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Drip irrigation enhances shallow groundwater contribution to crop water consumption in an arid area

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Abstract

Shallow groundwater plays a key role in agro-hydrological processes of arid areas. Groundwater often supplies a necessary part of the water requirement of crops and surrounding native vegetation, such as groundwater-dependent ecosystems. However, the impact of water-saving irrigation on cropland water balance, such as the contribution of shallow groundwater to field evapotranspiration, requires further investigation. Increased understanding of quantitative evaluation of field-scale water productivity under different irrigation methods aids policy and decision-making. In this study, high-resolution water table depth and soil water content in field maize were monitored under conditions of flood irrigation (FI) and drip irrigation (DI), respectively. Groundwater evapotranspiration (ET_g) was estimated by the combination of the water table fluctuation method and an empirical groundwater–soil–atmosphere continuum model. The results indicate that daily ET_g at different growth stages varies under the two irrigation methods. Between two consecutive irrigation events of the FI site, daily ET_g rate increases from zero to greater than that of the DI site. Maize under DI steadily consumes more groundwater than FI, accounting for 16.4% and 14.5% of ET_a, respectively. Overall, FI recharges groundwater, whereas DI extracts water from shallow groundwater. The yield under DI increases compared with that under FI, with less ET_a (526 mm) compared with FI (578 mm), and irrigation water productivity improves from 3.51 kg m^{-3} (FI) to 4.58 kg m^{-3} (DI) through reducing deep drainage and soil evaporation by DI. These results highlight the critical role of irrigation method and groundwater on crop water consumption and productivity. This study provides important information to aid the development of agricultural irrigation schemes in arid areas with shallow groundwater.

KEYWORDS

evapotranspiration, groundwater-dependent ecosystems, maize growth

1 | INTRODUCTION

With nearly 70% of withdrawals worldwide (Food and Agriculture Organization, 2014), agriculture is the largest user of water. Water-saving agriculture is one of the key issues for any place with water resources shortage. In many areas around the world, such as riparian zone of streams, wetland areas, and cropland accessing river water for irrigation, shallow groundwater occurs (Babajimopoulos et al., 2007). Groundwater evapotranspiration (ET_g) contributes to a significant portion of crop water requirements (Kahlown, Ashraf, & Zia ul, 2005; Luo & Marios, 2010; Wu, Liu, Paredes, Duan, & Pereira, 2015). Thus, ET_g should be included in cropland water balance analysis.

The contribution of groundwater in meeting water requirements for crops, such as wheat, sugarcane, maize, sorghum, berseem, and sunflower, has been investigated using lysimeters (Kahlown et al., 2005; Wang, Huo, et al., 2016). The results show that the allocation of irrigation supplies, especially in areas where groundwater is shallow, needs to be modified to improve the efficiency of water use and to maintain an optimal depth to groundwater. In addition, nearby native groundwater-dependent ecosystems might be influenced by changes in groundwater depth as a result of irrigation extracted from either streams or groundwater (Barron et al., 2014; Elmore, Mustard, & Manning, 2003). In the San Joaquin Valley of America, large-scale irrigation occurs, which lacks drainage-water disposal facilities, and results in severe salinity and land retirement (Hanson, May, Šimůnek, Hopmans, & Hutmacher, 2009). In Australia, soil salinization impacts the natural vegetation creating poor health and death in relation to changes of the surface water regime of the River Murray, which alters groundwater–surface water interactions (Doody, Holland, Benyon, & Jolly, 2009; Jolly, Walker, & Thorburn, 1993). Faced with reductions in stream water availability, introduced vegetation is often removed from within riparian areas in Australia and the United States, in order to return water to streams (Doody et al., 2011; Doody, Benyon, Theiveyanathan, Koul, & Stewart, 2014). Therefore, monitoring use of shallow groundwater and increasing water use efficiency are of significant importance for water resources and vegetation condition in arid and semi-arid areas globally.

Traditional flood irrigation (FI) has been commonly applied due to its low capital cost in comparison with more advanced irrigation methods. As a result of excess deep drainage, inefficient water use and secondary salinization may occur (Hanson et al., 2009; Jolly et al., 1993; Karimov, Šimůnek, Hanjra, Avliyakulov, & Forkutsa, 2014). This calls for better irrigation practices to deliver appropriate water quantities for crops (Reyes-Cabrera, Zotarelli, Dukes, Rowland, & Sargent, 2016) and to improve agricultural water productivity (Sampathkumar, Pandian, Rangaswamy, Manickasundaram, & Jeyakumar, 2013; Zwart & Bastiaanssen, 2004). As one of the most efficient irrigation methods, drip irrigation (DI) effectively controls water supply with a reduction of soil evaporation and excessive deep drainage, while providing a reliable and regulated plant water source. Moreover, DI offers an opportunity to inject soluble fertilizers, allowing nutrients to quickly reach the root zone and be retained for prolonged periods (Burt, 1998; Lamm et al., 2011). It seems obvious that DI uses less water than FI and improves irrigation water productivity (IWP). It is surprising that few studies have quantitatively compared water use between different irrigation methods (Pascual-Seva, San Bautista, López-Galarza, Maroto, & Pascual, 2014; Tl, Pang, & Li, 2009), especially in shallow groundwater areas (Kang et al., 2012; Karimov et al., 2014; Wang, Jin, Šimůnek, & van Genuchten, 2014).

Deep drainage can be greatly reduced in DI compared with FI. Thus, applications of DI help stop groundwater level rising in shallow groundwater areas, which reduces the risk of secondary salinization (Kang et al., 2012; Reyes-Cabrera et al., 2016). On a large scale, a change of irrigation practice can lead to a change of water balance of the entire irrigation region. Implementing DI in a regional climate model in Syria and Turkey decreased *ET* by 30% and irrigation water demand by 60% compared with FI (Evans & Zaitchik, 2008). Upscaling analysis in two irrigation areas in Australia indicates that considerable water could be saved depending on the type of efficient water application technologies. Potential water saving would range from 100 to 150 mm in sprinkler and up to 400 mm in DI for vineyards (Khan & Abbas, 2007). Reduced extraction from surface water and groundwater can also preserve native groundwater-dependent vegetation. Therefore, in areas where groundwater promotes the growth of vegetation or natural plants, water use efficiencies will protect and preserve the environment by reducing irrigation losses (Doody et al., 2014; Mata-González, McLendon, Martin, Trlica, & Pearce, 2012).

A quantitative understanding of the dynamic hydrological processes under different irrigation methods is required to evaluate the impacts of irrigation management changes (Babajimopoulos et al., 2007; Gao, Bai, et al., 2017; Liu et al., 2017). In an area with a shallow groundwater, the impact of ET_g can be an important component in the water balance equation. On one hand, a shallower water table likely from FI can enhance groundwater evapotranspiration; on the other hand, under more efficient irrigation (e.g., DI), crops may uptake more groundwater to supplement their water requirements. Numerous studies have investigated how ET_g supports crop water consumption based on experimental and mathematical models (Doorenbos & Pruitt, 1977; Jorenush & Sepaskhah, 2003; Wang, Huo, et al., 2016; Xu et al., 2015). However, it is not known how ET_g is quantitatively influenced by different irrigation methods.

