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Assessment of irrigation performance and water productivity in irrigated areas of the middle Heihe River basin using a distributed agro-hydrological model

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ABSTRACT

Irrigation is essential for agriculture in the middle Heihe River basin, Northwest China, due to water scarcity and dryness of climate. The diverted river water for agriculture is being gradually reduced which requires an increased water use performance to meet crop water requirements and to maintain crop yields. It is therefore crucial to better know about the present agro-hydrological processes, irrigation performance and water productivity, and to further investigate the potential water saving on a regional scale. In this study, a distributed agro-hydrological model was developed by close coupling of an agro-hydrological model (SWAP-EPIC) and ArcInfo geographic information system. Combined effects of weather, crop, soil and irrigation factors were considered. The Yingke Irrigation District (YID), in the middle Heihe River basin, was chosen as case study, where experiments were conducted at both field and regional scales in 2012–2013. Parameters relative to soils and crops were first calibrated with field observed data and the model was later used in a distributed manner to simulate the agro-hydrological process of YID. Results showed that water productivity was spatially varied and quite small due to excessive irrigation water use. Crop evapotranspiration averaged 589 mm and deep percolation was 125 mm on average, which accounted for 21% of total irrigation. Analysis of the target scenario simulation indicated that the improvement of water conveyance and irrigation scheduling could lead to a 30% reduction of deep percolation, and save 15% of irrigation water without negative effects on crop yields.

1. Introduction

The Heihe River basin, located in arid area of Northwest China, is the second largest inland river basin of China. The middle Heihe River basin is an important food production base, where irrigation uses about 83% of the total water resource available in the basin (Zhao et al., 2010). Excessive water diversion is primarily due to the poor regulation and control of the conveyance and distribution canals and to inappropriate field irrigation practices. Meanwhile, the downstream areas are facing increasingly serious ecological challenges, e.g., degradation of lacustrine ecosystems, demise of large tracts of vegetation, and desertification of land due to less water allocation (Feng et al., 2004). In recent decades, water scarcity and water conflicts are increasing due to water environment degradation and the growing demand for water (Qi and Luo, 2005), which leads to the reduction of water allocation for agriculture in the middle oasis. According to the plans of the Heihe River Water Conservancy Commission, the amount of irrigation water diverted to the middle oasis will be gradually reduced from 900 to 600 million m^3. The total volume of water resources is reduced to about 1190 m^3 per person in the middle oasis, which is only 57% of the national average (Shi et al., 2011). Thus, water-saving practices (WSPs) on both the district scale and the farm level are essential. The implementation of WSPs requires not only to save water but also to ensure better yields, especially in this low income area. Therefore, it is crucial to understand and regulate the agro-hydrological processes on a regional scale, including soil water dynamics, crop growth, deep percolation and water productivity (WP).

Field experiments have been widely conducted to quantify water management practices in irrigation systems. However

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experiments are expensive, time consuming and site specific. Thus simulation models were developed to support irrigation management (Liu et al., 1998; Kroes and van Dam, 2003; Steduto et al., 2009). Models can simulate the complex processes of water and solute transport coupled with crop growth. They also allow scenario analysis that permit to explore more efficient ways of crop and water management under different hydrological conditions (Ramos et al., 2011). Traditionally, these models are considered as point-scale models and are not commonly used for larger areas (Droogers et al., 2000). Studies focusing on plot and field scale may not reasonably reflect the actual conditions due to the spatial differences at regional scale. The regional hydrological processes are complex and diverse because of the spatial variability of soil, crop, weather, groundwater, irrigation and management practices. The results from typical field experiments or simulation models, taken as the result of an entire region, often lead to discrepancies with the actual situations. For regional scale issues, different approaches have been brought up to simulate the geo-hydrological processes such as lumped modeling, stochastic modeling and distributed modeling (Chen et al., 2005; Xu et al., 2010; Shah et al., 2011). The advantage of distributed modeling is that it could synthetically consider the spatial variability of soil, crop and climate on a regional scale, and provide detailed insights into the system behavior. Recently, the concept of distributed modeling becomes dominant when based on geographic information systems (GIS), and can be used for simulation of agro-ecosystems on regional scale. There are a few previous studies of spatial simulation modeling, which are related to different issues, e.g., agro-hydrological process, irrigation water optimization, crop water productivity analysis, distributed ecosystem simulation (Singh et al., 2006; Ines et al., 2006; van der Knijff et al., 2010; Noory et al., 2011). Distributed hydrological models like SWAT (Arnold et al., 1993) and AGNPS (Young et al., 1989) have also been widely used at watershed and basin scale. To our knowledge, previous studies in the middle oasis of the Heihe River basin concentrated on plot or field scale (Zhao et al., 2010; Li et al., 2012). Some researches related to regional issues mainly focus on the large basin scale (Wang et al., 2007; Jia et al., 2009), where the agro-hydrological processes in irrigated areas are usually oversimplified. Thus, in this study, the agro-hydrological processes are to be simulated with appropriate detail in a typical irrigation district of the middle Heihe oasis, on the basis of a distributed agro-hydrological model using observation experiments at regional scale.

