Ekoloji 27(104): 1-8 (2018)

Modeling on Water Dynamics of Irrigated Winter Wheat and WUE under Limited Water Supply

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Abstract

Irrigation improves grain yield, but excessive irrigation might not increase yield at all. Field experiments and simulations on water dynamics of winter wheat, as influenced by a distinct water supply in Tianjin region, were investigated. Hydrus-1D was applied to simulate soil water dynamics of winter wheat under different irrigation regime. The results showed that Hydrus-1D performed well in simulating soil water dynamics under flood irrigation with a different water supply considering crop growth and groundwater table variation. Root-mean-square error values were within 0.008–0.03384cm^3cm^{-3}, compared with experimental results. Evapotranspiration was the highest under high irrigation amount with four irrigations, as well as downward drainage. However, grain yield was not the highest under this condition, and water use efficiency (WUE) was relatively low due to insufficient water irrigation supply. Water stress was the highest under no irrigation condition due to water scarcity. The maximum value of WUE occurred with low irrigation amount with two irrigations as a result of low leaf area index and water stress. Therefore, applying two irrigations in winter wheat during growing season is an efficient irrigation regime for the Tianjin region of North China.

Keywords: winter wheat, Hydrus-1D, water stress, water use efficiency

Qingyun Z, Baozhong Z, Nana H (2018) Modeling on Water Dynamics of Irrigated Winter Wheat and WUE under Limited Water Supply. Ekoloji 27(104): 1-8.

INTRODUCTION

Winter wheat is the main cereal in Haihe river basin, which is located in the semi-arid region of North China, and is one of the three grain production bases in China. However, irrigation water scarcity is serious in this region due to relatively low annual rainfall (approximately 600mm per year) and surface water shortage. The irrigated water must be pumped from deep wells (approximately 300m or more in depth) in Tianjin. Thus, producing increased grain yield by using limited water resources is challenging for food security.

Irrigation can improve grain yield, but excessive irrigation water might not produce increased yield (Mustafa *et al.* 2017, Sun *et al.* 2006). Moderate water stress in the crop-growing period has been found to prevent reduction and improve the quality of the grain yield of winter wheat (Rathore *et al.* 2017, Tari, 2016, Yan *et al.* 2018, Zhang *et al.* 2008). Deficit irrigation has been widely used in arid and semi-arid regions to cope with the scarcity of irrigation water. Crop response to water stress during different growth stages is influenced by irrigation scheduling (Mon *et al.* 2016, Wang 2017, Xu *et al.* 2018). Single irrigation applied at the end of the second inter node elongation resulted in significantly low leaf area development, which led to less water consumption than four irrigations of winter wheat, and did not always reduce the grain yield in the Beijing region(Zhang *et al.* 1998). Zhang *et al.* (2008) found that maximum grain production was generally achieved for two and three irrigations during the winter wheat growth period. In the wet season, the irrigation numbers could decrease to one. Moreover, crop water consumption (ET) increases as water increases. Additionally, luxury evapotranspiration is ineffective for crop biomass. Generally, high water use efficiency (WUE) corresponds to low ET (Ali *et al.* 2018, Rathore *et al.* 2017, Sun *et al.* 2006, Wei *et al.* 2018, Xu *et al.* 2018, Zhang *et al.* 2008).

ET is related to crop growth, soil water condition, groundwater table, water application, and

 Received: 22 Oct 2017 / Accepted: 28 Mar 2018

meteorological conditions. In general, water balance method is widely used for calculating growing season or stage ET. Moreover, HYDRUS performs well on soil water dynamic simulation (Dutta *et al.* 2016, Forkutsa *et al.* 2009, Jha *et al.* 2017, Karimov *et al.* 2014, Shahrokhnia and Sepaskhah 2018, Zhou *et al.* 2007, Zhou *et al.* 2008). The simulation results might be able to compute season ET and daily evaporation and transpiration.

The objectives of this study were (1) to investigate the effects of water supply on grain production under different irrigation schedules in the Tianjin region; (2) and to simulate the soil water dynamics of winter wheat under different irrigation schedules, with the aim to analyze water stress and water use efficiency.

