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Impact of agricultural water-saving practices on regional evapotranspiration: The role of groundwater in sustainable agriculture in arid and semi-arid areas

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ABSTRACT

Evapotranspiration (*ET*) is an important component of the water budget process and is characterized by complex spatiotemporal changes, especially in irrigated agricultural areas. The impact of various hydrological processes and human activities on *ET* is still a meaty theme to study and investigate. A typical agricultural irrigation district with shallow groundwater and arid climate conditions was selected as the case study area in this work. The impact of the supplied irrigation water, shallow groundwater, crop planting pattern, and weather conditions on regional *ET* was determined after the regional *ET* was estimated by a Surface Energy Balance Algorithm of Land (SEBAL) model with Moderate Resolution Imaging Spectroratiometer (MODIS) data. The results show that the regional *ET* in Hetao kept declining in the past 15 years. The positive correlation between the water input (water diversion and precipitation) and *ET* indicated that reduced water diversion controls the declining *ET*, also causing the drop of groundwater level. Due to capillary forces and root uptake, the shallow groundwater tended to move upward to support the crop water consumption because the soil suffered from a water deficit. Furthermore, we quantified the contribution of shallow groundwater to regional *ET* and found that the water supplied from shallow groundwater increased from 5% to 15% during the period of water–saving irrigation. However, the long–term decrease of irrigation water supply and groundwater level caused a soil water deficit over the crop growth period, and the variation of crop planting pattern reduced *ET* as well. Therefore, groundwater plays an important role in sustainable agricultural development in arid and semiarid areas and the contribution of shallow groundwater to regional water consumption cannot be neglected.

1. Introduction

Evapotranspiration (*ET*) isan important part of regional or watershed water budgets. Understanding the spatial and temporal *ET* change is foundation for regional water resource management, especially in arid and semiarid areas. However, assessing the *ET* change in agricultural irrigation areas is still a huge challenge due to complex water cycle processes driven by irrigation and shallow groundwater. On one hand, traditional irrigation strategies have been improved by application of water-saving measures (WSM) for sustainable water use in arid and semiarid areas worldwide to cope with the water shortage in agricultural development (Zhang et al., 2011). On the other hand, excessive agricultural water-saving will cause the groundwater to decline because the implementation of WSM is primarily responsible for the reduction of the seepage losses of irrigation water (Zhang et al., 2012). Supplied irrigation water will directly change the soil water deficit and induce a field *ET* change (Fig. 1). When the shallow groundwater is supplied from the infiltration of large amount of irrigation, less groundwater is consumed by evaporation because of the sufficient soil water. When the soil water deficit caused by a decreasing water supply negatively influences the regional *ET*, more of shallow groundwater moves upward to support the crop water consumption. Previous studies have proven that groundwater plays an important role in compensating for the high water consumption (*ET*) and the reduction of *ET* can be attributed to the decline of groundwater level (Liu et al., 2016; Balugani et al., 2017; Gao et al., 2017a, b; Jiang et al., 2017; Ramos et al., 2017;

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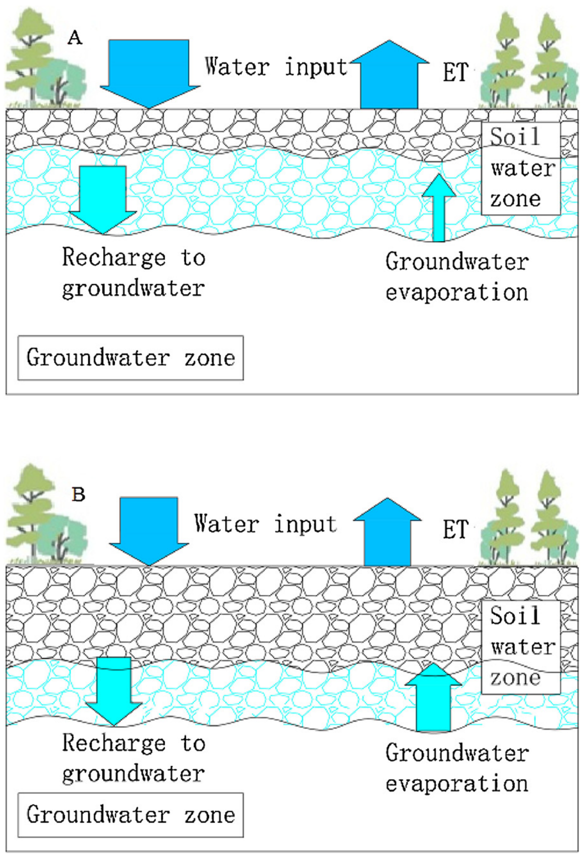

Fig. 1. Water cycle between surface water and groundwater.

Satchithananantham et al., 2017; Wang et al., 2016; Yang et al., 2017a, b). Both the WSM and groundwater decrease will therefore affect the *ET*.

