

# Change of winter wheat planting area and its impacts on groundwater depletion in the North China Plain

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**Abstract:** The North China Plain is one of the most water-stressed areas in China. Irrigation of winter wheat mainly utilizes groundwater resources, which has resulted in severe environmental problems. Accurate estimation of crop water consumption and net irrigation water consumption is crucial to guarantee the management of agricultural water resources. An actual crop evapotranspiration (ET) estimation model was proposed, by combining FAO Penman-Monteith method with remote sensing data. The planting area of winter wheat has a significant impact on water consumption; therefore, the planting area was also retrieved. The estimated ET showed good agreement with field-observed ET at four stations. The average relative bias and root mean square error (RMSE) for ET estimation were  $-2.2\%$  and  $25.5\text{ mm}$ , respectively. The results showed the planting area and water consumption of winter wheat had a decreasing trend in the Northern Hebei Plain (N-HBP) and Southern Hebei Plain (S-HBP). Moreover, in these two regions, there was a significant negative correlation between accumulated net irrigation water consumption and groundwater table. The total net irrigation water consumption in the N-HBP and S-HBP accounted for  $12.9 \times 10^9\text{ m}^3$  and  $31.9 \times 10^9\text{ m}^3$  during 2001–2016, respectively. Before and after 2001, the decline rate of groundwater table had a decreasing trend, as did the planting area of winter wheat in the N-HBP and S-HBP. The decrease of winter wheat planting area alleviated the decline of groundwater table in these two regions while the total net irrigation water consumption was both up to  $28.5 \times 10^9\text{ m}^3$  during 2001–2016 in the Northwestern Shandong Plain (NW-SDP) and Northern Henan Plain (N-HNP). In these two regions, there was no significant correlation between accumulated net irrigation water consumption and groundwater table. The Yellow River was able to supply irrigation and the groundwater table had no significant declining trend.

**Keywords:** North China Plain; planting area; winter wheat; remote sensing; net irrigation water consumption

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## 1 Introduction

Water shortages worldwide become a limiting factor for agricultural development, which can lead to a severe threat to global food security. The North China Plain (NCP) is one of the most important grain production bases in China (Shen *et al.*, 2002; Wang *et al.*, 2015) and produces approximately 20% of the nation's grain (Sun *et al.*, 2010; Yuan and Shen, 2013). Due to a summer monsoon climate, rainfall is highly variable, approximately 70%–80% of annual rainfall is concentrated in the period from June to September (Jin *et al.*, 1999). Annual crop water consumption greatly exceeds the annual precipitation. Therefore, irrigation is widely applied to maintain high yields and secure the food supply for the nation (Deng *et al.*, 2006).

In the NCP, approximately 75% of the agricultural land is irrigated (Lin *et al.*, 2000), and agricultural water consumption generally accounts for approximately 70% of the total water consumption (Liu and Wei, 1989; Li *et al.*, 2008). Due to the lack of surface water, approximately 70% of water resources for agricultural use are pumped from groundwater (Sun *et al.*, 2010). Continuous over-pumping of groundwater for irrigation has resulted in water-level declines in both shallow and deep aquifers. For example, the groundwater level of the piedmont plain has declined rapidly from 10 m below the ground surface in the 1970s to 46 m in 2015 (Pei *et al.*, 2017). With the persistent decline of groundwater levels, large-scale groundwater depression zones have formed (Jia and Liu, 2002). At the same time, persistent groundwater exploitation in excess of natural recharge in the NCP has induced negative environmental impacts (e.g., deterioration of groundwater quality, ecosystem degradation, land subsidence) (Liu *et al.*, 2001; Sophocleous, 2002; Fogg and LaBolle, 2006; Konikow, 2011). In addition, the competition for water use among various social production sectors has become increasingly intensified and the share of agricultural water use is decreasing. Consequently, agriculture is facing an unsustainable situation and water shortages have become the main constraint to agricultural development in the study area.

In the NCP, winter wheat is traditionally the most cultivated grain crop and has the highest water consumption among grain crops. Due to the monsoon influence, annual rainfall during the winter wheat growing period can only meet 20%–30% of the wheat water requirement (Liu *et al.*, 2001). Irrigation is very crucial to offset the water deficit of winter wheat in the growing season and maintain high yields. More than 70% of irrigation water resources are used for winter wheat production (Cao *et al.*, 2007; Zhou and Li, 2003). Since most of the irrigation water comes from groundwater sources with wells deeper than 30 m, irrigation for winter wheat production poses a threat to the sustainability of groundwater resources in the NCP (Zhang *et al.*, 2003). Therefore, it is vital to accurately estimate the water consumption and groundwater consumption of winter wheat in the NCP.

Crop water consumption is generally defined as evapotranspiration (ET) over the entire crop growing season (Shen *et al.*, 2013b). At the field scale, a variety of approaches have been used to monitor ET, including a weighing lysimeter (Liu *et al.*, 2002), an eddy covariance system (Shen *et al.*, 2013b) and water balance modeling (Sun *et al.*, 2011). These studies obtained credible results that can reveal the characteristics of ET and the water balance in the typical croplands. However, the cost of field experiments is high, and instrument operation is also very complicated. Moreover, due to the differences in soil conditions, crop variety, and weather conditions, it is difficult to acquire crop water consumption at a large spa-

tial scale. At the regional scale, Li *et al.* (2008) estimated the water consumption of winter wheat in the NCP using remote sensing technology and found that the average water consumption of winter wheat in 83 counties was 424 mm. Mo *et al.* (2005) found that the water consumption of winter wheat ranged from 330 mm to 500 mm and from 70 mm to 280 mm under irrigated and rain-fed conditions by using a SVAT crop growth model and remotely sensed data in the NCP. Yuan and Shen (2013) estimated that the irrigation water consumption for Hebei Province during 1984–2008 was up to 139 km<sup>3</sup>. However, estimations of the amount of actual water consumption and groundwater consumption of winter wheat in recent decades in the NCP are still rare.

The FAO Penman-Monteith equation combined with crop coefficient was widely used to estimate crop water requirement around the world. Estimation of actual crop ET is of vital importance in agricultural water management and irrigation scheduling. In the study area, soil moisture is a crucial factor for crop production. Generally, the soil water content can be measured by direct information from one variable of the soil-water-plant system such as the neutron probe and time-domain-reflectometry (TDR) at the field scale. However, it is very difficult to obtain soil moisture data at large spatial and temporal scales. In this study, soil moisture information was indirectly reflected by using remote sensing data. Therefore, we proposed a simple method to calculate actual crop ET by combining the FAO Penman-Monteith method with remote sensing data. The main objectives of the study are as follows: (1) to retrieve the planting area of winter wheat using remote sensing data; (2) to estimate actual water consumption and net irrigation water consumption of winter wheat; and (3) to analyze the impact of changes in winter wheat planting area on groundwater depletion in the NCP. The results from this study will provide valuable information for water management and the development of sustainable agriculture in the study area.

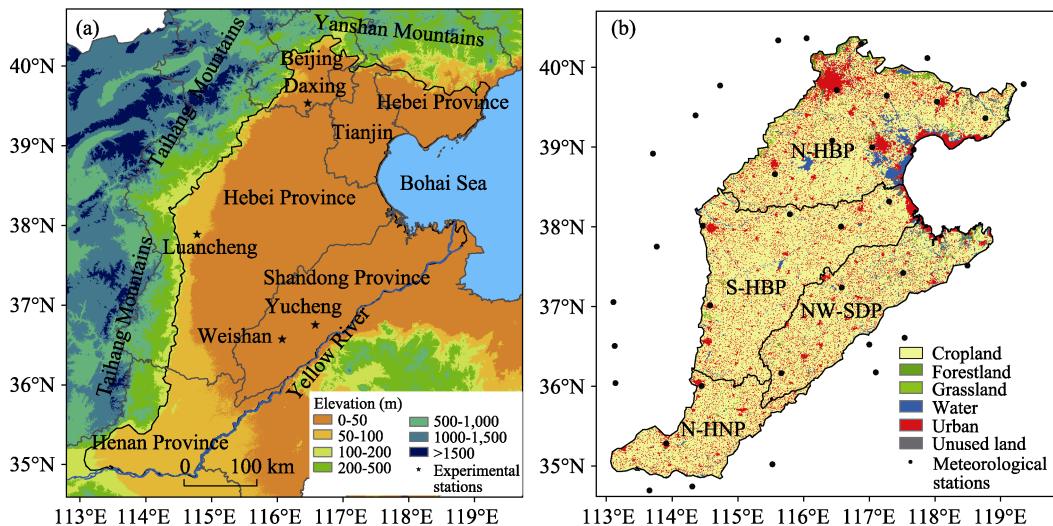
## 2 Materials and methods

### 2.1 Study area

The NCP is located in the eastern coastal region of China. It ranges from the Yanshan Mountains in the north to the Yellow River in the south, and from the Taihang Mountains in the west to the Bohai Sea in the east (Cao *et al.*, 2013; Pei *et al.*, 2015). It includes Hebei Plain, the main plain of the cities of Beijing and Tianjin, and the northern plain of Shandong and Henan Provinces. The total area of the NCP is approximately 140,000 km<sup>2</sup>, and the altitude of most of the NCP is less than 50 m above sea level. In this study, NCP is divided into four parts: Northern Hebei Plain (N-HBP), Southern Hebei Plain (S-HBP), Northwestern Shandong Plain (NW-SDP) and Northern Henan Plain (N-HNP) (Figure 1). The study area belongs to a typical temperate continental monsoon climate and 70% of precipitation is concentrated from late June to September. The average annual precipitation is 500–600 mm, and the annual spatial distribution of precipitation in the NCP has a decreasing trend from the southeast to the northwest (Yang *et al.*, 2010).

