Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2018.22339

118 (2018) 26–38
June

Optimization of irrigation schedule based on the response relationship of water consumption and yield for winter wheat in North China Plain

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Received 7 November 2017; Accepted 4 February 2018

ABSTRACT

It is very important for regional agricultural sustainable development by researching the relationship between water consumption and yield, determining the reasonable irrigation threshold and proposing the optimal irrigation schedule. The Aquacrop model was verified by the measured data, and then, the variations of water consumption, yield, and water productivity for winter wheat under various irrigation schedules in North China Plain were analyzed by this model. Meanwhile, the irrigation thresholds under the highest yield and the highest water productivity were determined. Finally, the optimal irrigation schedules for the winter wheat were proposed after taking irrigation water use productivity (IWP) and water consumption productivity (WP) as the objective, respectively. The results show that (1) the determination coefficient (*R2*) > 0.747 between the simulated and observed values of the soil water content and canopy cover, and the Nash efficiency coefficient (EF) > 0.482, and *R2* > 0.865 between the simulated and observed values of the biomass and yield, and EF > 0.864, so the model can simulate the soil water content, canopy cover, crop biomass, and final yield accurately. (2) When irrigation amount ranged from 150 to 400 mm, the water consumption increased along with the increase in irrigation amount. When the irrigation amount reached 400 mm, the water consumption remained unchanged. (3) When the irrigation amount ranged from 150 to 300 mm, the yield and WP increased with the increase in irrigation amount, and the increasing trend of the yield and the WP slowed down and even reduced when the irrigation amount exceeded 300 mm. (4) Optimization of irrigation schedule in various hydrological years shows that after taking the maximal IWP as the objective, the yield reached 3,821–5,959 kg hm^{-2} with the irrigation frequency of two times, and the optimal irrigation amount of 140–220 mm. After taking the maximum WP as the objective, the yield reached 6,727–6,926 kg hm^{-2} with irrigation frequency of three times, and the irrigation amount of 240–330 mm. For the areas with the shortage of water resource such as North China Plain, this study may provide theoretical basis for irrigation water management of winter wheat.

Keywords: Aquacrop; Water consumption; Productivity; Optimization of irrigation schedule; Winter wheat

1. Introduction

North China Plain has the area of more than 400,000 km^2 and occupies 23% of agricultural acreage and 40% of the grain yield in China. But the utilization limit of water resource has been "reached or broken" in this area, which impacts economic development, people's living standard, and regional ecological environment [1–8]. As winter wheat is the largest grain crop in this area, its yield accounts for 50%–61% in China [9]. As affected by monsoon, the precipitation during the growth period of winter wheat is only 25%–40% of the water requirement [10,11], so the water requirement must be supplemented through irrigation. At present, the irrigation

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amount of winter wheat reaches 70% of the agricultural water use in this area [12]. For optimization of irrigation schedule for winter wheat in North China, it is important to relieve the shortage of water resource by reducing water consumption of winter wheat when maintaining moderate winter wheat yield.

Most studies have investigated crop water consumption characteristics and yield from various irrigation schedules using field experiments and propose the proper water management under the current precipitation condition through the analysis of yield and water use efficiency under different treatments [13–22]. But it has large limitation, bad practicability, and long period due to manpower, material resources, and precipitation randomness [23,24]. However, studying the crop water consumption using the model may shorten the experimental cycle, reduce the cost, increase the system observable, eliminate the interference factors, and find out the real relationship between experimental factors [25,26].

There are two main types of models in optimizing crop irrigation schedule. One type is the programming model, which is represented by dynamic programming model [27,28]. For the programming model, in order to solve the optimum allocation of irrigation water among different crop growth stages, the crop yield is calculated by the crop water production function, but the water consumption process and the yield formation mechanism are considered simply [29]. Meantime, for the programming model, the optimization results of irrigation schedule mainly depend on the rationality of the parameter of crop water production function. Therefore, the parameter of crop water production function is calculated from unreasonable experimental design or no representative hydrological year, which could be caused by unreasonable optimization results of irrigation schedule. The other type is the model of crop growth and development, which mainly considers the influence of soil moisture and nutrient on crop growth. It has advantages such as clear explanation, wide application, the consideration of many influencing factors, and easy to control, so it can provide decision support for crop growth management [30,31]. However, most crop growth models are complex, lack the transparency, and need many input parameters. Thus, the Food and Agricultural Organization (FAO) has proposed the Aquacrop model based on crop growth by water driving. Compared with other crop growth models, the Aquacrop model has advantages such as fewer input parameters, easy operation, and relatively high precision [32–35]. The coupling between the Aquacrop model and the soil water balance model may simulate the process of crop growth under water stress condition and calculate the daily water consumption during the crop growth period, which reflects the responding mechanism between crop growth and water use, so this model can be as a tool for the optimization of the irrigation schedule. Since the Aquacrop model is developed, lots of researches are done about the suitability of the model around the world and the yield formation mechanism of various crops under different irrigation treatments [36–49]. Researches are also conducted about the response to climate change [50,51], the optimization of irrigation schedule [52,53], the assessment of economic benefit [54], and so on.

In many researches, the optimization objective of irrigation schedule is maximum yield or maximum economic value [55,56]. However, for the most severe water shortage in North China, it is better to decrease the regional water consumption with stable production that the irrigation water use efficiency has been increased, which would be benefit to sustainable utilization of regional water resources. Accordingly, in this study, the Aquacrop was calibrated and validated by the field observed data, and then, the variations of water consumption, yield, and water productivity were analyzed using the model for winter wheat under various hydrological years and different irrigation schedules. At last, based on the objective of WP or irrigation water use productivity (IWP), respectively, the optimal irrigation schedules were presented to provide theoretical basis in irrigation management of winter wheat in North China Plain.

2. Materials and methods

2.1. Experimental site

The field experiments were conducted during October 2008–June 2010 at the Irrigation Experiment Station of China Institute of Water Resources and Hydropower Research (IWHR) at Daxing in Beijing (39°37′N latitude, 116°26′E longitude and 40.1 m a.s.l. elevation), about 15 hm^{-2}. The mean annual temperature is 12.1°C, the annual accumulated temperature is 4730°C (>10°C), the mean frost-free days is 185 d, and the annual sunshine duration is about 2,600 h, and the site belongs to a semiarid and continental monsoon climate. The irrigation water source is from ground water with the depth of about 10 m. The soil texture in the experiment site is mainly sandy loam with high organic matter content. Table 1 shows soil physical properties in the profile within 0–100 cm.

2.2. Experimental design

Winter wheat (Jingmai 9428) was taken as experimental crop. In 2008–2009, the sowing date and the harvesting date of winter wheat are October 9, 2008 and June 12, 2009, respectively, and the precipitation was 120 mm during the growth period. In 2009–2010, the sowing date and the harvesting date of winter wheat are October 12, 2009 and June 20, 2010, and the precipitation was 169 mm during the growth period. During the experimental period, the irrigation amount for preseeding was 60 mm for water supply during the seedling stage of winter wheat. After turning green, water treatment was started. And irrigation was started when the soil water contents reached the lower irrigation limits at 70% and 50%

Table 1
Soil physical properties in the profiles

Depth (cm)	Soil dry bulk density (g m^{-3})	Water content of saturated soil (m^3 m^{-3})	Field capacity (m^3 m^{-3})	Wilting point (m^3 m^{-3})
0–10	1.30	0.46	0.32	0.09
10–20	1.46	0.46	0.34	0.13
20–40	1.48	0.47	0.35	0.10
40–60	1.43	0.45	0.33	0.11
60–100	1.39	0.44	0.31	0.16

of the field capacity, respectively. Two water treatments are high water and low water, and each treatment was repeated three times, and the experimental plots were arranged randomly. The management measures such as seeding, fertilizing, and cultivating were the same as local peasants.

2.3. Measurements

2.3.1. Soil water content

The soil water contents at the 0–20, 20–40, 40–60, 60–80, and 80–100 cm layers are measured with the TRIMER-T3/IPH. Measurements were done every 3–5 d and additional measurement after irrigation and rainfall.

