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ORIGINAL ARTICLE

Impacts of agricultural water saving practice on regional groundwater and water consumption in an arid region with shallow groundwater

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Abstract Irrigation is important to agricultural production and can induce changes in the regional hydrological cycle. In particular, in areas with shallow groundwater, fluctuation of groundwater levels will be present with irrigation events and groundwater evaporation. To deal with the shortage of water resources, agricultural water saving (AWS) has been conducted in arid and semiarid area. The Jiefangzha irrigation district was selected as the study area to investigate groundwater dynamics in response to AWS. With the abundant various data, the trend of groundwater level change from 1980 to 2013 was evaluated based on geographic information systems. Groundwater net consumption (ET_{ng}) and regional evapotranspiration (ET) during crop growth period were estimated by water fluctuation method and the water balance method. The results indicate that the groundwater depth was relatively stable before 2002, remaining at around 1.7 m. Due to reduction of the water diversion from the Yellow River and the implementation of water saving measures (WSMs), the canal seepage and irrigation infiltration declined, leading to groundwater levels declining by 0.4 m in recent 10 years. Groundwater net consumption of crop growth period was estimated since 1990 and increased from 50 mm/year in 1990 to 110 mm/year in 2013 with the reduction of water diversion. At the same time, regional evapotranspiration has shown a slightly decreasing trend. Thus, the contribution of groundwater to regional evapotranspiration has an obvious increasing trend, accounting for 20 % in 2013, which is doubled compared with that in 1980. Groundwater is very important to sustain crop production and healthy ecology, and it is quite essential to consider groundwater response to regional WSMs and water management.

Keywords Irrigation district · Shallow groundwater · Agricultural water saving · Groundwater consumption

Introduction

One-third of the world land is classified as arid or semiarid areas, which are identified as the regions with a lack of rainfall, strong evaporation, dry climate and severe water shortage problems. Compared with the scarce surface water resources, groundwater is regarded as an important water resource to maintain local sustainable development, especially in arid areas with agricultural irrigation (Li 2003; Amer et al. 2012). As an essential water source to maintain and restore ecosystems in arid regions, shallow groundwater is also critical for environmental protection (Naumburg et al. 2005; Newman et al. 2006; Wang et al. 2014; Shouse et al. 2010). With increasing water demand for irrigation and food production, groundwater in arid areas has attracted more attention recently. However, due to climate change and human activities, decline in regional groundwater levels has resulted in severe ecological problems in many arid areas (Umar and Absar 2003),

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including Northwest China, the Western United States and Central Australia.

With the looming pressure of extreme water shortages, AWS, which can reduce seepage losses from diversion canals and fields and enhance water use efficiency (Zhang et al. 2012), is widespread to sustain agricultural production. However, AWS with high irrigation efficiency at large scales can lead to significant decline in groundwater levels and induce negative effects on hydrology and ecology such as desertification and vegetation deterioration, which are particularly apparent when they occur in arid regions.

Groundwater processes in arid areas are particularly prone to impacts from the application of WSMs. The groundwater is essential to support ecosystems in arid and semiarid areas and closely connected with soil water (Naumburg et al. 2005; Soylu et al. 2011). When soil moisture cannot meet crop water requirement, the capillary upward movement of groundwater to crop root zones driven by soil suction can support the high water demand of crop growth, and this is especially significant in arid and semiarid regions where potential evaporation is much more than supplied water resources (Shouse et al. 2010). As an important component of the hydrological cycle, the contribution of groundwater to water requirement of plants in areas with shallow groundwater has been shown using various methods (Han et al. 2015). The above-demonstrated importance of groundwater highlights the importance of improved understanding of the complex spatial and temporal groundwater dynamics in arid regions.

The previous researches have concentrated on groundwater dynamics with various methods, including regional groundwater level measurements, thermal and temperature measurements (Duque et al. 2010; Wang et al. 2014), groundwater and soil numerical simulation (Xu et al. 2012; Sapriza-Azuri et al. 2015; Colombani et al. 2016) and hydrological models (Hattermanm et al. 2004; Pfannerstill et al. 2014). Regarding evapotranspiration studies, stomatal conductance measurements (Steinwand et al. 2001), Bowen ratio systems (Zhang et al. 2008) and sap flow meters (González-Altozano et al. 2008) are applied to quantify ET at point or field scale, while remote sensing technique is applied at regional scale (Yang et al. 2012). The upward movement of shallow groundwater resulted from soil moisture deficit and crop root uptake induces groundwater level decline when the groundwater directly sustains the strong evapotranspiration demand during the crop growth period. The accurate estimation of groundwater net consumption, including phreatic evaporation and root uptake due to capillary rise, plays an important role in proper water-resource management (Chen and Hu 2004; Fan et al. 2014).

As an efficient approach to alleviating water scarcity, AWS has significant impact on groundwater dynamics (Ibragimov et al. 2007; Chávez et al. 2009; Huo et al. 2012; Zhang et al. 2014). Xu et al. (2010) simulated various water saving scenarios based on lumped parameter groundwater balance model and found that the decline of groundwater table depends on the level of implements of WSMs. Zhang et al. (2014) studied water balance components and found that the exchange flux at the groundwater table is downward, while the upward flux is trivial due to the moderate groundwater depth caused by AWS. As a critical driver that impacts crop growth, the contribution of groundwater to agriculture water consumption has attracted widespread attention as well (Han et al. 2015). The capillary upward flow from groundwater is supposed to be resource for crop water consumption in arid and semiarid areas (Jorenush and Sepaskhah 2003). Furthermore, the previous studies have also shown that the crops can extract considerable amount of water from groundwater by deep roots in arid area (Kleidon and Heimanm 2000; Saleska et al. 2007; Maraux and Lafolie 1998). Soppe and Ayars (2003) figured out that groundwater contributed up to 40 % of daily safflower water use at a depth of 1.5 m, while Cohen et al. (2006) proved that groundwater contributed to 12 % of the total evapotranspiration in a watershed of Minnesota. The contribution of groundwater to crop growth indicates that cutting down the irrigation water can be one of the WSMs in shallow groundwater area. When groundwater levels tend to decline due to the decreasing seepage caused by WSMs, total evapotranspiration (ET) and groundwater evaporation (ET_{ng}) in irrigation district will change accordingly. Thus, the contribution of groundwater to evapotranspiration is supposed to be related to regional water input. Based on lysimeter experiment with controlled groundwater and numerical simulation research, Huo et al. (2012) showed there is a linear relationship between ET_{ng}/ET and groundwater depth.

In the area with groundwater pumping for agricultural irrigation, reducing irrigation water is effective to decrease the rate of groundwater drawdown (Kendy et al. 2004; Yang et al. 2006; Kumar and Gupta 2010). Yet, the result concluded in the arid area with water diverted from rivers for irrigation is contrary to the above studies. By conducting field experiments for maize, sunflower and watermelon crops, Ren et al. (2016) figured out that the shallow groundwater kept declining due to the reduced irrigation water, while Xu et al. (2010) came to the similar conclusion in Hetao irrigation district. However, there is still a lack of regional-scale study to evaluate the impact of AWS on groundwater dynamics and evaporation (Yeh and Famiglietti 2009; Feng et al. 2005). Employing long-term agricultural water use and groundwater monitoring data from an typical irrigation system for Northwest China, the objectives of this study are: (1) to investigate the regional temporal and spatial dynamics of groundwater levels associated with AWS over the past 30 years and (2) to estimate the change of groundwater net consumption and its contribution to regional evapotranspiration during the crop growth season.