The NCP accounts for only 1.5% of China's total land area but supports 10% of China's total population (Cao *et al.*, 2014). The proliferation of mechanized wells since the 1960s has intensified agricultural production, mainly in the form of winter wheat and summer maize rotations (Shu *et al.*, 2011). The growing season of winter wheat is from early October

to mid-June of the following year. During the growing season of winter wheat, annual precipitation is usually less than 200 mm, but the ET of winter wheat is more than 400 mm (Li *et al.*, 2012). Thus, irrigation is necessary to ensure high yields of winter wheat, which mainly relies on groundwater resources. Additionally, with rapid population growth, industrialization and urbanization, water shortages and groundwater over-exploitation have led to a great constraint on sustainable development in the NCP (Li *et al.*, 2008).



**Figure 1** Topographic map (a) and land use map of the North China Plain in 2010 (b) (Luancheng station: 37°57'N, 114°41'E; Weishan station: 36°39'N, 116°03'E; Yucheng station: 36°50'N, 116°34'E; Daxing station: 39°37'N, 116°26'E)

## 2.2 Data

The data used in this study mainly included meteorological data, remote sensing data, statistical data, and field observation data. (1) The meteorological data for 2001–2016 was obtained from the China Meteorological Data Sharing Service System (<http://data.cma.cn>) of 38 national weather stations located within and around the NCP (Figure 1). The meteorological data were mainly used to calculate the reference crop ET. (2) The remote sensing data included the Normalized Difference Vegetation Index (NDVI) of MOD13Q1 for 2001–2016 and yearly land cover data of MCD12Q1 for 2001–2013. The spatial resolution of MOD13Q1 was 250 m, and the temporal resolution was 16 days. The spatial resolution of MCD12Q1 was 500 m. (3) The growth stages of winter wheat in the study area were collected from the agricultural meteorological station (<http://data.cma.cn>). (4) Statistical data of the planting area of winter wheat for 2001–2015 were derived from the Statistical Yearbook of Hebei Province, Shandong Province, Henan Province, Beijing City, and Tianjin City. (5) The field-observed ET from four sites were as follows: Luancheng station (2007–2016) (Shen *et al.*, 2013b; Zhang *et al.*, 2018), Weishan station (2005–2013) (Lei and Yang, 2010; Lei *et al.*, 2018), Yucheng station (2003–2005) (Yu and Sun, 2006; Yu *et al.*, 2006a, 2006b; Yu *et al.*, 2008; Yu *et al.*, 2013), and Daxing station (2008–2010) (Jia *et al.*, 2012; Liu *et al.*, 2013; Liu and Xu, 2013). Figure 1 shows the location of each experimental station. (6) Groundwater level monitoring data from 1996 through 2008 were obtained from the China Institute of Geo-Environmental Monitoring (CIGEM), and 2010 data were obtained from the

published yearbook on groundwater (Gao and Yin, 2011).

### 2.3 Retrieve the winter wheat planting area using remote sensing data

To calculate the volume of winter wheat water consumption, net irrigation water consumption and analyze the impacts of the change in winter wheat planting area on groundwater depletion, the planting area of winter wheat was retrieved based on remotely sensed data. In this study, the planting ratio of winter wheat in one pixel was estimated. First, the spatial resolution of the land cover product (MCD12Q1) was resampled from 500 m to 250 m using the nearest neighbor method. Then, the croplands of the NCP from 2001 to 2013 were extracted based on the land cover classification system of the International Geosphere-Biosphere Programme (IGBP). Due to the lack of MCD12Q1 data after 2013, cropland maps during 2014–2016 were the same as that in 2013. Winter wheat is sown in early October and harvested in mid-June of the following year. To acquire the spatial distribution of winter wheat, the maximum NDVI images of the winter wheat growing season were selected. Based on cropland maps, the planting ratio of winter wheat ( $fc_{wheat}$ ) was determined according to Gutman and Ignatov (1998) using the maximum NDVI images. The calculation formula was expressed as:

$$fc_{wheat} = (NDVI - NDVI_{soil}) / (NDVI_{wheat} - NDVI_{soil}) \quad (1)$$

where  $fc_{wheat}$  is the planting ratio of winter wheat in a pixel;  $NDVI$  is the NDVI value in a pixel;  $NDVI_{wheat}$  refers to the pixel that is completely covered by winter wheat.  $NDVI_{soil}$  refers to the pixel that is completely covered by soil. In this study,  $NDVI_{wheat}$  is defined as the average NDVI value of the pixels where the cumulative frequency is more than 90%.  $NDVI_{soil}$  is defined as the NDVI value when the cumulative frequency is up to 10%.

In addition, to clarify the characteristic of the change trend of winter wheat planting area from 2001 to 2016, the spatial heterogeneity of the temporal variation in the planting area of winter wheat was analyzed by simulating the trend variability using a linear regression for each pixel. The least squares regression coefficient was calculated as:

$$Slope = \frac{\sum_{i=1}^n x_i t_i - \frac{1}{n} (\sum_{i=1}^n x_i) (\sum_{i=1}^n t_i)}{\sum_{i=1}^n t_i^2 - \frac{1}{n} (\sum_{i=1}^n t_i)^2} \quad (2)$$

where  $Slope$  refers to the change slope of the planting ratio of winter wheat in a pixel;  $i=1, 2, 3, \dots, n$  represents the number of years,  $x_i$  represents the planting ratio of winter wheat of the  $i$ th year, and  $t_i$  is the time. The positive slope represents an increasing trend with time, while a negative slope indicates a decreasing trend. The correlation coefficient between the planting ratio and time was used to detect whether the change trend of the planting ratio of winter wheat is significant or not. The equation of the correlation coefficient ( $r$ ) was expressed as:

$$r = \frac{n(\sum_{i=1}^n x_i t_i) - (\sum_{i=1}^n x_i)(\sum_{i=1}^n t_i)}{\sqrt{[n\sum_{i=1}^n x_i^2 - (\sum_{i=1}^n x_i)^2][\sum_{i=1}^n t_i^2 - (\sum_{i=1}^n t_i)^2]}} \quad (3)$$

where  $r$  is the correlation coefficient,  $i=1, 2, 3, \dots, n$  is the number of years,  $x_i$  is the planting ratio of winter wheat of the  $i$ th year, and  $t_i$  is the time. When the absolute value of the correlation coefficient is more than  $r_{0.01}$ , the planting ratio has a significant change trend. In contrast, the change trend of the planting ratio is not significant. According to the value of  $Slope$

and  $r$ , the change trend of the winter wheat planting ratio was divided into four categories: significant reduction (Slope  $< 0$  &  $|r| \geq r_{0.01}$ ), nonsignificant reduction (Slope  $< 0$  &  $|r| < r_{0.01}$ ), significant increase (Slope  $> 0$  &  $|r| \geq r_{0.01}$ ), and nonsignificant increase (Slope  $> 0$  &  $|r| < r_{0.01}$ ).

## 2.4 Estimation of actual crop evapotranspiration

Crop ET is affected by weather conditions, crop type, soil moisture conditions and so on. In this study, a model combining the FAO Penman-Monteith equation with the crop coefficient, and remote sensing data was developed to estimate actual crop ET. First, reference crop ET ( $ET_0$ ) was calculated using the FAO Penman-Monteith equation. Crop ET ( $ET_c$ ) under standard conditions was calculated by multiplying  $ET_0$  by the crop coefficient ( $K_c$ ). The NCP is a typical water-stressed area, so the soil water condition is a crucial factor impacting crop ET. The soil moisture condition was taken into consideration when estimating actual crop ET in this study. Actual crop ET was calculated by using the following equation:

$$ET_a = ET_0 \times K_c \times K_s \quad (4)$$

where  $ET_a$  is the actual crop ET;  $ET_0$  is the reference crop ET;  $K_c$  is the crop coefficient; and  $K_s$  is the soil moisture correlation coefficient.