MATERIALS AND METHODS

Experimental Site

The experiment was conducted by Tianjin Agricultural University, particularly at the Agricultural Water-saving Irrigation Experimental Center, located in Xiqing District (N 39°08′, E116°57′, altitude 5.49m), Tianjin, China. The site is a typical warm temperate continental monsoon climate zone with a mean annual temperature value of 11.6°C and mean annual precipitation of 586mm. The groundwater table is 2.6–3.7m below the ground surface. The soil has an average bulk density of 1.46g/cm^3 and pH value of 7.98. The top 20cm soil layer is uniform and contains organic matter of 1.20%.

Experimental Design and Measurements

The winter wheat was sown on October 8, 2008 and harvested on June 18, 2009. The whole planting area was 0.667ha^{-1}.The field was divided into experimental plots of 4m ×10m each in a randomized block design. Buffer sat 3m were set around the experimental field, where winter wheat was also sown.

Flood irrigation method was employed in this study. A total of four irrigation treatments and three replicates for each treatment were designed (**Table 1**). The treatments were (1) high irrigation water amount by four irrigations, based on the growing stage of winter wheat (HI); (2) medium irrigation water amount by three irrigations (MI); (3) low irrigation water amount by two irrigations (LI); and (4) no irrigation (NI). The fields of the first three treatments were fertilized with 137 Kg N ha^{-1} in the form of ammonium nitrate and urea. After manuring of 69 Kg N ha^{-1}, irrigation was conducted in joint stage. For HI, winter wheat was irrigated on December 2, 2008, April 9, May 7, and May 18, 2009. For MI, winter wheat was irrigated on December 2, 2008, April 9, and May 18, 2009. For LI, winter wheat was irrigated on April 9 and May 18, 2009. The total amounts of irrigation water used in the winter wheat growing period were 240, 180, and 120mm for HI, MI, and LI treatments, respectively. The precipitation in winter wheat growing season was 84.6mm.

Table 1. Irrigation dates and amounts in different treatments to winter wheat

Treatment	Irrigation date and amount (mm)			
	Before winter	Jointing stage	Heading	Grain fill
	12-2-2008	4-9-2009	5-7-2009	5-18-2009
HI	60	60	60	60
MI	60	60	-	60
LI	-	60	-	60
NI	-	-	-	-

Observation and Equipment

Soil volumetric moisture contents were measured by tubes installed in the center of each experimental plot using a neutron meter (IH-II, Cambridge). The vertical profile of soil water content in each tube was determined by a neutron probe that measured the average volumetric soil water content at 20cm intervals at a measured depth of 140cm. Gravimetric sampling method was used to calibrate the measured soil moisture content by the neutron probe. The soil water content was measured at 10day intervals during the whole growing period.

Root Growth and LAI

From March 27 to June 15, 2009, the crop growing dynamics was measured at 7day intervals. The maximum rooting depth and root maximum depth were determined by using a soil borer. Leaf area index (LAI) was determined during the growth season by randomly sampling 15–20 plants in a 40cm×100cm area and counting all the plants in this area.

Groundwater

The groundwater table depth was monitored with an observation well installed in the center of the experimental field. The groundwater table depth was measured concurrently with soil water measurement.

Meteorological Data

An automatic meteorological station was set up in the experimental field. Half-hourly data of relative humidity, radiation, temperature, precipitation, and wind speed at 2m above ground were recorded. The meteorological data were downloaded via laptops. The potential evapotranspiration was calculated by using the Penman–Monteith equation (Allen *et al.* 1998), as recommended by the Food and Agriculture Organization, using the meteorological data.

Table 2. Hydraulic parameters used in Hydrus-1D

Soil depth (cm)	Bulk density (gcm^{-3})	θ_r (cm^3cm^{-3})	θ_s (cm^3cm^{-3})	a (cm^{-1})	K_s (cmd^{-1})	n (-)	l (-)
0-25	1.494	0.0305	0.408	0.0323	17	1.28	0.5
26-100	1.492	0.044	0.408	0.027	21	1.256	0.5
101-300	1.546	0.01	0.45	0.019	15	1.18	0.5

Soil Physical Properties

To describe the soil genetic layers and assess soil physical properties, 1.6m soil pits were dug in the experiment site on July 23, 2008. Undisturbed soil cores were obtained from each genetic horizon. Soil water characteristic curve were determined by using the centrifuge method, which can provide similar results with the pressure plate method and at a considerably shorter time (Reatto *et al.* 2008).

Yield

At the end of crop-growing season, plants in 1m×1m area of each plot were harvested manually and then threshed using a movable thresher. The grains were air dried prior to weight recording.