Quantifying crop water productivity (WP) under different irrigation methods is particularly important in semi-arid and arid environments around the world, such as North-western China, Central Asia, South-eastern Australia, and Western United States. Considering many environmental benefits of DI against conventional FI, such as water saving (Evans & Zaitchik, 2008; Pascual-Seva et al., 2014; Qin et al., 2016; Reyes-Cabrera et al., 2016), reduction of greenhouse gas emission (Tian et al., 2017; Wang, Liang, et al., 2016), and fertigation improvement (Lamm et al., 2011; Wang et al., 2014), the Chinese Government aims to convert irrigation practices of 1.2 million ha cropland with DI under plastic film mulch, around four provinces in North China, thus solving the difficulty of severe agricultural water shortage (Qin et al., 2016). However, the experience from the United States suggests that it is not straightforward to convert FI to DI, primarily due to high capital cost of DI and the potential risk of salinization resulting from a reduced drainage (Tl et al., 2009). To remove this barrier, it is necessary to quantify the benefits of DI for policymakers and farmers. Quantifying the impact of alternative irrigation methods on WP and large-scale water balance is one important element to address this issue.

This study aims to investigate the hydrological influences of FI and DI in an arid area with a shallow groundwater and the consequent crop productivity. The specific objectives are (a) to investigate the response of soil water content (SWC) and water table fluctuation (WTF) under FI and surface DI methods in a shallow groundwater area; (b) to estimate ET_g under two different irrigation conditions and their contribution to ET_a, and (c) to evaluate the effects of different irrigation methods on agricultural water productivity and cropland water balance.

2 | MATERIALS AND METHODS

2.1 | Site description

The study area is in the arid upper reaches of the Yellow River, Inner Mongolia, China. As the third largest irrigation district of China, the Hetao Plain covers an area of 1.12 million ha, and about 570,000 ha of land are irrigated (Xu et al., 2015). The area has a typical arid continental climate with low rainfall and high potential evaporation. Mean annual temperature and precipitation are 6.9 °C and 142 mm, respectively. Mean annual potential evaporation is about 2,000 mm. There are about 160 frost-free days per annum and 9 sunshine hours per day. Maize and sunflower are the dominant crops growing in the Hetao Plain.

About 4.8 billion m^3 of water have been diverted from the Yellow River to irrigate the Hetao Plain per year, which is estimated to be greater than crop irrigation requirements (Xu et al., 2015; Xu, Huang, Qu, & Pereira, 2010). Water is diverted from the Yellow River through a canal system mainly used to irrigate crop fields by flooding. In order to balance water uses among different sectors to achieve better socio-economic performance in the Yellow River Basin, the amount of diverted water for irrigation is aimed to be reduced to 4.0 billion m^3 per year according to the Yellow River Water Conservancy. Therefore, DI is being widely promoted.

Long-term excessive water diversion has also resulted in shallow groundwater depth (less than 4 m) in this area (Xu et al., 2010). Large amounts of groundwater are consumed by soil evaporation and plant transpiration through capillary rise (Xu et al., 2015). It is found that more than 20% surface evapotranspiration originates from the shallow aquifer during the crop growing period in a subdomain of the Hetao Plain (Liu, Chen, Huo, Wang, & Shock, 2016).

2.2 | Field experiments

The experiment was carried out at Shuanghe of the Bayannaoer City, Inner Mongolia, in the north-west China (40°41′N, 107°18′E, 1,040 m altitude). Two crop fields were planted with spring maize (variety Ximeng 6, a widely used variety) under FI and surface DI, respectively. The two experimental sites were about 100 m apart and located in the same geomorphic and geological setting (Figure 1). The south site A (about 0.5 × 0.7 ha) was irrigated by FI. Irrigation at site B was conducted by DI (about 0.5 × 0.7 ha). Maize was sowed on May 6, and harvested on September 30, 2015. Crop plantation densities were the same between the two plots and typical to the study area. For both fields, two rows of maize (the width between the two rows was 50 cm) were covered by one sheet of 70-cm-wide plastic mulch. The drip tube between two rows of maize was covered by plastic mulch. At both sites, SWC and water table depth (WTD) were monitored in situ simultaneously.

SWC was monitored using Hydra Probe Soil Sensors (Stevens Water Monitoring System Inc., USA) installed in both treatment plots. Soil moisture was measured at 5 depths, with a 0.3-m interval from the surface to the maximal soil depth of 1.5 m. Sensors were installed below the plastic mulch fringe. The SWC reading interval was 30 min. Sensors were connected to data loggers and downloaded via wireless transmission. Calibration was conducted from the SWC using the oven drying method (Gao, Bai, et al., 2017).

WTD was measured by piezometers (HOBO Water Level Logger-U20, Onset Computer Corp, MA, USA) recorded at 0.5-hr intervals. Two observation wells (6 m PVC pipe, 9 cm diameter) containing piezometers were installed to measure WTD and monitor the effects of irrigation treatments and rainfall on groundwater level throughout the growing season. Piezometer cable length was measured before installation to obtain an accurate reading of WTD.

Soil physical properties, such as field capacity (θ_{fc}) and bulk density, were obtained from laboratory experiments using 100 cm^3 cutting rings. Soil texture at different depths was analysed by Laser Grain-size Analyzer (Table 1). The soil texture was mainly silty loam in the two experimental plots, with 70–90 cm depth having a relatively high proportion of sand. Maize growth height was measured with three fixed plants and two random plants during the growing period. The biomass of every component of maize was measured on August 9 (95 days after sowing) using the average of the five plants. Maize yield (Y, kg ha^{-1}) was derived from hand harvest and air-dry treatment.

2.3 | Methods of estimating ET_g and water balance in cropland

2.3.1 | WTF method

Effective and convenient estimate of ET_g is important for groundwater use and water-saving agriculture development in arid areas. With

