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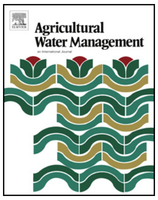

Research paper

Water saving practices enhance regional efficiency of water consumption and water productivity in an arid agricultural area with shallow groundwater

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ABSTRACT

Improving the efficiency of water consumption and water productivity is the key approach to satisfy sustainable water resource supply and food demand. As effective measures, water saving practices are implemented in arid and semi-arid regions. For areas with shallow groundwater, water used for irrigation is not entirely consumptively used. The majority of irrigation water infiltrations below the root zone are stored in shallow groundwater. This can be reused as groundwater based evapotranspiration (ET_g) at the regional scale. Thus, actual regional efficiency of water consumption (REWC) based on all water within the hydrological system is greater than based on consumptive use only. Accurately evaluating the response of REWC and regional water productivity (RWP) to water saving practices is essential due to the complexity of the hydrological system. In this study, regional ET_g and regional evapotranspiration (ET) of the past 20 years were reproduced in a typical arid irrigation district with shallow groundwater based on the water balance method. Furthermore, REWC and RWP were estimated to investigate the impact of water saving practices to regional water use. Simulation results show that groundwater is a significant water source of regional ET in arid regions with a shallow aquifer and contributes more than 16% of regional ET for the irrigation district. Water saving practice implementation enhances the contribution of groundwater to ET. After water saving practices implementation, annual REWC and RWP have been improved by 0.07 and 0.1 kg/m^3, respectively. Furthermore, negative correlation between REWC and I + P (the total water supply including rainfall and irrigation water diversion) and positive correlation between RWP and REWC demonstrate that water saving practices can reduce the non-beneficial water losses by evaporation and enhance productivity by a lower groundwater table. Overall, shallow groundwater plays an important role to enhance REWC and RWP and the contribution of groundwater to regional water use needs to be considered as part of a reasonable water saving strategy towards a sustainable agricultural system.

1. Introduction

Water scarcity is challenging the sustainability of conventional agricultural irrigation globally. Fiftyfour percent of the agricultural area in developing countries is located in arid and semi-arid regions with one-third of its rural population living in these areas (Rijsberman, 2010; Vörösmarty et al., 2000). Irrigation becomes essential to agricultural production because precipitation is not sufficient to meet crop water requirements in these areas. In some cases, the excessive use of water resources has led to some negative effects such as soil salinization and ecological degradation. For example, unsustainable use of groundwater in places like the North China Plain, Ganges Plain and Indus Plain makes regionally declining groundwater levels a major concern globally (Clemmens and Allen, 2005; Feng and Li, 2005; Jhorar et al., 2009). Poor water management and decreasing water resources in some arid regions require water saving practices to make agricultural irrigation sustainable (Gonçalves et al., 2007; Han et al., 2011; Pereira et al., 2007). Besides, to satisfy increasing water and food demands, it has been a top priority to the improve efficiency of water consumption (EWC) and water productivity (WP), which are basically two different terms (Heydari, 2014; Lamaddalena et al., 2005; Perry et al.,

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2009; Wang et al., 2015). The former is the ratio of crop actual evapotranspiration and total water supply, which is different from water use efficiency (WUE) (Chun et al., 2011; Prior et al., 2010). The latter refers to crop production in relation to total water consumed. Water saving management practices, such as reduced irrigation water diversion, and canal concrete lining, have been implemented to increase EWC and WP in arid and semi-arid areas.

In some arid and semi-arid irrigation areas, intensive irrigation (some of which recharged the groundwater) may cause shallow groundwater table depths (e.g., <2 m). Water cycling in arid regions with shallow groundwater is complex, especially when deep percolation is stored in groundwater and reused by the crop through groundwater based evapotranspiration (ET_g). ET_g contributes to supplying water for crop and natural ecosystems, and regional evapotranspiration (ET) is enhanced by an upward capillary flux (Wang et al., 2016). Fluctuation of a shallow groundwater table significantly impacts the water balance (Cui and Shao, 2005). Many researchers have quantified the contribution of ET_g at the field scale with lysimeter experiments (Huo et al., 2012a), field observation (Gao et al., 2015) and process models (Huo et al., 2012b). Recently, Wang et al. (2016) developed a method to estimate ET_g for farmland, and some studies have attempted to understand the exchange between groundwater, irrigation, ET at the regional scale (Peña-arancibia et al., 2015; Xu et al., 2010; Yue et al., 2016).