Hydrus-1D

Hydrus-1D is a software (Šimůnek *et al.* 2012) that simulates one-dimensional water dynamics in variably saturated media. This model numerically solves the Richards equation using Galerkin-type linear finite element schemes, and was used in this study to simulate the soil water dynamics under flood irrigation with different water supplies. The soil water retention and soil hydraulic conductivity were described by using the Genuchten model (1980):

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \quad (1)$$

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \quad (2)$$

where, θ_r and θ_s are the residual and saturated water contents, respectively; K_s is the saturated hydraulic conductivity; α is the inverse of the air-entry value (or bubbling pressure); *n* is the pore-sized distribution index; and *l* is the pore-connectivity parameter assumed to be 0.5,as an average for many soils types. The parameters α, *n*, and *l* in HYDRUS are considered to be empirical coefficients affecting the shape of the hydraulic functions.

The Genuchten (1980) water retention parameters α, θ_r, K_s, and *n* were predicted by Rosetta software. The parameters α and *n* were optimized by inverse estimation (**Table 2**). θ_s was set to measure values.

The upper boundary was atmospheric boundary condition, and defined by evaporation, irrigation, and precipitation. The potential evaporation and transpiration (root uptake) required in Hydrus-1D were calculated from potential evapotranspiration, considering the interception of solar energy by the canopy. The lower boundary was described by measured groundwater table depth linearly interpolated to daily inputs.

Root water up take, as defined by Feddes *et al.* (1978), was affected by the soil matrix near the root system. For the root water uptake, water-stress response functions, h_1, h_2, h_3, and h_4, are-10, -25, -800, and -8000cm in this study, respectively. The root growth was simulated based on experimental measurements.

RESULTS

Soil Water Dynamics

Prior to sowing of winter wheat, 26.4mm of rainfall was recorded on October 5, 2008.Thus, the soil moisture in each layer of the four treatments was high at sowing, as shown in **Fig. 1**. Soil moisture declined throughout the whole growing season. And from sowing to winter dormancy, the water use for winter wheat was small and had a slight declining trend. Moreover, the effects of irrigation and precipitation on soil moisture of topsoil were noticeable. Soil moisture content at 0–20cm soil depth increased significantly after irrigation and precipitation. With less evapotranspiration before recovery, the soil moisture at 40-60cm soil depth slightly decreased in all treatments. For HI and MI, soil moisture was slightly higher than those in LI and NI because of an irrigation event on December 2, 2008. As crop growth accelerated after regreening, the soil moisture content decreased significantly due to the increased root water uptake. At 100-120cm soil depth, soil moisture was stable for all treatments, which might have been unaffected by irrigation events.