Materials and methods

The study area

The Hetao irrigation district of the Inner Mongolia, located in the upstream part of the Yellow River basin, is the third largest irrigation district in China and Asia's largest irrigation district with one single headwork (Xu et al. 2010). Due to the arid climate and the lack of rainfall, a large amount of water is diverted from the Yellow River for agricultural irrigation, resulting in shallow groundwater. However, various WSMs have been applied in response to shortages of water resources since the 1980s. The Jiefangzha irrigation district (JID) in the west of the Hetao irrigation district is used as a case study to assess the impacts of water saving on groundwater dynamics.

The JID, located southeast of the Lang Mountains and northwest of the Yellow River (Fig. 1), covers an area of 2293 km^2, 55 % of which is farmland. It is an arid–semi-arid continental climate with the annual maximum and minimum mean monthly temperatures of −10.1 °C in January and 23.8 °C in July. There is little snowfall with multi-annual average precipitation of 155 mm, 70 % of which is concentrated from July to September. The mean annual pan evaporation based on a 20-cm-diameter evaporation pan is 2243.5 mm, far more than the precipitation. The frost-free period is 145–160 days, while the freezing period is 180 days. The elevation of the district is higher in the southwest and is lower in the northwest with an elevation ranging from 1032 to 1050 m above sea level (Xu et al. 2010). The topography is flat with 0.02 % slope from southeast to northwest.

Agriculture in the JID heavily relies on water diversion from the Yellow River. Due to climate change and increasing water demand for agriculture, however, Yellow River flow shows a declining trend over the past 50 years (Zhang et al. 2011). AWS is of great urgency. Since 1995, the main canals have been lined gradually to reduce water delivery losses, to control groundwater levels and to improve water use efficiency. The improvement of drainage systems also plays an important role in groundwater discharge. Meanwhile, according to the water resources management issues identified by the Yellow River Conservancy Commission, the mean annual water diversion for Hetao irrigation district will decline from 5.2 billion m^3 to 4 billion m^3 by 2020, and water allocation for the JID will decline accordingly.

The mean annual groundwater depth of the study area is about 1.5–2.5 m. In mid-March, the depth is greatest at 2.5–3 m because of upward water flux during soil freezing; from the mid-/end of September to early/mid-November,

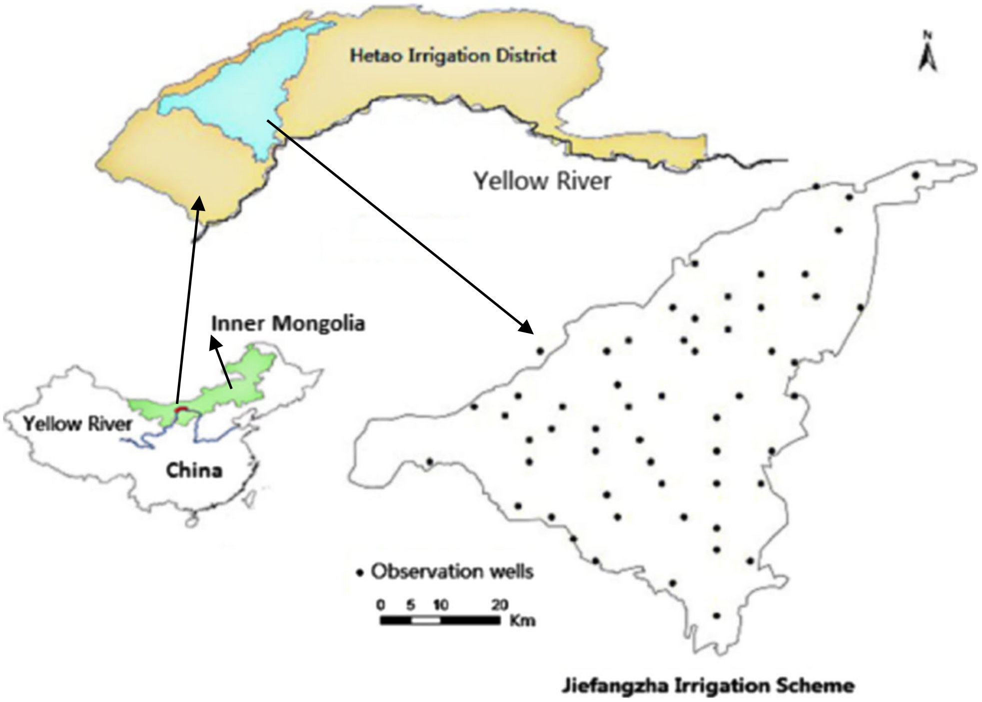


Fig. 1 The location of the study area and the observation wells

the large amount of water diverted for autumn irrigation increased the infiltration for groundwater, and the table rose rapidly to the peak of the year at a depth of 0.5–1 m (Bameng 2005).

The JID is a closed rift basin that formed in the late Jurassic Cenozoic period. Soils in the southeast area are alluvial sediments with main textures of silt loam and sandy loam. Soils in the northern area are composed by lake sediment and alluvial sediments with main textures of silty clay. The mean hydraulic conductivity is 12 cm/days (Xu et al. 2010). Due to the small hydraulic gradient (about 0.017 %), the estimated Darcy velocity is slow at 0.002 cm/days, showing that there is no rapid groundwater horizontal flow in study area. Thus, the groundwater dynamics of study area is classified as vertical infiltration–evaporation type (Yu et al. 2010), and the groundwater lateral recharge is negligible in this study (Bameng 2005).

Since the local groundwater is of high salt content at a TDS value of 4–4.5 g/L, the groundwater in JID is generally used for domestic and industrial service, but rarely for irrigation for controlling soil salinization problems. Well irrigation is used for only a small amount of total irrigated lands associated with low salinity groundwater, assumed to have little effect on overall groundwater dynamics. The river water generally has high sediment concentrations and low salt content (Xu et al. 2010), which is more appropriate for agricultural irrigation than local groundwater. So the water diversion from the Yellow River is the main source for agricultural irrigation in the study area.

Data collection

In the JID, 56 monitoring wells (Fig. 1) are installed to monitor the groundwater level every 5 days, i.e., on 6, 11, 16, 21, 26 every month from 1980 to 2013. The data of groundwater level and depth in 1980–2013 are used to analyze the groundwater dynamics, while the data of 1983, 1984, 1988, 1996 and 2000 are missing. To measure the soil moisture, the soil profile is divided into five layers as follows: for 10-cm layer to a depth of 20 cm, for 20-cm layer to a depth of 40 cm and for 30-cm layer to a depth of 1 m. The soil moisture is estimated by the average of the five layers data measured every 5 days by 22 wells in 2007–2013. Owing to the shallow groundwater in JID, the soil layers between 1 m and groundwater table are supposed to be the capillary water zone with constant soil moisture, and the variation is negligible. The data of water diversion (1985–2013) and groundwater drainage (1990–2009) are supplied by Shahao experimental station, and the absent drainage data during 2010–2013 are calculated as following method:

$$k_i = \frac{D_i}{I_i}$$

$$\bar{k} = \frac{\sum k_i}{N}$$

$$D_j = \bar{k} \times I_j$$

where D_i, D_j, I_i, I_j are the drainage and irrigation data of i or j year, $i = 1990, 1991, \ldots, 2009$, $j = 2010, 2012, 2013$; k_i is the ratio of available drainage data to irrigation water during 1990–2009, $\bar{k}$ is the average of k_i, estimated to be 13.7 %. N is the number of years with available data, which is a constant of 20 here.

