water

MDPI

Article

Optimization of Spring Wheat Irrigation Schedule in Shallow Groundwater Area of Jiefangzha Region in Hetao Irrigation District

Zhigong Peng [1,2], Baozhong Zhang [1,2,*], Jiabing Cai [1,2], Zheng Wei [1,2,*], He Chen [1,2] and Yu Liu [1,2]

1 State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China; pengzhg@iwhr.com (Z.P.); caijb@iwhr.com (J.C.); chenhe@iwhr.com (H.C.); liuyu@iwhr.com (Y.L.)

2 National Center of Efficient Irrigation Engineering and Technology Research-Beijing, Beijing 100048, China

* Correspondence: zhangbaozhong333@163.com (B.Z.); weizheng@iwhr.com (Z.W.); Tel.: +86-10-6878-6510 (B.Z.); +86-10-6878-5226 (Z.W.)

Received: 28 September 2019; Accepted: 10 December 2019; Published: 13 December 2019

Abstract: Due to the large spatial variation of groundwater depth, it is very difficult to determine suitable irrigation schedules for crops in shallow groundwater area. A zoning optimization method of irrigation schedule is proposed here, which can solve the problem of the connection between suitable irrigation schedules and different groundwater depths in shallow groundwater areas. The main results include: (1) Taking the annual mean groundwater depth 2.5 m as the dividing line, the shallow groundwater areas were categorized into two irrigation schedule zones. (2) On the principle of maximizing the yield, the optimized irrigation schedule for spring wheat in each zone was obtained. When the groundwater depth was greater than 2.5 m, two rounds of irrigation were chosen at the tillering–shooting stage and the shooting–heading stage with the irrigation quota at 300 mm. When the groundwater depth was less than 2.5 m, two rounds of irrigation were chosen at the tillering–shooting stage, and one round at the shooting–heading stage, with the irrigation quota at 240 mm. The main water-saving effect of the optimized irrigation schedule is that the yield, the soil water use rate, and the water use productivity increased, while the irrigation amount and the ineffective seepage decreased.

Keywords: crop model; water consumption; yield; water production function; irrigation schedule optimization

1. Introduction

In a shallow groundwater area, the groundwater is supplied to the aeration zone through capillary rise becoming soil water available to the crops. The interaction between soil water and groundwater varies due to the depth of groundwater [1–4]. For the sake of greater water economy, crop yield, and seeking the greatest advantage from the regulating effect of groundwater in soil water, scholars are particularly interested in the impact of different groundwater depths on crop growth. Kong et al. [5] studied the effect of different groundwater depths on crop growth using a lysimeter, finding that a depth of 1.5–2.5 m was conducive to crop growth, and when this depth was more than 2.0 m, the existent irrigation schedule was unable to meet the normal growth of crops. Kruse et al. [6] pointed out that in the areas with shallow groundwater depth, the groundwater recharge affected the water and the biological and chemical processes of the soil–plant–atmosphere continuum, and if no irrigation was provided, the optimal groundwater depth for winter wheat was about 1.5 m. Wang et al. [7] studied the effect of different groundwater depths on crop growth, showing that different groundwater depths led to differences in crop root distribution, which in turn affected the crops' water-yield response mechanism. Zhang [8] using a lysimeter, studied the drought crops' groundwater utilization, suggesting that in the suitable groundwater depth, the groundwater used by drought crops accounted for 50% to 70% of the evapotranspiration. Yang et al. [9] using the HYDRUS software, simulated the influence of different groundwater depths on the irrigation quota of mulched, drip-irrigated cotton, finding that the drip irrigation quota was 330 mm, 450 mm, or 550 mm with the groundwater depth respectively at 1.5 m, 2.0 m, and 3.0 m. Zhuang et al. [10] studied the recharge effect of different groundwater depths on the cotton root layer, pointing out that when the groundwater depth did not exceed 2 m, the cotton irrigation schedule should be developed with the consideration of the groundwater recharge. Wang et al. [11] studied the spring wheat recharge modes under different groundwater depths, showing that the recharge was the largest at the groundwater depth of 1.0 m, and there was basically no replenishment with the groundwater depth at 3.0 m or greater. Liu et al. [12] technically supported by a lysimeter with controlled groundwater depth, determined the deficit irrigation schedule for crops under different groundwater depths. Relevant researchers pointed out that groundwater action was particularly critical in the analysis of the soil–crop–atmosphere system water balance in an arid oasis [13–18]. The deficit irrigation schedule in shallow groundwater areas could improve groundwater utilization but limited the influence on yield [19–21]. Karimov et al. [22] pointed out that a shallower groundwater depth promoted phreatic evaporation.

In summary, the proportion of phreatic evaporation varies notably with groundwater depth. To be rational, an irrigation schedule should fully consider the groundwater recharge under different groundwater depths. Previous studies on the effect of different groundwater depths on crop growth were mainly based on the controlled groundwater table by a lysimeter, with the groundwater table remaining unchanged during the whole crop growth period, which is not in line with the actual situation, because there is significantly daily variation in the groundwater table throughout the crop growth period. Therefore, the studies based on controlled groundwater table can hardly represent the actual change of groundwater depth throughout the crop growth period. The studies on the effect of different groundwater depths on crop growth, irrigation amount, and irrigation schedule optimization are mostly based on experiment stations; however, in shallow groundwater depth areas the groundwater table varies greatly from place to place. Therefore, the problem of how to apply the experimental results to a large expanse of areas in urgent need of a solution.

Hetao Irrigation District is the largest gravity irrigation district by water diverted from the Yellow River. According to the overall water allocation plan of the Yellow River watershed, the quota of water diversion to Hetao Irrigation District has decreased from 5.18×10^9 m^3 to 4.00×10^9 m^3. This ever-decreasing diversion will gravely affect the grain production in the irrigation district, making the conflict between supply and demand even more serious [23,24]. After the implementation of water-saving projects in the Hetao Irrigation District, the amount of water diversion for agricultural purposes has been cut notably. The result is that the groundwater table has been falling year on year [25]. Li et al. [26] pointed out that the spatial variation of groundwater depth was great in the Jiefangzha Region, and in the well irrigation area, the groundwater table was of a funnel shape with a groundwater depth more than 2.5 m, and in some localities, the groundwater table exceeded 4.5 m. It can be seen that with dwindling water diversion from the Yellow River and the growing well irrigation area, the spatial difference in groundwater depth is increasing.

The findings of previous studies on the crop irrigation schedule in Hetao Irrigation District were based on groundwater table at experiment stations in specific years. The results from experiment stations can hardly reflect the great difference in groundwater depth throughout the irrigation district, and so the application of related findings to a larger area has great limitations. Spring wheat is one of the main grain crops in Hetao Irrigation District, and wheat production plays an important role in grain production in this district. As spring wheat in Hetao Irrigation District grows in the dry season, irrigation is the key to its high yield. In Hetao Irrigation District, the net irrigation quota of spring wheat has been cut to about 300 mm. In shallow groundwater depth areas, it is difficult to maximize the use of the soil water in the soil and thus the water use efficiency is low. In areas with greater groundwater depth, the groundwater recharge is reduced, resulting in the water deficit during certain growth stages.

Compared with the field experiments, studying crop water consumption characteristics based on models has benefits such as the freedom from geographical restrictions, time and financial efficiency, and additional system observables. In addition to the above, it is also possible to remove some interference factors, thus helpful to expose some behaviors among variables. Therefore, technically built on a verified crop growth simulation model, this study investigates the water-yield response mechanism of spring wheat for different groundwater depths, and constructs a spring wheat water production function for each zone. From the above information, an optimization method of zoning irrigation schedule is developed, which solves the problem of groundwater spatial variability in shallow groundwater areas. It is hoped that this study may provide some useful reference for the optimization of irrigation schedules in shallow groundwater areas.