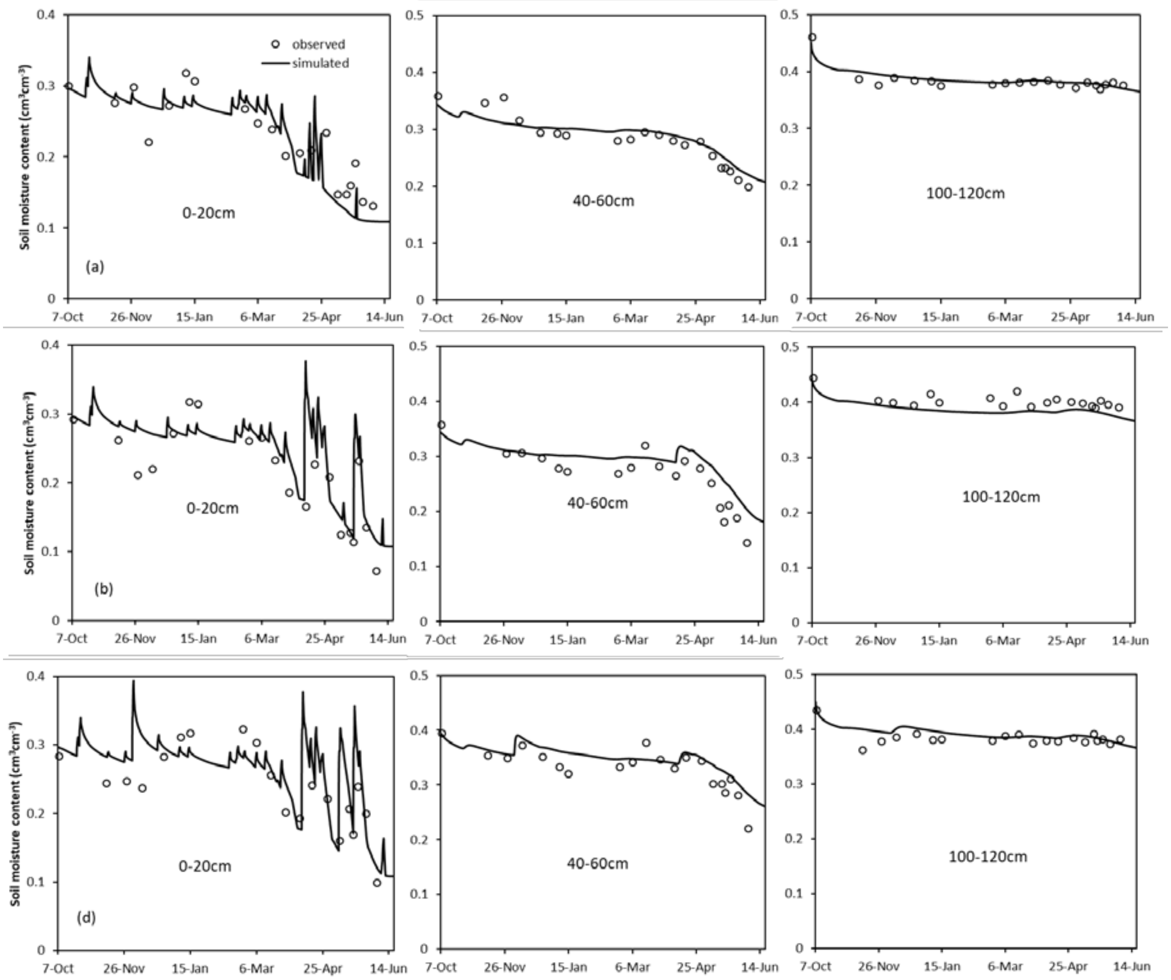

Fig. 1. Observed and simulated soil moisture contents at different soil depths for four treatments. (a) Soil moisture content of NI treatment; (b) soil moisture content of LI treatment; (c) soil moisture content of MI treatment; (d) soil moisture content of HI treatment.

Table 3. Correlation analysis and root-mean-square error (RMSE) of simulated and measured soil moisture

Soil depth (cm)	NI			LI		
	F	Correlation coefficient r	RMSE (cm^3cm^{-3})	F	Correlation coefficient r	RMSE (cm^3cm^{-3})
20	75.992[a]	0.899	0.027	86.442[a]	0.910	0.02987
60	555.161[a]	0.984	0.008	114.075[a]	0.933	0.01979
120	68.393[a]	0.890	0.009	23.979[a]	0.765	0.00855
	MI			HI		
20	69.444[a]	0.891	0.03348	55.967[a]	0.870	0.02947
60	131.206[a]	0.938	0.01419	75.694[a]	0.899	0.01756
120	507.705[a]	0.982	0.01673	1254[a]	0.993	0.01062

[a] Concomitant probability $P<0.001$

Correlation analysis (SPSS 16.0 statistic software) and root-mean-square error (RMSE) of simulated and measured soil moisture are shown in **Table 3**. The measured value was remarkably correlated with the simulated values of the four treatments. The RMSE values ranged from 0.008 cm^3cm^{-3} to 0.03384 cm^3cm^{-3}, and the correlation efficiency (*r*) was close to 1.0. Therefore, considering crop growth and groundwater table, Hydrus-1D can perform well in simulating the soil water dynamics under flood irrigation in the Tianjin region.

Crop Water Balance

During the winter wheat growing period between 84.6mm and 324.6mm of precipitation and/or irrigation water infiltrated into the soil for the four treatments (**Table 4**). Actual transpiration for HI is highest and lowest for NI. ET_a decreased with decreasing irrigation amounts varying from 416.62 mm (HI) to 208.7mm (NI), suggesting that ET_a was affected by irrigation application in this region (Irmak *et al.* 2016, Lobos *et al.* 2018, Sun *et al.* 2006).