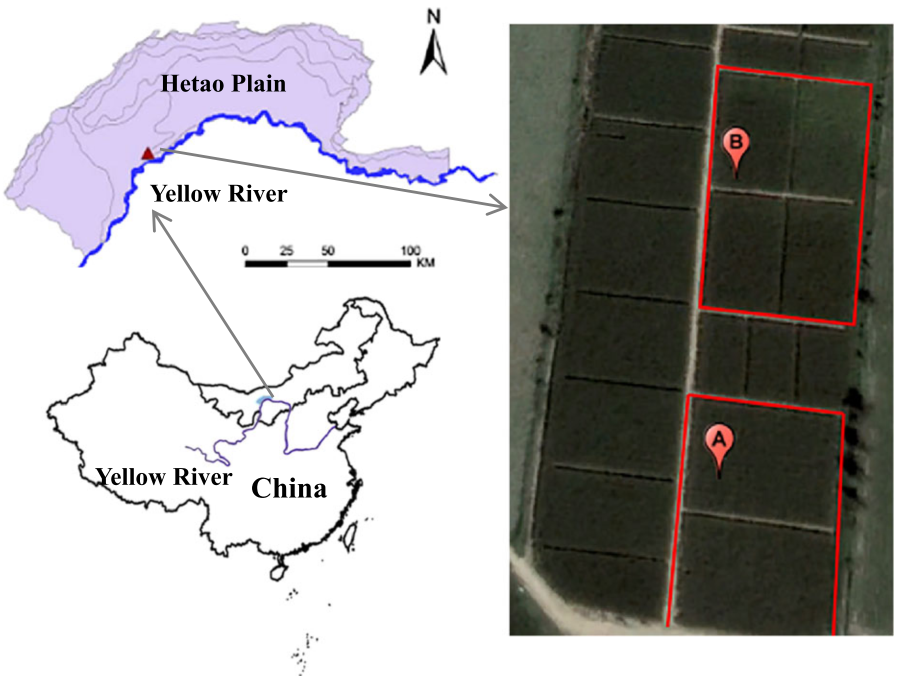

FIGURE 1 Left panel: Location of the field experiment in Hetao Plain. The blue line is the Yellow River; right panel: site A—flood irrigation and site B—drip irrigation (about 0.5 × 0.7 ha)

TABLE 1 Hydraulic characteristics of soil samples collected at selected depths

Irrigation methods	Depth (cm)	Sand 50–2,000 μm	Silt 2–50 μm	Clay 0.01–2 μm	θ_{fc} (m^3 m^{-3})	Bulk density (g cm^{-3})
FI	0–35	0.08	0.76	0.16	0.3	1.48
	35–70	0.00	0.8	0.2	0.34	1.57
	70–100	0.15	0.8	0.06	0.35	1.46
	150–170	0.12	0.79	0.09		
DI	0–30	0.04	0.84	0.11	0.32	1.36
	30–65	0.22	0.68	0.1	0.41	1.4
	65–100	0.20	0.72	0.07	0.35	1.43
	150–170	0.11	0.79	0.10		

Note. DI = drip irrigation; FI = flood irrigation.

long-term and high-resolution groundwater table fluctuation monitoring, the WTF method is recognized as simple and effective and requires only diurnal variation of WTD and specific yield. The WTF method was firstly proposed by White (1932) and was used to estimate ET_g from a hydrograph analysis of diurnal WTF (Fahle & Dietrich, 2014). The method has been used for estimating ET_g under various conditions. Apart from riparian areas where it is most applied (Shen, Gao, Fu, & Lü, 2015; White, 1932), several studies apply it in wetland areas or for phreatophyte transpiration (Gerla, 1992; Hughes, Kalma, Binning, Willgoose, & Vertzonis, 2001; Loheide, Butler, & Gorelick, 2005; Nachabe, Shah, Ross, & Vomacka, 2005), as well as for deep rooting plant species in desert environments (Cheng et al., 2013). The common features of these applications are shallow groundwater and substantial groundwater extraction by vegetation.

Generally, the diurnal WTD fluctuation corresponds to a similar cycle of solar radiation, temperature, and humidity (Gribovszki, Kalicz, Szilágyi, & Kucsara, 2008). Using data from the DI site, a typical diurnal patter of WTD along with photosynthetically active radiation (PAR) is illustrated in Figure 2. Meteorological data were measured from a weather station 50 m south from the FI site. Note that the observed WTD at site B declines more rapidly at the time when PAR reaches a peak around noon (Figure 2). With zero PAR at midnight, WTD recovers (Figure 2b) or declines more slowly (Figure 2a) compared with that of daytime. Fluctuation at night is due to groundwater lateral inflow (Figure 2b) or outflow (Figure 2a) in surrounding area when crop evapotranspiration is too small at night. The decline of WTD during the day is faster than that at night. The day and night dynamics of WTD are closely associated with that of PAR, showing good evidence that the WTF method can be used for groundwater evapotranspiration estimation at the study sites.

The key assumption of the WTF method is that evapotranspiration is negligible relative to the groundwater inflow between midnight and 4 a.m., and the net inflow of groundwater is constant during the 24-hr period (White, 1932). Comparing the variation of shallow groundwater in this site, the delayed effect of WTD periodic variation was inconspicuous. On the basis of a better analysis of hydrographs, Hays (2003) developed an ET_g estimation method, which includes a more flexible time component for the recharge period (Figure 3).

$$ET_g = \left[(H_1 - L) + \frac{H_2 - L}{T_2} \times T_1\right] \times S_Y, \quad (1)$$

where S_Y is the specific yield of the groundwater fluctuation aquifer, H_1 is the groundwater level in early morning (mm) of the study day, H_2 is the groundwater level in early morning of the following day (mm), L is the lowest point of groundwater depth hydrograph on the target day (m), T_1 is the number of hours of the drawdown period, from H_1 to L (hr), and T_2 is the number of hours of the rising period, from L to H_2 (hr). This method separates the time periods of WTD descending and recovery, partitioning the diurnal hydrograph into two constituent parts of T_1 and T_2 (Mould, Frahm, Salzmann, Miegel, & Acreman, 2010). This method is adopted in this study.

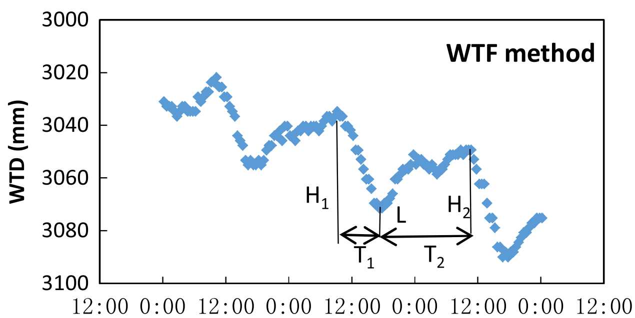

FIGURE 3 The variables included in the water table fluctuation (WTF) method proposed by Hays (2003). WTD = water table depth

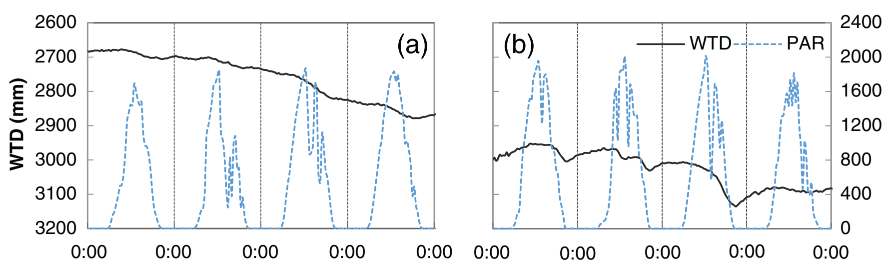

FIGURE 2 Groundwater table depth (WTD) fluctuation and photosynthetically active radiation (PAR) dynamics for selected days at site B—drip irrigation: (a) is from May 28 to May 31 and (b) is from June 6 to June 9