The precipitation data from Hangzhou weather station located in southwest of JID are available during 1980–2013.

Methods

Spatial analysis of regional groundwater levels

A large amount of data were analyzed to determine the inter-annual trend of the groundwater table and the seasonal dynamics of the groundwater levels. 1980, 1985, 1990, 1995, 2001, 2006 and 2011 were chosen as the typical years in this study. All the 5-day interval groundwater data were pre-processed into annual average of 56 wells. Then based on geographic information systems (GIS), the Kriging interpolation method was chosen to draw the annual mean groundwater level distribution maps of seven typical years. The seasonal dynamics of groundwater were generated by annual average of groundwater depth data from 56 wells monitored every 5 days per month in the past 30 years, devoted to showing the regularity and periodicity of groundwater fluctuation within the year.

Water table fluctuation (WTF) method for estimating groundwater net consumption (ET_{ng}) over crop growth period

Among the multitude of methods for estimating discharge, the water table fluctuation (WTF) method may be the most widely used technique (Healy and Cook 2002). The superiority of the WTF method, which is best applied to estimate discharge ratios when water levels show an obvious declining trend within specified period in areas with a relatively thin vadose zone (Moon et al. 2004), exists in its simplicity and ease of use (Healy and Cook 2002). In JID, the well irrigation method applied in few parts of study area is supposed to have little effect on the whole groundwater dynamics. The recharge from Lang Mountain and the Yellow River is negligible as well as the lateral exchange of groundwater flow due to the slight hydraulic gradient (Xu et al. 2010). The vertical movement is the main behavior of water flux exchange, and the groundwater dynamics is influenced by infiltration of irrigation water and precipitation, groundwater capillary uptake for evaporation and discharge through lateral drainage ditches. With enough groundwater levels observation data, the WTF method can be used to estimate the groundwater net consumption during the crop growth season (Fig. 2). During the crop growth season lasting from end May to end September, the slope of the groundwater depth curve means the rate of groundwater levels decline. The WTF equation for estimating groundwater net consumption can be expressed as follows:

$$\mathrm{ET_{ng}} = \mu \frac{\Delta H}{\Delta t} \times \Delta t' - Dr \tag{1}$$

where $\mathrm{ET_{ng}}$ is the estimated groundwater net consumption (mm); ΔH is the decline in groundwater level during the actual crop growth season (mm); Δt is the actual duration of the crop growth season in different years (d); $\Delta t'$ is the uniform crop growth period which is supposed to be constant of 124 days from May 26th to September 26th; μ is the specific yield (nondimensional) of 0.07 (Hao et al. 2013); Dr is the groundwater drainage through the drain ditches in the same period (mm).

Water balance method for estimating regional ET in crop growth period

Different kinds of methods have been introduced by hydrologists and meteorologists for estimating evapotranspiration (Xu and Chen 2005). However, estimation of ET is still challenging, especially at the regional or basin scale (Vinukollu et al. 2011). With a solid theoretical background, the traditional water balance method is still a good alternative to estimate ET for a closed basin (Billah et al. 2015). The regional balance equation can be expressed in a simple way as:

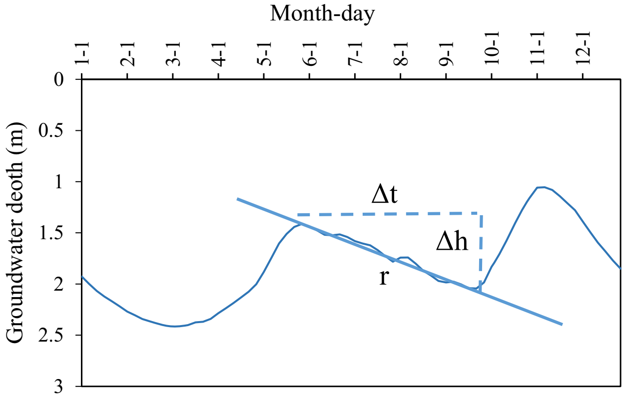


Fig. 2 The schematic diagram of water table fluctuation (WTF) method

$$\Delta W = R - D \tag{2}$$

where ΔW represents the variation of water storage in the study area (mm); R and D are the total recharge to and discharge in the study area (mm), respectively.

In this study, the total variation of water storage is partitioned into the changes of soil moisture and shallow groundwater. Because of the limitation of soil water content data, which had changed little during 2007–2013, the average of available data is adopted to count the change of soil moisture during 1990–2013. The soil moisture storage change is computed by the difference of total average soil water content at the top 1-m soil before and after crop growth period. Because of the vertical infiltration–evaporation type of groundwater flux exchange in JID, irrigation water and precipitation infiltration are the main recharge sources of groundwater, while the recharge from well irrigation consumed groundwater is negligible (Xu et al. 2010), and the main discharge of groundwater is evapotranspiration and drainage through the ditches. Considering the conditions above, the groundwater balance equation during crop growth period for the study area can be expressed as:

$$\Delta W_{\mathrm{S}} + \Delta W_{\mathrm{g}} = I + P - \mathrm{ET} - Dr, \tag{3}$$

where ΔW_{S} is the variation of soil moisture storage (mm), computed by the difference of average soil water content between two consecutive years; ΔW_{g} is the variation of groundwater storage (mm), which is converted from the change in groundwater depth of crop growth season by multiplying the specific yield based on WTF; I is the irrigation water diversion from Yellow River for the study area (mm); P is the total precipitation (mm); ET is the estimated evapotranspiration (mm); and Dr is the drainage through drain ditches (mm). All the parameters are limited to the crop growth period.

Results and discussion

Temporal and spatial change of groundwater

Groundwater levels

The distribution of groundwater level divided into 11 bands by 2-m interval is shown in Fig. 3. The higher groundwater levels in south attain about 1044 m and decrease by degrees with the ground from south to north. Overall, groundwater levels have declined in response to the AWS in past 30 years. In 1980s, the distribution of groundwater levels had little change because of the stable irrigation