Table 4. Water balance for different treatments of winter wheat

Treatment	I (mm)	P	Tp	Ep	Ta	Ea	ETa	ΔW	D
HI	240	84.6	326.41	231.27	253.3	163.32	416.62	-132.49	40.47
MI	180	84.6	328.6	228.82	209.19	155.0	364.19	-136.63	37.04
LI	120	84.6	270.99	286.44	181.75	150.16	331.91	-133.48	6.17
NI	0	84.6	188.6	368.86	85.7	123.0	208.7	-124.55	0.45

I: irrigation; P: precipitation; Ta, Tp: actual or potential transpiration; Ea, Ep: actual or potential evaporation; ΔW: stored water change in 0–100cm soil depth, D: downward drainage from 100cm soil depth. D=I+P-ΔW-Eta

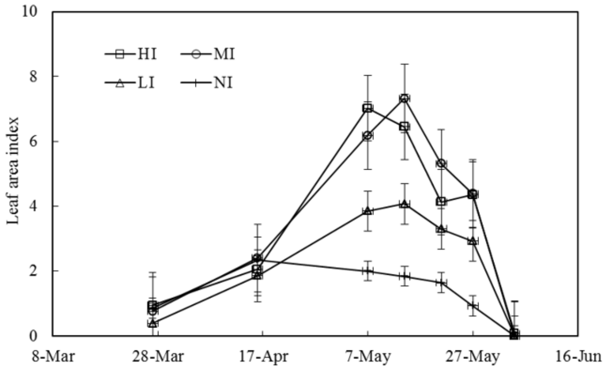

Fig. 2. LAI of winter wheat for different treatments. Bars mean standard error

The depletion of soil water stored was ranged from 124.55mm to 132.49mm for the four treatments. The depletion of soil water stored for MI was the highest and lowest for NI. Winter wheat growth was poor for NI with low LAI (**Fig. 2**), undeveloped root system, and lower T_p (**Table 4**), which lead to the lowest depletion of soil water stored. With the increase in irrigation amount, the contribution of the soil water stored was reduced.

Downward drainage beyond 100cm soil depth occurred in all four treatments. The downward drainage was extremely small with 0.45mm for NI, possibly due to the groundwater table declining. The downward drainage for HI and MI was distinctly larger than that for LI, indicating that more irrigation can cause percolation from crop root zone.

Daily actual transpiration (T_a) and potential transpiration (T_p) were simulated by Hydrus-1D. Relative transpiration rate (T_a/T_p) for different treatments and precipitation after recovering is shown in **Fig. 3**. Water stress appeared in all treatments, and it could be mitigated by irrigation and precipitation. Water stress for NI was mitigated by precipitation with 17.0mm on April 19, 2009. The heaviest water stress occurred in treatment NI for serious water shortage, leading to low LAI (**Fig. 2**) and grain yield (**Table 4**). Relative transpiration rate was dropped to around or even below 0.5 for NI, LI and MI. Two irrigations for both MI and LI treatments were observed after

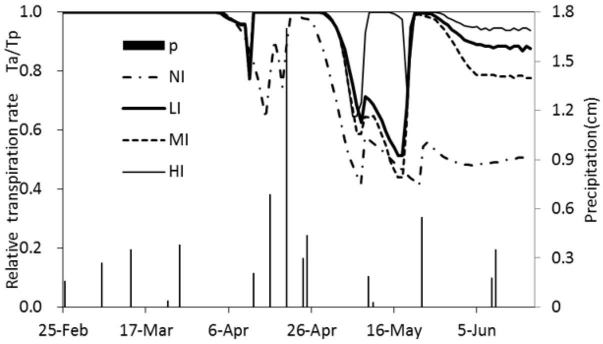

Fig. 3. Relative transpiration rate (T_a/T_p) for different treatments and precipitation after recovering stage

Table 5. Water use efficiency (WUE) and grain yield of winter wheat for different treatments

Treatment	Infiltration (mm)	Grain Yield (Kg ha^{-1})	WUE (Kg m^{-3})
HI	324.6	6281.8±61.8a	1.51
MI	264.6	6296.7± 435.6a	1.73
LI	204.6	6655.1± 634.0a	2.04
NI	84.6	3780.2± 319.5b	1.81

recovering, but water stress of MI was heavier than that of LI. The high LAI of MI and HI appeared after jointing, which might lead to higher T_a. Relative transpiration rate of HI was the largest with more irrigation water application.

