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Effects of shallow water tables on the water use and yield of winter wheat (*Triticum aestivum* L.) under rain-fed condition

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Abstract

The experiments were conducted to quantify the effects of shallow water tables on the water use and yield of winter wheat under rain-fed condition through lysimeter. The result showed that, under rain-fed condition, the seasonal groundwater contribution met more than 65% of the potential evapotranspiration of winter wheat with precipitation together as water table depth was within 40-150 cm. As water table was not deeper than 110 cm from ground, the water table contribution nearly met the entire water requirement of winter wheat with the total precipitation in winter wheat season. It was found that 150 cm was a desired depth for yield formation due to the full development of root and the high spike numbers when water table depth was not more than 150 cm. The water use efficiency and ground water use efficiency increased with the increase of water table depth, varying from 1.27 to 2.09 kg m^{-3} and from 1.45 to 2.95 kg m^{-3}, respectively. The water table contribution should be recognized as the predominant source of evapotranspiration when water table was very shallow (≤ 150 cm), and the irrigation and drainage system should be managed to maximize the WUE and yield of winter wheat by controlling water table at desired depth. This study helps to raise the yield of winter wheat and control shallow water tables.

Keywords: shallow water table, winter wheat, seasonal water use, yield.

Abbreviations: D- Deep percolation from the root zone to water table; e_a- Actual vapour pressure; e_s- Saturation vapour pressure; ET- Evapotranspiration; ET_0- Reference evapotranspiration; ET_a- Actual evapotranspiration; ET_c- Potential evapotranspiration; ET_{gw}- Water table contribution to actual evapotranspiration; G- Soil heat flux density; GWUE- Ground water use efficiency; K_c- Crop coefficient; Kr- Yield response factor to root dry weight density; R_n- Net radiation at the crop surface; T- Mean daily air temperature at 2 m height; u_2- Wind speed at 2 m height; WUE- Water use efficiency; W_{ra}- the average root dry weight density within 0-100 cm soil layer; W_{rm}- the maximum average root dry weight density within 0-100 cm soil layer, (g cm^{-3}).Y- Crop yield; Y_a- Actual yield in each year; Y_m- Maximum yield in each year; Δ- Slope vapour pressure curve; ΔW- Depletion in soil water storage in unsaturated zone; γ- Psychrometric constant.

Introduction

Capillary rise may be considered as an important contribution to agroproductivity (Beltrao et al., 1996). Under dry climate water table contribution to crop evapotranspiration may reduce or even completely eliminate irrigation requirements without compromising on crop yields (Pratharpar and Qureshi 1998; Nosetto et al., 2009). Shallow water table may have negative effects on crops also. If water table is too shallow, crop yield could decrease due to waterlogging and root anoxia (Nosetto et al., 2009). For example, in South and South-East Asia, excess moisture caused by shallow water table is the second most important production constraints for maize crop (Rathore et al., 1996). Improper irrigation would deteriorate the waterlogging condition (Bandyopadhyay and Mallick, 2003). When water table is very shallow, soil waterlogging limited the root growth of winter wheat due to the reduced oxygen concentration of the soil (Brisson et al., 2002). In general, water table contribution decreases with the increase of water table depth or irrigation quantity, or the reduction of irrigation spacing (Ayars et al., 2006). When water table is very shallow, irrigation may be eliminated to maximize water table contribution and avoid waterlogging problem. However, under the rain-fed condition, few literatures are available on the study on the groundwater use and the yield of winter wheat. The Yellow River is the second largest river in China, and flows through Shandong province, China. In the irrigation district of the Yellow River Basin in Shandong, the area with shallow water table is widely distributed due to the recharge from precipitation and irrigation practice. The average area with water table depth less than 2.5 m in the early period of flood is more than 8000 km^2. In the irrigation district, winter wheat is the predominant crop. The study on the effects of shallow water table on winter wheat helps to the improvement of the irrigation management in the irrigation district. The objectives of this paper are to: (1) quantify the seasonal groundwater contribution to the water use of winter wheat under rain-fed condition, and quantify the depth range within which water table contribution can meet the water requirement of winter wheat with precipitation together, and (2) evaluate the effects of shallow water tables on the root distribution in soil profile, the yield and its components of winter wheat under rain-fed condition, and (3) determine the effects of shallow water tables on the water use efficiency (WUE), ground water use efficiency (GWUE) under rain-fed condition.