2.3.2. Leaf area index and canopy cover

The leaf area index (LAI) was measured every 10 d. Selecting 10 representative plants from each plot, the length and width of all leaves in each plant were measured, and then, the leaf area of individual plant was calculated taking 0.75 as the coefficient for wheat leaf area. The LAI was calculated based on the planting density. Canopy cover (CC) was obtained by the LAI with the following formula [32]:

$$CC = 1.005\left[1 - \exp\left(-0.6\,\text{LAI}\right)\right]^{1.2} \quad (1)$$

2.3.3. Biomass

When winter wheat comes out, the aboveground biomass was measured every 10 d. Selecting 10 representative plants from each plot, the aboveground parts were cut out. After drying to constant weight, the biomass was weighed using an electronic balance with the precision of 0.01 g. And then, the aboveground biomass per unit area was calculated based on the planting density.

2.3.4. Yield

Yield of winter wheat was measured after harvesting. Selecting a 1 m^2 plot from each plot, grain weight was measured after natural drying, and then, the yield per hectare was converted.

2.3.5. Meteorological data

Solar radiation, wind speed, air temperature, relative humidity, precipitation, and other meteorological data are measured using the automatic meteorological station at the field, and the meteorological data are recorded every 30 min. The reference crop evapotranspiration (ET_0) is calculated according to the Penman–Monteith equation recommended by FAO [57]. Fig. 1 shows the changing of the air temperature, precipitation, and reference crop evapotranspiration (ET_0).

2.4. Irrigation schedules design

By analyzing the precipitation frequency during the years 1960–2009 in Daxing, the multiyear average precipitation during the winter wheat growth period is 128 mm, and the precipitations in the 25% (wet), 50% (normal),

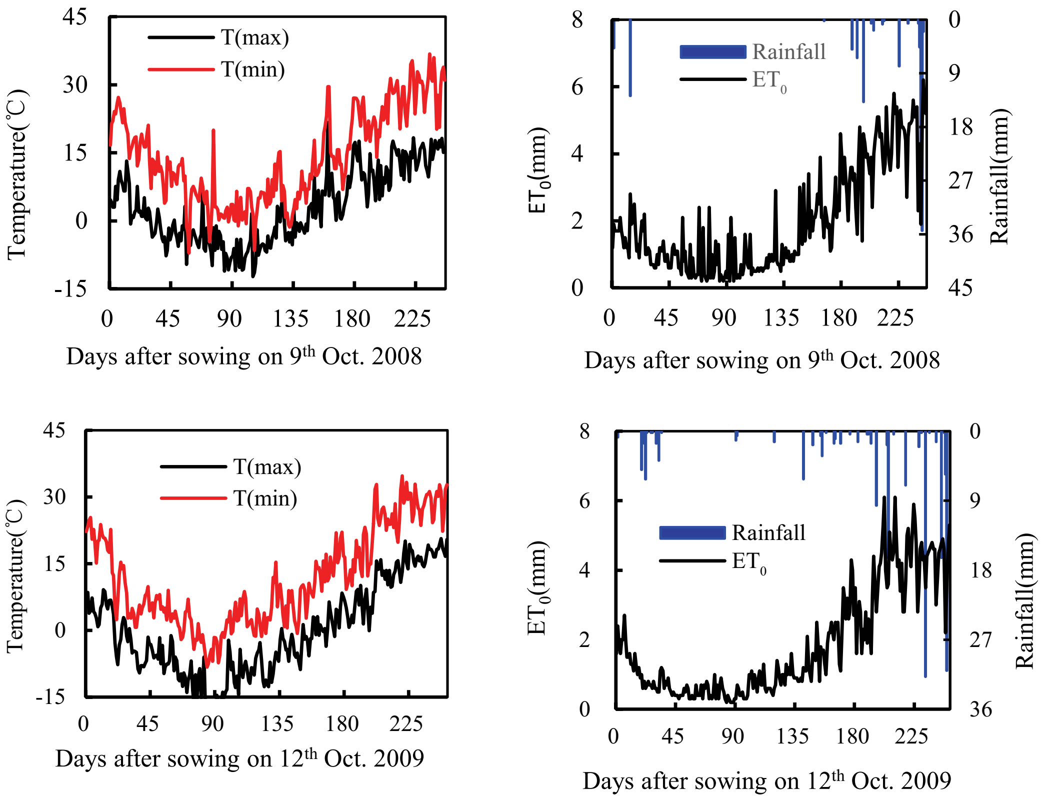

Fig. 1. Changes of weather variables during the growth period of winter wheat.

75% (dry), and 90% (extremely dry) frequency years are 163, 114, 79, and 57 mm, respectively. According to the precipitation, the corresponding years of wet, normal, dry, extremely dry, and average are in the years 2005, 1962, 1974, 1975, and 1997, respectively.

Design of irrigation schedules for winter wheat considers mainly the soil moisture content and the irrigation amount per time. In the design of irrigation schedules, soil readily available water in the root-zone soil (RAW) is the maximum amount of water that a crop can extract from 1 m layer without inducing stomata closure and reduction in crop transpiration [32]. Besides rain-fed condition, there are 12 relative soil moisture content levels, that is, 125%, 120%, 110%, 100%, 90%, 80%, 70%, 60%, 50%, 40%, 30%, and 20% of the RAW, and there are 9 irrigation levels, that is, 30, 40, 50, 60, 70, 80, 90, 100, and 110 mm, respectively, totally 109 irrigation schedules.

2.5. Water productivity

The IWP and the WP were respectively calculated as follows:

$$\text{IWP} = \frac{Y - Y_r}{I} \quad (2)$$

$$\text{WP} = \frac{Y}{\text{ET}} \quad (3)$$

where IWP is the irrigation water use productivity (kg m^{-3}), Y is the yield under irrigation treatment (kg hm^{-2}), Y_r is the yield under rain-fed treatment (kg hm^{-2}), I is the irrigation amount (mm), WP is the water consumption productivity (kg m^{-3}), and ET is the actual water consumption during the growth period of winter wheat (mm).

2.6. Model description

The main characteristics of the Aquacrop model included in the following [58], (1) dividing the evapotranspiration into evaporation and transpiration can guarantee the crop biomass estimation is only relevant to the crop transpiration, (2) calculating the water consumption based on growth and aging of the crop canopy can avoid the error of model simulation from uncertain processes such as the LAI calculation, (3) the effects of environmental stress on biomass and harvest index are distinguished according to the different response of biomass and harvest index to environmental stress, and (4) the influence of soil water stress on crop growth is described in detail, the model can be used to simulate the crop yield under various irrigation schedules, and it has more advantage in the arid region and semi-arid region where irrigation influences crop growth remarkably. The input data of the model include the meteorological parameters, crop parameters, soil parameters, and field and irrigation management data. The calculation principle and the operational process of the model are referred to the literature [32–34].

2.7. Simulated evaluation indexes

Four evaluation indexes, such as the root-mean-square error (RMSE), mean absolute error (MAE), mean bias error (MBE), Nash efficiency coefficient (EF), were calculated as follows [59–61]:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(M_i - O_i\right)^2} \quad (4)$$

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}\left|M_i - O_i\right| \quad (5)$$

$$\text{MBE} = \frac{1}{n}\left[\sum_{i=1}^{n}\left(M_i - O_i\right)\right] \quad (6)$$

$$\text{EF} = 1.0 - \frac{\sum_{i=1}^{n}\left(O_i - M_i\right)^2}{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2} \quad (7)$$

where O_i, M_i, $\bar{O}$ are the measured value, simulated value, and average measured value, and n is the times of measurement.

3. Results and discussion

3.1. Calibration and verification of Aquacrop model

From Fig. 2, the difference of soil water content between high and low water treatment during the growth period of winter wheat (October 2009–June 2010) was larger than that during October 2008–June 2009. In order to improve the model capability under nonstress or stress condition separately, the Aquacrop model was calibrated by the measured data during the growth period of winter wheat (October 2009–June 2010) and then verified by the measured data (October 2008–June 2009). Table 2 shows main parameters for Aquacrop simulation of winter wheat in North China Plain, and Figs. 2–4 show the results of model calibration and verification.