Specific yield S_y is defined as the water volume released from storage per unit surface area per unit decline in groundwater table (Freeze & Cherry, 1979). The specific yield based on the sediment texture is estimated using the saturated–unsaturated flow numerical simulation by Loheide et al. (2005). Zhang, Yuan, Shao, Yi, and Du (2016) confirmed that a constant S_y value for a defined porous medium can often be assumed. The soil texture in the vertical interval of the water level fluctuation does not obviously change. Without agricultural management, such as ploughing, it is suggested that the deep layer soil texture for both sites is the same. Loheide et al. (2005) drew a triangle-coordinate figure on the basis of sediment texture for estimating readily available specific yield. The specific yield is dependent on the soil texture and essentially independent of the magnitude of the diurnal fluctuations and antecedent moisture conditions. With silty loam dominant in the deep layer of the soil profile (average content of sand, silt, and clay were 0.11, 0.79, and 0.09, respectively), a constant S_y of 0.04 is adopted for this study (Loheide et al., 2005).

2.3.2 | An empirical groundwater–soil–atmosphere continuum method

The WTF method can be applied when the system reaches a dynamic equilibrium, and groundwater shows a steady fluctuation. However, when canals continually convey water and nearby areas of the study sites are irrigated, unstable dynamics of groundwater may occur. Thus, the WTF method is not suitable during this period to estimate ET_g.

Optionally, ET_g can be estimated by groundwater–soil–atmosphere continuum simulations (Wang, Huo, et al., 2016). Such a model should consider ET_g influencing factors, such as crop-dependent atmospheric demand, groundwater depth, and root zone soil hydraulics, as well as applicable irrigation rates. With lysimeter experiments, an integrative ET_g estimation method was developed for croplands with different irrigation treatments and shallow groundwater conditions (Wang, Huo, et al., 2016).

$$ET_g = K_c \times ET_0 \times \left(1 - \frac{H}{H_{max}}\right)^n \times \frac{\theta_{fc} - \theta}{\theta_{fc} - \theta_r}, \quad (2)$$

where K_c is crop coefficient (−), ET_0 is reference crop evapotranspiration (mm day^{-1}), H is the actual WTD (m), H_{max} is the potential maximum depth (m) beyond, which no ET_g occurs, n is the soil characteristics parameter (−), θ is the actual averaged SWC in the root zone (it is about 90 cm below the soil surface for maize crop) (cm^3 cm^{-3}), θ_{fc} is the field capacity of the soil in the root zone (cm^3 cm^{-3}), and θ_r is the SWC close to permanent wilting point (cm^3 cm^{-3}).

This method empirically estimates groundwater transfer to the atmosphere through the root zone by incorporating the effects of groundwater depth, soil texture and moisture state, and atmospheric demand. For simplicity, we refer to it as the empirical groundwater–soil–atmosphere continuum model (hereafter referred to as the EGSA model).

The continuous water table decline stage (such as the stage after mid-August) without irrigation or large precipitation events was selected to calculate ET_g by the WTF method. The WTF results are then used to calibrate the coefficients related to soil texture in root zone (H_{max} and n) in the integrative EGSA model. Thus, daily ET_g in different irrigated crop fields during the whole growing period can be obtained.

2.3.3 | Soil water balance and water productivity

Daily ET_g during the growing period under two irrigation methods is calculated by combining the WTF and EGSA methods. ET can be obtained by the water balance method as follows:

$$ET = I + P - \ W + ET_g - G_r, \quad (3)$$

where I is irrigation, P is precipitation, ΔW is the soil water storage change during the period, and G_r is the groundwater recharge due to irrigation or heavy precipitation. When FI is implemented, the water table often rises in the following days and then drops. Groundwater recharge (G_r) by deep seepage from the irrigation event can be estimated by

$$G_r = S_y \times \ h, \quad (4)$$

where S_y is the specific yield and Δh is the rise of groundwater table after large irrigation or precipitation (mm).

WP (kg m^{-3}) and IWP (kg m^{-3}) are defined in this study as follows:

$$WP = Y/ET, \quad (5)$$

$$IWP = Y/I, \quad (6)$$

where Y is the maize yield (kg ha^{-1}). WP and IWP denote how efficient crop water and irrigation water are used in producing crop yield, respectively.

3 | RESULTS AND DISCUSSION

3.1 | SWC variation

3.1.1 | Different irrigation schedules and soil moisture responses at different depths

The differences in irrigation schedule and the amount of water for each irrigation event are shown in Figure 4a. During the whole growing season, the amount of DI and FI totaled 357 and 430 mm, respectively. Each FI amount was much larger than that of DI. DI was carried out 16 times in total, with about 23 mm water applied for each DI except for once 20 mm on June 30. The irrigation time and irrigation amount of FI followed the local traditional irrigation schedule, where water is allocated by regular water diversion from the Yellow River, based on crop water requirement at the different growth stages. The DI schedule was designed by tensiometer controlled irrigation, keeping the soil matric potential directly below the dripper above −30 KPa. The DI design also took into account the prevention of salt accumulation in the crop root zone. Overall, the irrigation schedules have been set to prevent crop water stress. It can be seen that irrigation was mainly implemented in July and August, that is, the late jointing stage and tasseling stage, when crop water requirement is greatest.

Figure 4b,c shows the SWC at different depths under two irrigation methods. For FI, SWC at 35-cm depth increased rapidly to 0.4 m^3 m^{-3} after the first large irrigation on June 15. SWC at other

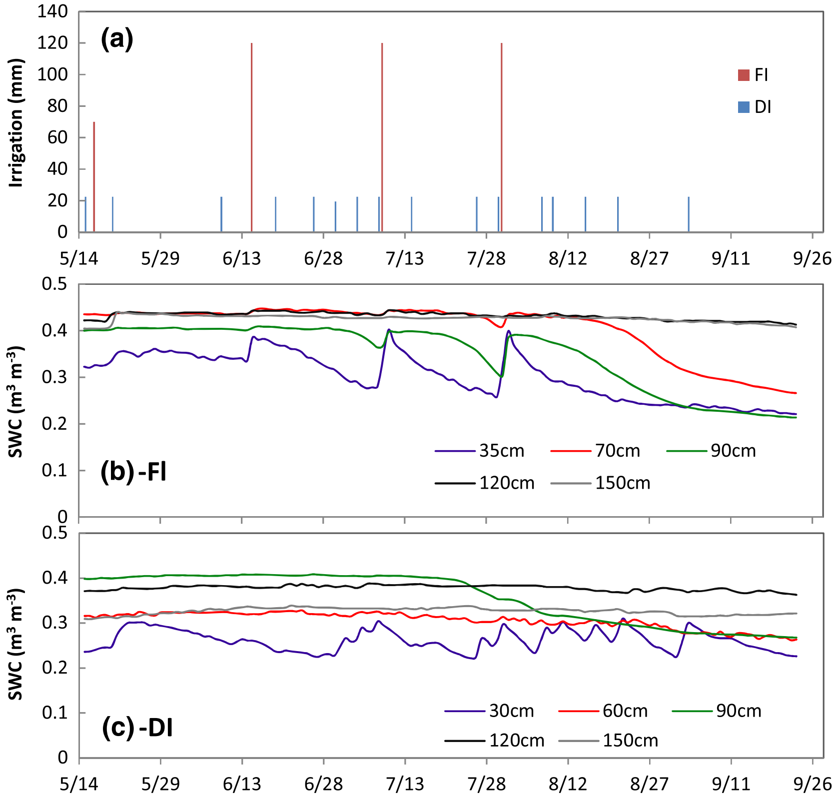

FIGURE 4 (a) Irrigation schedule under flood irrigation (FI) and drip irrigation (DI) conditions; (b) and (c) soil water content (SWC) at different depths of the two sites