2. Materials and Methods

2.1. Study Area

The experiment was carried out from March 2015 to July 2016 in the Jiefangzha Region of Hetao Irrigation District, Inner Mongolia. The Jiefangzha Region is at N 40°32′–N 41°11′, E 106°51′–107°23′, and its elevation varies between 1030–1046 m. Most of the irrigation area is located within the jurisdiction of Hangjinhouqi of Inner Mongolia Autonomous Region. The Jiefangzha Region, with a controlled area of 21.57×10^4 hm^2 and an irrigated area of 14.21×10^4 hm^2, is the second largest in Hetao Irrigation District. This irrigation area has a comparatively flat terrain, and the overall terrain, high in the southwest and low in the northeast, has an average slope of about 0.02%. The Jiefangzha Region is featured by the arid or semiarid climate. The average annual precipitation and evaporation from a free water surface are 140 mm and 2096 mm respectively, and the annual average temperature is 9 °C. The average annual sunshine hours are 3181 h, the frost-free period is 130–150 d, and the annual average groundwater depth is 1.86 m. According to the American soil classification system, the soil of this irrigation area is dominated by silt loam. Table 1 summarizes the soil's physical properties in the study area.

Table 1. Soil physical properties in the study area.

Depth (cm)	Dry Bulk Density (g/cm^3)	Saturated Moisture Content (m^3/m^3)	Field Capacity (m^3/m^3)	Wilting Point (m^3/m^3)
0–10	1.45	0.46	0.36	0.09
10–20	1.40	0.47	0.38	0.09
20–40	1.34	0.49	0.41	0.09
40–60	1.38	0.48	0.41	0.08
60–100	1.34	0.50	0.42	0.09

2.2. Design of the Experiment

The spring wheat variety tested was Yongliang No. 4. The spring wheat in 2015 was sowed and harvested on 19 March and 19 July, respectively, with the precipitation during the growth period being 61 mm. The spring wheat in 2016 was sowed and harvested on 14 March and 18 July, respectively, with the precipitation during the growth period being 55 mm. According to the water distribution of the irrigation region in previous years, a total of four rounds of irrigation are made throughout the spring wheat growth period. However, at the time of the fourth irrigation, the spring wheat had already been at the ripening stage, and therefore this irrigation contributed little to wheat yield. For this reason, local farmers rarely make the fourth irrigation. To improve the water productivity of spring wheat, the experiment included the first three rounds of irrigation only.

Five treatments were provided, as shown in Table 2, with three replications. Each experiment plot area was 20 m^2. In order to preclude lateral permeability between the plots, each plot was fringed with a 1 m-wide protection row. According to the soil moisture of each experiment treatment at the time of water distribution, the irrigation quota was estimated such that the irrigation upper limit should not exceed the field capacity. Each experiment plot area was irrigated by pumping from the canal. The irrigation volume of the experiment plots was measured by water meters. The field management practice, such as sowing, fertilizing, and farming, for each experiment plot was the same as that of the local farmers.

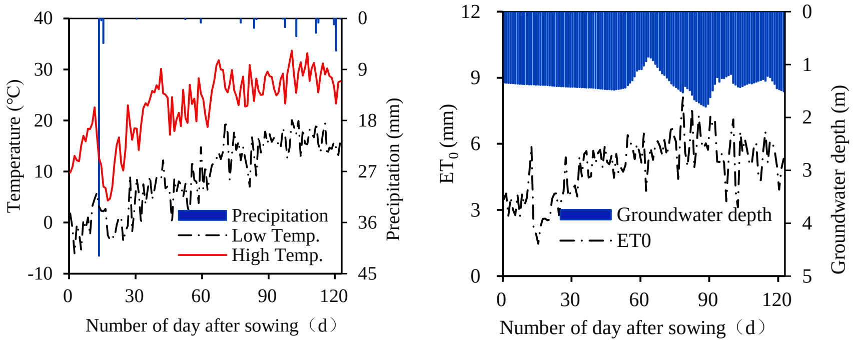
Table 2. Experiment treatments.

Treatment	Tillering–Shooting	Shooting–Heading	Heading–Filling	Irrigation Quota (mm)	
				2015	2016
T1				-	-
T2		√		100	100
T3	√	√		160	160
T4	√		√	160	135
T5	√	√	√	260	235

Note: "√" means irrigation at this growing stage.

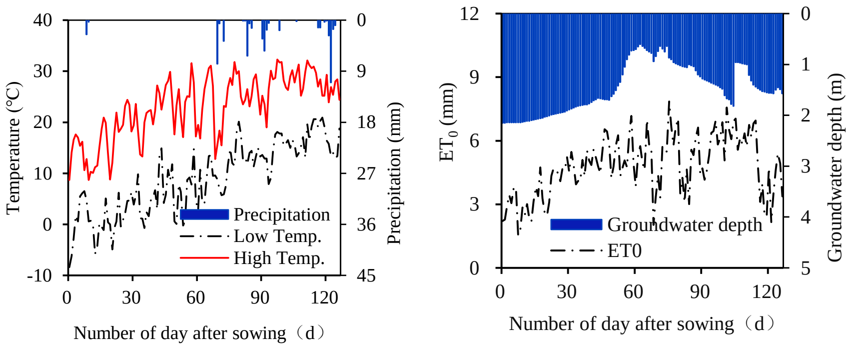
2.3. Data Observation

The relevant meteorological data include solar radiation, wind speed, temperature, atmospheric humidity, and rainfall, all taken from the Hangjinhouqi National Meteorological Station, close to the study area about 1 km. The Penman–Monteith formula, recommended by FAO, was utilized to estimate the reference crop evapotranspiration (ET_0) based on the longitude, latitude, and altitude of the weather station [27]. From the Shahaoqu Experimental Station in this irrigation area, the study area groundwater table data of 57 observation wells from 1990–2016 were collected. A groundwater table distribution map was generated using the inverse distance weighting interpolation. At the same time, the groundwater table monitoring wells were also installed in the experimental site, which were read once every 2 or 3 days during the study period. The soil moisture content was determined by the oven drying method. Samples were taken from each plot at an interval of 5 days, and extra measurements were taken before and after rainfall and irrigation. Sampling depths were at 0~20 cm, 20~40 cm, 40~60 cm, 60~80 cm, and 80~100 cm. Upon the harvest, the yield of spring wheat was evaluated. For this purpose, a representative 1 m^2 quadrat was chosen from each experiment plot to determine the grain yield after natural air drying. The temperature, precipitation, reference crop evapotranspiration, and groundwater table change in the experiment plots throughout the experiment period are as shown in Figure 1. The interannual variation of the groundwater table in this irrigation area is shown in Figure 2.



(**a**) 2015

Figure 1. *Cont.*



(**b**) 2016

Figure 1. Meteorological data and groundwater table of the study area during the growth period of spring wheat.

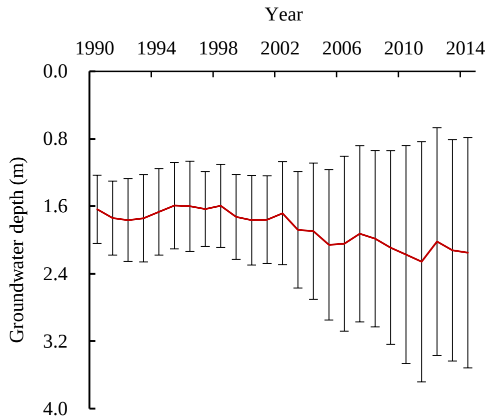


Figure 2. Interannual variation of groundwater table in Jiefangzha Region.

2.4. The Aquacrop Model

The evapotranspiration is divided into two parts by the model [28–31]: Evaporation and transpiration. In order to separate the evaporation, the transpiration was estimated based on the variation of the crop canopy ground cover instead of leaf area index in the whole growth period. Crop yield is calculated based on the biomass on the ground and the harvest index. Based on the difference in the influence mechanism of environment on biomass and on harvest index, the effects of environmental stresses on biomass and harvest index were distinguished. By limiting canopy stretching, accelerating canopy senescence, controlling stomatal closure, and regulating harvest index after the start of reproductive growth, the soil water stresses on crop growth were further refined. From this basis, the crop yields under different irrigation schedules were simulated. The input data of the crop's water-yield response mechanism simulation included crop species, meteorology, soil, groundwater, and irrigation schedule, field management, and initial conditions.