Description of lysimeters

The experiment was conducted in Yucheng Comprehensive Experimental Station of Chinese Academy of sciences, at 116°36′E and 36°57′N, which is located at Yucheng City, Shandong Province, China. The annual mean temperature is 13.1 ℃ and precipiation is 600.0 mm (Liu and Luo, 2010). The average precipitation is about 150 mm in the growth season of winter wheat, which is far less than the water requirement of winter wheat, and the changing range of water table depth is from 50 to 300 cm (Luo et al., 2008). The crop evapotranspiration (ET) of winter wheat is low due to the low air temperature and small leaf area from sowing (early or mid October) to tillering stage (mid-March in next year). The ET begins to rise due to the increases of air temperature and leaf area since mid-March. In total 4 sets of lysimeters were involved in this study. Each lysimeter (Fig. 1) comprises the outside soil container and the inner water supply and drainage system. The soil container was installed 0.5 m apart from each other. Each soil container has an area of 1 m×1 m, depth of 1.9 m below ground, and height of 0.1 m above ground. Within the soil container, the lowest 0.3 m is a filter layer which is made of gravel and sand mixture for drainage. The soil surface is 0.1 m below the top of the soil container. A neutron probe tube was installed in the middle of each soil container for soil water content measurements. The original silt soil with a bulk density of 1.42 g cm^{-3} was filled above the filter layer. Its wilting point and field capacity are 0.07 and 0.32 cm^3 cm^{-3} respectively. A basement of 2.0 m in depth was constructed for installing the water supply and drainage systems and for observation. A drainage pipe was installed in the filter layer and connected to a Marriott bottle, through which the water table within the soil container is stabilized. The amount of water supplied to soil container can be measured by recording the change of water surface height in the water supplement bottle. The amount of water that drains out of soil container can be measured by the drainage tank. The water with electrical conductivity of 2.0 dS m^{-1} was supplied to the soil column in soil container by using Mariotte bottle. The daily water table contribution to crop water use was obtained by measuring the reduction of water depth in mariotte bottle, and the deep percolation from root zone to water table was obtained by measuring the water amount in a container which collects drainage water out of the pipe. The soil containers can be sheltered from precipitation.

Treatments

The experiments were conducted in 2004-2005 and 2009-2010 respectively. The planting crop was winter wheat (*triticum aestivum L.*) and the variety was Kenong 199 whose growing period length was about 240 days. The sowing date was October 14 in 2004 and October 13 in 2009 respectively. The planting density was 420 plants per square meter with the row spacing of 25 cm in 2004, and 270 plants per square meter with the row spacing of 20 cm in 2009. In the experimental periods, the treatments did not receive irrigation. The total precipitations were 122.9 and 224.3 mm in the growth seasons in 2004-2005 and 2009-2010 respectively. Four constant water tables were 70, 90, 110 and 150 cm from 23 March to 8 June in 2005, and 40, 70, 110 and 150 cm from 14 March to 14 June in 2010. The treatments received 122.9 mm precipitation during the growth season in 2004-2005. In the growth season in 2009-2010, the treatments received 69.3 mm precipitation before they were sheltered by canopy since 14 March in 2010. The daily precipitations and average temperatures in two growth seasons are shown in Fig. 2.

Measurements

The water table contribution to the actual evapotranspiration, ET_{gw}, was measured daily from 23 March to 8 June in 2005 and from 14 March to 14 June in 2010. Soil moisture was measured with neutron probe (CNC503B, China) at 5-7 day intervals, and in 10 cm increments from 10 to 120 cm deep into the soil profile. Meteorological data were measured in a standard weather station, and it was about 50 m distance from the lysimeters. Root samples were collected at 14 June 2010. Samples were collected in 10 cm increments to 100 cm depth using root auger with an inner diameter of 8 cm. Two samples were collected for each soil container, and one was on the centre of the cut stem of sampled wheat and another was from the mid-point between the rows. Samples were washed in nylon meshes to clean root as soon as possible. Root samples were dried in the oven at 75 ℃, and the root dry weights were measured with electronic balance. The sum of the root dry weight of two root samples in each depth was taken as the root dry weight of the depth. At harvest, 1000-seed weight, spike number, spike grain number and grain yield were measured.