depths also increased and was maintained at a high level for about 20 days until the next irrigation on July 9. The SWC at 90-cm depth also changed substantially after irrigation (Figure 4b). In the soil water redistribution phase, SWC at 35-cm depth decreased quickly after irrigation; whereas at 70- and 90-cm depth, it gradually decreased until the next irrigation event. SWC below 120-cm depth was relatively stable.

For DI, only SWC at 30-cm depth was influenced by irrigation of about 23 mm per event (Figure 4c). SWC at 60-cm depth at first remained steady and began to decline from July 20. At 90-cm depth, SWC also decreased sharply from this stage (the heading stage). After this stage, SWC at 90-cm depth was not recharged by DI, which illustrated that irrigation water did not recharge the groundwater. These differences in soil moisture responses between DI and FI sites suggest that the leakage loss of soil water under FI is larger than that under DI, in line with a study by Qin et al. (2016). This may explain the experimental founding by Sharmasarkar, Sharmasarkar, Miller, Vance, and Zhang (2001) in which DI tends to result in greater residual soil NO_3 as compared with FI in a sugarbeet field.

3.1.2 | Variation of soil moisture in root zone and deep soil zone

In order to compare the dynamic change of soil moisture in a concise and clear way, relative SWC (ΔSWC, defined as the difference in soil moisture relative to the initial value on May 15) is shown in Figure 5. Root zone soil moisture changed intensely after FI, whereas the root zone soil moisture for DI had a slower decrease for its high frequent irrigation. After a large irrigation of FI, SWC in the root zone was replenished quickly and became higher than that of DI. Although between two FI events, the root zone soil moisture decreased continuously and fell below that of DI. It is obvious that DI can maintain a relatively stable matric potential in the root zone due to its slow rate and high frequent application (Irfan, Arshad, Shakoor, & Anjum, 2014).

Differences in deep seepage by the two irrigation methods drive differences in groundwater evapotranspiration. The irrigation water of DI seems to be more accessible for crop demand because of less deep seepage. In contrast, the greater deep seepage in the days following FI reduced crop water consumption sourced from direct irrigation

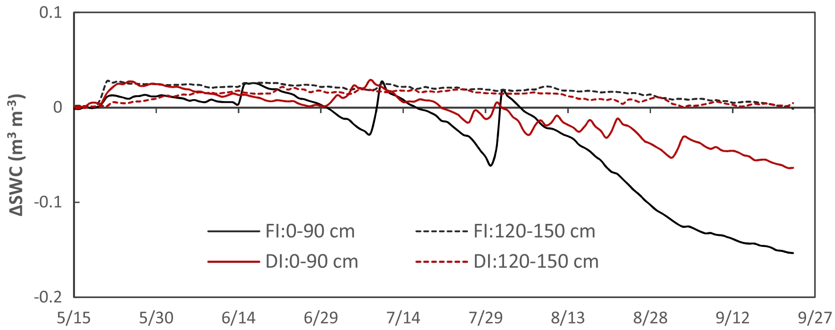

FIGURE 5 Variations of soil water content (relative to the initial value, ΔSWC), in the root zone (the average of 0–90 cm) and deep soil zone (the average of 120–150 cm) for flood irrigation (FI) and drip irrigation (DI), respectively

water for the whole season. After the final FI event, SWC in the root zone continuously and rapidly declined, which forced greater crop reliance on groundwater as shown in a previous study where less available water in the root zone leads to greater groundwater evapotranspiration (Wang, Huo, et al., 2016).

3.1.3 | Soil water dynamics at the groundwater evapotranspiration stage

Soil water distribution during the groundwater evapotranspiration period at the late stage is shown in Figure 6. The surface zone (0–30 cm) soil water was smaller for FI than that for DI, because there was no FI at this stage, whereas DI was applied on August 21. Temporal variation of SWC at different depths suggests that crop water consumption mainly comes from the shallow soil (0–60 cm) at the DI site but that for FI occurs mainly in deep root zone (60–90 cm).

As shallow groundwater can contribute to crop water requirement, less irrigation water is needed by irrigation (Liu et al., 2017; Reyes-Cabrera et al., 2016). The soil water distribution during this period is quite distinct between FI and DI. Thus, the influence factor between the two irrigation methods is different. For the whole growth season, the influence factors of ET_g, such as groundwater depth, crop growth state, irrigation events, and soil texture, should be comprehensively considered.

3.2 | WTF and estimated ET_g

3.2.1 | Water table response to irrigation and WTF estimated ET_g

There were four obvious rise–fall fluctuations during the growing period, and it can be seen that they were mainly related to the large FI events (Figure 7a). Hence, WTF amplitude under FI was larger than that under DI. WTD under FI ranged from 1.72 to 3.20 m, whereas for DI, it was from 2.02 to 3.14 m. WTD at both FI and DI sites were likely affected by large FI of the surrounding crop fields. Therefore, rapid lateral groundwater flow after irrigation made the WTD fluctuation similar between the two sites.