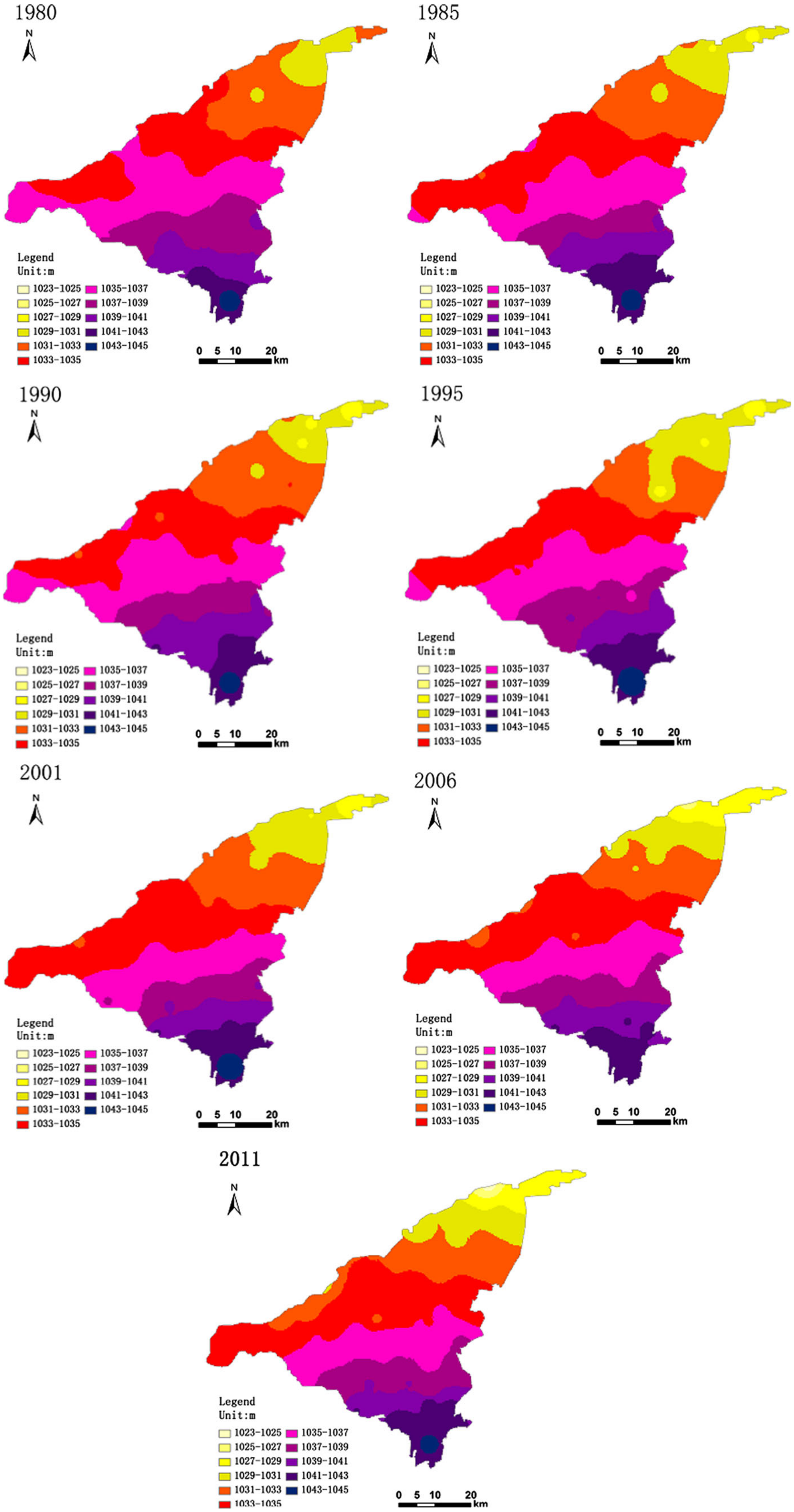


Fig. 3 The distribution of groundwater levels over the study area during 1980–2011

patterns. With the development of canals from 1990s, the land area with lower groundwater levels expanded, while the area with higher groundwater levels had slight shrink. Influenced by the comprehensive AWS referring to water diversion reduction, canals lining and upgrading drainage systems from 2003, the area of groundwater levels distribution appeared to change. The low-groundwater level area in north enlarged with the lowest groundwater level declining from 1027 to 1023 m with a few cones of depression, which is attributed to application of well irrigation method by groundwater exploitation in parts of irrigation land. Meanwhile, the area with high groundwater level in south also decreased. The groundwater level has been falling continuously since 1990s, and the rate of decline rate has increased since 2003 in response to the reduced water diversion.

The mean groundwater level before the application of WSMs in the JID, which remained around 1035.2 m, was steady with a large supply of water diversion from Yellow River. However, due to the substantial cuts in water diversion since 2003, the groundwater level began to decline rapidly (Table 1). The data show that the groundwater level dropped by 0.2 m during 1980–2002 while 0.4 m during 2003–2013, and the groundwater level kept relatively stable in 1990–2002 than that in 2003–2013.

As shown in Fig. 4, the amount of water diversions remained high in 1980s and increased in 1990s with the maximum reaching up to 14.2 × 10^8 m^3 in 1999. Water diversions dropped to 10.4 × 10^8 m^3 in 2003 due to the application of AWS. Furthermore, the relationship between groundwater level and water diversion from the Yellow River in 1985–2013 (Fig. 5) indicates that the groundwater level is positively related to the water diversion. Before the AWS, the groundwater level was high because of the large amount of infiltration from abundant water diversion; then, it began to fall as a feedback to the WSMs, one of which is cutting down the water diversion. Thus, the acceleration of the water level decline rate was mainly caused by the reduction of water diversion for irrigation since 2003.

Table 1 The average groundwater levels and variation for every 5 years

Year	Groundwater level (m)	Variation of GW levels (m)
1980	1035.25	
		−0.05
1985	1035.20	
		0.04
1990	1035.24	
		0.06
1995	1035.30	
		−0.12
1999	1035.18	
		−0.21
2005	1034.97	
		−0.29
2010	1034.68	

Seasonal dynamics of groundwater level

The seasonal variation of the monthly average groundwater levels during 1980–2002 and 2003–2013 is shown in Fig. 6. Owing to the climate characteristic and irrigation pattern, the fluctuation of groundwater level over one year can be divided into four periods (Yu et al. 2010). The first period is thawing period from mid-March to mid-/end May. With the rise of temperature, the melted water seepage from upper soil layers becomes the major recharge source of the groundwater, causing the groundwater level to increase rapidly (Bameng 2005; Guo et al. 2013). In addition, the first irrigation applied in the end of April provides a large quantity of recharge for groundwater as well. In the end of the period, the frozen layers melt through completely, and the groundwater level reaches the peak at a depth of 1.5 m. The second period is the crop growth season from mid-/end May to end September. The strong evaporation consuming groundwater far more than the groundwater recharge leads to an obvious decline in groundwater level, while the groundwater level appears to fluctuate during the period indicated by the recharge of irrigation and rainfall events. During the third period, from end September to early March, the autumn flood irrigation is applied after harvest to leach salts and keep soil moisture for crops planting next year. The large amount of water diversion for autumn flood irrigation accounts for about one-third of the total annual water diversion from Yellow River, originating a large percolation and a rapid rise of groundwater level. The groundwater level reaches to the peak of the year in the end of period. The fourth period is freezing period from early/mid-November to subsequent mid-March. With the temperature decreasing, the surface soil begins to freeze with the capillary rise recharging the upper freezing layers driven by temperature gradient (Bameng 2005). The frozen soil layer keeps increasing, while the groundwater level withdraws. In the end February to mid-March, the groundwater level drops to the lowest level over the year with a depth of 2.0–2.5 m.