2.5. Model Verification

The input database for crop model consists of crop growth data, meteorological data, soil properties, irrigation schedules, and field management data. For the study area, the soil properties and field management data have remained unchanged during the 2-year experiment. The measured data such as crop growth data, meteorological data and irrigation schedules and so on from the 2015 spring wheat were used to calibrate the model, and those from the 2016 spring wheat were used to verify the model. Soil moisture and yield were used to verify the model parameters. The major parameters of the Aquacrop model for simulating the growth of spring wheat in the Hetao Irrigation District are as shown in Table 3.

Table 3. Some parameters of spring wheat for the crop growth simulation model.

Parameter	Default	Calibrated
Cutoff temperature (°C)	26	26
Crop coefficient	1.10	1.05
Upper and lower thresholds of soil water depletion coefficient	0.20~0.65	0.15~0.35
Shape factor for water stress coefficient for canopy expansion	5.0	5.0
Upper stomatal control limit coefficient of soil stress	0.65	0.35
Soil water depletion fraction for stomatal control-upper threshold	2.5	2.5
Canopy growth coefficient	0.04901	0.07600
Canopy decline coefficient	0.07179	0.18506
Maximum canopy cover in fraction soil cover	0.96	0.98
Minimum effective rooting depth (m)	0.30	0.30
Maximum effective rooting depth (m)	1.50	0.90
Normalized water productivity (g/m^2)	15.0	19.7
Harvest index (%)	48	48
Number of plants per hectare	4,500,000	6,500,000

In the verification process, the degree of agreement between the simulated and the observed value was evaluated by root mean square error (RMSE), mean absolute error (MAE), mean relative error (MBE), and the Nash efficiency coefficient (EF). RMSE and MAE is used to test the unbiasedness of the model, resulting in that the lower their values, the less biased the model, and thus the more accurate the simulation. The EF is a kind of relative error index, also a dimensionless model evaluation index. When taking a value close to 1, the model was believed to have high credibility. A value close to zero suggests that, though the simulation result is generally credible, the simulation process involves larger errors. When the MBE is greater than 0, the simulation result is believed to be on the greater side; otherwise, on the smaller side. The model evaluation indices are determined by [32–34]:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(M_i - Q_i)^2} \quad (1)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|M_i - O_i| \quad (2)$$

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(M_i - Q_i) \quad (3)$$

$$EF = 1.0 - \frac{\sum_{i=1}^{n}(O_i - M_i)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2} \quad (4)$$

where, O_i, M_i, and $\overline{O}$ stand for the measured value, simulated value, measured mean value; n is the times of measurement

2.6. Scenarios

2.6.1. Determination of the Typical Year

The precipitation data in the study area from 1961 to 2014 were analyzed, finding that the average annual precipitation during the spring wheat growth period was 61 mm; the year closest to the typical annual precipitation was 2013, with a precipitation of 58 mm.

2.6.2. Determination of Groundwater Depth

In light of the gentle terrain in the Jiefangzha Region, the year-by-year groundwater depth data of the 57 monitoring wells from 1990 to 2015 were interpolated using the inverse distance weighting method, which indicated the mean annual groundwater depth in this area was 1.6–2.3 m and the depth exceeded 2.2 m, in 2010, 2011, and 2014.

According to the phreatic evaporation data of the Shahaoqu Experimental Station, once the groundwater depth exceeded 2.5 m, the phreatic evaporation was significantly reduced. Groundwater depth was closely related to grain yield, for which the shallower the depth, the more serious the soil salinization was and the lower the grain yield was [35]. Still, relevant studies showed that when groundwater depth exceeded 2.5 m, the ecological environment in an arid irrigation district might be adversely affected [36].

Without compromising the ecological safety, and for the sake of preventing soil salinization and minimizing water diversion from the Yellow River, the average annual groundwater depth was taken to be 2.5 m for the future scenario. The interannual spatial variation and the intraanual difference of groundwater table were based on the mean value of 2010, 2011, and 2014. For the future scenario, the spatial distribution of groundwater depth and the zoning of the irrigation schedule are shown in Figure 3. With a groundwater depth of 2.5 m as the divide, the area was divided into zones with significant influence of phreatic evaporation and zones with insignificant influence of phreatic evaporation, which has solved the problem of spatial variability of groundwater depth. As for the future scenario simulation, Figure 4 shows the annual temperature, precipitation, reference crop evapotranspiration, and groundwater depth variation during spring wheat growth period in the typical year. When the annual mean groundwater depth is less than 2.5 m, the groundwater depth during the spring wheat growth period is 1.29–2.61 m. However, when the annual mean groundwater depth is more than 2.5 m, the groundwater depth during the growth period is between 2.59 and 3.63 m. In practical application, the groundwater depth of 2.5 m in the previous year can be used to provide dynamic division so as to ensure that the irrigation schedule optimization can be better applied to shallow groundwater areas.

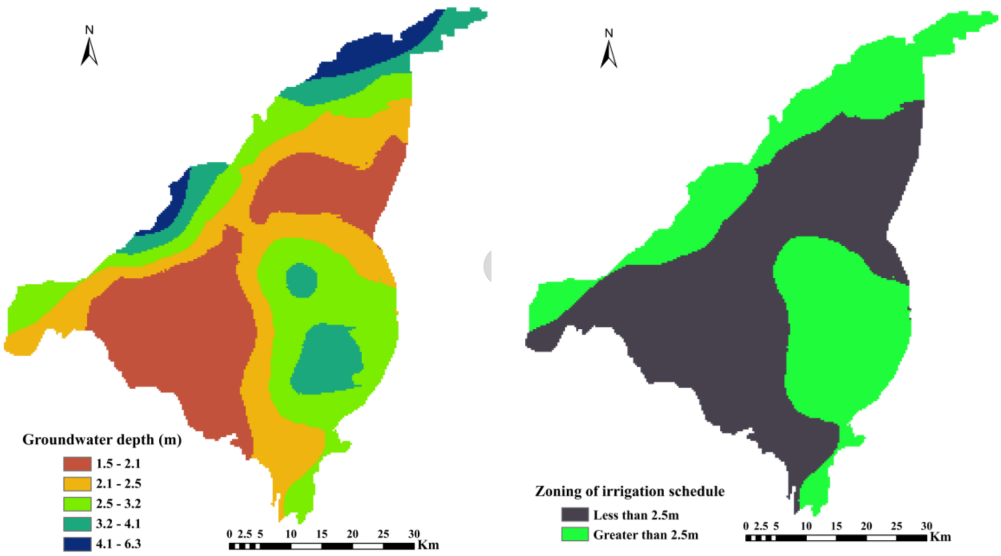


Figure 3. Spatial variation pattern of groundwater depth and irrigation schedule zoning in Jiefangzha region for the future scenario.

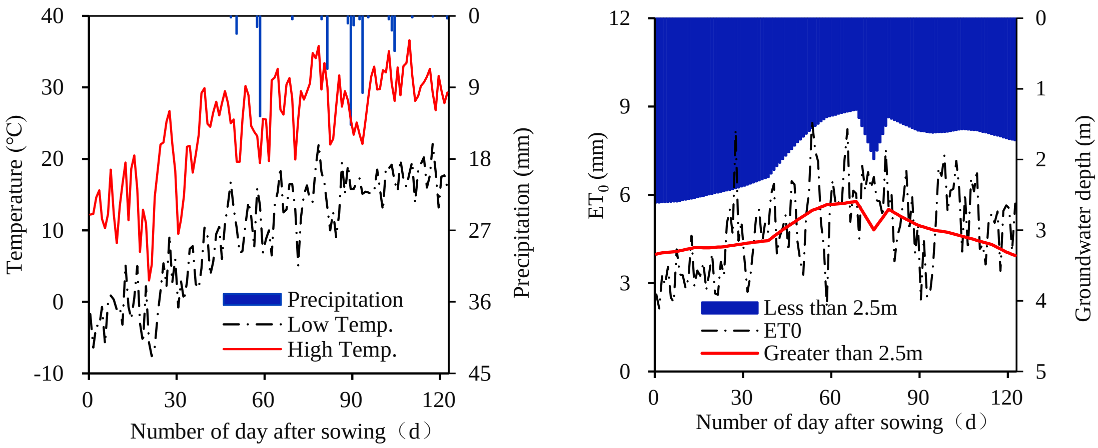


Figure 4. Annual temperature, precipitation, ET_0, and groundwater depth variation of the typical year for the future scenario.