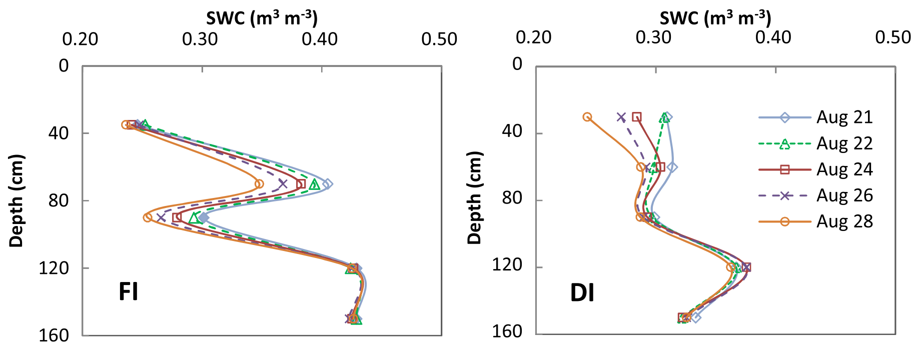

FIGURE 6 Dynamics of the soil moisture profiles from soil surface to 150 cm depth during the period from August 21 to August 28 for the two sites. DI = drip irrigation; FI = flood irrigation; SWC = soil water content

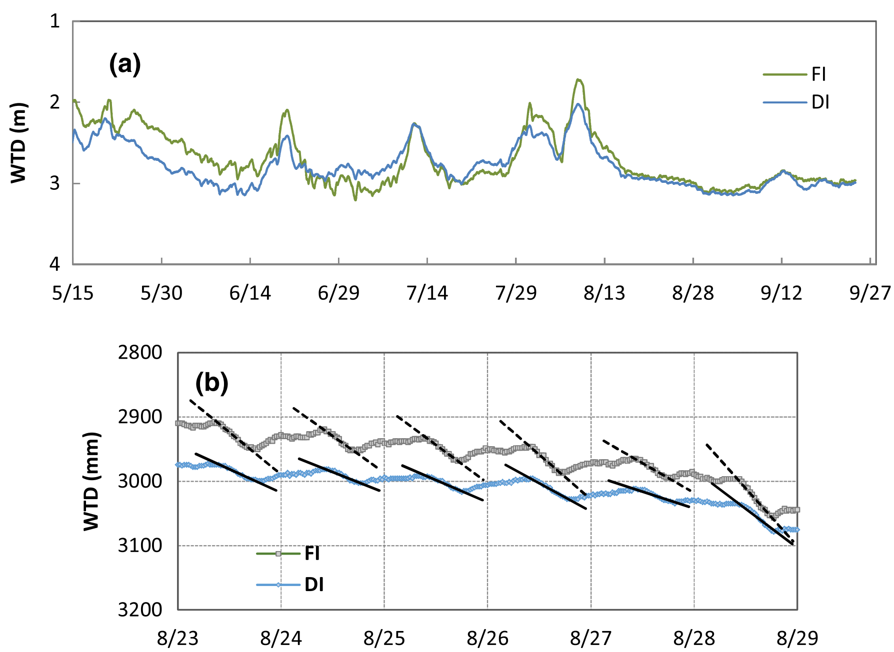

FIGURE 7 (a) Water table depth fluctuation under flood irrigation (FI) and drip irrigation (DI) conditions, (b): Diurnal water table depth (WTD) dynamics. Green line represents FI condition, and blue line represents DI condition. The slopes on the curve indicate the rate of WTD decline during the day (dash lines for FI and solid lines for DI)

Without considering the complex influencing factors, the diurnal WTF method can be used to estimate ET_g. Stable stages without the effect of heavy rainfall or irrigation were selected for both two irrigation conditions. Water table diurnal variation from August 23 to August 28 was considered representative for late stage of crop growth (Figure 7b). During the night, WTD had a slight recovery corresponding to lateral inflow; whereas during the day, it declined more rapidly, and this was associated with plant water demands. Diurnal fluctuation was similar for both sites. However, WTD under two irrigation methods showed distinct slopes of water table decline, with a steeper decline rate occurring for FI (Figure 7b). Different decline rates on the same day may reflect the difference in the effect of two irrigation schedules on the demand of groundwater for crop survival. In general, the calculated ET_g during the selected period for DI was smaller than that for FI (Table 2). Average daily ET_g under DI and FI conditions are 1.70 and 2.31 mm day^{-1} during this period, respectively.

TABLE 2 Water table decline rate and calculated ET_g from August 23 to August 28

	FI		DI	
	Decline rate (mm hr^{-1})	ET_g (mm day^{-1})	Decline rate (mm hr^{-1})	ET_g (mm day^{-1})
8/23	5.46	2.78	3.05	1.73
8/24	4.75	2.04	2.66	1.41
8/25	4.93	2.30	2.88	1.79
8/26	5.78	2.40	3.66	2.12
8/27	3.85	1.33	2.20	1.15
8/28	7.50	3.04	5.05	2.01

Note. DI = drip irrigation; FI = flood irrigation.

3.2.2 | The EGSA method calibration and EGSA-estimated ET_g

The continuous steady groundwater decline stage after mid-August has been selected to calculate ET_g by the WTF method, which was then used to calibrate the coefficients in the EGSA model (Figure 8a, b). Daily average values of WTD and SWC were used. Crop coefficient K_c was determined by the single crop coefficient method (Allen, Pereira, Raes, & Smith, 1998) and published literature for maize in the region (Liu et al., 2017). K_c was generalized into four stages for the annual crop (Table 3). Because maize growth height under two irrigation methods was similar, K_c at both sites was set the same. It indicates the average of crop water requirement during a period. ET_c, the product of ET_0 and K_c, was the reference water requirement of certain crops at different stages. The calibration results show that ET_g extinction depth (H_{max}) is deeper than 6 m, and parameter n (soil characteristics) is small. This is consistent with the fact that silt loam dominates in the soil profile (Wang, Huo, et al., 2016). A small n maintains stable capillary rise from groundwater.

Figure 8c shows daily ET_g estimated by the EGSA method for the whole growth season under the two irrigation schemes. At the early stages of the growth season, ET_g of DI was larger than that of FI. This is mainly because large FI events meet crop demand with soil water. In the middle stage, ET_g at the DI plot declined with continuous irrigation events before July 14. After the large FI on July 9 and July 31, ET_g decreased sharply to around zero due to deep percolation of irrigation water into groundwater. Between two consecutive FI events, ET_g increased to be greater than ET_g of the DI site. This trend continued through the final stage with ET_g of FI greater than DI. This is related to more water consumption in the deep root zone under FI (Figure 6) than that under DI.