For thawing and freezing periods, the change trend of groundwater levels is almost consistent before and after AWS, though the groundwater level after water saving is evidently lower than before. This can be attributed to that the water movement induced by soil freezing dominated water redistribution of these two periods. However, it is noticed that groundwater levels over crop growth period declined more rapidly since AWS in 2002. The detailed

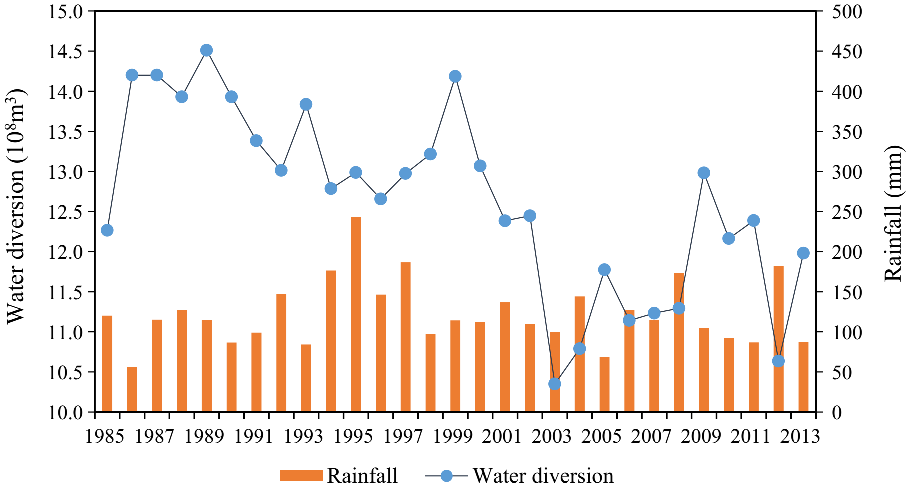


Fig. 4 The amount of water diversion and rainfall during 1985–2013 in the JID

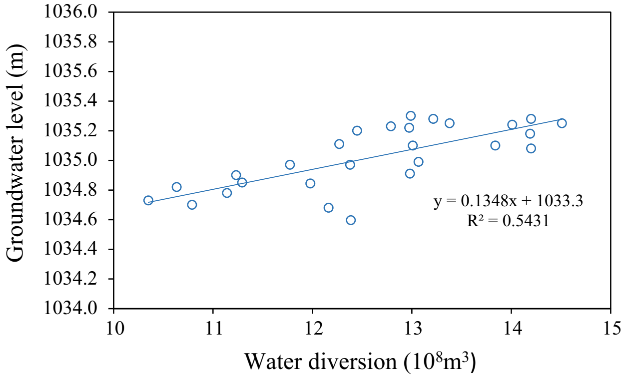


Fig. 5 The relationship between water diversion and groundwater levels

analysis is included in "Groundwater net consumption (ET_{ng}) change in past 30 years" section. As the autumn irrigation always keeps a high amount through study period, groundwater levels still rise rapidly over this stage after AWS. Due to lower porosity in deeper soil layers (Ren et al. 2016), however, the groundwater table rises more rapidly in autumn irrigation period to reach generally the same level after comprehensive AWS.

Distribution change of different groundwater depths

Distributions of groundwater depth for last 30 years are shown in Fig. 7. With the implementation of AWS during 1980–2013, groundwater depth in the study area has obviously changed. It is noticeable that groundwater depth has a small range and lands with groundwater depth of 1.5–1.8 m make up more than 50 % of the total area before the implementation of water saving in 2002. However, groundwater depth range becomes widespread, and areas with groundwater depth of 1.5–2.4 m account for more than 70 % of the total area after 2002.

Detailed proportions of land area with groundwater depth range for different periods are listed in Table 2. Generally, groundwater depth is lower than 1.8 m for most area before 2002, but the proportion of area with groundwater depth of less than 1.8 m rapidly decreases with AWS. However, land area with groundwater depth of 1.8–3.0 m significantly expands after 2001. In detail, areas with groundwater depth of less than 1.8 m accounting for 66.0–72.8 % total area during 1980–1985 decrease to only 31.1–32.4 % during 2006–2011, with the results that area with groundwater depth of 1.8–3.0 m accounting for 27.2–34.0 % total area during 1980–1985 decreases to only 60.5–63.5 % during 2006–2011. In particular, since 2001, shallow groundwater depth increases gradually to more than 3.0 m, and land area with groundwater depth of more than 3.0 m accounts to 8.4 % of total area in 2011. In 1995, because of the abundant rainfall increasing the recharge for groundwater, the land area with groundwater depth of less than 1.8 m has a little rise.

Impact of AWS on groundwater dynamics

The main recharge of groundwater in the JID is rainfall and infiltration of water diversion from the Yellow River, including canal seepage and field irrigation infiltration (Xu et al. 2010; Yu et al. 2010; Yang et al. 2012). Due to the low annual rainfall varying from 100 to 200 mm with an average of 148 mm during 1980–2013 (Fig. 4), the weak variation of precipitation compared with the large amount of water diversion is supposed to have little effect on groundwater dynamics within the study period. Before the implementation of WSMs in the JID, the conveyance efficiency was lower than 0.4. The large amount of canal seepage caused by the vast irrigation system resulted in a high groundwater levels. Since 1998, however, lining of canals has been implemented as one of the WSMs. The