2.6.3. Irrigation Schedule Scenarios

Because the study area is a canal irrigation area, there are only four times of irrigation in the growth period of spring wheat. According to the actual water distribution in the irrigation area, a total of irrigation scenarios was considered as rain-fed, one round of irrigation, two rounds of irrigation, three rounds of irrigation, and four rounds of irrigation for the four growth stages of spring wheat. When the total irrigation times of the whole growth period were determined, all possibilities for irrigation growth period were considered. There were 16 irrigation schedules, as shown in Table 4.

Table 4. Irrigation schedule scenarios.

Treatment	Tillering–Shooting	Shooting–Heading	Heading–Filling	Filling–Ripening	Irrigation Quota (mm)
T00					-
T11	√				60
T12		√			100
T13			√		100
T14				√	100
T21	√	√			160
T22	√		√		160
T23	√			√	160
T24		√	√		200
T25		√		√	200
T26			√	√	200
T31	√	√	√		260
T32	√	√		√	260
T33	√		√	√	260
T34		√	√	√	300
T44	√	√	√	√	360

Note: "√" means irrigation at this growing stage.

3. Results

3.1. Model Verification

It can be seen from Figure 5 and Table 5 that in calibration of the model, except for the T2–T4 treatments with slightly larger simulation values for the ripening stage, the simulated values for other growth stages are in good agreement with the measured soil moisture contents. The RMSE and the MAE between the simulated and measured soil moisture contents were less than 1.740% and 1.526%, respectively, and the R^2 was greater than 0.764, and the EF was greater than 0.722. For all irrigation treatments, in calibration of the model, the RMSE, MAE, R^2, and EF were 1.203%, 0.780%, 0.860, and 0.849, respectively. In model verification, the model simulation values satisfactorily reflected the change process of the measured soil moisture contents. As shown in Figure 6 and Table 5, the RMSE and MAE between simulated and measured values of soil moisture contents were below 1.802% and 1.429%, respectively, and the corresponding R^2 exceeded 0.651 and the EF was greater than 0.349. In model verification of all water treatments, the RMSE, MAE, R^2, and EF were 1.612%, 1.333%, 0.761, and 0.538, respectively. It can be seen that the fitting degree and accuracy of the soil moisture after model verification were both high, quite able to meet the simulation accuracy requirements of spring wheat soil water balance.

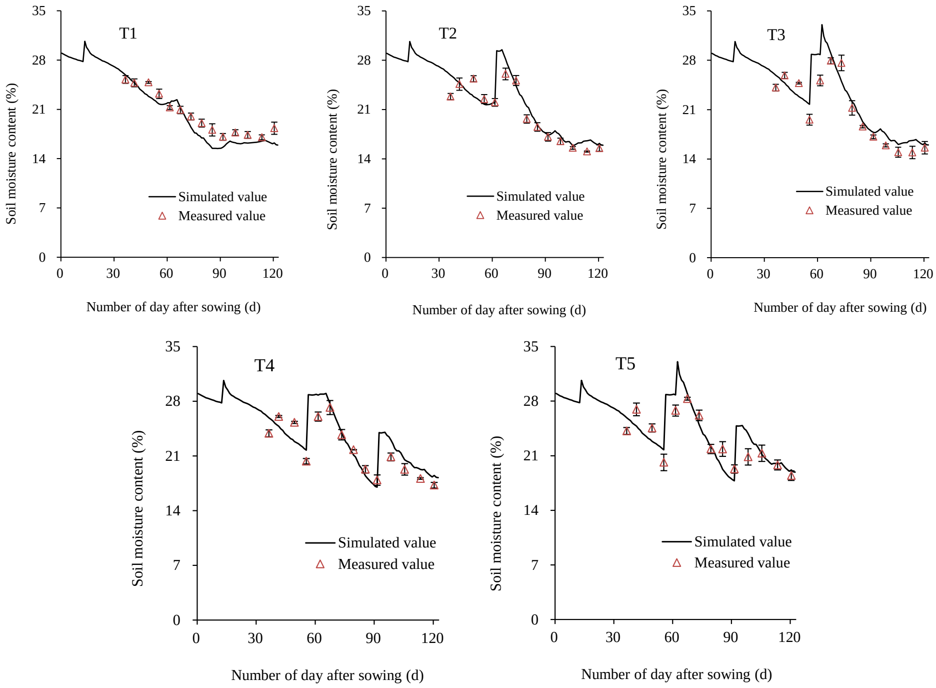


Figure 5. Simulated vs. measured values of spring wheat soil moisture content in model calibration.

Table 5. Evaluation indices of spring wheat soil moisture content simulation. RMSA: root mean square error.

		R^2	RMSE (%)	MAE (%)	MBE (%)	EF
Model calibration	T1	0.927	1.481	1.290	−1.045	0.747
	T2	0.887	1.417	1.083	0.495	0.869
	T3	0.887	1.740	1.526	0.735	0.862
	T4	0.825	1.522	1.343	0.473	0.784
	T5	0.764	1.635	1.383	0.066	0.722
	All treatments	0.860	1.203	0.780	0.037	0.849
Model verification	T1	0.710	1.578	1.278	−0.136	0.464
	T2	0.810	1.647	1.431	0.825	0.601
	T3	0.805	1.802	1.429	0.691	0.349
	T4	0.651	1.564	1.288	0.090	0.472
	T5	0.755	1.445	1.241	0.633	0.581
	All treatments	0.761	1.612	1.333	0.421	0.538

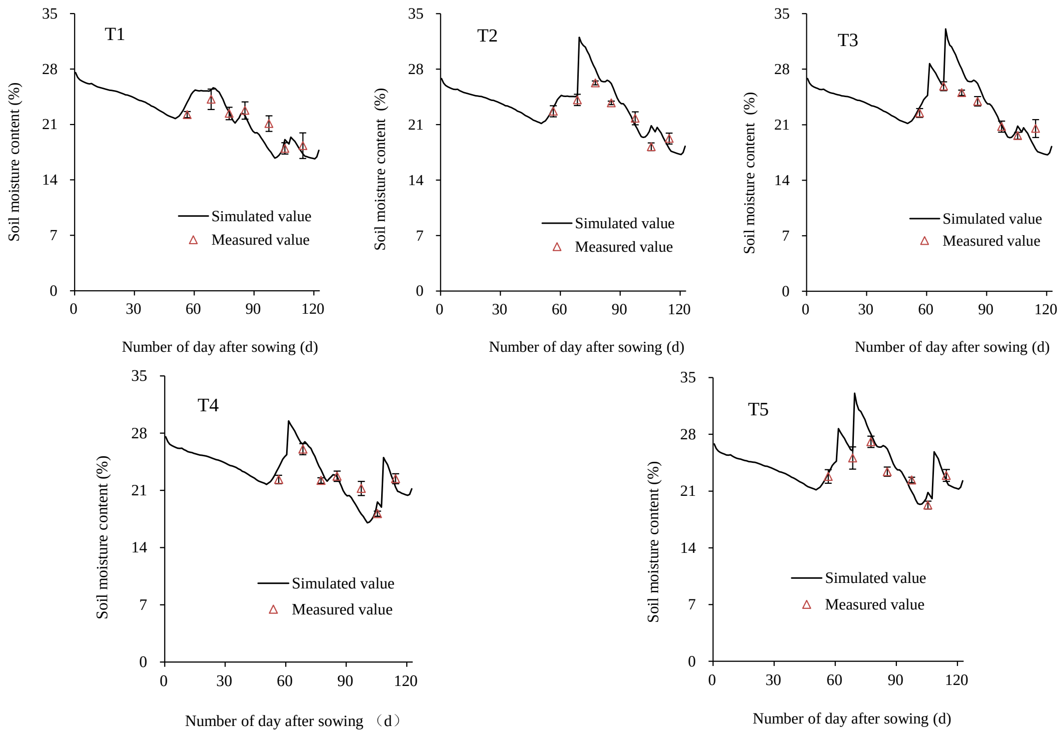


Figure 6. Simulated vs. measured values of spring wheat soil moisture content in model verification.