Result and discussion

ET_a and seasonal ET_{gw}

The actual evapotranspiration ET_a and seasonal water table contribution ET_{gw} in two growth seasons are showed in Table 2. The potential evapotranspirations ET_c calculated by using the Eq. (2) for two seasons were 409.6 and 435.6 mm. In two seasons, ET_a, ET_{gw} and ET_a/ET_c declined with the increase of water table depth. The differences in ET_a among the treatments with different water table depths were mainly due to the differences of ET_{gw}. A linear relationship between water table depth and ET_{gw} has been regressed (R^2=0.76) with MS-Excel (Fig. 3). In the season in 2004-2005, there were small differences in ET_a and ET_a/ET_c among the treatments except T1 (150). The ET_a/ET_c were more than 97% in T1(70), T1(90) and T1(110). It indicated that the water available to winter wheat nearly met the crop water requirement through ET_{gw}. ET_{gw} was the dominant source of ET_a, and the ET_{gw}/ET_a varied from 66.9% to 83.4%. The maximum of ET_{gw} reached 341.5 mm when water table was at 70 cm depth. At 150 cm water table depth, the ET_{gw} decreased with 14.3% diminution of ET_a. The ET_a/ET_c in 2009-2010 was less than in 2004-2005, and varied from 7.9% to 35.0% reduction in ET_c in the treatments. This may be indicated water deficits due to less precipitation received in that season. However, 70.9% to 85.7% of groundwater contribution was added towards ET_a.

Root development and yield

Fig. 4 shows the distributions of root dry weight density in soil profile at harvest under different water table depths in 2010. The root dry weight within 0-100 cm layer increased with an increase in water table depth, and ranged from 54.78 to 185.06 g m^{-2}. T2(150) had the largest root dry matter weight, and produced 237.8% more root dry matter than T2(40). Tripathi and Mishra (1986) reported that avoiding irrigation caused shifting of the zone of peak root density downwards and concentration of roots near water table. It is similar with our result. The lower root dry matter of T2(40) mainly resulted from the restriction of water table on the downward penetration of root system. Fig. 4 shows that the root weight density decreased with the increase of the soil layer. The moisture was

Table 1. Development stages for winter wheat in 2004-2005 and 2009-2010 (days)

Year	Planting date	Cop growth stages				
		Initial	Development	Middle season	Late season	Total
2004~2005	2004/10/14	141	33	48	17	239
2009~2010	2009/10/13	141	33	48	22	244

Table 2. ET_a, ET_{gw} and ET_a/ET_c during two growth seasons in 2004-2005 and 2009-2010

Year	Treatment	ET_a (mm)	ET_{gw} (mm)	ET_{gw}/ET_a	ET_a/ET_c
2005	T1(70)	409.3	341.5	83.4%	99.9%
	T1(90)	400.0	301.1	75.3%	97.7%
	T1(110)	398.3	281.3	70.6%	97.2%
	T1(150)	350.5	234.5	66.9%	85.6%
2010	T2(40)	401.1	343.8	85.7%	92.1%
	T2(70)	337.8	270.5	80.1%	77.5%
	T2(110)	310.4	235.1	75.7%	71.3%
	T2(150)	283.2	200.9	70.9%	65.0%