### 2.4.1 Reference crop evapotranspiration

Reference crop ET ( $ET_0$ ) was calculated using the modified Penman-Monteith equation recommended by the FAO. The Penman-Monteith method was developed by defining the reference crop as a hypothetical crop with an assumed height of 0.12 m, a surface resistance of 70 s/m and an albedo of 0.23. The reference surface resembles an extension surface of the green grass of uniform height, actively growing, completely shading the ground and adequately watered (Allen *et al.*, 1998). Reference crop ET is only related to meteorological factors (Shahid, 2011), hence, it can be used in different regions. The FAO Penman-Monteith equation was as follows:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} \mu_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34\mu_2)} \quad (5)$$

where  $ET_0$  is the reference ET (mm/d);  $R_n$  is the net radiation at the crop surface (MJ/m<sup>2</sup>/d);  $G$  is the soil heat flux density (MJ/m<sup>2</sup>/d);  $T$  is the mean daily air temperature at 2 m in height (°C);  $\mu_2$  is the wind speed at 2 m in height (m/s);  $e_s$  is the saturation vapor pressure (kPa);  $e_a$  is the actual vapor pressure (kPa);  $e_s - e_a$  is the saturation vapor pressure deficit (kPa);  $\Delta$  is the slope of the vapor pressure curve (kPa/°C); and  $\gamma$  is the psychrometric constant (kPa/°C).

### 2.4.2 Crop coefficient

The crop coefficient ( $K_c$ ) is defined as the ratio of crop ET under standard conditions to reference crop ET (Shen *et al.*, 2013a) and it is one of the important parameters in estimating actual crop ET.  $K_c$  is typically taken from literature values, and it is affected by crop variety and the growth stage (Allen *et al.*, 1998, 2005). The  $K_c$  value of winter wheat varies during the six growth stages: the initial stage, the freezing and thawing stage, the overwintering stage, the rapid development stage, the middle stage, and the mature stage. The date of different growth stages was obtained from agricultural meteorological stations. The  $K_c$  of winter wheat was determined according to Duan *et al.* (2004). The  $K_c$  values of the initial and

overwintering stage were 0.6 and 0.4, respectively, while  $K_c$  value of the freezing and thawing stage varied from 0.6 to 0.4. The  $K_c$  values of the other growth stages at the typical stations are shown in Table 1.

**Table 1**  $K_c$  of winter wheat in different growth stages at the typical sites in the North China Plain

Typical station	Longitude (°)	Latitude (°)	Developing stage	Middle stage	Maturity stage	Growth period
Miyun (Beijing)	116.87	40.38	0.40–1.15	1.15	1.15–0.40	9/27–6/22
Baodi (Tianjin)	117.28	39.7	0.40–1.09	1.09	1.09–0.40	9/30–6/19
Tangshan (Hebei)	118.15	39.67	0.40–1.15	1.15	1.15–0.40	10/2–6/19
Luancheng (Hebei)	114.63	37.88	0.40–1.07	1.07	1.07–0.40	10/1–6.14
Huimin (Shandong)	117.53	37.5	0.40–1.17	1.17	1.17–0.40	10/5–6.13
Anyang (Henan)	114.37	36.12	0.40–1.15	1.15	1.15–0.40	10/10–6.11
Puyang (Henan)	115.01	35.7	0.40–1.16	1.16	1.16–0.40	10/10–6.9

### 2.4.3 Soil moisture correlation coefficient

The growth of crops mainly needs sunlight, temperature, water and so on. In the NCP, water is a major limiting factor for crop growth. Owing to the difficulty of obtaining soil moisture data at large spatial and temporal scales, remote sensing data are commonly used. NDVI is a composite indicator of vegetation activity, and it responds to several variables such as canopy, photosynthesis, biomass, and surface moisture and so on (Adegoke *et al.*, 2002). Some studies have linked the spatial and temporal patterns of NDVI with climate and plant ET (Cihlar *et al.*, 1991). Furthermore, NDVI has been associated closely with eco-climatological variables, such as potential ET and soil hydrologic properties (Hayes and Decker, 1996; Yang *et al.*, 1997). In this study, NDVI was used to reflect the soil moisture condition. We assumed that there was a positive linear correlation between the crop growth condition and soil moisture condition at a certain soil moisture range. Since NDVI can reflect the crop growth condition to a certain extent, there was also a positive linear correlation between NDVI and the soil moisture correlation coefficient.

Generally, winter wheat is sown in early October and regenerated in mid-to-late March of the following year. Its canopy coverage is up to the maximum value during the period from April to May, and it is finally harvested in early June. To acquire the soil moisture condition of winter wheat, the maximum NDVI images of the winter wheat growing season were obtained. It was assumed that at least 10% of winter wheat fields in the NCP had soil moisture condition that was very good and there was no water stress ( $K_s = 1$ ). Then, the NDVI value of the pixel when the cumulative frequency was up to 90% was selected as the reference value ( $K_s = 1$ ). The soil moisture correlation coefficient of other pixels can be calculated according to the ratio between NDVI and the reference value. The equation for estimating  $K_s$  was expressed as:

$$K_s = \begin{cases} 1, & NDVI \geq NDVI_{90} \\ NDVI / NDVI_{90}, & NDVI < NDVI_{90} \end{cases} \quad (6)$$

where  $K_s$  is the soil moisture correlation coefficient;  $NDVI$  is the NDVI value of any pixel;  $NDVI_{90}$  is the NDVI value of the pixel when the cumulative frequency is up to 90%.

## 2.5 Estimation of net irrigation water consumption

The concept of soil water balance provides a framework for studying the hydrological behavior. The equation of soil water balance was as follows:

$$ET = P + I - \Delta SWC - R - D \quad (7)$$

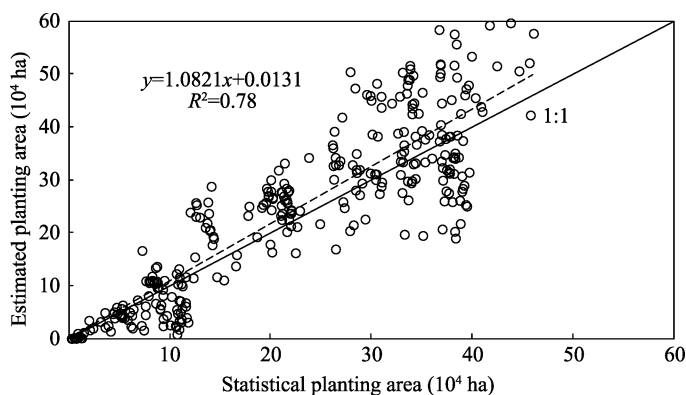
where  $ET$  is the actual crop ET (mm),  $P$  is the precipitation (mm),  $I$  is the irrigation (mm),  $\Delta SWC$  is the soil water change (mm),  $R$  is the surface runoff (mm) and  $D$  is the deep percolation (mm). It is generally considered that the surface water systems are limited in regions under severe water stress (Moiwo *et al.*, 2011). In fact, since the 1960s, surface runoff in the study area has dropped to a virtually negligible level (Fan *et al.*, 2010; Wu *et al.*, 2011). Under these hydrological conditions and the flat topography in the NCP, surface runoff can be ignored (Cao *et al.*, 2014). Soil water change can be measured through experiments at the field scale, but it is difficult to acquire soil water change at large spatial and temporal scales. In this paper, the average soil water change for multiple years in Luancheng station was used (Zhang *et al.*, 2018). Moreover,  $D$  can become the reused groundwater and it is difficult to obtain an accurate estimation (Yuan *et al.*, 2015). Therefore, the equation of the soil water balance can be simplified as follows, and the net irrigation water consumption ( $I_{net}$ ) can be calculated according to equation 8:

$$I - D = I_{net} = ET - P - \Delta SWC \quad (8)$$

## 3 Results and discussion

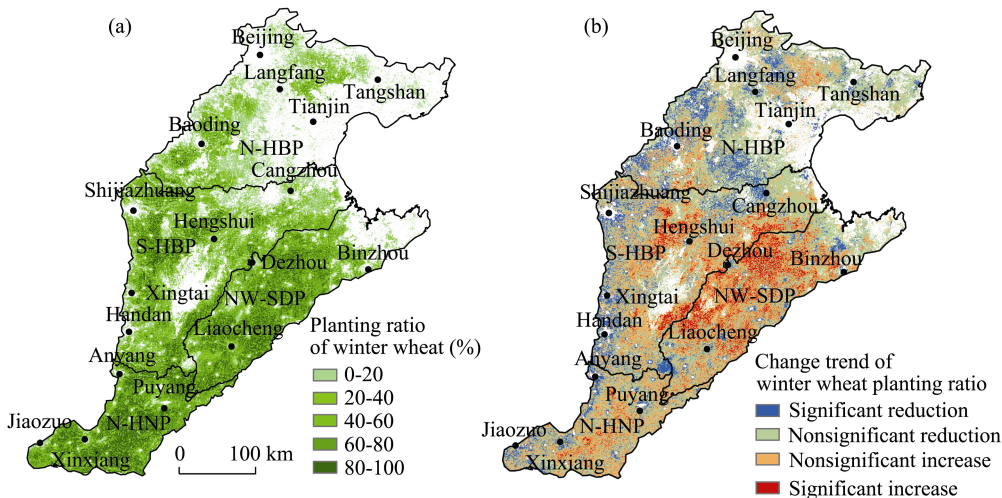
### 3.1 Validation and characteristics of planting area of winter wheat