Water saving practices can change the water cycle and crop water use at the regional scale (Liu et al., 2016; Yang et al., 2005). Pereira et al. (2007) indicated that lining canals, reducing water diversion and leveling farmland reduced groundwater recharge and thus lowered groundwater tables in an irrigation district with shallow groundwater. Liu et al. (2016) calculated ET and ET_g of farmland and found agricultural water saving can enhance the contribution of groundwater to ET. Meanwhile, water saving practices can change EWC and WP (Deng et al., 2006). Due to ET enhanced by ET_g in arid regions with shallow groundwater, the efficiency of water consumption is actually greater than in the case of what we conventionally consider "used up" water when deep percolation water cannot be reused (Lankford, 2006). Seckler et al. (2003) reported that the most commonly used concepts of the efficiency of water consumption inevitably underestimate the actual efficiency of the hydrological system by a very large amount. Many researchers have studied how EWC and WP respond to agricultural water saving at the field scale (Gowing et al., 2009; Igbadun et al., 2008; Karam et al., 2007; Rao et al., 2016; Zhou, 2009). However, it is difficult to quantify how many percent of total water supply can eventually be used efficiently at a regional scale and how many productions can be obtained due to the complex water exchange and spatial differences of crop type and growth. Mcvicar (2002) assessed regional water productivity for corn and wheat on the North China plain. A few researchers used remote sensing method to evaluate regional efficiency of water use (Awan and Martius, 2008; Huang et al., 2012). However, remote sensing only provides instantaneous estimates and remote sensing data continuity is highly dependent on weather conditions, thus uncertainty can be large. A simple water balance method over large areas provides a good alternative to avoid these problems including full consideration of its inner hydrological cycle processes and associated parameters.

This study extends previous studies on regional efficiency of water consumption (REWC) and regional water productivity (RWP) by assessing these indices under the impacts of regional water saving practices based on the water balance method. REWC is defined as the ratio of regional evapotranspiration and the total water supply including rainfall and irrigation water diversion, as follows:

$$REWC = \frac{ET}{I+P} \tag{1}$$

where $REWC$ [−] is the regional efficiency of water consumption, ET [L^3T^{-1}] is the regional evapotranspiration, I [L^3T^{-1}] is the total irrigation water amount, P [L^3T^{-1}] is the effective precipitation amount.

RWP is defined as the ratio of regional total grain yield Y_t and the regional evapotranspiration, as follows:

$$RWP = \frac{Y_t}{ET} \tag{2}$$

where, RWP [ML^{-3}] is the regional water productivity, Y_t [M] is the total irrigation water amount.

A typical arid irrigation district with shallow groundwater was selected as the study area. Based on a long term water balance, and water use and crop production analysis, the specific objectives of this study are to (1) determine long term water budget (especially ET_g and ET) changes in the irrigation district under water saving practices; and (2) examine how REWC and RWP respond to water saving practices.

2. Materials and methods

2.1. The study area and data collection

2.1.1. The study area

The Hetao Irrigation District (HID), located in the upper reaches of the Yellow River in Inner Mongolia, is one of the three largest irrigation districts in China. It has a typically arid and semi-arid continental climate with annual rainfall of less than 200 mm (Fig. 1). The HID covers an area of 1.12×10^4 km^2 and is a significant food production base in China. The district has been fed with diverted water from the Yellow river and the annual irrigation water diverted is about 5×10^3 Gl. The groundwater table in the HID has become very shallow (1.5–3.0 m) with long-term recharge from irrigation infiltration and canal seepage. With increasing water and food demands and rapid economic growth in the entire Yellow River basin, the Yellow River Water Conservation Commission (YRWCC) has implemented a water saving policy since 1998. So, water saving measures have become a common strategy to alleviate the regional scale water scarcity in this region (Blanke et al., 2007; Chen et al., 2003; Goncalves et al., 2007; Pereira et al., 2003).

Jiefangzha irrigation sub-district (JFISD) is the second largest sub-district of the HID and covers an area of 2157 km^2, of which 66% is irrigated land for agricultural purposes. The topography in the JFISD is very flat with a 0.02% slope. Meteorological data are collected from the Hangjinghouqi weather station and available for the period of 1986–2009. Mean annual precipitation is only 155 mm (70% occurs between July to September) and mean annual pan evaporation is greater than 2000 mm. The mean annual temperature is 7 °C, with a mean monthly minimum of −10.1 °C in January and a maximum of 23.8 °C in July. Soils in the JFISD are primarily silt loam and sandy loam. Wheat, maize, sunflower and sugar beets are the main crops and only one crop a year is taken in this region. Water saving practices (e.g., canal lining, irrigation technology upgrades, farmland leveling) in the JFISD have changed regional water supply and water consumption with positive and negative effects on agriculture in the area. Under this policy, water diversion from the Yellow River has decreased since 2000, and the amount of water diversion has been increased again during the period of 2005–2009 because of drought and the need for improving crop production (Xu et al., 2010). The groundwater table has declined gradually during the period of 2000–2009 due to the implementation of water saving practices such as reduced water diversion and canal lining.

2.1.2. Data collection and analysis