From Fig. 2 and Table 3, except for large deviation of soil moisture simulation at the seedling stage, the measured soil water content coincided well with the model simulation after the seedling stage. During the calibration and verification of the model, the RMSE and MAE between the simulation and the observed values of soil water content were less than 1.702% and 1.537%, respectively, with R^2 of more than 0.747 and EF of more than 0.593, showing that the model simulation had higher fitting degree and accuracy for soil moisture, which can meet the simulation precision requirement of water consumption.

As shown in Fig. 3 and Table 4, the canopy cover was lower than 20% after the winter wheat emerged and entered into the overwintering stage, increased quickly after the seedling stage in March of the following year, reached the maximum at the heading stage, and declined with the maturity stage. The RMSE and MAE between the simulated and observed values of the canopy cover were less than 9.808% and 8.600% respectively during calibration and verification of the model, and the simulation error was acceptable, with R^2 of more than 0.811 and EF of more than 0.482, showing that the results for simulation of the canopy cover were accurate and credible.

Fig. 4 and Table 5 show that the simulated value coincided well with the measured value of the biomass, and

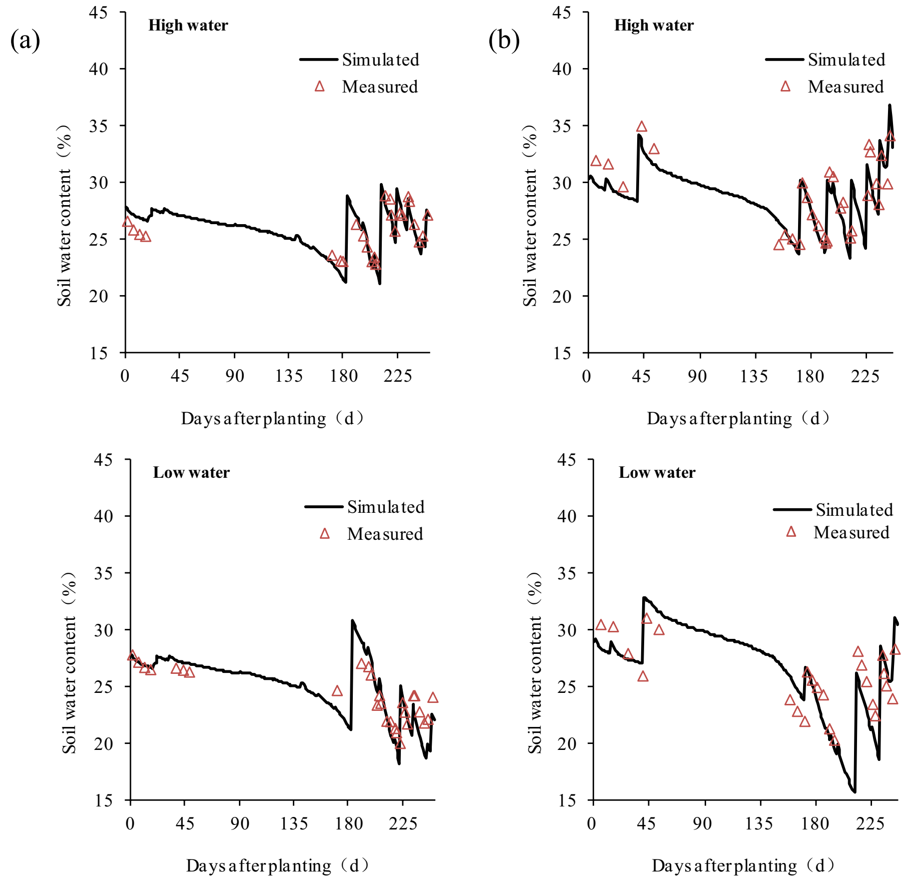

Fig. 2. Comparison of the simulated and measured values of soil water content in the 0–100 cm layers. (a) Calibration, (b) validation.

Table 2
Preliminary input parameters for the winter wheat in Aquacrop

Parameter	Model input
Cutoff temperature (°C)	26
Crop coefficient ($K_{cb,}x$)	1.2
Upper and lower thresholds of soil water depletion factor	0.15–0.60
Shape factor for water stress coefficient for canopy expansion	4.5
Soil water depletion fraction for stomatal control (p – sto) – upper threshold	0.65
Shape factor for water stress coefficient for stomatal control	2.5
Canopy growth coefficient (CGC)	0.02937
Canopy decline coefficient (CDC)	0.16106
Maximum canopy cover (CC_x) in fraction soil cover	0.92
Minimum effective rooting depth (m)	0.3
Maximum effective rooting depth (m)	1.0
Building up of harvest index starting at flowering (days)	34
Normalized water productivity (WP) (g m^{-2})	18
Harvest index (percentage)	39
Number of plants per hectare	5,200,000

all points were around 1:1, and the RMSE, MAE, and MBE between the simulated and observed values of biomass were 194.708, 173.620, and –6.945 kg hm^{-2}, respectively, with the R^2 of 0.994 and EF of 0.988, indicating that the model can simulate the change in dry mass accumulation of winter wheat well [62–64]. The RMSE, MAE, and MBE between the simulated and observed values of yield were 154.213, 128.750, and 13.750 kg hm^{-2}, respectively, with R^2 of 0.865 and

Table 3
Evaluation indexes to simulations of soil water content for high and low water treatments

	Treatment	R^2	RMSE (%)	MAE (%)	MBE (%)	EF
Calibration	High water	0.836	0.773	0.666	0.176	0.814
	Low water	0.873	1.424	1.230	–0.426	0.593
	All data	0.871	1.146	0.948	–0.125	0.742
Validation	High water	0.798	1.483	1.231	–0.258	0.698
	Low water	0.747	1.702	1.537	–0.122	0.658
	All data	0.816	1.620	1.418	–0.175	0.768

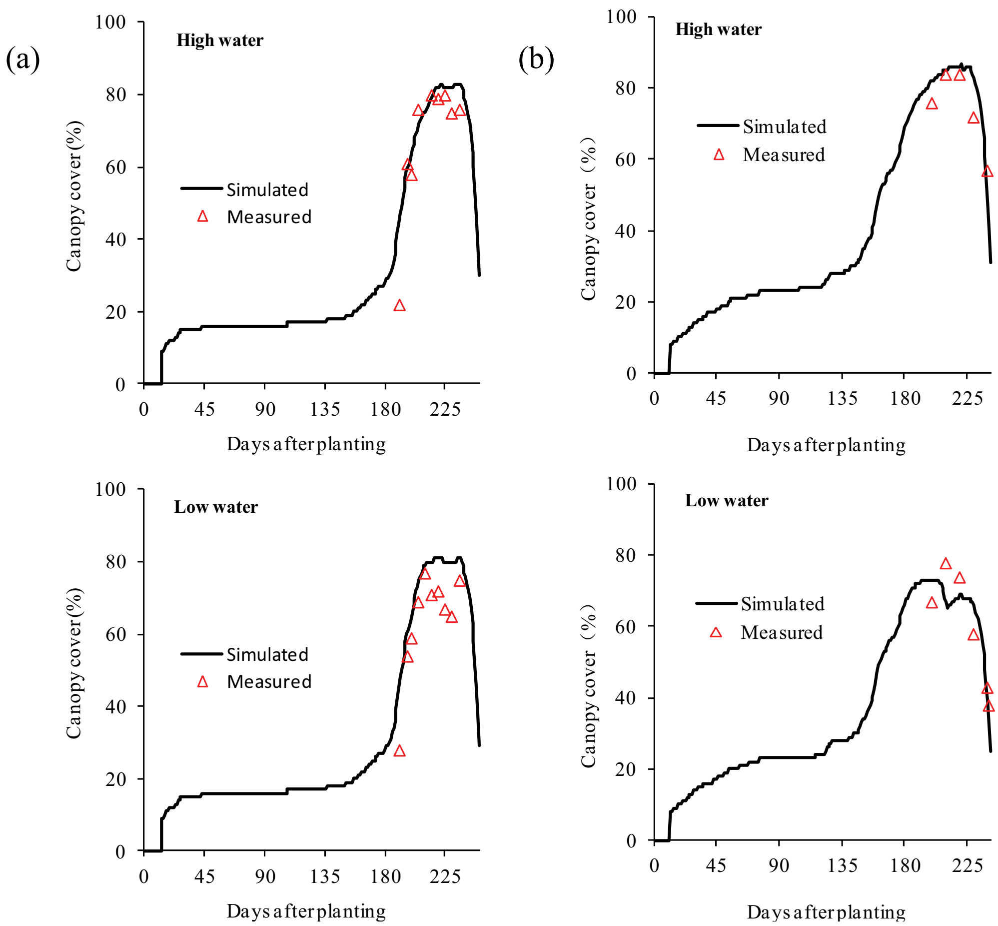

Fig. 3. Comparison of the simulated and measured values of canopy cover. (a) Calibration, (b) validation.