As can be seen from Figures 7 and 8, and Table 6, the simulated yields agreed well with the measured values. In model calibration, the RMSE, MAE, and MBE between the simulated and the observed values were 275.883 kg/hm^2, 246.190 kg/hm^2, −159.370 kg/hm^2 respectively, and the R^2 and EF were 0.985 and 0.976 respectively. In model verification, the RMSE, MAE, and MBE between the simulated and observed yields were 375.097 kg/hm^2, 242.402 kg/hm^2, and 145.004 kg/hm^2 respectively, and the R^2 and EF are 0.970 and 0.618 respectively. It can be seen that the RMSE and MAE between the simulated and observed values were less than 376 kg/hm^2 and 247 kg/hm^2, respectively, and the R^2 and EF were greater than 0.96 and 0.61 respectively. Hence, the model after verification is able to simulate satisfactorily spring wheat yield.

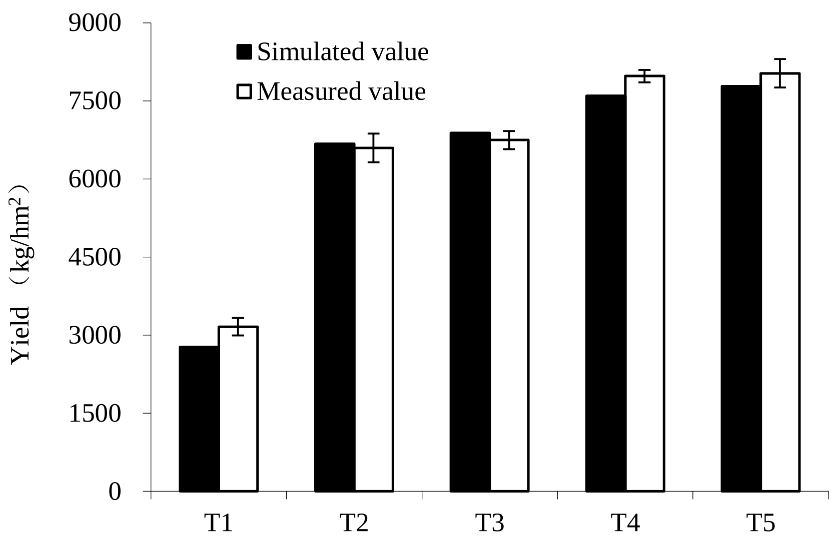


Figure 7. Simulated vs. measured values of spring wheat yield in model calibration.

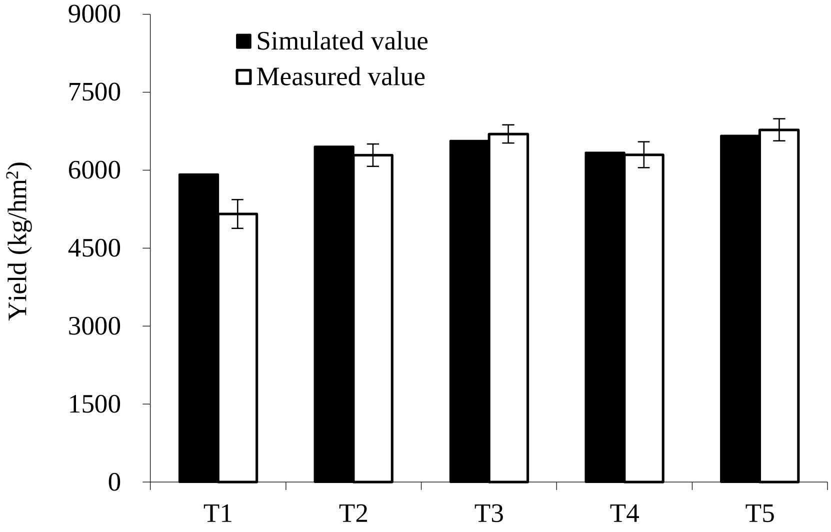


Figure 8. Simulated vs. measured values of spring wheat yield in model verification.

Table 6. Evaluation indices of spring wheat yield simulation.

	R^2	RMSE (kg/hm^2)	MAE (kg/hm^2)	MBE (kg/hm^2)	EF
Model calibration	0.985	275.883	246.190	−159.370	0.976
Model verification	0.970	357.097	242.402	145.004	0.618

In summary, the verified Aquacrop model is able to simulate the dynamic process of the soil moisture contents during the spring wheat growth period as well as the yield in shallow groundwater zones under different irrigation schedules. The model is useful in studying the relation between soil moisture contents and yield of spring wheat in shallow groundwater areas.

3.2. Water Consumption by Spring Wheat in Different Zones under Different Irrigation Schedules

Water consumption by spring wheat in different zones under different irrigation schedules is shown in Figure 9. As can be seen, where the groundwater depth was within 2.5 m, water consumption by rain-fed was 260 mm, and that by one round of irrigation was in the range of 284–387 mm. Water consumption by two rounds of irrigation was in the range of 326–424 mm. For three rounds and four rounds, the figures were 398–436 mm and 449 mm respectively. Where the groundwater depth was over 2.5 m, the water consumption by rain-fed was 210 mm. Water consumption by one round of irrigation was in the range of 234–326 mm. For two rounds and three rounds, the figures were in the range of 256–389 mm and 338–432 mm respectively. Water consumption by four rounds was 445 mm. It can be seen that within the irrigation quota of 360 mm, the water consumption of spring wheat increased with the irrigation quota. For a given irrigation number and a given irrigation quota, the water consumption varied greatly with the irrigation date. For the same irrigation schedule, less water was consumed when the groundwater depth exceeded 2.5 m than when the groundwater depth was less than 2.5 m, but the difference dwindled with the increase of irrigation quota.