To validate the estimated area of winter wheat, the statistical data were mainly used for comparison. In this study, the planting area of winter wheat at the city-level from the Statistical Yearbook was used. Figure 2 illustrated the correlation between the statistical and estimated planting area of winter wheat. The relative bias was 2.4%, and the root-mean-square error (RMSE) was  $7.7 \times 10^4$  ha. A regression analysis between estimated and statistical area was performed, and the Pearson correlation coefficient  $r$  was 0.88 ( $N = 314$ ,  $p < 0.001$ ). The estimated result had a good match with the statistical planting area. Consequently, the method to retrieve the planting area of winter wheat based on remote sensing data is acceptable.



**Figure 2** Correlation between estimated and statistical planting area of winter wheat in the North China Plain (2001–2015)

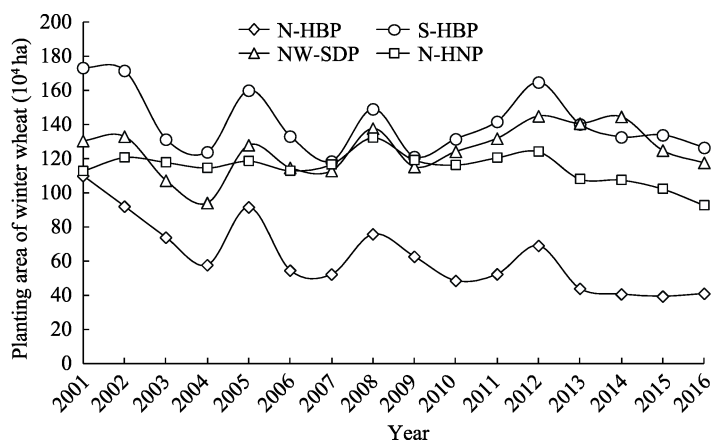
Figure 3a illustrated that average spatial distribution of winter wheat during 2001–2016. The result showed that the planting ratio of winter wheat in the south was higher than that in the north. Winter wheat was mainly distributed in the piedmont region of the Taihang Mountains and the irrigation district of the Yellow River Basin in Henan and Shandong provinces. In these two regions, the planting ratio of winter wheat was more than 80% because of good irrigation conditions. The planting ratio of winter wheat in Beijing and Tianjin City was less than 40% owing to more construction land, less arable land and the small proportion of primary industry. In coastal areas, planting ratio of winter wheat was less than 20% by reason of the saline soil. The planting ratio of winter wheat in the central plains was also low, mainly due to the sandy soil and high salinity of shallow groundwater. For these two reasons, the central plains are better suited for the cultivation of fruits (e.g., pear trees in Zhaoxian County of Shijiazhuang City, peach trees in Shenzhou City and jujube trees in Cangzhou city), peanuts (e.g., in Daming County of Handan City) and cotton (e.g., in Nan-gong and Qinghe counties of Xingtai City). Thus, water resources and soil conditions determined the spatial distribution of winter wheat.



**Figure 3** Spatial distribution (a) and change trend (b) of the winter wheat planting ratio in the North China Plain during 2001–2016

To analyze the spatial variation of the winter wheat planting area in the NCP, the change trend from 2001 to 2016 was calculated. Figure 3b showed that the planting area of winter wheat in most parts of the Northern Hebei Plain had a decreasing trend, and especially that in the cities of Langfang, Tianjin, Baoding, and Cangzhou had a significant decreasing trend. According to the field survey in August 2014, it was found that in Langfang and Tianjin, rural township enterprises were rather developed so that many farmers gave up the planting of winter wheat and worked there for a living. Additionally, many wells in these regions had no water, especially in Langfang. The irrigation water fee was so high that the economic benefit of planting winter wheat was low. While in Baoding, some counties have gradually developed nursery (e.g., Wangdu and Boye counties) and herbs (e.g., Anguo County) industries in the last decade. In the east of Shijiazhuang, north of Hengshui and in most parts of the Shandong Plain, especially in Dezhou, the planting ratio of winter wheat had a remarkable increasing trend. This was mostly because farmers gradually shifted from planting sin-

gle cotton to the double cropping of winter wheat and summer maize in recent years. Dezhou is the main cotton production region in China and has a cotton cultivation history of many years. However, the planting and management of cotton needs more labor than that of winter wheat and summer maize because it is difficult to plant and pick up cotton mechanically. Then, a cotton planter can only be kept in cotton fields all the year round. In addition, the net economic benefit of planting winter wheat and summer maize is higher than single cotton. Figure 4 illustrates the changes of the winter wheat planting area in the four parts of the NCP during 2001–2016. From the regional scale, the winter wheat planting area in the Northern Hebei Plain had a decreasing trend and declined from  $84.7 \times 10^4$  ha during 2001–2005 to  $46.5 \times 10^4$  ha during 2012–2016, a decrease of 45.1%. While the winter wheat planting area in the Southern Hebei Plain also had a decreasing trend and declined from  $151.7 \times 10^4$  ha during 2001–2005 to  $139.3 \times 10^4$  ha during 2012–2016, a decrease of 8.2%. While the winter wheat planting area in the Northwestern Shandong Plain had a slightly increasing trend and increased from  $118.3 \times 10^4$  ha during 2001–2005 to  $134.3 \times 10^4$  ha during 2012–2016. The winter wheat planting area in the Northern Henan Plain had a slightly decreasing trend and decreased by 8.5%.



**Figure 4** Change of winter wheat planting area in the four parts of the North China Plain during 2001–2016

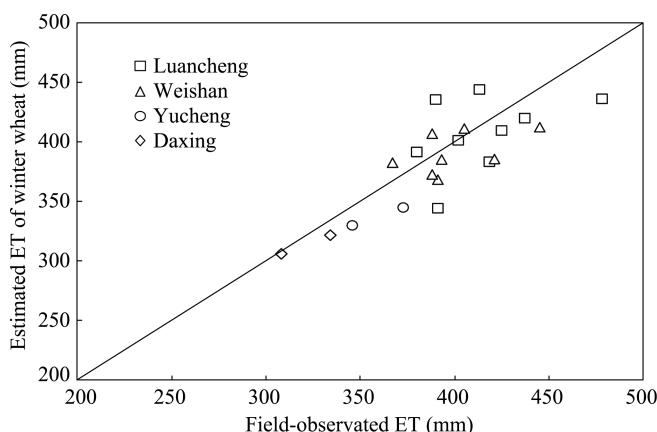
### 3.2 Evaluation of ET model performance and characteristics of winter wheat ET

Winter wheat ET from 2001 to 2016 in the NCP was estimated based on the proposed model. The estimated ET was compared with field-observed ET of the winter wheat growing season at Luancheng, Weishan, Yucheng, and Daxing stations (Figure 5). The relative error of each sample between estimated and field-observed ET varied from 0.2%–12%. The mean absolute deviation between estimated and field-observed ET was 21.5 mm, the relative bias was –2.2% and the RMSE was 25.5 mm. Therefore, the proposed ET estimation model performed well in the study area. Thus, the method for estimating crop water consumption based on the Penman-Monteith method and remote sensing data is acceptable.

Combined with the planting ratio of winter wheat, the spatial distribution of the average ET contribution of winter wheat from 2001 to 2016 in the NCP is shown in Figure 6a. Winter wheat ET was higher in the piedmont regions of the Taihang Mountains and the irrigation district of the Yellow River Basin in Henan and Shandong provinces, and relatively lower in the northern and central parts of the Hebei Plain. Winter wheat ET was more than 350 mm in

the piedmont regions of the Taihang Mountains because of good soil texture, climatic conditions, and excellent irrigation conditions, while winter wheat ET in the northern and central Hebei Plain was less than 350 mm because spring maize (e.g., in Langfang), jujube trees (e.g., in Cangzhou) and cotton (e.g., in Xingtai) were the main crops. In addition, winter wheat ET was less than 300 mm in coastal areas because of the saline-alkali land.