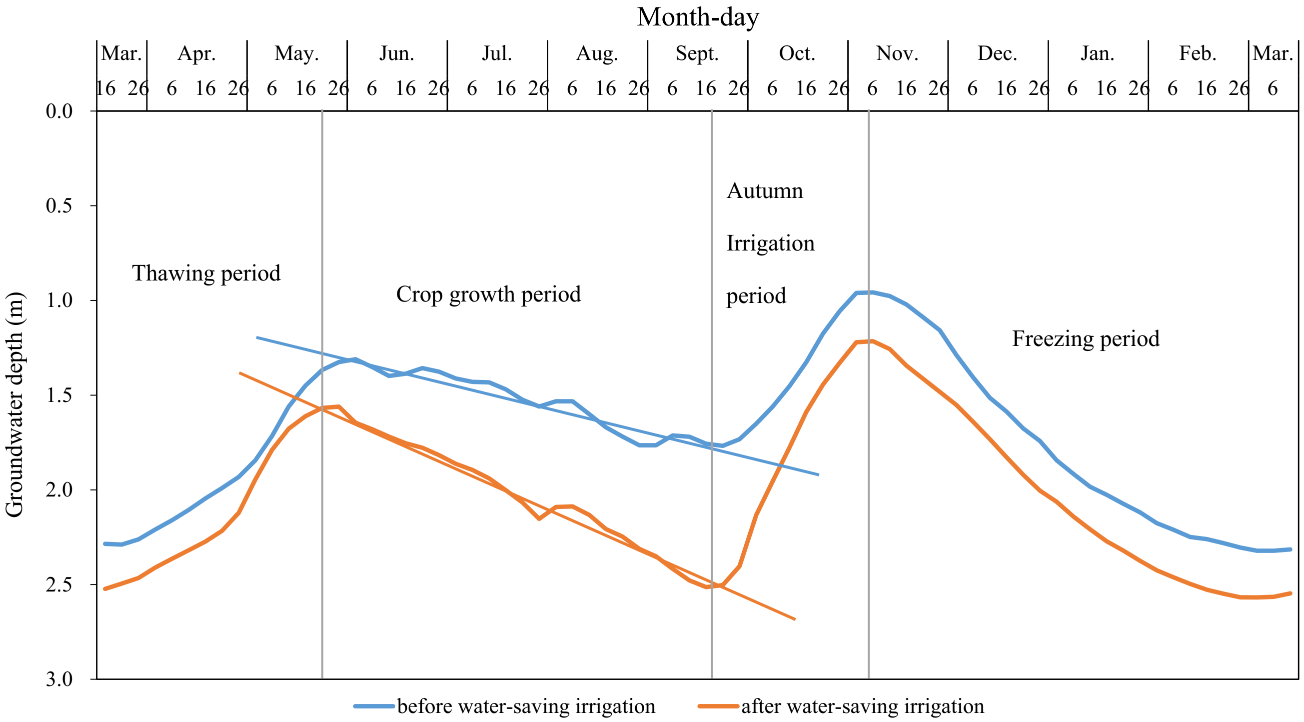


Fig. 6 The seasonal change of groundwater depth during 1980–2002 and 2003–2013

conveyance efficiency in irrigation area has enhanced to 0.428 (Tian 2013), reducing the seepage losses from canals. In the most recent 20 years, although the irrigation area has extended by 20 % compared to the 1980s, water diversions have decreased in response to AWS (Xu et al. 2010). The annual water diversion decreased from 13.3×10^8 m^3 in 1985 to 10.4×10^8 m^3 in 2003 (Fig. 4). Influenced by agricultural water saving, the groundwater levels showed a slight declining trend since 1980, and an acceleration of decline rate occurred in 2003 due to the reduction of water diversion.

Groundwater net consumption (ET$_{ng}$) change in past 30 years

Slop of groundwater levels curve over crop growth period

Due to the large water consumption over crop growth period from end May to end September, groundwater levels have a declining trend through the study period. The rate of groundwater levels decline was obtained from the simple WTF curve (Fig. 8). Furthermore, groundwater net consumption over crop growth period can be estimated by various slopes of WTF curves. It is significant that groundwater levels appear to fluctuate following irrigation events before 2000. However, as the irrigation amount decreases evidently, groundwater levels almost decline through the whole crop growth period. This is attributed to that the reduction of water diversion leads to reduced recharge and declining groundwater levels. As a result, the slope of the WTF curve increased from 2.2 mm/days in 1981 to 9.8 mm/days in 2011 and groundwater level decline rate over crop growth period increased almost three times over 30 years. Moreover, we found the rate of groundwater levels decline is negatively correlated with the amount of regional water input with the correlation coefficient of 0.547 (Fig. 9), further verifying that the decline of groundwater levels is related to reduction of water diversion.

ET$_{ng}$ change

Based on the WTF method, we estimated the total ET$_{ng}$ over crop growth period (Table 3). It is noticed that water input (water diversion and rainfall) in the irrigation district decreased by 25 % from 1990–1995 to 2008–2013. Meanwhile, the average ET$_{ng}$ increased gradually from 45.65 mm/year in 1990–1995 to 81.94 mm/year in 2008–2013. This could be attributed to more groundwater consumption by root uptake through capillary rise to meet the soil moisture deficit, which is caused by decreasing groundwater levels (Kahlown et al. 2005; Liu et al. 2016).

Over the crop growth period, the evaporation keeps increasing because of the rising temperature and radiation, while the increased transpiration is mainly ascribed to the growing leaf area index (LAI). When soil moisture is