In view of previous studies, strategies for GIS and model integration can be categorized as loose coupling, close coupling and embedded coupling (Tim, 1996; Fortes et al., 2005; Li et al., 2007). In loose coupling, the software packages to be linked are kept as independent systems, and the data transfer is performed through input/output model pre-defined files. The advantage of loose coupling is that it eases future changes of the model, but it is too much time-consuming for data processing. In close coupling, GIS data is exported to the model and GIS tools can interactively access input model subroutines; thus, data exchange is fully automatic, while it is also easy to make changes in the linkage with GIS when there are model changes or a new module is added. When a model is created using the GIS programming language, or when a simple GIS is assimilated by a complex modeling system, then the embedded coupling is used. Contrary to other coupling methods, embedded coupling requires a significant investment in programming and data management. Both approaches impose more constraints when changes are needed (Gogu et al., 2001; Li et al., 2007). Considering the above information, the close coupling was selected for linkage between an agro-hydrological model and ArcInfo GIS in this study.

Taking into account the considerations above, this paper aims at establishing a distributed agro-hydrological model and assessing the irrigation performance, water productivity and water saving ability in the middle oasis of the Heihe River basin on a regional scale. In this study, the Yingke Irrigation District (YID) in the middle Heihe River basin was selected as the case study area because of its good representativeness of irrigation management and cropping pattern and because former studies and adequate data at regional scale were available. The observation experiments related to soil, crop and irrigation were conducted on both farm and district scales. The Soil-Water-Atmosphere-Plant model, SWAP (Kroes and van Dam, 2003) embedded with the crop growth model EPIC (Williams et al., 1989), named SWAP-EPIC, was selected for the simulation of agro-hydrological processes in this study. The SWAP-EPIC was closely coupled with ArcInfo GIS using programs of Visual Basic Application (VBA). It was extended in a distributed manner for simulation with consideration of the combination of weather-crop-soil-irrigation in YID. Finally, the distributed model was used to assess the present irrigation performance and WP, and to investigate the water saving ability for YID when adopting improved management at canal and field scales. The ultimate objectives of this study are to provide recommendations for the reasonable agricultural water use and further implementation of water management practices in irrigation districts of the middle Heihe River basin.

2. Materials and methods

2.1. Study area

The YID, located in the arid middle reaches of the Heihe River basin, northwest China (38°50′–38°58′N, 100°17′–100°34′ E), is the third largest irrigation district of the middle oasis region (Fig. 1). It covers an area of 19,200 ha, 68% of which (13,147 ha) is irrigated land. YID comprises six townships (including seventy-four villages) with 106,000 people, mostly farmers and rural people. It is part of an alluvial or proluvial plain, with elevations varying from 1450 to 1600 m above sea level. The soil texture varies from sandy to loamy. The soil physical properties for 0–140 cm depth are provided in Table 1. The winter flood irrigation (with about 200 mm depth) is always applied to leach salts and to store soil water for next season. The groundwater depth is large and the soil does not show salinity problems during the crop growth period in most parts of YID. The electrical conductivity of a saturated soil paste extract (i.e. EC_e) ranges from 1.5 to 4.0 $dS\,m^{-1}$ as reported by Zhang et al. (2006). The main crops are corn and spring wheat, with their cropped area accounting for 83% of total crop area; commercial crops account for 15% of the area. There are also small areas with grass and other plants in YID.

The study area has a typically cold, arid continental climate. The cold dry winter and hot summer are long while the spring and autumn are short, windy and rainless. The annual mean temperature is 6.5–7.0 °C with a minimum of −28 °C and a maximum of 33.5 °C. The average annual precipitation in YID is small, averaging 125 mm, with 90% of rainfall during the crops growing season (March to September). The annual reference evapotranspiration (ET_o) was computed with the PM-ET_o method (Allen et al., 1998) and is around 1200 mm, which changes little in YID. Compared with the spatial variability of soil water, crop and irrigation, the changes of ET_o and rainfall data have small effect on regional simulation in YID. Annual sunshine hours are about 3000 h, and the frost free period lasts 140 days per year.

YID has an extensive canal network consisting of a main canal, 2 sub-main canals and 27 secondary canals with more than 1000 distributors (Fig. 1). The network is served by the Yingke main canal, which directly diverts water from the Heihe River. The main, secondary and 70% of tertiary canals are lined, and the hydraulic construction is also re-updated since 2002. The river water has a