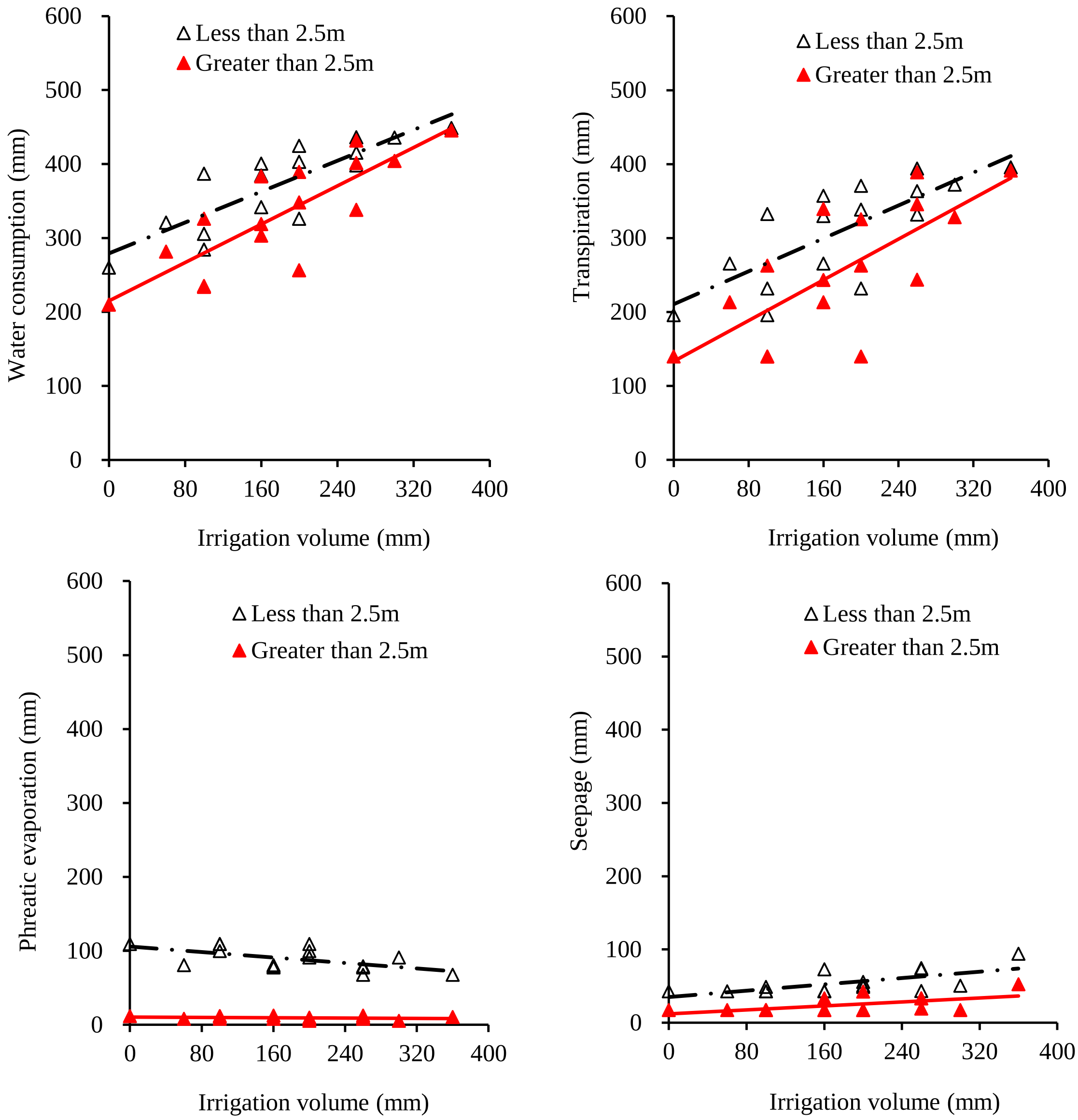


Figure 9. Water consumption by spring wheat in different zones under different irrigation schedules.

Where the groundwater depth was less than 2.5 m, the transpiration of rain-fed spring wheat was 196 mm, this figure was in the range of 196–333 mm for one round of irrigation or 232–370 mm for two rounds of irrigation, and for three rounds and four rounds of irrigation the transpiration was 332–394 mm and 396 mm respectively. Where the groundwater depth was greater than 2.5 m, the transpiration of rain-fed spring wheat was 140 mm, and for one round, two rounds, and three rounds of irrigation the figure was in the range of 140–263 mm, 140–339 mm, and 244–389 mm respectively. The transpiration was 391 mm for four rounds of irrigation. It can be seen that the way the transpiration of spring wheat varied with the groundwater depth parallels the relation between water consumption and the groundwater depth. It therefore follows that the change of transpiration is one of the most critical factors affecting the change of water consumption.

Where the groundwater depth was less than 2.5 m, the phreatic evaporation of rain-fed spring wheat was 109 mm, this figure was in the range of 81–109 mm for one round of irrigation or 77–109 mm for two rounds of irrigation, and for three rounds and four rounds of irrigation the phreatic evaporation was 67–91 mm and 67 mm respectively. Where the groundwater depth was greater than 2.5 m, the phreatic evaporation of rain-fed spring wheat was 12 mm, and for one round, two rounds, and three rounds of irrigation the figure was in the range of 8–12 mm, 5–12 mm, and 5–12 mm respectively. The phreatic evaporation was 10 mm for four rounds of irrigation. It could be seen that when the groundwater depth was more than 2.5 m, the phreatic evaporation of spring wheat was less than 12 mm, and it did not change much with the irrigation quota. When the groundwater depth was less than 2.5 m, the groundwater utilization decreased with the increase of irrigation quota.

Where the groundwater depth was less than 2.5 m, the seepage, in the case of rain-fed spring wheat, was 43 mm, this figure was in the range of 43–49 mm for one round of irrigation or 43–73 mm for two rounds of irrigation, and for three rounds and four rounds of irrigation the seepage was 43–74 mm and 94 mm respectively. Where the groundwater depth was greater than 2.5 m, the seepage, in the case of rain-fed spring wheat, was 17 mm, and for one round, two rounds, and three rounds of irrigation this figure was 17 mm, 17–42 mm, and 17–33 mm respectively. The seepage was 53 mm for four rounds of irrigation. It could be seen that, within the net irrigation quota of 360 mm, the amount of seepage increased with the irrigation quota; with the same irrigation schedule, when the groundwater depth was more than 2.5 m, the seepage was smaller than when the depth was less than 2.5 m.

3.3. Yield of Spring Wheat in Different Zones under Different Irrigation Schedules

The yields of spring wheat in different zones under different irrigation schedules are shown in Figure 10. Where the groundwater depth was less than 2.5 m, the yield of rain-fed spring wheat was 2505 kg/hm^2, and this figure was in the range of 2505–6283 kg/hm^2, for one round of irrigation, 4384–7091 kg/hm^2 for two rounds of irrigation, or 6272–7640 kg/hm^2 for three rounds of irrigation. For four rounds of irrigation, the yield was 7672 kg/hm^2. Where the groundwater depth was greater than 2.5 m, there was zero yield of the rain-fed spring wheat. The yield of spring wheat for one round of irrigation was in the range of 0–4844 kg/hm^2, and this figure was in the range of 0–6498 kg/hm^2 for two rounds of irrigation or 4548–7600 kg/hm^2 for three rounds of irrigation. For four rounds of irrigation, the yield of spring wheat was 7650 kg/hm^2. Where the groundwater depth was less than 2.5 m, the yield of T12 for one round of irrigation was up to 6283 kg/hm^2, the yield of T24 for two rounds of irrigation was up to 7091 kg/hm^2, and the yield of T31 for three rounds of irrigation was up to 7640 kg/hm^2. Where the groundwater depth was more than 2.5 m, the yield of T12 for one round of irrigation was up to 4844 kg/hm^2, the yield of T21 for two rounds of irrigation was up to 6498 kg/hm^2, and the yield of T3 for three rounds of irrigation was up to 7600 kg/hm^2. It could be seen that with the increase of irrigation quota, the yield of spring wheat generally increased. The timing of irrigation was especially important if the total times of irrigation remained constant. As shallow groundwater replenished available water to the crop, the yield in shallow groundwater depth zones was higher than that in deeper groundwater depth zones under the same irrigation schedule. In light of this, in the case of one round of irrigation, it is important to meet the wheat water demand at shooting–heading stage. Where the groundwater depth is less than 2.5 m, in order to take greater advantage of groundwater, the key is to satisfy water demand at the shooting–heading and heading–filling stages in the case of two rounds of irrigation, and where the groundwater depth is more than 2.5 m, it is important to satisfy the wheat water demand at the tillering–shooting and shooting–heading stages. In the case of three rounds of irrigation, the key is to satisfy the water demand at the tillering–shooting, shooting–heading, and heading–filling stages.