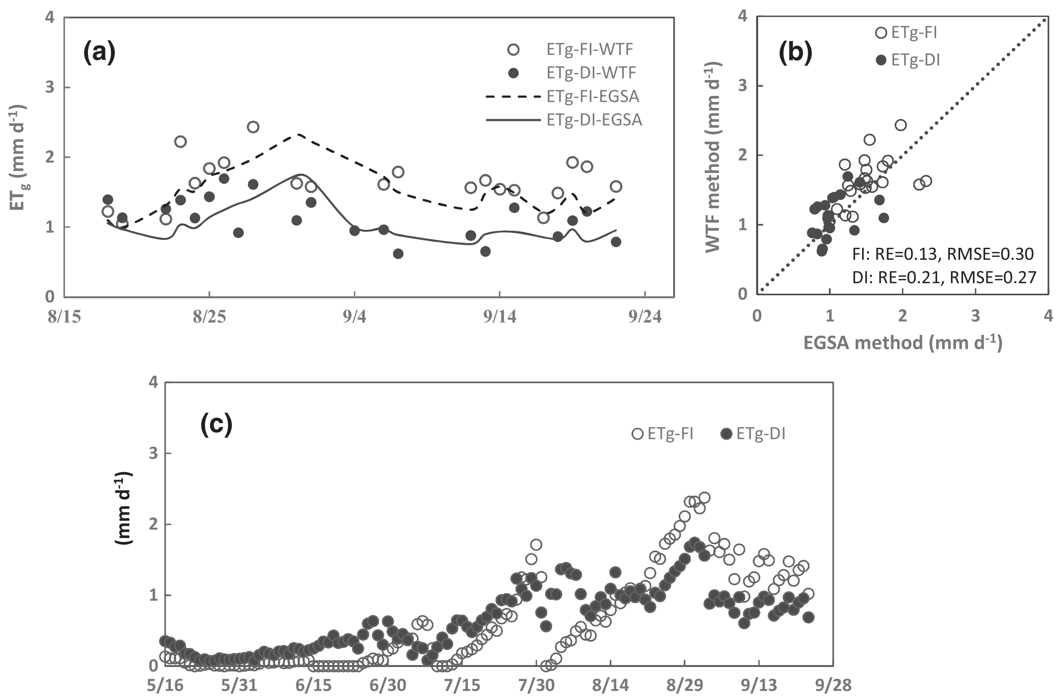

FIGURE 8 Comparison of EGSA (empirical groundwater–soil–atmosphere continuum model) estimate of ET_g with WTF (water table fluctuation method) estimated ET_g for the calibration period (a and b), and (c) is ET_g estimated by the calibrated EGSA model for the whole experimental period

TABLE 3 Crop coefficients (K_c) and calibrated parameters H_{max} and n

	K_c					
	Initial May 6–June 10	Development June 11–July 15	Middle July 16–August 31	End September 1–September 30	H_{max}	n
FI	0.5	0.5–1.19	1.19	1.19–0.6	6.28	0.08
DI	0.5	0.5–1.19	1.19	1.19–0.6	6.11	0.11

Note. DI = drip irrigation; FI = flood irrigation.

In comparison with the early growth stage, SWC at 90-cm depths decreased faster from the middle stage (Figure 4b,c). This may be because with crop growth, the deep-soil proportion of maize root water uptake increases, which is consistent with the results investigated using stable oxygen isotope by Wu et al. (2016). When SWC in the root zone could not fully satisfy crop water requirement, ET_g occurred to support maize evapotranspiration, especially during the late phase where ET_g is higher for FI (Figure 8c). In addition, a combination of the WTF and EGSA methods appears to be feasible to estimate ET_g temporal variation for irrigated cropland.

3.3 | Water budget

The values of actual evapotranspiration (ET_a) and potential evapotranspiration (ET_c) after irrigation events were the average of several days (about 3 to 5 days; Figure 9). It is obvious that the seasonal dynamic of ET_a is similar to that of maize ET_c. After large FI, the soil surface was too wet to step on for a few days, thus the surface soil evaporation was higher than that before FI. Except for four FI events increasing ET_a, ET_a-FI was less than ET_c during the crop growth season. The frequent irrigations by DI made the variation of ET_a-DI more variable.

Table 4 shows each of the water budget components for different months. The largest difference of soil water consumption (ΔSW) between FI and DI occurred in July. After over-irrigation by FI, SWC at 35-cm depth increased for approximately 2 days (Figure 4b). This is common for FI and results in higher and non-beneficial soil evaporation. ET_{aa} (the average of daily ET_a for every month) between FI and DI differed most significantly in July, suggesting that the effect of DI on water saving was the most efficient during this period. The ratio of soil water consumption to crop evapotranspiration ($\Delta SW/ET_a$) during the

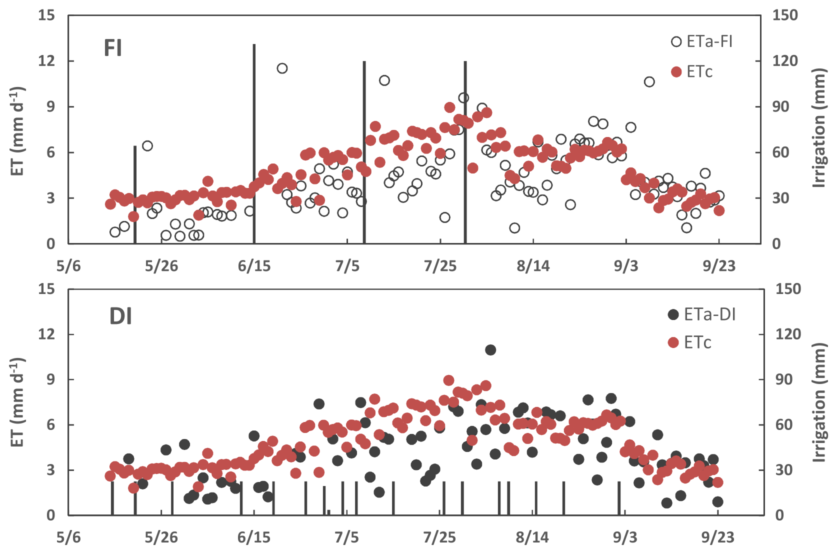

FIGURE 9 Evapotranspiration determined by the soil water balance under two irrigation conditions (ET_a-FI and ET_a-DI) and crop potential evapotranspiration (ET_c, the product of K_c and ET_0). Bars are irrigation conditions. DI = drip irrigation; FI = flood irrigation

TABLE 4 Water budget components for different months of the maize growth season

	Date	I	P	ΔSW	ET_g	G_r	ET_a	ET_c	ET_{aa}
FI	5/15–5/31	70	1.0	27.23	0.72	10.80	33.69	49.08	1.98
	6/1–6/30	120	4.8	−14.08	1.28	32.6	107.56	113.82	3.59
	7/1–7/31	120	2.0	−55.34	16.70	28.96	165.08	204.70	5.33
	8/1–8/31	120	1.4	−50.22	31.48	26.56	176.54	189.48	5.69
	9/1–9/23	0	21.8	−39.42	33.76	0	94.98	81.06	4.13
	Sum/Avg	430	31	−131.83	83.94	98.92	577.85	638.13	4.41
DI	5/15–5/31	45	1.0	28.58	2.82	—	20.24	49.08	1.19
	6/1–6/30	87	4.8	−17.53	8.85	—	118.18	113.82	3.94
	7/1–7/31	112.5	2.0	2.39	19.12	—	131.23	204.70	4.23
	8/1–8/31	90	1.4	−53.59	34.48	—	179.47	189.48	5.79
	9/1–9/23	22.5	21.8	−11.36	21.16	—	76.82	81.06	3.34
	Sum/Avg	357	31	−51.51	86.43	0	525.94	638.13	4.01

Note. Each component (mm) is the sum of each month, except that ET_{aa} (mm day^{-1}) is the average daily value.

DI = drip irrigation; FI = flood irrigation.

growing season for FI was 0.23 whereas that for DI was only 0.10. DI reduction of soil evaporation has been also demonstrated elsewhere (Lamm et al., 2011; Reyes-Cabrera et al., 2016; Shock, Pereira, & Eldredge, 2007) to be distinctly different at different growth stages. In addition, the non-beneficial water loss by soil evaporation under FI may result in salt accumulation in the root zone, which could be a contributing factor affecting crop yields.