Many studies focused on the impact of water-saving irrigation and groundwater on *ET*. By designing irrigation levels according to soil water content as a percentage of field capacity, Ran et al. (2017) found that *ET* under irrigation amount being 60%–55% and 50%–45% of field capacity decreased by 14% and 28.1% respectively, compared with *ET* under irrigation level of 70%–65%. Based on the application of WSM, the mean annual *ET* decreased from 752 mm to 610 mm in the North China Plain (Pei et al., 2017). Meanwhile, the soil water storage decreases with decreasing water input and groundwater level (Zdenek et al., 2017; Greaves and Wang, 2017; Alrajhi et al., 2017; Kisekka et al., 2017). As the shallow groundwater declined excessively, water deficit-induced stress negatively affected *ET* (Luo and Sophocleous, 2010). By conducting field experiments with different water treatments, Kirnak et al. (2002) observed that the soil water remained higher during full irrigation treatment and experienced less stress than using deficit irrigation. Based on a long–term field observation data, Liu et al. (2016) found that the soil moisture decreased significantly as the groundwater depth increased from near the ground surface to 2.5 m below the surface. Gao et al. (2017a, b) reached similar results using a process-based model.

Compared with scare surface water resources, shallow groundwater is essential for the maintenance of the high *ET* in arid and semiarid areas (Sepaskhah et al., 2003; Namuburg et al., 2005; Ghamarnia et al., 2013; Wang et al., 2014a; Wang et al., 2016). Previous studies confirm that the capillary upward movement of shallow groundwater by soil suction and root uptake can meet the water deficit when the soil moisture is insufficient to meet the crop water demand (Xue et al., 2017; Jorenush and Sepaskhah, 2003; Shouse et al., 2010; Wang et al., 2016). Soppe and Ayars (2003) showed that 40% of the daily crop water use originated from groundwater on the west side of the San Joaquin Valley with shallow groundwater (< 1.5 m). Coincidentally, Cohen et al. (2006) proved that groundwater–supported *ET* accountd for as much as 12% of the total *ET* in a watershed of Minnesota. In addition to the irrigation water and groundwater, the long–term regional *ET* change also depends on the variation of the crop pattern considering the fact that the water consumption varies depending on the crop variety (Yang et al., 2017c; Yang et al., 2018; Bai et al., 2017).

Note that previous research about the influences on *ET* highly depending on field observations was limited to point or field scales (Kang et al., 2003; González–Altozano et al., 2008; Zhang et al., 2008; Zeppel et al., 2009; Wylie, 2003). Recently, the development of remote sensing techniques (RS) provided an effective way to understanding *ET* change at the regional scale. Based on the surface energy balance equation, the Surface Energy Balance Algorithm of Land (SEBAL) model has been successfully tested, it performs well with respect to in *situ* measurements and catchment hydrologic models in many regions (Allen et al., 2007; Li et al., 2008; Chang et al., 2017; Bastiaanssen et al., 2005; Lee and Kim, 2016; Bala et al., 2015; Bastiaanssen et al., 2010). Various RS–based–*ET* models have been developed over the past decades to study *ET* (Mu et al., 2011; Miralles et al., 2011; Norman et al., 1995).

To study the variation of *ET* and impact factors at a regional scale, the SEBAL model has been applied to estimate the *ET* in a typical irrigation district over the past 15 years. The main objectives of this study are: (1) to clarify the spatial and temporal variation of *ET* under water–saving irrigation conditions, (2) to assess the variation of the groundwater contribution to *ET*, and (3) to evaluate the long–term soil water deficit at the regional scale.

2. Material and methods

2.1. Study area

The Hetao Irrigation District (HID), located in the upstream part of the Yellow River Basin in China was selected as the study area. With a total area of $11.2 \times 10^3\,km^2$, the HID is the third largest irrigation district in China (Wu et al., 2017) and includes five irrigation subdistricts: Yigan Irrigation District (YGID), Jiefangzha Irrigation District (JID), Yongji Irrigation District (YJID), Yichang Irrigation District (YCID) and Wulate Irrigation District (WID) (Fig. 2). The YGID is surrounded by the Gobi Desert and includes only one third of farmland. The farmland of the other four irrigation districts accounts for 60% of the total land area.

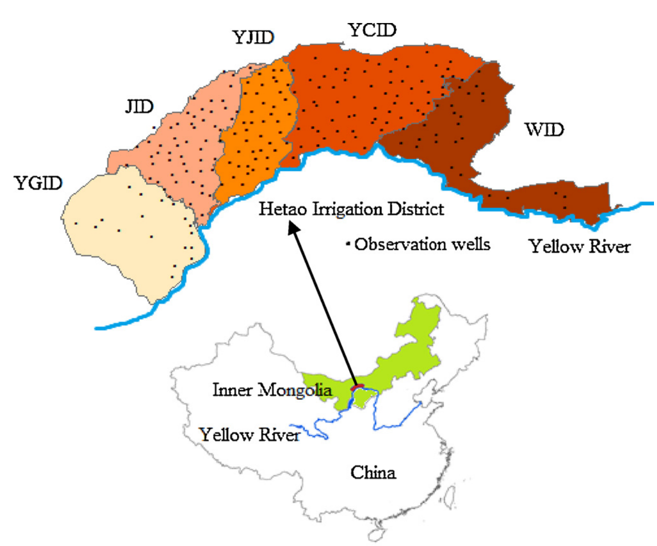

Fig. 2. Location of the study area (the solid black points reflect the distribution of the observation wells).