Based on the planting area of winter wheat, the amount of water consumption of winter wheat was calculated in the NCP. The average water consumption of winter wheat during 2001–2016 was  $20.5 \times 10^8 \text{ m}^3$  in the Northern Hebei Plain,  $49.7 \times 10^8 \text{ m}^3$  in the Southern Hebei Plain,  $48.5 \times 10^8 \text{ m}^3$  in the Northwest Shandong Plain, and  $46.5 \times 10^8 \text{ m}^3$  in the Northern Henan Plain, respectively. Moreover, the water consumption of winter wheat in the Northern Hebei Plain decreased from  $29.7 \times 10^8 \text{ m}^3$  during 2001–2005 to  $12.2 \times 10^8 \text{ m}^3$  during 2012–2016, a decrease of 56.0%. The water consumption of winter wheat in the Southern Hebei Plain also had a downward trend and decreased from  $55.1 \times 10^8 \text{ m}^3$  during 2001–2005 to  $45.9 \times 10^8 \text{ m}^3$  during 2012–2016. The reduction in the winter wheat planting area was one of the reasons for the decrease in water consumption of winter wheat in the Northern Hebei Plain and Southern Hebei Plain. Water consumption of winter wheat in the Northwest Shandong Plain had a slight increase, and that of the Northern Henan Plain had a slight reduction.

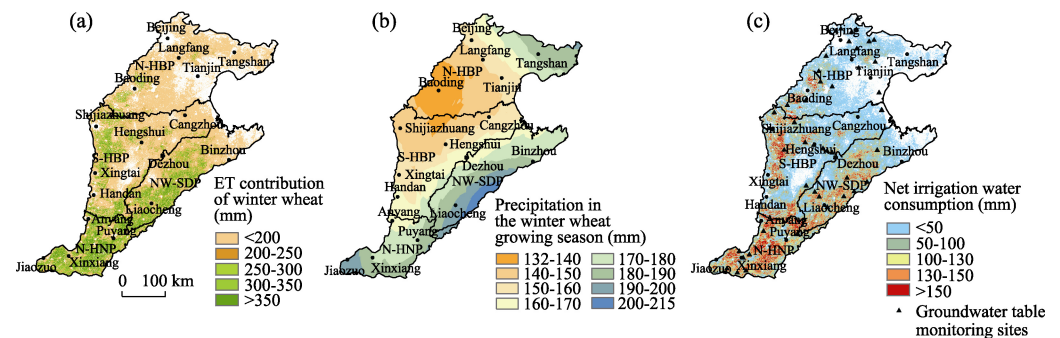


**Figure 5** Comparison of estimated and field-observed ET of the winter wheat growing season at Luancheng (2007–2016), Weishan (2005–2013<sup>a</sup>), Yucheng (2003–2005) and Daxing stations (2008–2010) (<sup>a</sup> Field observed ET data during 2007.11.13–2008.02.29 were missing and winter wheat ET during 2007–2008 was not included in this figure)

### 3.3 Characteristics of net irrigation water consumption of winter wheat

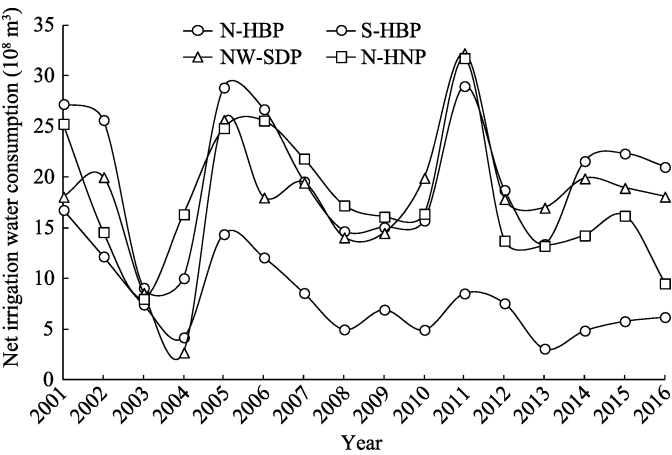
The above characteristics of winter wheat ET were analyzed (Figure 6a). Based on precipitation and equation 8, the net irrigation water consumption (Figure 6c) in the winter wheat growing season during 2001–2016 was calculated. Figure 6b showed the spatial distribution of average precipitation in the winter wheat growing season from 2001 to 2016. Precipitation in the winter wheat growing season in the NCP increased from 132 mm in the northwest to 215 mm in the southeast. In the piedmont regions of the Taihang Mountains, precipitation was less than 180 mm and these regions need irrigation of approximately 150 mm. In most parts of the Northern Hebei Plain and Southern Hebei Plain, precipitation in the winter wheat growing season was approximately less than 170 mm, and these regions need the irrigation of less than 100 mm. Compared with the Hebei Plain, precipitation in the Northwest

Shandong Plain and Northern Henan Plain was relatively higher and ranged from 170 mm to 215 mm. In the irrigation district of the Yellow River Basin in Henan and Shandong provinces, net irrigation water consumption was more than 150 mm.



**Figure 6** Spatial distribution of ET contribution of winter wheat (a), precipitation (b) and net irrigation water consumption (c) in the winter wheat growing season in the North China Plain (2001–2016)

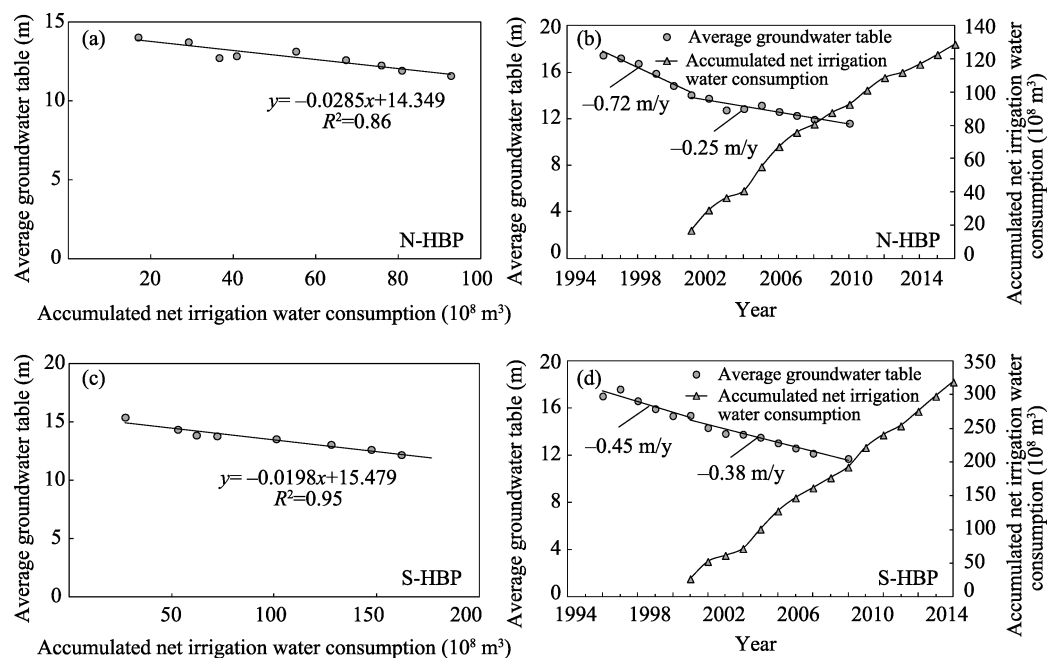
Based on the planting area of winter wheat, net irrigation water consumption in the four parts from 2001 to 2016 was estimated (Figure 7). The average net irrigation water consumption from 2001 to 2016 was up to  $8.0 \times 10^8 \text{ m}^3$  in the Northern Henan Plain,  $19.9 \times 10^8 \text{ m}^3$  in the Southern Henan Plain,  $17.8 \times 10^8 \text{ m}^3$  in Northwestern Shandong Plain and  $17.8 \times 10^8 \text{ m}^3$  in the Northern Henan Plain, respectively. The net irrigation water consumption in the Northern Hebei Plain had a decreasing trend and decreased from  $11.0 \times 10^8 \text{ m}^3$  during 2001–2005 to  $5.5 \times 10^8 \text{ m}^3$  during 2012–2016. The net irrigation water consumption in the Southern Hebei Plain decreased from  $20.2 \times 10^8 \text{ m}^3$  during 2001–2005 to  $19.4 \times 10^8 \text{ m}^3$  during 2012–2016. The net irrigation water consumption in the Northwestern Shandong Plain changed from  $15.0 \times 10^8 \text{ m}^3$  during 2001–2005 to  $18.3 \times 10^8 \text{ m}^3$  during 2012–2016 and that of the Northern Henan Plain changed from  $17.8 \times 10^8 \text{ m}^3$  during 2001–2005 to  $13.4 \times 10^8 \text{ m}^3$  during 2012–2016.