nearly saturated in the vicinity of water table. Brisson et al. (2002) reported that root growth slowed down and stopped when oxygen concentration of the soil was below a critical value due to saturation. It explained why the root depths were not more than water table depth for T2(40) and T2(70). Under different water table conditions the yields and its components were presented in Table 3. The results suggested that, water table depth had notable effect on the yield of winter wheat. It was consistent with the finding in other studies which were under the irrigation condition. The maximum yields were 610.3 and 592.9 g m^{-2} in T1(150) and T2(150). When water table depth was not more than 150 cm, the yield of winter wheat increased with the increase of water table depth. The yield was 19.9%, 17.2% and 16.7% larger in T1(150) than T1(70), T1(90) and T1(110) respectively , and was 18.6%, 10.7%, 1.9% larger in T2(150) than T2(40), T2(70) and T2(110). The yield is primarily dependent on the environment in the root zone, root depth and sensitivity of crop for water (Kahlown et al., 2005). When water table was at 150 cm depth, the moisture condition in root zone was appropriate for the root development of winter wheat, and the fully development of the root system contributed to get a high yield. The yields of T1(70) and T1(110) were 4.9% and 10.1% lower than those of T2(70) and T2(110), while the yield of T1(150) was 2.9% higher than that of T2(150). Under shallower water table (e.g. 70 and 110 cm depth), the precipitation in 2005 might deteriorate the soil water environment of root zone and reduce the yields. Under deeper water table (e.g. 150 cm depth) which was favorable to the root development, the precipitation in 2005 might increase the available water for root uptake and the yield. However, though there were differences among the corresponding treatments between the two seasons, the increasing trends of yields with the increase of water table depth were similar. Waterlogging under shallow water table depth deteriorated the physiological and environmental conditions in the root zone, and was not conducive for crop growth and ultimately for yields (Kahlown and Azam, 2002). It explained why the yields of T1(70) and T2(40) were the lowest for both growth seasons respectively. From Table 3, it was observed that the yield increased with the spike number. Garcia et al. (2003) reported that spike number was the most important yield component for wheat. The results showed that spike number and spike grain number increased generally with the increase of water table depth. As indicated in Table 3, the spike number was 14.5% larger for T1(150) than T1(70) and 32.2% larger for T2(150) than T2(40). The spike grain number was 16.6% larger for T1(150) than T1(70) and 15.7% larger for T2(150) than T2(40). Cannell (1980) reported that 1000-seed weight dropped when waterlogging happened in booting and flower stage, which might explain why 1000-seed weight of T2(40) was the least one in 2010.

Water use efficiency

Table 4 shows water use efficiency and ground water use efficiency. It is clear that, for both growth seasons, WUE and GWUE increased with water table depth, varying from 1.27 to 2.09 kg m^{-3} and from 1.45 to 2.95 kg m^{-3}, respectively. The increase of water table depth resulted in the reduction of ET_a and ET_{gw}, and the increase of yield, WUE and GWUE. The WUE and GWUE in the season in 2009-2010 were higher than those in the season in 2004-2005. Compared with T2(70) and T2(110), the larger ET_a and ET_{gw} and smaller yield resulted in the lower WUE and GWUE for T1(70) and T1(110). Though the yield of T1(150) was 2.9% higher than that of T2(150), the accumulative ET_a and ET_{gw} of T1(150) were 23.8% and 16.7% lower than T2(150), respectively. Thereby, T1(150) had lower WUE and GWUE compared with T2(150). In addition, CV values indicated that the WUE and GWUE in 2005 had large variability than those in 2010.

Yield and root dry weight density relationship

From the experimental data of root dry weight and yield, it was found that the yield of winter wheat increased with the root dry weight in 0-100 cm layer. A relationship between the yield and the root dry weight density in 0-100 cm layer can be formulated as:

$$\left(1-\frac{Y_a}{Y_m}\right)=K_r\left(1-\frac{W_{ra}}{W_{rm}}\right) \qquad (6)$$

where Y_a is the actual yield in each year, (g m^{-2}); Y_m is the maximum yield in each year, (g m^{-2}); K_r is yield response factor to root dry weight density; W_{ra} is the average root dry weight

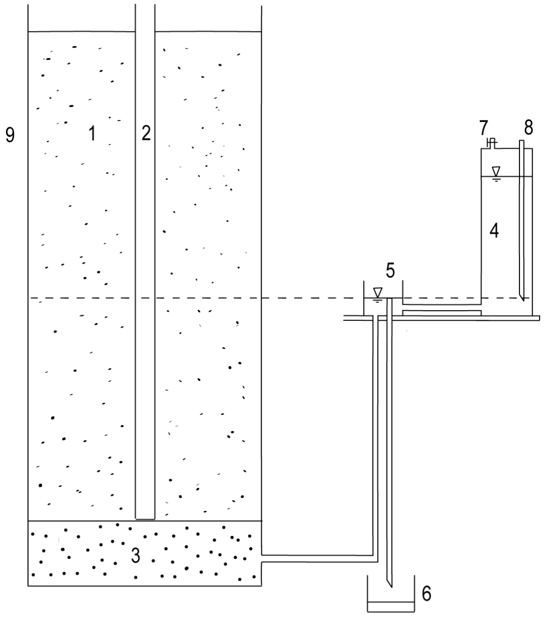

Fig 1. A description of the lysimeter used in the experiment
1- Filling soil 2- Al pipe 3- Filter bed 4- Water supplement bottle 5- Mariotte bottle 6- Drainge tank 7- Valve 8- Air inlet pipe 9- Soil container