Grain Yield and WUE

Table 5 shows the grain yield and WUE of winter wheat for different irrigation treatments. No significant difference of grain yield was found among HI, MI, and LI, indicating that water stress, which appeared in anthesis stage, cannot affect grain yield remarkably. The grain yield reduced significantly for NI, suggesting that rainfall cannot meet the water requirements of winter wheat after recovery. Irrigation is an efficient way to improve the grain yield of winter wheat in this region. WUE was calculated as the ratio of yield to the total water used. The letters indicate statistical significance at $P_{0.05}$level. WUE for NI with 1.81 kg m^{-3} is not the lowest because of low water consumption. WUE is highest for LI with 2.04 kg m^{-3} because of lower water consumption and higher grain yield. Due to high irrigation amount, WUE for HI is lowest with 1.51 kg m^{-3}. Under adequate soil moisture conditions before sowing, two irrigations at jointing stage and grain fill stage with 120mm irrigation amount is the optimal limited irrigation practice for wheat production in the North China plain.

DISCUSSION

Irrigation, precipitation and available soil water stored during the whole growing season are the main water sources for crop production in arid and semiarid regions. The soil water storage at winter wheat sowing time and the precipitation were stable during the crop entire growing season. In the NCP, the rainfall is small during the winter wheat growing season. So, additional irrigation was required to improve crop production. From sowing to winter dormancy of winter wheat, the soil moisture content declined slightly because small evaportranspiration. The soil water could supply the water use of winter wheat in this growth period. With the increased crop growth after recovery, the soil moisture content declined obviously (**Fig. 1**) and the irrigations at jointing stage and grain fill stage were critical for winter wheat.

The ET_a was determined by soil water depletion, precipitation, irrigation and downward drainage. In arid and semi-arid region, downward drainage was forbidden through reducing irrigation water amount. The soil water depletion contributed approximately 40-50% of ET_a under rainfed and limited water supply conditions. The results from this study indicated that the soil water depletion contributed approximately 60% for NI and 40% for LI. The soil moisture content before winter wheat sowing was very important for obtained higher crop yield under limited water supply (Peake *et al*. 2016).

Different frequency under same irrigation method affected both the WUE and grain production under the same seasonal irrigation amount. Zhang *et al*. (1998) reported that yield was not always reduced by single irrigation. Xu *et al*. (2018) reported that irrigation at jointing stage can improve grain yield and WUE by increasing biomass. Many studies indicated that the yield of winter wheat with one irrigation application was increased by 24-80% using flooding irrigation method in the NCP. Two irrigation applications further increased yield by 18% (Fang *et al*., 2018). The results from this study also showed that crop yield increased by 76% with two irrigations for winter wheat, which was the optimized irrigation under limited water supply with highest grain yield and WUE (**Table 5**).

WUE of winter wheat varied between 1.51and 2.04 kg m^{-3}. The values were higher than those (0.4–0.88kg m^{-3}) for irrigated winter wheat (Musick *et al.*, 1994; Howell *et al.*, 1995; Schneider and Howell, 1997), but the results were consistent with other studies of winter wheat in North China (Xu *et al*., 2018). WUE value ranged from 0.97 kg m^{-3}to1.83 kg m^{-3} in North China plain (Sun *et al*., 2006) and from 1.0 kg $m^{-3}$to 2.2 kg m^{-3}in the northern part of the NCP at the base of Mt. Taihang (Zhang *et al*., 2008) . The WUE for NI was not the lowest, which is not consistent with the result of Zhang *et al.* (1998) in Beijing, this finding may be explained by the lower water consumption. The WUE for LI was larger than that of HI and MI, and similar result was found by Sun *et al*. (2006). The twice irrigation applications was the optimized irrigation schedule under limited water supply in Tianjin region of China.

CONCLUSION

Soil water dynamics was influenced by irrigation, evaporation, root water uptake, and LAI. Hydrus-1D performed well in simulating soil moisture dynamics of winter wheat under flood irrigation with a different water supply. Evapotranspiration was the highest under HI condition, as well as downward drainage. However, grain yield was not the largest under this condition, and WUE was relatively low because of inefficient irrigation water supply. The soil water storage played an important role in the water balance of winter wheat during growing season. The consumption of soil water storage was the least under NI condition because of low LAI, and the water stress was the highest under this condition because of water scarcity. Maximum value of WUE occurred under LI condition due to low LAI and water stress. Therefore, applying two irrigations in winter wheat during growing season is a better irrigation regime in Tianjin region of North China, and Hydrus-1D is an efficient way to simulate soil water dynamic during crop-growing season.

ACKNOWLEDGEMENTS

This work was supported by the Chinese National Natural Science Fund (51609170 and 51379217).

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