Table 4
Evaluation indexes to simulations of canopy cover for high and low water treatments

	Treatment	R^2	RMSE (%)	MAE (%)	MBE (%)	EF
Calibration	High water	0.862	8.570	6.111	4.111	0.768
	Low water	0.889	9.808	8.600	8.600	0.482
	All data	0.849	9.242	7.421	6.474	0.660
Validation	High water	0.836	6.148	4.600	3.800	0.618
	Low water	0.811	6.506	5.333	0.000	0.811
	All data	0.850	6.346	5.000	1.727	0.819

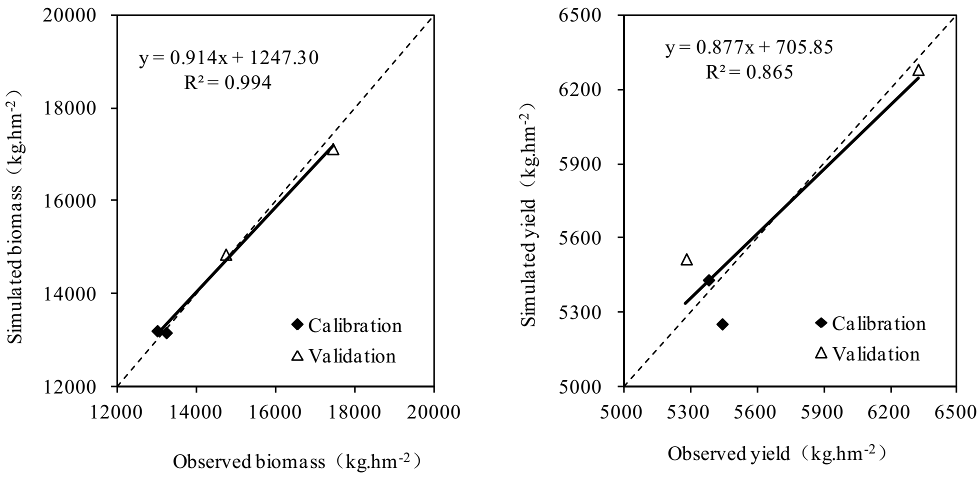

Fig. 4. Comparison of the simulated and measured values of biomass and yield.

Table 5
Evaluation indexes to simulations of biomass and yield for high and low water treatments

	R^2	RMSE (kg hm^{-2})	MAE (kg hm^{-2})	MBE (kg hm^{-2})	EF
Biomass	0.994	194.708	173.620	–6.945	0.988
Yield	0.865	154.213	128.750	13.750	0.864
All data	0.999	175.631	151.185	3.403	0.999

EF of 0.864, illustrating that the model can simulate the yield of winter wheat well.

Thus, the Aquacrop model can simulate the dynamic change of soil moisture and the canopy cover during the growth period of winter wheat, the biomass, and the yield for various irrigation schedules, so the model can be used to study the relationship between the irrigation and the yield of winter wheat [65–67].

3.2. Water consumption characteristics of winter wheat under different irrigation schedules

Fig. 5 shows water consumption (ET) during the growth period of winter wheat for different irrigation schedules. The water consumption increased with the increase in irrigation amount. When the irrigation amount increased to 400 mm, water consumption was not increased with the increase in the irrigation amount. When the irrigation amount was less than 400 mm, the total water consumption of winter wheat was higher in the wet year than in the dry year.

The change of soil water storage in the 0–100 cm layers under different irrigation schedules is shown in Fig. 6. When there was no irrigation or low irrigation amount, the crop roots can absorb the water from deep soil and then reduced soil moisture storage capacity. Otherwise, the soil water storage showed an increasing trend when the irrigation amount was large. For the precipitation during the growth period of winter, wheat was small under all hydrological years; meanwhile, soil water storage capacity was limited, so the difference of soil water storage in various hydrological years was not obvious under same irrigation amount.

3.3. Change of winter wheat yield under different irrigation schedules

Fig. 7 illustrates the changing of winter wheat yield under different irrigation schedules. For different hydrological years, the change trend of the winter wheat yield is consistent. When the irrigation amount ranged from 150 to 300 mm, yield increased with the increase in irrigation amount, but when the irrigation amount reached 300 mm, the yield reached 7,000 kg hm^{-2}. Since the coupling between precipitation distribution and water demand of winter wheat was bad, the water shortage was serious during the winter wheat growth period. Thereby, if there was no irrigation, the winter wheat yield was very small or even no harvest. When the irrigation amount was less than 300 mm, the winter wheat yield was higher in the wet year than in the dry year, and if the irrigation amount exceeded 300 mm, the difference of winter wheat yield was not obvious under various precipitation years.

3.4. Winter wheat water productivity under different irrigation schedules

The IWP of winter wheat under different irrigation schedules is illustrated in Fig. 8. When the irrigation amount was around 150 mm, the yield of each irrigation schedule under different hydrological years was more than 2,773 kg hm^{-2}, and its IWP was higher than 2.0 kg m^{-3}, even to 2.7 kg m^{-3} in the wet and average years. When the irrigation amount exceeded 150 mm, the overall IWP declined with the increase in irrigation amount. When the irrigation amount ranged

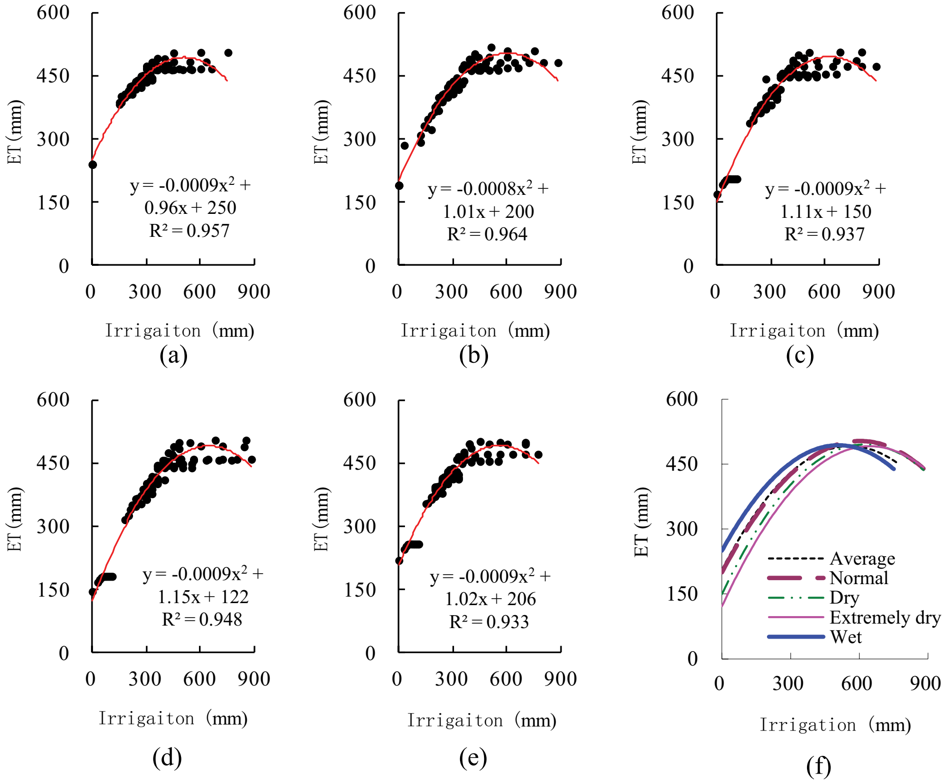

Fig. 5. Changes of ET during the growth period of winter wheat under different irrigation schedules. (a) Wet, (b) normal, (c) dry, (d) extremely dry, (e) average, (f) comparison among hydrological years.