**Figure 7** Change in net irrigation water consumption for the winter wheat growing season in the four parts of the North China Plain during 2001–2016

During the winter wheat growing season, approximately 4–5 times of irrigations of 60–80 mm from groundwater are used to offset the water deficit (Sun *et al.*, 2010). The drops in the groundwater table in the NCP mainly occurred during the winter wheat growing season due

to the extraction of groundwater for irrigation (Luo *et al.*, 2018). Therefore, the relationship between net irrigation water consumption and the change in the groundwater table was performed and groundwater table data were collected in the four parts of the NCP. The distribution of groundwater table monitoring sites is shown in Figure 6c. Figure 8 illustrates the relationship between the average groundwater table and accumulated net irrigation water consumption in the Northern Hebei Plain and Southern Hebei Plain of the NCP. The total net irrigation water consumption of winter wheat during 2001–2016 was up to  $12.8 \times 10^9 \text{ m}^3$  in the Northern Hebei Plain and  $31.9 \times 10^9 \text{ m}^3$  in the Southern Hebei Plain. The result (Figures 8a and 8c) showed that there was a significant negative correlation between the groundwater table and accumulated net irrigation water consumption in the Northern Hebei Plain and Southern Hebei Plain. In these two regions, with the increase of the accumulated net irrigation water consumption, the groundwater table dropped. This result implied that water consumption for winter wheat production had a significant impact on groundwater resources. During 2001–2010, the average groundwater table in the Northern Hebei Plain declined from 14.1 m to 11.6 m, and the total net irrigation water consumption was up to  $9.3 \times 10^9 \text{ m}^3$ , while the average groundwater table in the Southern Hebei Plain declined from 15.4 m to 11.7 m in 2010, and the total net irrigation water consumption accounted for  $19.2 \times 10^9 \text{ m}^3$  during 2001–2010. Before 2001, the rate of decline of the groundwater table in the Northern Hebei Plain was 0.72 m/a, while after 2001, that of the Northern Hebei Plain decreased to 0.25 m/a. Likewise, the rate of decline of the groundwater table in the Southern Hebei Plain decreased from 0.45 m/a to 0.38 m/a. The net irrigation water consumption in the Northern Hebei Plain had a significant decreasing trend and decreased from  $16.8 \times 10^8 \text{ m}^3$  in 2001 to  $5.0 \times 10^8 \text{ m}^3$  in 2010, while the net irrigation water consumption of the Southern Hebei Plain also had a decreasing trend and decreased from  $27.2 \times 10^8 \text{ m}^3$  in 2001 to

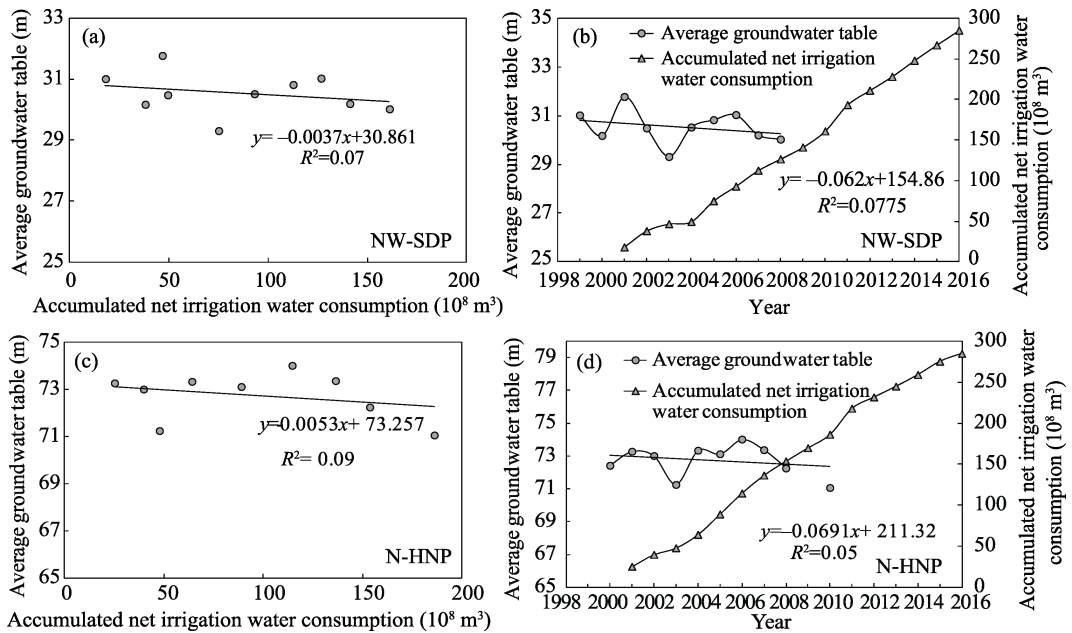


**Figure 8** The relationship between the average groundwater table and accumulated net irrigation water consumption (a, c), and the change of average groundwater table and accumulated net irrigation water consumption (b, d) in the Northern Hebei Plain and Southern Hebei Plain

$15.7 \times 10^8$  in 2010.

According to the results mentioned above, the planting area of winter wheat had a decreasing trend from 2001 to 2016 in the Northern Hebei Plain and Southern Hebei Plain, and at the same time, the rate of decline of the groundwater table in these two regions before and after 2001 both decreased to different extents (Figure 8). Thus, in the Hebei Plain, the decrease of planting area of winter wheat can reduce water withdrawals and has a positive effect on the protection of groundwater resources. It was found that the main factor leading to the decline of the groundwater table was the expanding area of winter wheat (Hu *et al.*, 2002). Moreover, Kendy *et al.* (2004) reported that the only means to reduce net water consumption for agriculture is to reduce crop ET, and this can be accomplished by reducing the crop area. Shen *et al.* (2013b) had the same suggestion, that shifting the winter wheat-summer maize double cropping to single maize could be expected to reduce water pumping for irrigation significantly. Wang *et al.* (2014) found that the water resources conserved owing to the reduction in sown area of winter wheat in the Hebei Plain during 1998–2010 were approximately  $15.96 \times 10^8 \text{ m}^3/\text{a}$ . Pei *et al.* (2015) also suggested that switching crop rotations from double-cropping wheat and corn to single cropping corn with an extended growing season in the NCP might achieve similar yields and would reduce irrigation demand. In addition, the Chinese government has attempted to propose some policies to solve the problem of exploitation of groundwater in Hebei Province since 2014. Accordingly, in the large groundwater depression zones (including Cangzhou, Hengshui, Xingtai and Handan), the ‘one season fallow, one season rain-fed’ policy was proposed. This policy was put forward due to the high irrigation water consumption of winter wheat, and it suggested that winter wheat should not be planted. In addition, spring maize, potatoes, and beans were proposed for cultivation. According to this policy, each hectare of land can save 2700–3000  $\text{m}^3$  of water. At the same time, to guarantee the economic benefit for farmers in these experimental regions, farmers can receive a subsidy of 7500 yuan per hectare per year. Through these efforts, the reduction in amount of groundwater extraction was up to  $2.2 \times 10^8 \text{ m}^3$  in 2016.

Compared with changes of the groundwater table in the Northern Hebei Plain and Southern Hebei Plain, there was no significant correlation between average groundwater table and accumulated net irrigation water consumption in the Northwestern Shandong Plain and Northern Henan Plain (Figures 9a and 9c). In these two regions, with the increase of accumulated net irrigation water consumption of winter wheat during 2001–2010, the groundwater table had no significant declining trend. The Yellow River is the main irrigation water resource in these two regions; thus, the groundwater table had no continuous decreasing trend. Moreover, the total net irrigation water consumption during 2001–2016 in the Northwestern Shandong Plain and in the Northern Henan Plain was both up to  $28.5 \times 10^9 \text{ m}^3$ . According to the statistical data for 2003–2010 from the Yellow River Conservancy Commission, the average extracted agricultural water of the Northern Henan Plain from Yellow River was approximately  $12.5 \times 10^8 \text{ m}^3$ , and this amount of water accounted for 96% of the total extracted water from the Yellow River. In the Northwestern Shandong Plain, the average extracted agricultural water from the Yellow River was about  $27.7 \times 10^8 \text{ m}^3$ , and this amount of water accounted for 94% of the total extracted water from the Yellow River. Consequently, water resources from the Yellow River can supply irrigation for agriculture and sometimes alleviate the decline of the groundwater table in the irrigation district of the



**Figure 9** The relationship between the average groundwater table and accumulated net irrigation water consumption (a, c), and change of the average groundwater table and accumulated net irrigation water consumption (b, d) in the Northwestern Shandong Plain and Northern Henan Plain

Yellow River Basin in Henan and Shandong provinces. Water withdrawal from the lower reaches of the Yellow River started in the 1970s. Owing to the lack of rainfall, little runoff and human activities (Chen *et al.*, 2004), the lower reaches of the Yellow River have dried up since 1972 (Wu *et al.*, 1998). After 2000, there was no cutoff in the lower reaches of the Yellow River. However, in drought years and peak periods of agricultural irrigation, irrigation from the lower reaches of the Yellow River is not sufficient, and agricultural irrigation mainly relies on groundwater resources. From the long-term development of agriculture, it is also crucial to decrease the planting area of winter wheat in the irrigation district of the Yellow River Basin in Henan and Shandong provinces. In addition, since the Yellow River is the transit water and it cannot meet the needs for agricultural irrigation water in terms of time and amount, some plain reservoirs should be constructed. These reservoirs can retain water in the wet season and provide water in the drought season, then it can greatly alleviate the water stress from agriculture (Bian *et al.*, 2009). At the same time, a scientific and reasonable water price formation mechanism should be established so that farmers' awareness of water-saving irrigation can be improved (Pan *et al.*, 2010).