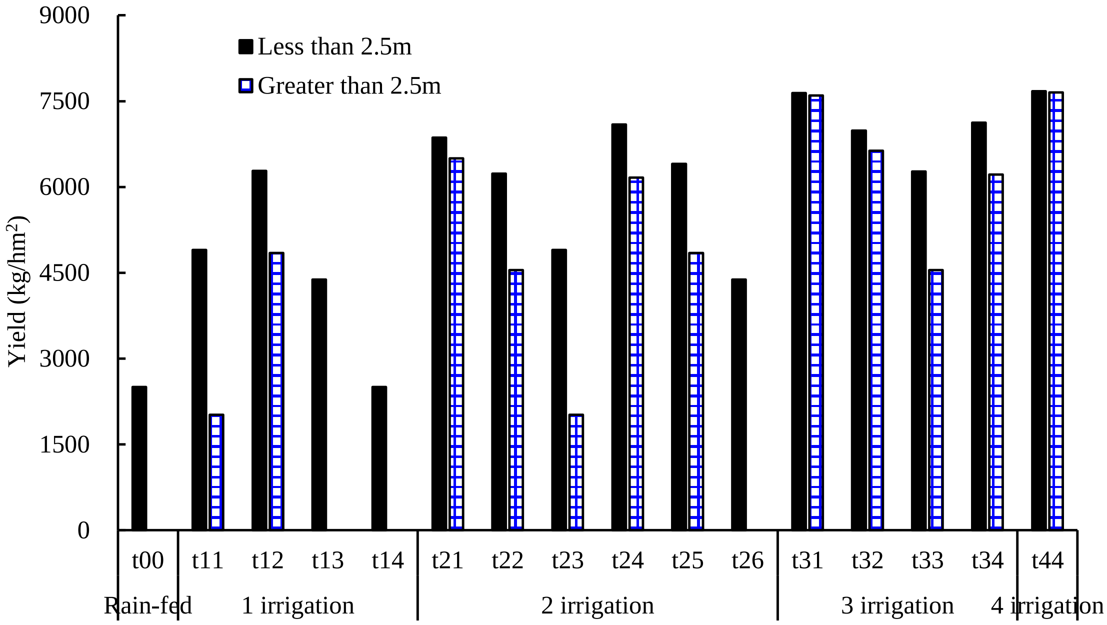


Figure 10. Yields of spring wheat in different zones under different irrigation schedules.

3.4. Optimization of Spring Wheat Irrigation Schedule Considering Groundwater Spatial Variability

The sensitivity indices and test parameters of the spring wheat water production function model are shown in Table 7. When the groundwater depth was greater than 2.5 m, the absolute values of the sensitivity indices, evaluated by Jensen and Minhas models, at some growth stages were greater than 1, in conflict with the theoretical value. Therefore, the two models are not suitable for simulating the relationship between the yield and water consumption at the growth stages when the groundwater depth is greater than 2.5 m. In the three models of Blank, Stewart, and Singh, the Stewart model gave the largest R^2, which was up to 0.98, and the lowest RMSE, which was only 410.58 kg·hm^{-2}. Therefore, it is advisable to take Stewart model as the water production function of spring wheat at the growth stages when the groundwater depth is greater than 2.5 m. From the results given by the Stewart model, the sensitivity coefficient for the tillering–shooting stage was up to 0.7614 when the groundwater depth was greater than 2.5 m, suggesting that it is most sensitive to water shortage at this stage. The sensitivity coefficient was 0.6691 for the shooting–heading stage or 0.5060 for the heading–filling stage. The minimum sensitivity coefficient was −0.0109, which was for the filling–ripening stage, indicating that it is not sensitive to water shortage at this growth stage. When the groundwater depth was less than 2.5 m, the values of the sensitivity indices, evaluated by Minhas and Steward models, at some growth stages were greater than 1, in conflict with the theoretical value. Therefore, the two models are not suitable for simulating the relationship between the yield and the water consumption at the growth stages when the groundwater depth is less than 2.5 m. In the three models of Jensen, Blank, and Singh, the Jensen model gave the largest R^2, which was up to 0.99, and the lowest RMSE, which was only 165.32 kg·hm^{-2}. Therefore, it is advisable to take the Jensen model as the water production function of spring wheat at the growth stages when the groundwater depth is less than 2.5 m. From the results of the Jensen model, when the groundwater depth was less than 2.5 m the sensitivity index was up to 0.9930 for the tillering–shooting stage, was 0.6202 for the heading–filling stage, but was only 0.3591 for the shooting–heading stage. The sensitivity index for the filling–ripening stage was negative, indicating that this stage, too, is not sensitive to water shortage. By comparing the sensitivity for different spring wheat growth stages under different zones, we can see a big difference between the two zones at the shooting–heading stage. When the groundwater depth is greater than 2.5 m, spring wheat is more sensitive to water shortage, while when the depth is less than 2.5 m, the sensitivity to water shortage at this stage is lower because the groundwater supplies the crops with available water. Therefore, the challenge of greater spatial variation of groundwater can be practically taken care of by zoning method. Spring wheat is most sensitive to water deficiency at the tillering–shooting stage, is less sensitive to water deficiency at the heading–filling stage, and is least sensitive to water deficiency at the filling–ripening stage, irrespective of the zone. It can be seen that the water-sensitive results at different growth stages under different zones suggest an agreement with the above-described order of importance of satisfying water demand at different growth stages.

Table 7. Sensitivity indices and test parameters of water production function model of spring wheat at different growth stages.

Groundwater Depth	Model	Tillering–Shooting	Shooting–Heading	Heading–Filling	Filling–Ripening	R^2	RMSE (kg/hm^2)	MAE (kg/hm^2)	MBE (kg/hm^2)
Greater than 2.5 m	Jensen	−2.4901	4.3914	−0.4899	0.0252	0.77	1565.50	1059.55	128.87
	Minhas	38.0809	4.9308	0.3486	0.0112	0.94	692.37	441.15	141.82
	Blank	−0.3555	0.8647	0.4171	0.0344	0.97	458.34	327.79	−4.24
	Stewart	0.7614	0.6691	0.506	−0.0109	0.98	410.58	306.51	22.58
	Singh	−0.6875	0.8138	0.6344	0.0714	0.96	530.17	459.80	0.11
Less than 2.5 m	Jensen	0.9930	0.3591	0.6202	−0.0280	0.99	165.32	136.03	30.87
	Minhas	37.7041	−0.0287	0.8584	0.0743	0.95	487.17	319.54	−265.34
	Blank	−0.0437	0.4508	0.5864	−0.0434	0.98	198.21	166.18	−2.04
	Stewart	1.0475	0.3265	0.5562	−0.0134	0.99	145.73	125.48	−2.28
	Singh	−0.7359	0.9530	0.5868	0.0490	0.98	231.57	169.90	−0.54

With the verified Aquacrop as the technical support and the soil moisture content of the root layer as the control index, lower irrigation limits were set in light of the sensitivity variation across the growth stages under different groundwater depths conditions. Where the groundwater depth was greater than 2.5 m, no irrigation was given at the sowing–tillering and filling–ripening stags, but irrigation started when the soil moisture of root layer dropped below the lower irrigation limit at the tillering–shooting stage or when the content dropped below 10% of this lower irrigation limit at the shooting-filling. Where the groundwater depth was less than 2.5 m, no irrigation was given at the sowing–tillering stage and the filling–ripening stage, but irrigation started once the soil moisture of root layer dropped below the lower irrigation limit at the tillering–shooting stage or when it dropped below 20% of this lower irrigation limit at the shooting-filling stage. With per irrigation quota of 60–120 mm, the optimized irrigation schedules under different groundwater depth conditions were developed. Where the groundwater depth was greater than 2.5 m, there were two rounds of irrigation both at the tillering–shooting stage and the shooting–heading stage, with the irrigation quota being 300 mm, the water consumption being 486 mm, the yield being 8236 kg/hm^2, and the water productivity being 1.694 kg/m^3. Where the groundwater depth was less than 2.5 m, there were two rounds of irrigation at the tillering–shooting stage and one round of irrigation at the shooting–heading stage, with the irrigation quota of 240 mm, the water consumption of 474 mm, the yield of 8014 kg/hm^2, and the water productivity of 1.690 kg/m^3. Still, throughout the growth stages of spring wheat, full irrigation schedules were developed for spring wheat under different groundwater depth conditions such that irrigation started once the soil moisture content of the root layer dropped below the lower irrigation limit with the per irrigation quota being 60–120 mm. Where the groundwater depth was greater than 2.5 m, the irrigation quota was 360 mm and the water consumption was 492 mm, with the yield of 8343 kg/hm^2 and the water productivity of 1.697 kg/m^3. Where the groundwater depth was less than 2.5 m, the irrigation quota was 320 mm and the water consumption was 493 mm, with the yield of 8384 kg/hm^2 and the water productivity of 1.701 kg/m^3.