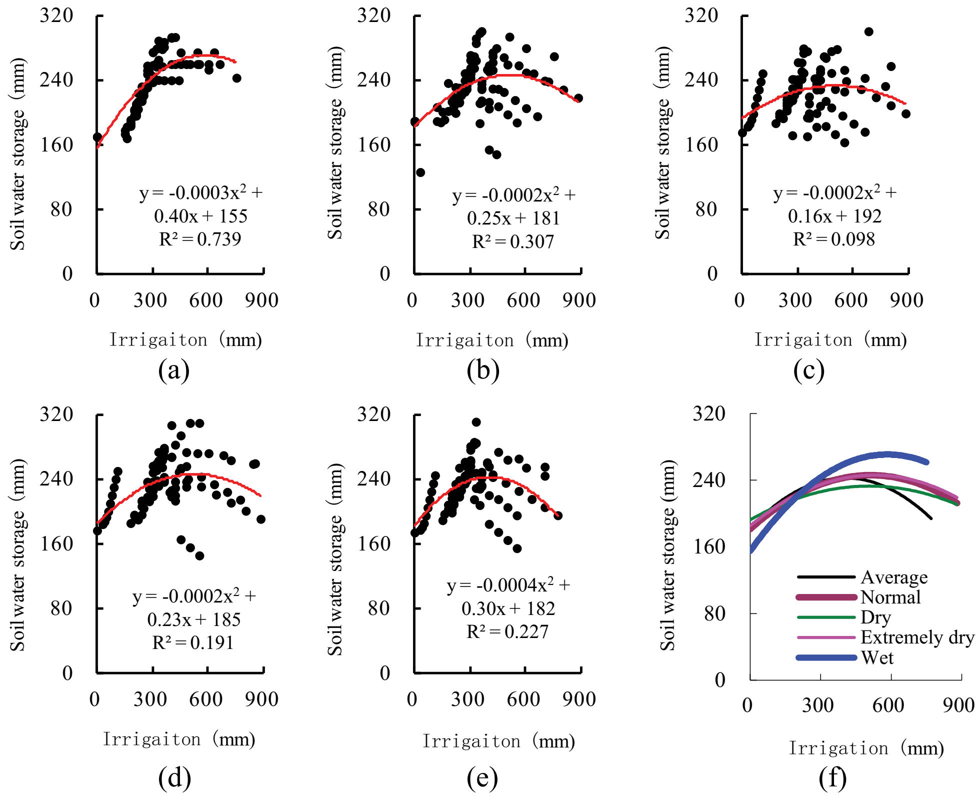

Fig. 6. Soil water storage in the 0–100 cm layers after harvesting under different irrigation schedules. (a) Wet, (b) normal, (c) dry, (d) extremely dry, (e) average, (f) comparison among hydrological years.

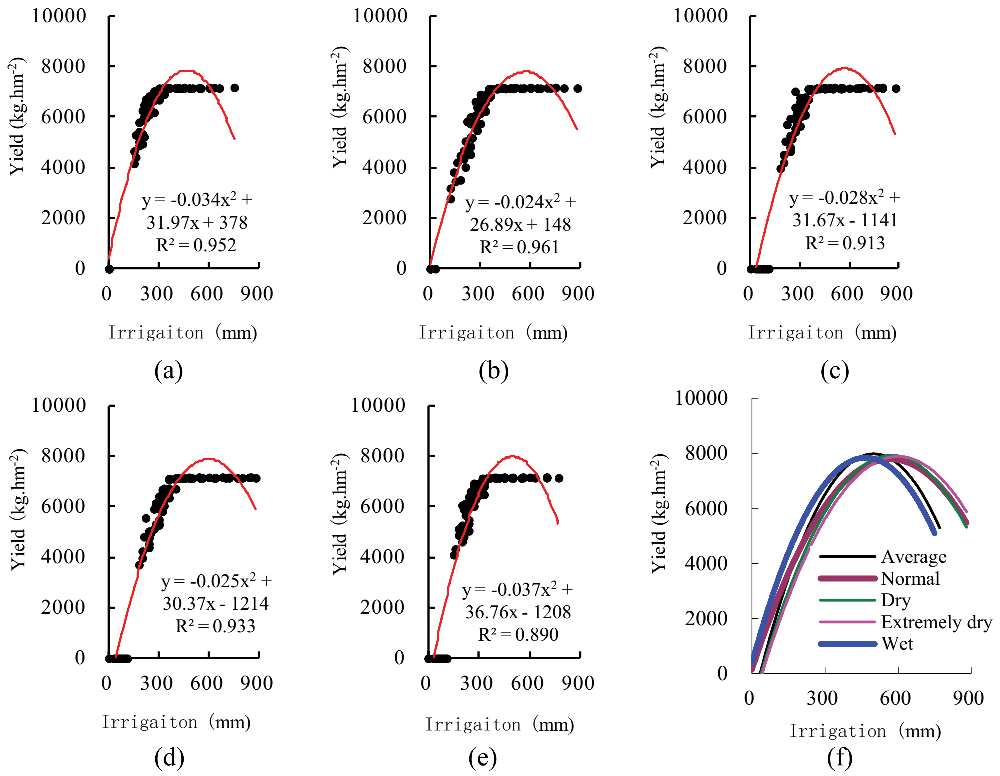

Fig. 7. Yield of winter wheat under different irrigation schedules. (a) Wet, (b) normal, (c) dry, (d) extremely dry, (e) average, (f) comparison among hydrological years

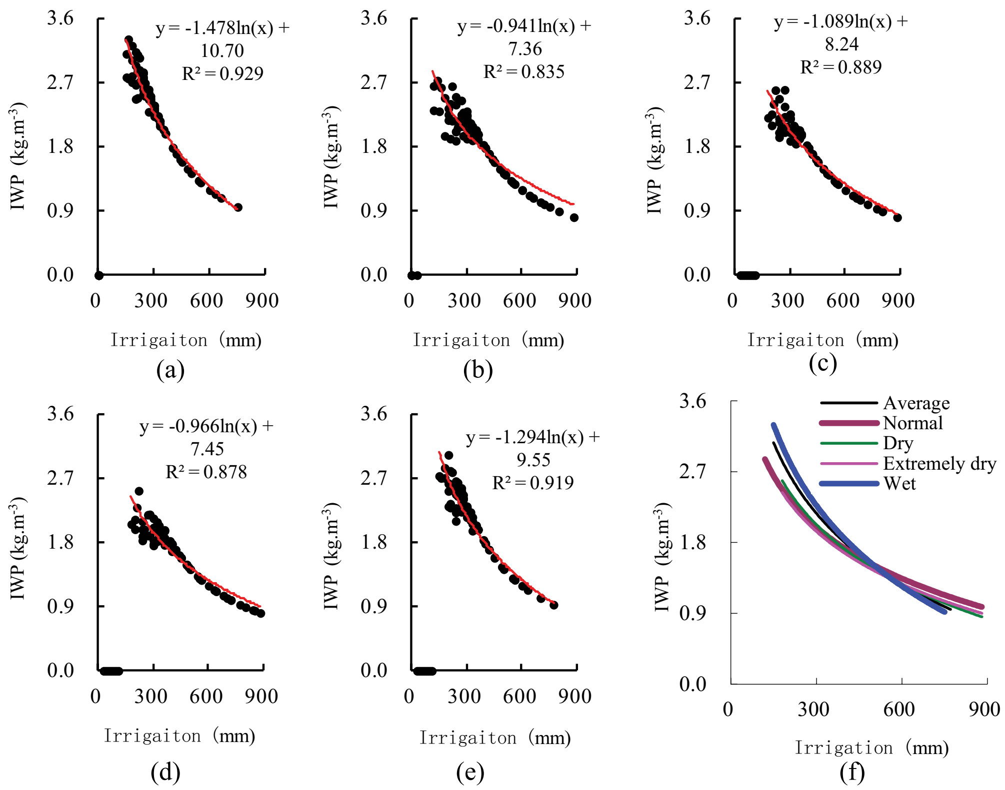

Fig. 8. IWP of winter wheat under different irrigation schedules. (a) Wet, (b) normal, (c) dry, (d) extremely dry, (e) average, (f) comparison among hydrological years

from 150 to 300 mm, the difference of the IWP was large under different irrigation schedules. In Fig. 8(f), if fixed irrigation amount, for example, when the irrigation amount was less than 300 mm, and the IWP was higher in the wet year than in the dry year, but when the irrigation amount was more than 300 mm, the difference of IWP was not obvious under various hydrologic years.