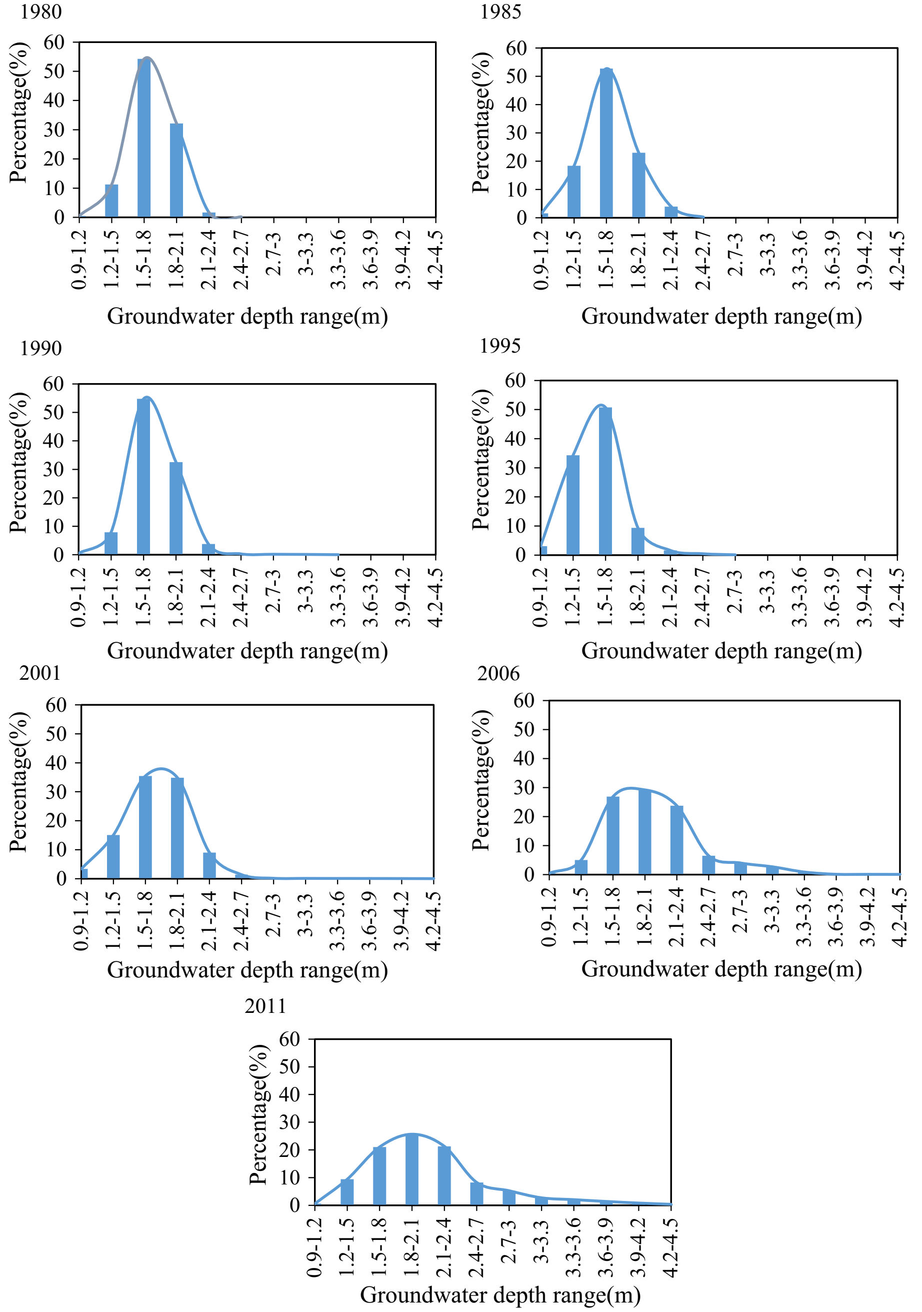


Fig. 7 The histogram of distribution of groundwater depth in the JID

insufficient for crop water requirement, the groundwater will be taken up to meet the crop water demand. Groundwater evaporation is related to groundwater depth and unsaturated soil moisture. The previous studies have shown the similar results. Based on maize field experiments with shallow groundwater, Zhang et al. (1999) figured out that the proportion of groundwater in Lucerne evapotranspiration varied between 25 and 65 % with a nonsaline groundwater table of 60–100 cm. Yang et al. (2012) reported that with a groundwater depth between 0.7 and 1.3 m, 15.69 % of maize evapotranspiration was supplied by groundwater. For our study area, due to the large amount of water diversion before AWS, the groundwater level in crop growth period declined slowly, which means that the groundwater net consumption was small accordingly. With the implementation of various WSMs, the noticeable decline in the water diversions from the Yellow River resulted in groundwater level decline, which is supposed to induce groundwater evaporation decrease as well. However, decline of water diversion will also induce soil water deficit to crop growth, resulting in an upward capillary flux from the groundwater to maintain the strong evapotranspiration demand. Under the comprehensive influence of the two above factors, an increase of

Table 2 The proportion of area with different groundwater depth ranges

	<1.8 m (%)	1.8–3 m (%)	3–4.5 m (%)	>4.5 m (%)
1980	66.0	34.0	0	0
1985	72.8	27.2	0	0
1990	63.1	36.7	0.1	0
1995	88.4	11.6	0	0
2001	54.2	45.4	0.4	0
2006	32.4	63.5	3.9	0.2
2011	31.1	60.5	7.3	1.1

groundwater net consumption was found with implementation of AWS in the JID. This means much more groundwater consumption occurred though the groundwater depths are deeper than before. However, shallow groundwater evaporation will significantly decrease to vanish when groundwater levels decline to threshold depth (Steinwand et al. 2006). The appropriate depth of water table for crop growth in JID is 1.5–2 m during the crop growth period (Xu et al. 2010). Thus, the implementation of water saving for controlling a proper groundwater level is essential to crop normal growth.

Contribution of groundwater to regional ET

Regional ET change

With calculated ET_{ng} based on WTF method, average regional evapotranspiration (ET) in crop growth period from 1990 to 2013 can be estimated by the water balance equations. The result shows that ET during the crop growth period is relatively high with average value of 575 mm within 1990–2002. From 2000 or so, however, the reduced irrigation water diversions resulted in soil moisture deficit and a substantial drop in groundwater levels. Furthermore, the regional evapotranspiration has declined from 595 mm in 2002 to 465 mm in 2012 (Fig. 10). Although regional ET is also related to weather, farm pattern, it is significant that ET is controlled by supplied irrigation water as the extremely arid climate. However, the decreasing trend of ET is smaller than that of water diversion over the study period. ET over the crop growth season decreased from 575 mm/year of 1990–2002 to 535 mm/year of

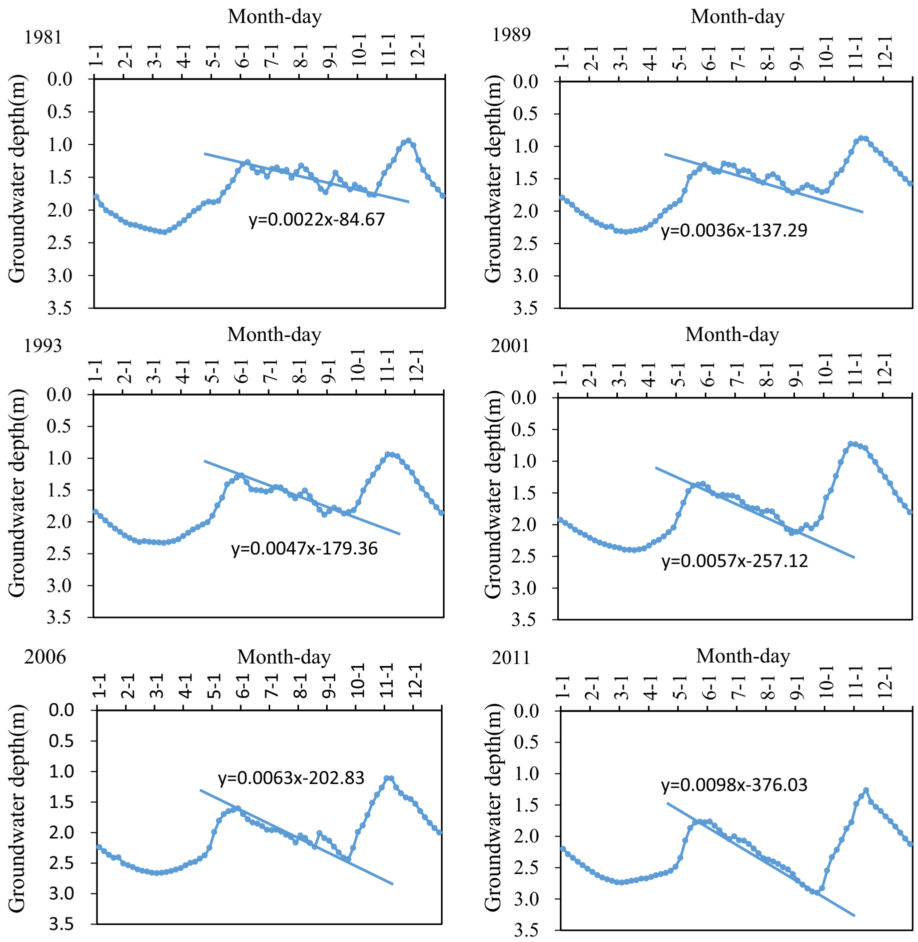


Fig. 8 The groundwater levels decline rate over the period of June to September for different years

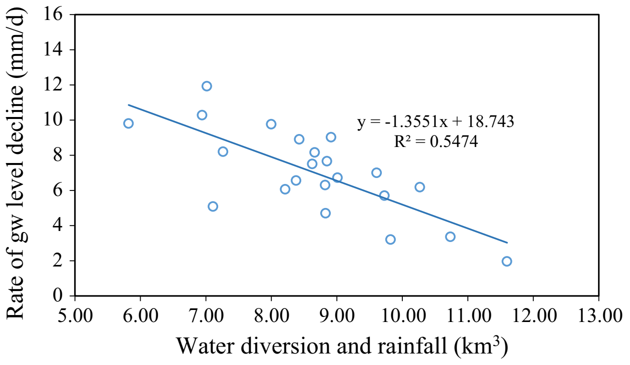


Fig. 9 The relationship between the rate of groundwater levels decline and the water diversion and rainfall during crop growth period

2003–2013, while the irrigation amount dropped to 220 mm/year from 290 mm/year during the same periods. This means that shallow groundwater has significant contribution to regional ET to supply the irrigation water deficit, providing further evidence for the increasing groundwater net consumption.