In July and August, when maize was at the tasseling stage and filling stage, daily ET_{aa} was relatively high, owing to the larger ET_c than other stages. Total ET_a over this growth season under DI was lower than that under FI by about 9%. The sum of ET_g under FI and DI conditions were 83.9 and 86.4 mm, respectively (Table 4). The groundwater recharge coefficient (i.e., the ratio of G_r to I) under FI was estimated to be 0.23, which indicated the amount of water seepage from FI to groundwater.

3.4 | Contribution of groundwater and water productivity

Although the total ET_g under two irrigation schedules were similar, the pattern of groundwater use was different. With traditional FI, crop water requirements in the Hetao Plain can be met by three or four irrigation events. This also suits other crops such as sunflower and wheat. Large amounts of irrigation water percolate through the soil due to over-irrigation, but reuse through capillary rise (ET_g) is also quite large. This part of groundwater evapotranspiration is indirectly sourced by the FI crop. Although DI does not result in significant percolation, the contribution of groundwater (ET_g) partly comes from the rapid lateral migration of groundwater in nearby areas. Thus, net consumption of groundwater (ET_{gn}), that is, the difference between ET_g and G_r, was different between the two methods (−15 mm for FI and 86 mm for DI). ET_{gn} of FI was negative, suggesting the FI method recharges groundwater. DI maize made use of shallow groundwater and irrigation water with no recharge occurring.

The proportion of ET_g in ET_a was estimated to be 14.5% and 16.4% for FI and DI, respectively (Table 5). The contribution of irrigation to ET_a (I/ET_a) was estimated to be 74.4% and 67.9% under FI and DI conditions, respectively. This result indicates that crops using DI consume more groundwater and less irrigation water. IWP under DI was 4.58 kg m^{-3}, larger than 3.51 kg m^{-3} under FI. WP was estimated to be 3.11 and 2.61 kg m^{-3} for DI and FI, respectively. WP and IWP under traditional FI are slightly larger than the results of experiments considering different amounts of FI by Gao, Bai, et al., 2017. One reason could be the better soil characteristics for crop growth in this site. WP and IWP under DI generally agree with the results of the experiment of Liu et al. (2017), in which six DI treatments in maize field were conducted. The present results show that WP by DI is greatly improved from traditional inefficient FI. This is not only because of the benefits of DI practice but also the use of shallow groundwater.

TABLE 5 Contribution of groundwater and crop water productivity with comparison with published studies

	Y (kg ha^{-1})	ET_g/ET (%)	I/ET (%)	WP (kg m^{-3})		IWP (kg m^{-3})	
FI	15,088	14.5	74.4	2.61	2.15[a]	3.51	2.70[a]
DI	16,360	16.4	67.9	3.11	4.10[b]	4.58	4.95[b]

[a]is from Gao, Bai, et al. (2017). [b]is from Liu et al. (2017).

WP is affected significantly by irrigation methods. Whether at field scale or large regional scale, FI is considered as a wasteful and inefficient use of water, which is important in arid and semi-arid areas especially (Evans & Zaitchik, 2008; Wang, Liang, et al., 2016). In this study, excessive soil evaporation in June and July (at seedling and jointing stage) made ET_a under FI much larger than ET_a under DI (Table 3). Deep percolation from FI reduces the consumption of shallow groundwater, leading to an inefficient use of water resources. In contrast, DI is more water efficient. The maize yield under DI also increased with less water consumption (ET_a) in comparison with FI.

If DI were to be applied to the whole irrigation district and soil water factors the same as that in this study, the groundwater depth at the end of the maize growth season would be deeper than the present WTD by about 1 m according to our modelling. WTD in this site should always decline, which is due to no groundwater recharge by DI. The effect of change in groundwater table on crop water consumption was analysed in many studies, and the contribution of groundwater to evapotranspiration decreases with the decline of WTD (Karimov et al., 2014; Gao, Huo, et al., 2017). On the other hand, lowering the groundwater table decreases the actual evaporation rate at the soil surface and consequently decreases the root-zone salinity (Askri, Ahmed, Abichou, & Bouhlila, 2014; Chen & Hu, 2004). Therefore, lowering groundwater may also have an effect on the hydrological processes of riparian vegetation (Doody et al., 2009) or natural patches adjacent farmland. In the Hetao Plain, natural patches are always considered as dry drainage areas of excess water and salts. Lowered groundwater table increases the capacity of rainfall to flush salts in natural patches, which can provide positive results for the vegetation community and species composition in natural landscapes (Cooper, Sanderson, Stannard, & Groeneveld, 2006; Mata-González et al., 2012).

Although a widespread DI application may cause a drop of groundwater table after the growing season, the local traditional extra irrigation in autumn to leach salts from the soil profile contributes to water table recovery for the next growing season (Feng, Wang, & Feng, 2005; Liu et al., 2017). In this context, Wang et al. (2014) concluded that DI adopted in the growth season, and FI with freshwater after harvesting is a sustainable irrigation practice that could also control soil salinization. Compared with traditional FI, the alternative DI has an excellent effect on water saving in arid areas with shallow groundwater and should be promoted for precision agriculture development in the future.

4 | CONCLUSION

On the basis of 4-month groundwater level and soil water data in maize fields under FI and DI conditions, the response of soil water dynamics and ET_g to irrigation methods was investigated. WP under the two irrigation methods was examined and compared.

Different irrigation schedules of the two methods appear to cause different depth ranges of soil wetting. Irrigation induced soil wetting reaches to about 90 cm deep by FI, whereas DI only wets shallower depth soil. DI only stores irrigation water in the soil profile with soil water supplemented continuously. The largest difference of soil water consumption between FI and DI occurs in July, when daily ET_a differs most significantly. Surface evaporation from soil under FI was the probable reason for the difference, and this does not contribute to productivity. It suggested that the effect of DI on water saving was likely the most efficient during this period.

The combination of the WTF and EGSA methods is proposed to estimate the different groundwater evapotranspiration in situ under FI and DI conditions. Results indicate that DI creates great advantages in using groundwater over traditional FI. Considering the net groundwater consumption, deep drainage results in groundwater recharge by FI, whereas for DI, only ET_g occurs. IWP under DI is 4.58 kg m^{-3}, larger than that under FI by about 1.07 kg m^{-3}. Improvement of agricultural water productivity resulting from groundwater and irrigation by DI is evident. This is considered helpful in cropland and natural landscapes with shallow groundwater. Further work towards understanding the effect of long-term water saving on the process of regional water balance and vegetation growth in arid areas with shallow groundwater needs to be studied in the future. It is important to ensure that native groundwater-dependent ecosystems are not affected by a large reduction in groundwater but that groundwater is not too shallow to contribute to salinity, so a balance is required.

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