Fig. 9 shows the WP of winter wheat under various irrigation schedules. During the growth period, when the irrigation amount was less than 100 mm, the crop growth mainly depends on limited precipitation or small irrigation to maintain crop water requirement, so the WP of winter wheat was very low or even invalid water consumption. When the irrigation amount exceeded 150 mm, the overall WP showed an increasing trend with the increase in the irrigation amount. When the irrigation amount exceeded 300 mm, the increasing trend of its WP was slow, even the decreasing trend with the increase in the irrigation amount. In addition, the difference of WP was large under different irrigation schedules when the irrigation amount ranged from 150 to 300 mm during the growth period of winter wheat. In Fig. 9(f), when the irrigation amount was less than 300 mm, the WP was higher in the wet year than that in the dry year, but the difference of WP was not obvious in various hydrological years when the irrigation amount exceeded 300 mm.

3.5. Optimization of irrigation schedule

According to the 109 irrigation schedules, and taking the maximal IWP or WP as the objective, respectively, the optimal irrigation schedules of winter wheat were obtained for various objectives and different hydrological years.

Table 6 shows the optimal irrigation schedule after taking maximal IWP as the objective. The irrigation amount pretime

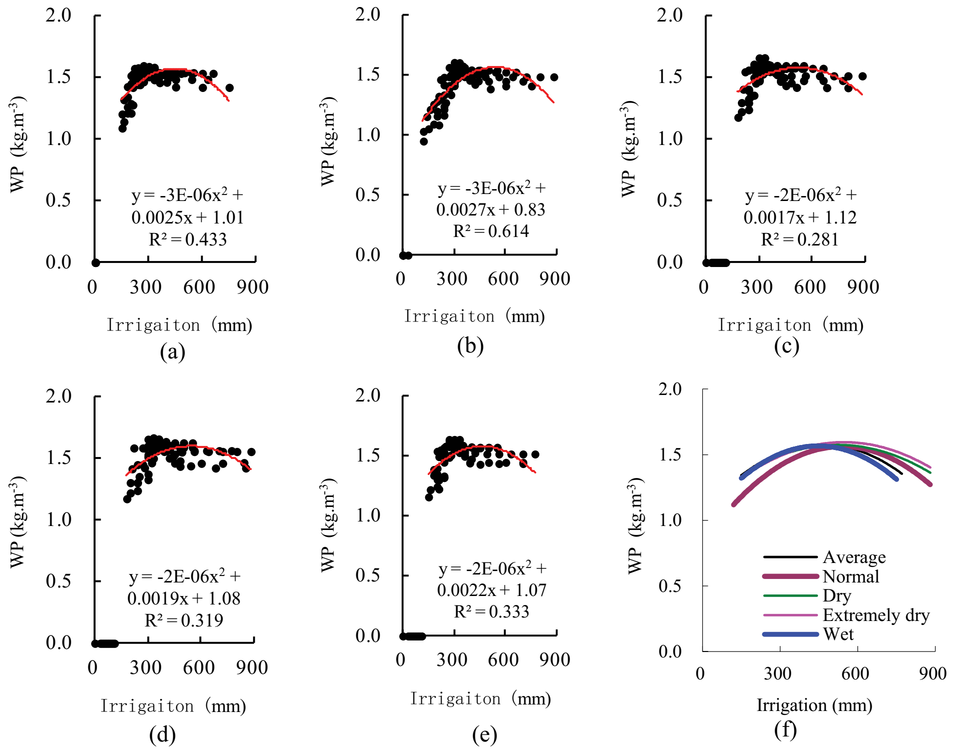

Fig. 9. WP of winter wheat under different irrigation schedules. (a) Wet, (b) normal, (c) dry, (d) extremely dry, (e) average, (f) comparison among hydrological years

Table 6
Optimization of irrigation schedule after taking maximal IWP as the objective

Hydrological year	Irrigation regimes		ET (mm)	IWP (kg m^{-3})	WP (kg m^{-3})	Yield (kg hm^{-2})
	Irrigation frequency	Irrigation amount (mm)				
Wet	2	140	402	3.79	1.32	5,294
Normal	2	180	332	2.12	1.15	3,821
Dry	2	200	370	2.85	1.54	5,708
Extremely dry	2	220	351	2.53	1.58	5,557
Average	2	160	387	3.72	1.54	5,959

Table 7
Optimization of irrigation schedule after taking maximal WP as the objective

Hydrological year	Irrigation regimes		ET (mm)	IWP (kg m^{-3})	WP (kg m^{-3})	Yield (kg hm^{-2})
	Irrigation frequency	Irrigation amount (mm)				
Wet	3	240	433	2.87	1.59	6,905
Normal	3	300	430	2.30	1.60	6,895
Dry	3	330	410	2.06	1.66	6,784
Extremely dry	3	330	404	2.04	1.66	6,727
Average	3	270	424	2.57	1.64	6,926

ranged from 70 to 110 mm under various hydrological years, with the irrigation frequency of two times. When the irrigation amount ranged from 140 to 220 mm, the water consumption varied with 332–402 mm, and the IWP of winter wheat reached the peak, in the range of 2.53–3.79 kg m^{-3}. Moreover, the irrigation amount and the IWP were lower in the dry year than in the wet year.

The optimal irrigation schedule is shown in Table 7 after taking maximal WP as the objective. The irrigation amount pretime ranged from 80 to 110 mm in various hydrological years, with the irrigation frequency of three times. When the irrigation amount ranged from 240 to 330 mm, the water consumption varied with 404–433 mm, and the WP reached the peak, in the range of 1.59–1.66 kg m^{-3}. Furthermore, the WP was greater in the dry year than in the wet year.

4. Conclusions

In summary, the following conclusions can be drawn from our study:

- The Aquacrop model can simulate the dynamic change of the soil water content and the crop growth process during the growth period of winter wheat, and final biomass and yield under various irrigation schedules in North China Plain accurately.
- Along with the increase in irrigation amount, the proportion of irrigation in water consumption increased. When the water consumption was increased about 500 mm, the increasing trend of the water consumption slowed down or even decreased.
- When the irrigation amount ranged from 150 to 300 mm, the yield and WP increased with the increase in irrigation amount. When the irrigation amount exceeded 300 mm, the increasing trend of the yield and WP slowed down or even decreased.
- When the irrigation amount ranged from 150 to 300 mm, the differences in the yield, IWP, and WP were larger. When the irrigation amount was less than 300 mm, the water consumption, yield, and IWP and WP were lower in the dry year than in the wet year.
- The optimization of irrigation schedule under different hydrological years shows that the yield reached 3,821–5,959 kg hm^{-2} with irrigation frequency of two times and irrigation amount of 140–220 mm after taking maximal IWP as the objectives, and the yield reached 6,727–6,926 kg hm^{-2} with irrigation frequency of three times and the irrigation amount of 240–330 mm after taking maximal WP as the objectives.

Acknowledgments

This study was supported by the National Key R&D Program of China (2017YFC0403202), IWHR Research & Development Support Program (ID0145B082017 and ID0145B742017), Governmental Public Industry Research Special Funds for Projects (201501016), the Chinese National Natural Science Fund (51379217, 91425302 and 51479210), the Special Fund of State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, and China Institute of Water Resources and Hydropower Research (2016TS06).