## 4 Conclusions

Water shortages have become a major limiting factor for the sustainable development of agriculture in the NCP. Winter wheat is the main cultivated crop, and irrigation for high yields is a threat to groundwater resources. To clarify how changes in the winter wheat planting area affect groundwater depletion, the winter wheat planting area was retrieved by using MODIS data. In addition, a method to combine the FAO Penman-Monteith equation with remote sensing data was developed to calculate the actual crop ET. The following conclusions were obtained:

- (1) There was good correlation between the estimated and statistical planting area of win-

ter wheat. The actual crop ET estimation model performed well for the estimation of crop water consumption in the NCP. The error of each sample between the estimated and field-observed ET was less than 12.0%. The average relative error between the estimated ET and field-observed ET was  $-2.2\%$ . Moreover, the proposed ET estimation method needs only the meteorological data and remotely sensed vegetation index and its implementation is quite simple.

(2) The planting area of winter wheat had a decreasing trend in the Hebei Plain. The water consumption of winter wheat also had a declining trend from 2001 to 2016 in the Hebei Plain. In addition, based on precipitation and the water balance equation, the net irrigation water consumption in the winter wheat growing season during 2001–2016 was calculated. Precipitation in the growing season of winter wheat was insufficient, and most areas of the NCP need irrigation. In the Northern Hebei Plain and Southern Hebei Plain, groundwater resources are the main source of irrigation. There was a significant correlation between accumulated net irrigation water consumption and the groundwater table in these two regions.

(3) The total net irrigation water consumption in the Northern Hebei Plain during 2001–2010 was up to  $9.3 \times 10^8 \text{ m}^3$ , and the groundwater table declined from 14.3 m to 10.6 m. The total net irrigation water consumption in the Southern Hebei Plain accounted for  $19.2 \times 10^8 \text{ m}^3$  during 2001–2010, and groundwater table decreased from 15.4 m to 11.7 m. Before and after 2001, the rate of decline of the groundwater table in the Northern Hebei Plain and Southern Hebei Plain had a significant declining trend. Therefore, it is necessary to decrease the planting of winter wheat in the Hebei Plain so as to alleviate the decline of the groundwater table, and consequently to guarantee the sustainable development of agricultural water resource. In the Northwest Shandong Plain and Northern Henan Plain, because of the water supply from the Yellow River, there was no significant correlation between accumulated net irrigation water consumption and the groundwater table.

(4) Because of the good consistency between estimated and field-observed ET, the ET estimation model can be applied to other regions where meteorological and remote sensing data are available.

Moreover, this method can also be applied to other related studies such as the estimation of water use efficiency and water footprint. In the future, the temporal scale of the ET estimation model should be extended by using the other related remote sensing data of high temporal resolution, such as the Normalized Difference Water Index (NDWI) obtained from surface reflectance products (8 days) or soil moisture products (daily) based on the Advanced Microwave Scanning Radiometer for EOS (AMSR-E) sensor.

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## References

- Adegoke J O, Carleton A M, 2002. Relations between soil moisture and satellite vegetation indices in the US Corn Belt. *Journal of Hydrometeorology*, 3(4): 395–405.
- Allen R G, Clemmens A J, Burt C M *et al.*, 2005. Prediction accuracy for projectwide evapotranspiration using crop coefficients and reference evapotranspiration. *Journal of Irrigation and Drainage Engineering*, 131(1): 24–36.
- Allen R G, Pereira L S, Raes D *et al.*, 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Re-

- quirements. FAO Irrigation and Drainage Paper 56. FAO, Rome, Italy.
- Bian S Z, Guo F, Si C S, 2009. Reflections on the development of irrigation in the lower Yellow River. *Yellow River*, 31(11): 81–82. (in Chinese)
- Cao G, Cun Y S, Meng J, 2007. The effect of irrigation systems in spring on grain yield of winter wheat. *Chinese Agricultural Science Bulletin*, 23(3): 466–468. (in Chinese)
- Cao G L, Han D M, Song X F, 2014. Evaluating actual evapotranspiration and impacts of groundwater storage change in the North China Plain. *Hydrological Processes*, 28(4): 1797–1808.
- Cao G L, Zheng C M, Scanlon B R *et al.*, 2013. Use of flow modeling to assess sustainability of groundwater resources in the North China Plain. *Water Resources Research*, 49(1): 159–175.
- Chen J Y, Fukushima Y, Tang C Y *et al.*, 2004. Water environmental problems occurred in the lower reach of the Yellow River. *Journal of Japan Society of Hydrology & Water Resources*, 17(5): 555–564.
- Cihlar J, Laurent L S, Dyer J A, 1991. Relation between the normalized difference vegetation index and ecological variables. *Remote Sensing of Environment*, 35(2/3): 279–298.
- Deng X P, Shan L, Zhang H P *et al.*, 2006. Improving agricultural water use efficiency in arid and semiarid areas of China. *Agricultural Water Management*, 80(1–3): 23–40.
- Duan A W, Sun J S, Liu Y *et al.*, 2004. Irrigation Water Quota of Main Crops in Northern China. Beijing: China Agricultural Science & Technology Press, 52–60. (in Chinese)
- Fan J, Tian F, Yang Y *et al.*, 2010. Quantifying the magnitude of climate and human effect on runoff decline in Mian River Basin via SWAT model. *Water Science and Technology: Water Supply*, 62(4): 783–791.
- Fogg G E, LaBolle E M, 2006. Motivation of synthesis, with an example on groundwater quality sustainability. *Water Resources Research*, 42(3): W03S05. doi: 10.1029/2005WR004372.
- Gao C R, Yin X L, 2011. China Geo-Environment Monitoring Yearbook on Groundwater in 2010. Beijing: China Land Press. (in Chinese)
- Gutman G, Ignatov A, 1998. The derivation of the green vegetation fraction from NOAA/AVHRR data for use in numerical weather prediction models. *International Journal of Remote Sensing*, 19(8): 1533–1543
- Hayes M J, Decker W L, 1996. Using NOAA AVHRR data to estimate maize production in the United States Corn Belt. *International Journal of Remote Sensing*, 17(16): 3189–3200.
- Hu C S, Zhang X Y, Cheng Y S *et al.*, 2002. An analysis on dynamics of water table and overdraft in the piedmont of Mt. Taihang. *System Sciences and Comprehensive Studies in Agriculture*, 18(2): 89–91. (in Chinese)
- Jia J S, Liu C M, 2002. Groundwater dynamic drift and response to different exploitation in the North China plain: A case study of Luancheng County, Hebei Province. *Acta Geographica Sinica*, 57(2): 201–209. (in Chinese)
- Jia Z Z, Liu S M, Xu Z W *et al.*, 2012. Validation of remotely sensed evapotranspiration over the Hai River Basin, China. *Journal of Geophysical Research: Atmospheres*, 117(D13). doi: 10.1029/2011JD017037.
- Jin M G, Zhang R Q, Gao Y F, 1999. Temporal and spatial soil water management: A case study in the Heilonggang region, PR China. *Agricultural Water Management*, 42(2): 173–187.
- Kendy E, Zhang Y Q, Liu C M *et al.*, 2004. Groundwater recharge from irrigated cropland in the North China Plain: Case study of Luancheng County, Hebei Province, 1949–2000. *Hydrological Processes*, 18(12): 2289–2302.
- Konikow L F, 2011. Contribution of global groundwater depletion since 1900 to sea-level rise. *Geophysical Research Letters*, 38(17): L17401. doi: 10.1029/2011GL048604.
- Lei H M, Gong T T, Zhang Y C *et al.*, 2018. Biological factors dominate the interannual variability of evapotranspiration in an irrigated cropland in the North China Plain. *Agricultural and Forest Meteorology*, 250/251(15): 262–276.
- Lei H M, Yang D W, 2010. Interannual and seasonal variability in evapotranspiration and energy partitioning over an irrigated cropland in the North China Plain. *Agricultural and Forest Meteorology*, 150(4): 581–589.
- Li H J, Zheng L, Lei Y P *et al.*, 2008. Estimation of water consumption and crop water productivity of winter wheat in North China Plain using remote sensing technology. *Agricultural Water Management*, 95(11): 1271–1278.
- Li Q Q, Zhou X B, Chen Y H *et al.*, 2012. Water consumption characteristics of winter wheat grown using different planting patterns and deficit irrigation regime. *Agricultural Water Management*, 105: 8–12.
- Lin Y M, Ren H Z, Yu J J *et al.*, 2000. Balance between land use and water resources in the North China Plain. *Journal of Natural Resources*, 15(3): 252–258. (in Chinese)
- Liu C M, Wei Z Y, 1989. Agricultural Hydrology and Water Resources in the North China Plain. Beijing: Science Press. (in Chinese)
- Liu C M, Yu J J, Eloise K, 2001. Groundwater exploitation and its impact on the environment in the North China Plain. *Water International*, 26(2): 265–272.
- Liu C M, Zhang X Y, Zhang Y Q, 2002. Determination of daily evaporation and evapotranspiration of winter wheat and maize by large-scale weighing lysimeter and micro-lysimeter. *Agricultural and Forest Meteorology*, 111(2): 109–120.
- Liu S M, Xu Z W, 2013. Multi-scale surface flux and meteorological elements observation dataset in the Hai River Basin (Daxing site-eddy covariance system), Cold and Arid Regions Science Data Center at Lanzhou, doi: 10.3972/haihe.005.2013.db.
- Liu S M, Xu Z W, Zhu Z L *et al.*, 2013. Measurements of evapotranspiration from eddy-covariance systems and large aperture scintillimeters in the Hai River Basin, China. *Journal of Hydrology*, 487(22): 24–38.
- Luo J M, Shen Y J, Qi Y Q *et al.*, 2018. Evaluating water conservation effects due to cropping system optimization on the Beijing-Tianjin-Hebei plain, China. *Agricultural Systems*, 159: 32–41.