ET_{ng}/ET change

With the annual mean water diversion decreasing in response to AWS since 2003, the groundwater net consumption increased to meet crop demand (Fig. 11). ET_{ng}/ET has an upward trend from 9 % of 1990 to 20 % of 2013 in addition to several years with different trends. It was found that there is an inversely proportional relationship between ET_{ng}/ET and water diversion and rainfall (Fig. 12), which confirms the proposed hypotheses that the contribution of groundwater to evapotranspiration is related to water input. Large water diversion results in high groundwater recharge during 1990–2003, and the ET_{ng}/ET ratio is relatively small. However, with the gradual reduction of the water diversion from Yellow River, the overall trend of ET_{ng}/ET ratio keeps increasing with fluctuations. With the Surface Energy Balance Algorithm for Land model in Hetao area, Yang et al. (2012) found the similar conclusion that the proportion of agricultural water consumption in total water consumption has been increasing. It is noticed that ET_{ng} is negative for 1994 and 1995, meaning groundwater recharge is much than groundwater evaporation.

Since the vertical movement is the main behavior of groundwater, groundwater dynamics is reflected comprehensively by events of rainfall, irrigation and groundwater depth. By setting different groundwater depths in soil column test, Li (2006) indicated that the amount of evapotranspiration in shallow groundwater area is proportionate to the groundwater levels; Zhang (2008) obtained the corresponding results with various meteorological data that the evapotranspiration appears to linearly decrease approximately along with the increasing of groundwater depth. Also, current study proved that regional ET has a decreasing trend with groundwater levels declining induced by AWS.

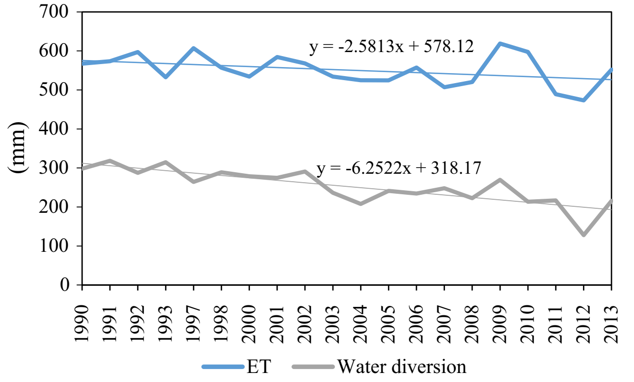


Fig. 10 The trend of ET and water diversion over crop growth period in 1990–2013

The precious studies have demonstrated the importance of groundwater to evapotranspiration as well. Cohen et al. (2006) found that groundwater contributes to 12 % of the total evapotranspiration for a watershed in Minnesota. York et al. (2002) reported that 5–20 % of evapotranspiration comes directly from shallow groundwater in Kansas. The results are useful to understand the contribution of groundwater to field or regional water consumption. At the regional scale, the present study obtained the similar results showing that contribution of groundwater to ET increased with the reduction of water division and declined groundwater levels, and cutting down water diversion is an effective water saving approach in irrigation area with shallow groundwater.

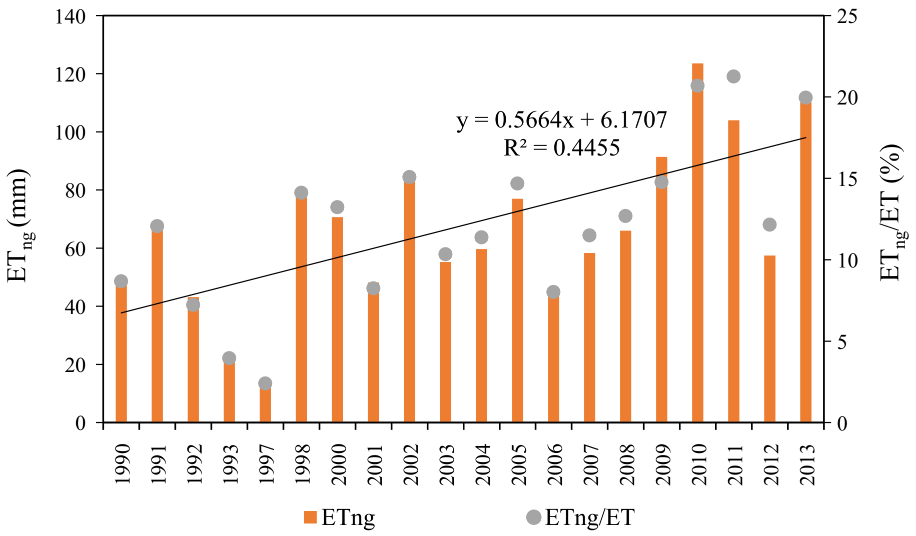
Reasons for the decline of groundwater table

As stated in "Temporal and spatial change of groundwater" section, the reduced water diversion for irrigation is recognized as the original reason to originate the decline of groundwater level, owing to the low change of annual

Table 3 The average groundwater net consumption and water input during crop growth season in 1990–1995, 1996–2001, 2002–2007 and 2008–2013

Year	1990–1995	1996–2001	2002–2007	2008–2013
GW net consumption (mm/year)	45.65	54.59	65.15	81.94
Surface water diversion and rainfall (10^8 m^3/year)	9.87	9.38	8.37	7.42

Fig. 11 The variation of ET_{ng} and ET_{ng}/ET in 1990–2013



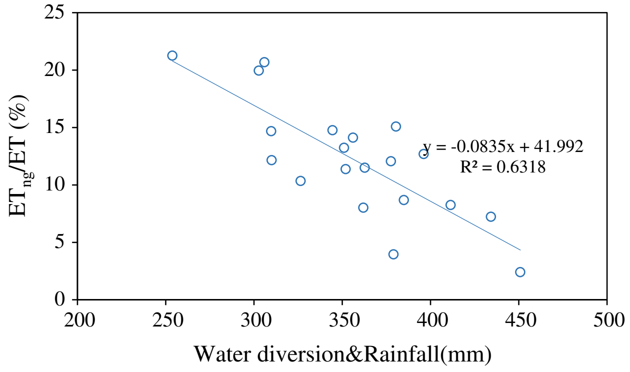


Fig. 12 The relationship between the percentage of ET_{ng}/ET and water diversion and rainfall in 1990–2013

precipitation varying from 100 to 200 mm. The decreased infiltration from lining canals cuts down the recharge for groundwater as well. The groundwater net consumption (ET_{ng}) also appeared to change as a feedback to the declined groundwater table. The phreatic evaporation as the main discharge of groundwater increased to meet the water demand deficit for crop growth caused by the declined groundwater table, which also increase the groundwater level decline in turn. The less recharge and more discharge for groundwater caused by AWS have disequilibrated the stable water table. Therefore, the groundwater level showed a declining trend due to the interactional effect of above factors.

Conclusions

With data on long-term groundwater levels, water diversions and drainage, groundwater dynamics and groundwater consumption were estimated in this study. After the implementation of WSMs, groundwater level declines were evident since 2003. The WTF method was used to evaluate the impact of AWS on groundwater over the crop growth period. The reduction of water inputs (the water diversion and rainfall) led to increased groundwater net consumption during the crop growth period, while the ET showed relatively smaller declining trend. At the same time, ET_{ng}/ET rose. As stated above, groundwater is very important to sustain crop production. It is essential to consider groundwater response to regional WSMs and water management to keep a proper groundwater level for crop growth.

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