Author contributions

All authors read and approved the manuscript. Zhigong Peng, Baozhong Zhang, Di Xu and Jiabing Cai built the model and put up with the mail idea of this research. Zhigong Peng and Baozhong Zhang revised the manuscript.

Conflicts of interest

The authors declare no conflict of interest.

References

[1] C. Chen, E. Wang, Q. Yu, Modeling the effects of climate variability and water management on crop water productivity and water balance in the North China Plain, Agric. Water Manage., 97 (2010) 1175–1184.
[2] Q. Li, C. Bian, X. Liu, C. Ma, Q. Liu, Winter wheat grain yield and water use efficiency in wide-precision planting pattern under deficit irrigation in North China Plain, Agric. Water Manage., 153 (2015) 71–76.
[3] C. Lu, L. Fan, Winter wheat yield potentials and yield gaps in the North China Plain, Field Crops Res., 143 (2013) 98–105.
[4] H. Sun, C. Liu, X. Zhang, Y. Shen, Y. Zhang, Effects of irrigation on water balance, yield and WUE of winter wheat in the North China Plain, Agric. Water Manage., 85 (2006) 211–218.
[5] H. Wang, L. Zhang, W. Dawes, C. Liu, Improving water use efficiency of irrigated crops in the North China Plain – measurements and modelling, Agric. Water Manage., 48 (2001) 151–167.
[6] Z. Wang, H. Zhang, X. Lua, M. Wang, Q. Chu, X. Wen, F. Chen, Lowering carbon footprint of winter wheat by improving management practices in North China Plain, J. Cleaner Prod., 112 (2016) 149–157.
[7] Y. Xie, H. Zhang, Y. Zhu, L. Zhao, J. Yang, F. Cha, C. Liu, C. Wang, T. Guo, Grain yield and water use of winter wheat as affected by water and sulfur supply in the North China Plain, J. Integr. Agric., 16 (2017) 614–625.

[8] G. Zhao, X. Chang, L. Liu, Y. Yang, Z. Li, S. Zhou, Q. Guo, Y. Liu, Grain yield and protein components responses to irrigation in strong gluten wheat, Acta Agron. Sinica, 33 (2007) 1828–1833 (in Chinese with English abstract).
[9] M. AIqbal, Y. Shen, R. Stricevic, H. Pei, H. Sun, E. Amiri, A. Penas, S. Rio, Evaluation of the FAO AquaCrop model for winter wheat on the North China Plain under deficit irrigation from field experiment to regional yield simulation, Agric. Water Manage., 135 (2014) 61–72.
[10] S. Ma, Z. Yu, Y. Shi, Z. Gao, L. Luo, P. Chu, Z. Guo, Soil water use, grain yield and water use efficiency of winter wheat in a long-term study of tillage practices and supplemental irrigation on the North China Plain, Agric. Water Manage., 150 (2015) 9–17.
[11] X. Wang, G. Huang, J. Yang, Q. Huang, H. Liu, L. Yua, An assessment of irrigation practices: sprinkler irrigation of winter wheat in the North China Plain, Agric. Water Manage., 159 (2015) 197–2008.
[12] C. Wang, J. Zhao, X. Li, Study on agricultural adaptation to warming and drying climate in North China, Arid Land Geogr., 29 (2006) 646–652 (in Chinese with English abstract).
[13] Z. Han, Z. Yu, D. Wang, Y. Zhang, Effects of supplemental irrigation based on testing soil moisture on dry matter accumulation and distribution and water use efficiency in winter wheat, Acta Agron. Sinica, 36 (2010) 457–465.
[14] Q. Li, B. Dong, Y. Qiao, M. Liu, J. Zhang, Root growth, available soil water, and water-use efficiency of winter wheat under different irrigation regimes applied at different growth stages in North China, Agric. Water Manage., 97 (2010) 1676–1682.
[15] X. Liu, L. Shao, H. Sun, S. Chen, X. Zhang, Responses of yield and water use efficiency to irrigation amount decided by pan evaporation for winter wheat, Agric. Water Manage., 129 (2013) 173–180.
[16] H. Liu, L. Yu, Y. Luo, X. Wang, G. Huang, Responses of winter wheat (*Triticum aestivum* L.) evapotranspiration and yield to sprinkler irrigation regimes, Agric. Water Manage., 98 (2011) 483–492.
[17] S. Ma, Z. Yu, Y. Zhang, J. Zhao, Y. Shi, D. Wang, Effect of field border width for irrigation on water consumption characteristics, yield and water use efficiency of wheat, Sci. Agricultura Sinica, 47 (2014) 1531–1540 (in Chinese with English abstract).
[18] W. Meng, Y. Zhang, X. Ma, Y. Shi, Z. Yu, Effects of irrigation stage and amount on water consumption characteristics, flag leaf photosynthesis, and grain yield in wheat, Acta Agron. Sinica, 35 (2009) 1884−1892 (in Chinese with English abstract).
[19] G. Qiu, L. Wang, X. He, X. Zhang, S. Chen, J. Chen, Y. Yang, Water use efficiency and evapotranspiration of winter wheat and its response to irrigation regime in the north China plain, Agric. For. Meteorol., 148 (2008) 1848–1859.
[20] I. Sinha, G. Buttar, A. Brar, Drip irrigation and fertigation improve economics, water and energy productivity of spring sunflower (*Helianthus annuus* L.) in Indian Punjab, Agric. Water Manage., 185 (2017) 58–64
[21] D. Wang, Z. Yu, Effects of irrigation amount and stage on water consumption characteristics and grain yield of wheat, Chin. J. Appl. Ecol., 19 (2008) 1965–1970 (in Chinese with English abstract).
[22] X. Yang, Z. Yu, Z. Xu, Effects of irrigation regimes on water consumption characteristics and nitrogen accumulation and allocation in wheat, Acta Ecol. Sinica, 29 (2009) 846–853.
[23] H. Cao, D. Ge, S. Zhao, Y. Liu, Y. Liu, W. Wang, Evaluation to application of computer simulation in crop growth and development study, J. Triticeae Crops, 30 (2010) 183–187 (in Chinese, with English abstract).
[24] Y. Wang, L. He, Overview of study and application of crop growth simulation model, J. Huazhong Agric. Univ., 24 (2005) 529–535 (in Chinese, with English abstract).
[25] H. Chi, Y. Bai, H. Wang, J. Zhao, X. Wang, HYRDUS-3D in the soil water infiltration process simulation, Comp. Appl. Chem., 31 (2014) 531–535 (in Chinese, with English abstract).
[26] K. Yasukawa, Experiment, Observation, and Modeling in the Lab and Field, in: Encyclopedia of Animal Behavior, Elsevier, Amsterdam, 2010, pp. 679–685.
[27] J. Epperson, J. Hook, Y. Mustafa, Dynamic programming for improving irrigation scheduling strategies of maize, Agric. Syst., 42 (1993) 85–101.
[28] N. Rao, P. Sarma, S. Chander, Irrigation scheduling under a limited water supply, Agric. Water Manage., 15 (1988) 165–175.
[29] X. Mao, S. Shang, Application of 0-1 programming model on optimization of crop deficit irrigation schedule, Trans. Chin. Soc. Agric. Mach., 45 (2014) 123, 153–158 (in Chinese with English abstract).
[30] M. El-Sharkawy, Overview: early history of crop growth and photosynthesis modeling, Biosystems, 103 (2011) 205–211.
[31] X. Yun, J. Kiniry, A review on the development of crop modeling and its application, Acta Agron. Sinica, 28 (2002) 190–195 (in Chinese, with English abstract).
[32] T. Hsiao, L. Heng, P. Steduto, B. Rojas-Lara, D. Raes, E. Fereres, AquaCrop – The FAO crop model to simulate yield response to water: III. Parameterization and testing for maize, Agron. J., 101 (2009) 448–459.
[33] D. Raes, P. Steduto, T. Hsiao, E. Fereres, AquaCrop – The FAO Crop model to simulate yield response to water: II. Main algorithms and software description, Agron. J., 101 (2009) 438–447.
[34] P. Steduto, T. Hsiao, D. Raes, E. Fereres, AquaCrop – The FAO crop model to simulate yield response to water: I. Concepts and underlying principles, Agron. J., 101 (2009) 426–437.
[35] E. Vanuytrecht, D. Raes, P. Steduto, T. Hsiao, E. Fereres, L. Heng, M. Vila, P. Moreno, AquaCrop: FAO's crop water productivity and yield response model, Environ. Model. Software, 62 (2014) 351–360.
[36] M. Abedinpour, A. Sarangi, T. Rajput, M. Singh, H. Pathak, T. Ahmad, Performance evaluation of AquaCrop model for maize crop in a semi-arid environment, Agric. Water Manage., 110 (2012) 55–66.
[37] B. Andarzian, M. Bannayan, P. Steduto, H. Mazraeh, M. Barati, M. Barati, A. Rahnama, Validation and testing of the AquaCrop model under full and deficit irrigated wheat production in Iran, Agric. Water Manage., 100 (2011) 1–8.
[38] N. Katerji, P. Campi, M. Mastrorilli, Productivity, evapotranspiration, and water use efficiency of corn and tomato crops simulated by AquaCrop under contrasting water stress conditions in the Mediterranean region, Agric. Water Manage., 130 (2013) 14–26.
[39] H. Li, Y. Liu, J. Cai, X. Mao, The applicability and application of AquaCrop model, J. Irrig. Drain., 30 (2011) 28–33 (in Chinese, with English abstract).
[40] M. Maniruzzaman, M. Talukder, M. Khan, J. Biswas, A. Nemes, Validation of the AquaCrop model for irrigated rice production under varied water regimes in Bangladesh, Agric. Water Manage., 159 (2015) 331–340.
[41] M. Mkhabela, P. Bullock, Performance of the FAO AquaCrop model for wheat grain yield and soil moisture simulation in Western Canada, Agric. Water Manage., 110 (2012) 16–24.
[42] F. Montoya, D. Camargo, J. Ortega, J. Córcoles, A. Domínguez, Evaluation of Aquacrop model for a potato crop under different irrigation conditions, Agric. Water Manage., 164 (2016) 267–280.
[43] P. Paredes, J. Melo-Abreu, I. Alves, L. Pereira, Assessing the performance of the FAO AquaCrop model to estimate maize yields and water use under full and deficit irrigation with focus on model parameterization, Agric. Water Manage., 144 (2014) 81–97.
[44] P. Paredes, Z. Wei, Y. Liu, D. Xu, Y. Xin, B. Zhang, L. Pereira, Performance assessment of the FAO AquaCrop model for soil water, soil evaporation, biomass and yield of soybeans in North China Plain, Agric. Water Manage., 152 (2015) 57–71.
[45] R. Stricevic, M. Cosic, N. Djurovic, B. Pejic, L. Maksimovic, Assessment of the FAO AquaCrop model in the simulation of rainfed and supplementally irrigated maize, sugar beet and sunflower, Agric. Water Manage., 98 (2011) 1615–1621.
[46] A. Tavakoli, M. Moghadam, A. Sepaskhah, Evaluation of the AquaCrop model for barley production under deficit irrigation and rainfed condition in Iran, Agric. Water Manage., 161 (2015) 136–146.