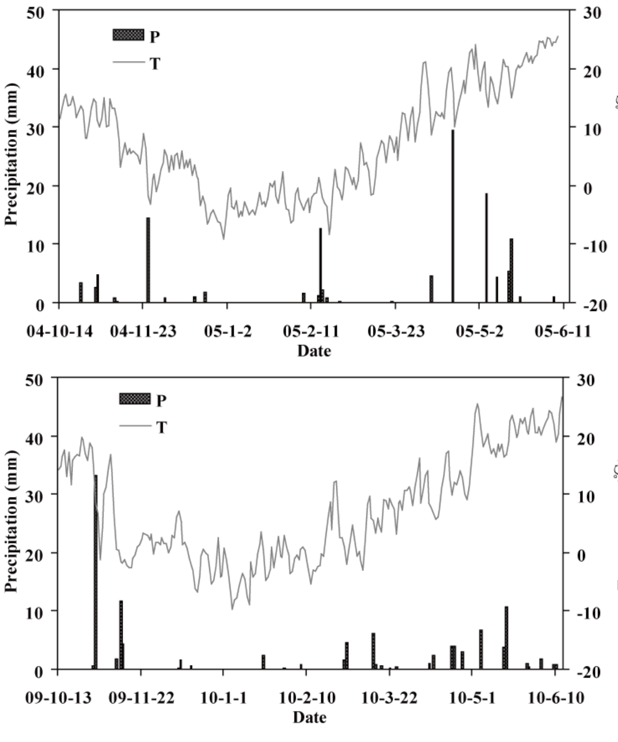

Fig 2. Daily precipitations and average temperatures in two growth seasons

density within 0-100 cm soil layer, (g cm^{-3}); W_{rm} is the maximum average root dry weight density within 0-100 cm soil layer, (g cm^{-3}).

In our study, the relationship between yield of winter wheat and the root dry weight density in 0-100 cm layer is expressed as:

$$\left(1-\frac{Y_a}{Y_m}\right)=4.904\left(1-\frac{W_{ra}}{W_{rm}}\right) \qquad R^2=0.615 \qquad D_{gw}\le 1.5m \tag{7}$$

Materials and methods

Actual evapotranspiration

The actual evapotranspiration was estimated using water balance equation:

$$ET_a = ET_{gw} + P - D - \Delta W \tag{1}$$

where ET_a is the actual evapotranspiration, (mm); ET_{gw} is the groundwater contribution to evapotranspiration measured by lysimeter, (mm); D is the deep percolation from the root zone to water table, (mm); ΔW is the depletion in soil water storage in unsaturated zone, (mm).

Potential evapotranspiration

The potential evapotranspiration ET_c was estimated by using the procedures described in FAO-56 (Allen et al., 1998).

$$ET_c = K_c ET_0 \tag{2}$$

where K_c is crop coefficient; ET_0 is reference evapotranspiration, (mm). According to the approach in FAO-56 (Allen et al., 1998), the growth season of crop can be divided into four growth stages, initial stage, development stage, mid-season stage and late season stage. The growth stages for winter wheat in 2004-2005 and 2009-2010 are listed in Table 1. The crop coefficients of winter wheat for initial, middle season and late season stage given by FAO-56 were 0.4, 1.15 and 0.4, and the given $K_{c\ mid}$ and $K_{c\ end}$ were adjusted for climatic conditions (Allen et al., 1998). The daily reference crop evaporation ET_0 was calculated using Penman-Monteith equation (Allen et al., 1998).

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}\mu_2(e_s - e_a)}{\Delta + \gamma(1+0.34\mu_2)} \tag{3}$$

where R_n is net radiation at the crop surface, (MJ m^{-2} day^{-1}); G is soil heat flux density, (MJ m^{-2} day^{-1}); T is mean daily air temperature at 2 m height, (ºC); u_2 is wind speed at 2 m height, (ms^{-1}); e_s is saturation vapour pressure, (kPa); e_a is actual vapour pressure, (kPa); es-ea is saturation vapour pressure deficit, (kPa); Δ is slope vapour pressure curve, (kPa $ºC^{-1}$); γ is psychrometric constant, (kPa $ºC^{-1}$).

