the middle oasis (abbreviated as MOIS) of the Heihe River basin. The GIS-based SWAP-EPIC