[47] X. Teng, Y. Dong, J. Shen, L. Meng, H. Feng, Winter wheat irrigation simulation in arid area based on AquaCrop model, Sci. Agricultura Sinica, 48 (2015) 4100–4110 (in Chinese, with English abstract).
[48] J. Toumi, S. Er-Raki, J. Ezzahar, S. Khabba, L. Jarlan, A. Chehbouni, Performance assessment of AquaCrop model for estimating evapotranspiration, soil water content and grain yield of winter wheat in Tensift Al Haouz (Morocco): application to irrigation management, Agric. Water Manage., 163 (2016) 219–235.
[49] X. Wang, Q. Wang, J. Fan, Q. Fu, Evaluation of the AquaCrop model for simulating the impact of water deficits and different irrigation regimes on the biomass and yield of winter wheat grown on China's Loess Plateau, Agric. Water Manage., 129 (2013) 95–104.
[50] A. Soddu, R. Deidda, M. Marrocu, R. Meloni, C. Paniconi, R. Ludwig, M. Sodde, G. Mascaro, E. Perra, Climate variability and durum wheat adaptation using the AquaCrop model in Southern Sardinia, Procedia Environ. Sci., 19 (2013) 830–835.
[51] D. Voloudakis, A. Karamanos, G. Economou, D. Kalivas, P. Vahamidis, V. Kotoulas, J. Kapsomenakis, C. Zerefos, Prediction of climate change impacts on cotton yields in Greece under eight climatic models using the AquaCrop crop simulation model and discriminant function analysis, Agric. Water Manage., 147 (2015) 116–128.
[52] R. Linker, I. Ioslovich, G. Sylaios, F. Plauborg, A. Battilani, Optimal model-based deficit irrigation scheduling using AquaCrop: a simulation study with cotton, potato and tomato, Agric. Water Manage., 163 (2016) 236–243.
[53] N. Shrestha, D. Raes, S. Sah, Strategies to improve cereal production in the Terai region (Nepal) during dry season: simulations with Aquacrop, Procedia Environ. Sci., 19 (2013) 767–775.
[54] M. García-Vila, E. Fereres, Combining the simulation crop model AquaCrop with an economic model for the optimization of irrigation management at farm level, Eur. J. Agron., 36 (2012) 21–31.
[55] D. Wilks, D. Wolfe, Optimal use and economic value of weather forecasts for lettuce irrigation in a humid climate, Agric. For. Meteorol., 89 (1998) 115–129.
[56] K. Knapp, A. Dinar, Production with optimum irrigation management under saline conditions, Eng. Costs Prod. Econ., 14 (1988) 41–46.
[57] R. Allen, L. Periera, D. Raes, M. Smith, Crop Evapotranspriation, Guidelines for Computing Crop Water Requirement. FAO Irrigation and Drainage Paper No.56, FAO, Rome, 1998.
[58] W. Zhang, W. Liu, Y. Wang, Aquacrop model based on water-driven principle and its research progress, Agric. Res. Arid Areas, 32 (2014) 96–101 (in Chinese, with English abstract).
[59] F.C. Kahimba, P.R. Bullock, R. Sri-Ranjan, H.W. Cutforth, Evaluation of the SolarCalc model for simulating hourly and daily incoming solar radiation in the Northern Great Plains of Canada, Can. Biosyst. Eng., 51 (2009) 1–11.
[60] C.J. Willmott, Some comments on the evaluation of model performance, Bull. Am. Meteorol. Soc., 63 (1982) 1309–1313.
[61] C.J. Willmott, K. Maasuura, Advantages of the mean absolute error (MAE) over the root mean square error (RMSE) in assessing average model performance, Clim. Res., 30 (2005) 79–82.
[62] S.C.A. Mana, M.M. Hanafiah, A.J.K. Chowdhury, Environmental characteristics of clay and clay-based minerals, Geol. Ecol. Landscapes, 1 (2017) 155–161.
[63] G. Chelladurai, Influence of diets on growth and biochemical parameters of *Babylonia spirata*, Geol. Ecol. Landscapes, 1 (2017) 162–166.
[64] M.J. OmaraShahestan, S. OmaraShastani, Evaluating environmental considerations with checklist and delphi methods, case study: Suran city, Iran, Environ. Ecosyst. Sci., 1 (2017) 01–04.
[65] S.M. Hejazi, F. Lotfi, H. Fashandi, A. Alirezazadeh, Serishm: an eco-friendly and biodegradable flame retardant for fabrics, Environ. Ecosyst. Sci., 1 (2017) 05–08.
[66] M. Foroozanfar, Environmental control in petroleum operations, J. CleanWAS, 1 (2017) 18–22.
[67] R. Radmanfar, M. Rezayi, S. Salajegheh, V.A. Bafrani, Determination the most important of hse climate assessment indicators case study: HSE climate assessment of combined cycle power plant staffs, J. CleanWAS, 1 (2017) 23–26