- Mo X G, Liu S X, Lin Z H *et al.*, 2005. Prediction of crop yield, water consumption and water use efficiency with a SVAT-crop growth model using remotely sensed data on the North China Plain. *Ecological Modelling*, 183(2/3): 301–322.
- Moiwo J P, Yang Y H, Yan N N *et al.*, 2011. Comparison of evapotranspiration estimated by ETWatch with that derived from combined GRACE and measured precipitation data in Hai River Basin, North China. *Hydrological Sciences Journal*, 56(2): 249–267.
- Pan Y H, Zhang C Y, Li Q C, 2010. Study on the necessity of water-saving irrigation in the lower Yellow River. *Yellow River*, 32(5): 64–65. (in Chinese)
- Pei H W, Min L L, Qi Y Q *et al.*, 2017. Impacts of varied irrigation on field water budgets and crop yields in the North China Plain: Rainfed vs. irrigated double cropping system. *Agricultural Water Management*, 190: 42–54.
- Pei H W, Scanlon B R, Shen Y J *et al.*, 2015. Impacts of varying agricultural intensification on crop yield and groundwater resources: Comparison of the North China Plain and US High Plains. *Environmental Research Letters*, 10: 044013.
- Shahid S, 2011. Impact of climate change on irrigation water demand of dry season Boro rice in northwest Bangladesh. *Climatic Change*, 105 (3/4): 433–453.
- Shen Y J, Kondoh A, Tang C Y *et al.*, 2002. Measurement and analysis of evapotranspiration and surface conductance of a wheat canopy. *Hydrological Processes*, 16(11): 2173–2187.
- Shen Y J, Li S, Chen Y N *et al.*, 2013a. Estimation of regional irrigation water requirement and water supply risk in the arid region of Northwestern China 1989–2010. *Agricultural Water Management*, 128: 55–64.
- Shen Y J, Zhang Y C, Scanlon, B R *et al.*, 2013b. Energy/water budgets and productivity of the typical croplands irrigated with groundwater and surface water in the North China Plain. *Agricultural and Forest Meteorology*, 181: 133–142.
- Shu Y Q, Stisen S, Jensen K H *et al.*, 2011. Estimation of regional evapotranspiration over the North China Plain using geostationary satellite data. *International Journal of Applied Earth Observation and Geoinformation*, 13(2): 192–206.
- Sophocleous M, 2002. Interactions between groundwater and surface water: The state of the science. *Hydrogeology Journal*, 10(1): 52–67.
- Sun H Y, Shen Y J, Yu Q *et al.*, 2010. Effect of precipitation change on water balance and WUE of the winter wheat-summer maize rotation in the North China Plain. *Agricultural Water Management*, 97(8): 1139–1145.
- Sun H Y, Zhang X Y, Chen S Y *et al.*, 2011. Analysis of field water consumption, its pattern, impact and driving factors. *Chinese Journal of Eco-Agriculture*, 19(5): 1032–1038. (in Chinese)
- Wang X, Li X B, Xin L J, 2014. Impact of the shrinking winter wheat sown area on agricultural water consumption in the Hebei Plain. *Journal of Geographical Sciences*, 24(2): 313–330.
- Wang Y Y, Hu C S, Dong W X *et al.*, 2015. Carbon budget of a winter-wheat and summer-maize rotation cropland in the North China Plain. *Agriculture, Ecosystems & Environment*, 206: 33–45.
- Wu G H, Chen S R, Su R X *et al.*, 2011. Temporal trend in surface water resources in Tianjin in the Haihe River Basin, China. *Hydrological Processes*, 25(13): 2141–2151.
- Wu K, Xie X Q, Tang D Y, 1998. The causes of formation, the regularities, the effect estimation to the periphery agricultural production and the ecological environment and the countermeasures of the absence of flow in the Huanghe River. *Progress in Geography*, 17: 78–84. (in Chinese)
- Yang J Y, Mei X R, Yan C R *et al.*, 2010. Study on spatial pattern of climatic resources in North China. *Chinese Journal of Agrometeorology*, 31(Suppl.): 1–5. (in Chinese)
- Yang W, Yang L, Merchant J W, 1997. An assessment of AVHRR/NDVI-ecoclimatological relations in Nebraska, USA. *International Journal of Remote Sensing*, 18(10): 2161–2180.
- Yu G R, Fu Y L, Sun X M *et al.*, 2006a. Recent progress and future direction of ChinaFLUX. *Science in China Series D: Earth Sciences*, 49 (Suppl. II): 1–23.
- Yu G R, Sun X M *et al.*, 2006. Principles of Flux Measurement in Terrestrial Ecosystems. Beijing: Higher Education Press, 1–508.
- Yu G R, Wen X F, Sun X M *et al.*, 2006b. Overview of ChinaFLUX and evaluation of its eddy covariance measurement. *Agricultural and Forest Meteorology*, 137(3/4): 125–137.
- Yu G R, Zhang L M, Sun X M *et al.*, 2008. Environmental controls over carbon exchange of three forest ecosystems in eastern China. *Global Change Biology*, 14(11): 2555–2571.
- Yu G R, Zhu X J, Fu Y L *et al.*, 2013. Spatial patterns and climate drivers of carbon fluxes in terrestrial ecosystems of China. *Global Change Biology*, 19(3): 798–810.
- Yuan Z J, Shen Y J, 2013. Estimation of agricultural water consumption from meteorological and yield data: A case study of Hebei North China. *Plos One*, 8(3): e58685. doi: 10.1371/journal.pone.0058685.
- Yuan Z J, Xie L Y, Zhang B W *et al.*, 2015. Agricultural irrigation water net consumption in the Hebei Plain. *South to North Water Transfers and Water Science & Technology*, 13(4): 780–784. (in Chinese)
- Zhang X Y, Pei D, Hu C S, 2003. Conserving groundwater for irrigation in the North China Plain. *Irrigation Science*, 21(4): 159–166.
- Zhang Y C, Lei H M, Zhao W G *et al.*, 2018. Comparison of the water budget for the typical cropland and pear orchard ecosystems in the North China Plain. *Agricultural Water Management*, 198: 53–64.
- Zhou L Y, Li W M, 2003. Effects of nitrogen on photosynthesis of wheat plant in a dryland. *Chinese Journal of Soil Science*, 34(3): 195–197. (in Chinese)