Table 3. Yields and their components for the treatments.

Year	Treatments	1000-seed weight (g)	Spike number (spike m^{-2})	Spike grain number	Yield (g m^{-2})	
					Absolute value	Relative value
2005	T1(70)	/	265	509.2	509.2	83.4%
	T1(90)	/	272	520.6	520.6	85.3%
	T1(110)	/	270	523.1	523.1	85.7%
	T1(150)	/	310	610.3	610.3	100.0%
2010	T2(40)	35.14	425	500.0	500.0	84.3%
	T2(70)	40.56	451	535.5	535.5	90.3%
	T2(110)	37.67	473	582.0	582.0	98.2%
	T2(150)	38.97	627	592.9	592.9	100.0%

** Relative value is the ratio of absolute value to that of treatment 150 cm in each growth season.*

Table 4. Water use efficiency and ground water use efficiency (kg m^{-3}).

Year	Treatments	WUE		GWUE	
2005	T1(70)	1.27	CV*=0.138	1.49	CV*=0.216
	T1(90)	1.30		1.73	
	T1(110)	1.31		1.86	
	T1(150)	1.74		2.60	
2010	T2(40)	1.25	CV*=0.186	1.45	CV*=0.252
	T2(70)	1.59		1.98	
	T2(110)	1.88		2.48	
	T2(150)	2.09		2.95	

* CV- Relative value is the ratio of absolute value to that of treatment 150 cm in each growth season.

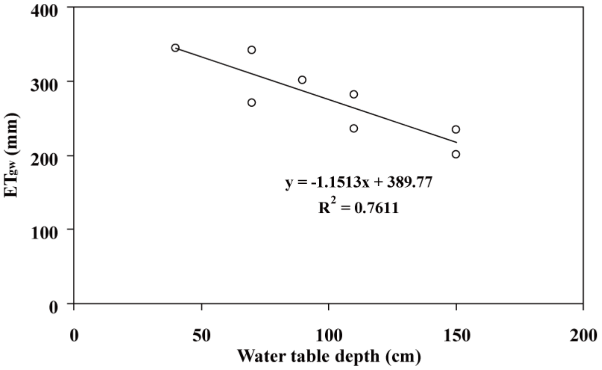

Fig 3. Relationship between the seasonal ET_{gw} and water table depths in under rain-fed condition for two growth seasons

WUE and GWUE

Water use efficiency and ground water use efficiency were calculated as:

$$WUE = \frac{Y}{ET_a} \quad (4)$$

$$GWUE = \frac{Y}{ET_{gw}} \quad (5)$$

where Y is the crop yield, (g m^{-2}).

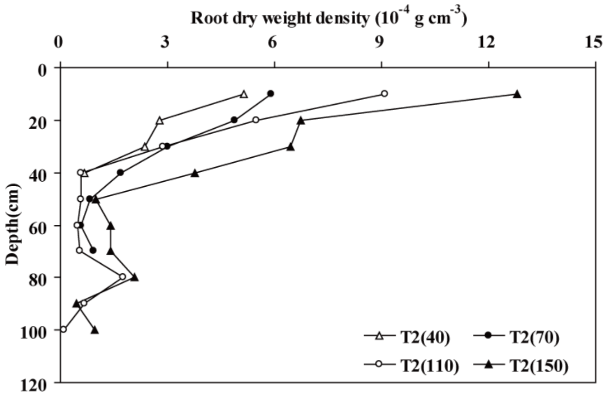

Fig 4. Distribution of root dry weight density in soil profile at harvest under shallow water tables and rain-fed

Conclusion

Under rain-fed condition, groundwater contribution was able to meet more than 65% of the potential evapotranspiration of winter wheat when water table was at or above 150 cm depth. However, it could meet the entire water requirement at or above 110 cm water table depth. The use of shallow ground water helps to reduce the reliance on irrigation (Gowing et al., 2009), and save water and energy, and avoid the risk of water table rising. Moreover, it is possible to control the water table depth by managing irrigation and drainage system to maximize the WUE and yield of winter wheat. After winter wheat is planted, the water table depth can be controlled by extending the irrigation interval and reducing the applied irrigation water to extend the root system (Ayars et al., 1999).

When groundwater table is less than 150 cm, the drainage system needs to be used to draw the water table down. This study is helpful to manage irrigation and control shallow water tables.

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