4. Discussion

4.1. Water Saving Performance Analysis

The soil water balance of spring wheat in different zones under different irrigation schedules is shown in Table 8. Where that the groundwater depth was less than 2.5 m, the irrigation quota, water consumption, phreatic evaporation, seepage, and soil water utilization under the current irrigation schedule were 335 mm, 440 mm, 65 mm, 127 mm, and 65 mm respectively. Under the full irrigation schedule these figures were 320 mm, 493 mm, 55 mm, 70 mm, and 85 mm respectively. Under the optimized irrigation schedule, they were 240 mm, 474 mm, 62 mm, 68 mm, and 139 mm respectively. It could be seen that under the optimized irrigation schedule, the seepage dropped by 46% and the soil water use increased by 114%. Where the groundwater depth was more than 2.5 m, the irrigation quota, water consumption, phreatic evaporation, seepage, and soil water utilization under the current irrigation schedule were 335 mm, 438 mm, 8 mm, 87 mm, and 102 mm respectively. Under the full irrigation schedule these figures were 360 mm, 492 mm, 7 mm, 84 mm, and 129 mm respectively. Under the optimized irrigation schedule, they were 300 mm, 486 mm, 7 mm, 47 mm, and 147 mm respectively. It could be seen that under the optimized irrigation schedule, the seepage dropped by 46% and the soil water use increased by 44%. The spring wheat soil water balance table shows that the optimized irrigation schedule cut the seepage loss and improved the soil water use on the current irrigation schedule. As far as the groundwater depth is concerned, a shallow depth has a more significant effect on reducing seepage and increasing soil water use. Where the groundwater depth was less than 2.5 m, the current irrigation schedule had a slightly higher irrigation quota than the full irrigation schedule; where the groundwater depth was greater than 2.5 m, the current irrigation schedule had a slightly lower irrigation quota than the full irrigation schedule. This suggests that the regional agricultural water saving potential lies mainly in the optimization of the crop irrigation schedule.

Table 8. Soil water balance of spring wheat in different zones under different irrigation schedules.

Groundwater Depth	Irrigation Schedule	Input (mm)		Output (mm)			Soil Water Use (mm)
		Precipitation	Irrigation Quota	Phreatic Evaporation	Seepage	Water Consumption	
Greater than 2.5 m	Current irrigation schedule	57	335	8	87	438	102
	Full irrigation	57	360	7	84	492	129
	Optimized irrigation schedule	57	300	7	47	486	147
Less than 2.5 m	Current irrigation schedule	57	335	65	127	440	65
	Full irrigation	57	320	55	70	493	85
	Optimized irrigation schedule	57	240	62	68	474	139

The water saving performance of the optimized irrigation schedule for spring wheat in each zone is shown in Figure 11. As can be seen, compared with the current irrigation schedule, when the groundwater depth was less than 2.5 m, with the optimized irrigation schedule the irrigation water consumption dropped by 95 mm, the yield increased by 377 kg/hm^2, the water consumption grew by

35 mm, the transpiration was up by 48 mm, the water productivity fell by 0.04 kg/m^3, the irrigation water productivity was higher by 0.31 kg/m^3, while with the full irrigation schedule the irrigation water quota dropped by 15 mm, the yield increased by 747 kg/hm^2, the water consumption grew by 53 mm, the transpiration was up by 67 mm, and the water productivity and the irrigation water productivity remained unchanged. When the groundwater depth was more than 2.5 m, with the optimized irrigation schedule the irrigation water quota dropped by 35 mm, the yield increased by 581 kg/hm^2, the water consumption grew by 49 mm, the transpiration was up by 63 mm, the water productivity fell by 0.06 kg/m^3, the irrigation water productivity grew by 0.46 kg/m^3, while with the full irrigation schedule the irrigation water quota dropped by 25 mm, the yield increased by 729 kg/hm^2, the water consumption grew by 54 mm, the transpiration was up by 68 mm, the water productivity fell by 0.04 kg/m^3, and the irrigation water productivity grew by 0.04 kg/m^3. It could be seen that where the groundwater depth was less than 2.5 m, with the optimized irrigation schedule the irrigation quota of spring wheat fell by 28%, the yield increased by 5%, the irrigation water productivity grew by 20%, the additional water consumption was all used for crop transpiration, and the water productivity reduction was less than 3%; where the groundwater depth was greater than 2.5 m, with the optimized irrigation schedule the irrigation quota was reduced by 10%, the yield increased by 8%, the irrigation water productivity grew by 20%, the additional water consumption was all used for crop transpiration, and the water productivity reduction was less than 4%. From the soil water balance data, the optimized irrigation schedule's water-saving effect is mainly seen in greater yield and higher irrigation water productivity, lower irrigation quota, less ineffective seepage and soil evaporation, and substantial increase in soil water use, while the amount of additional water consumption was all used for crop transpiration. Compared with the groundwater depth over 2.5 m, when this depth was less than 2.5 m, with the optimized irrigation schedule the irrigation quota dropped by 20% and the soil water use was significantly improved.

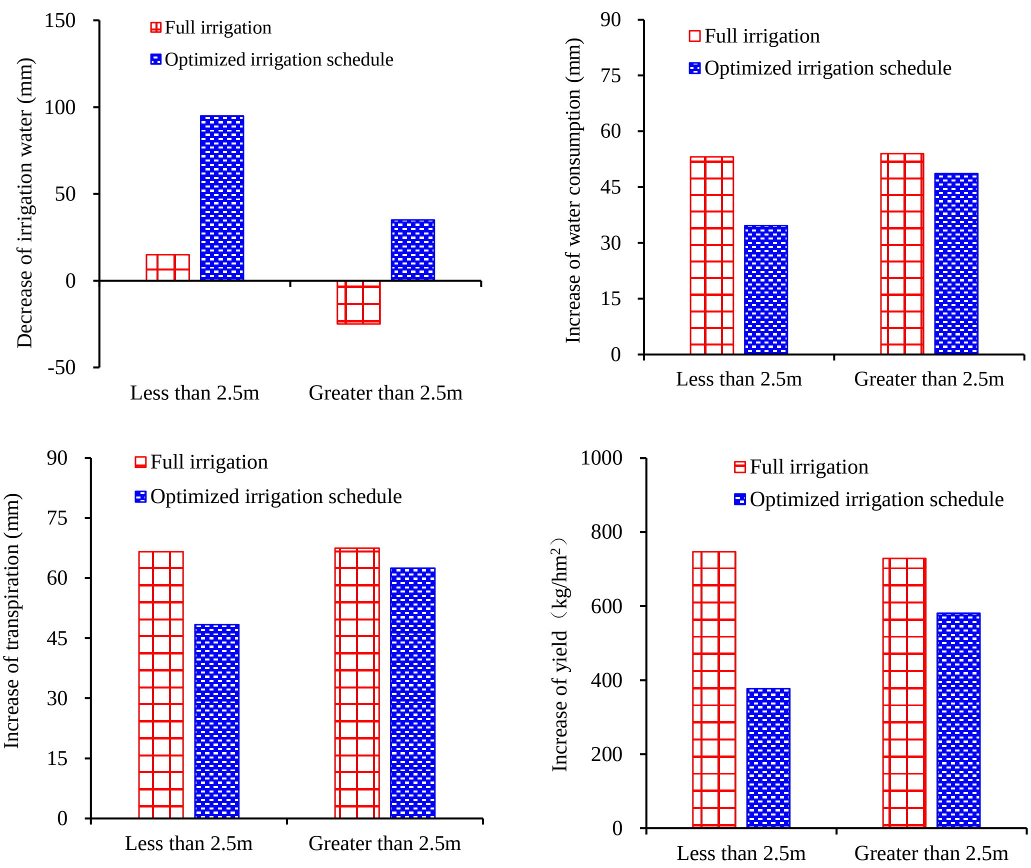


Figure 11. *Cont.*

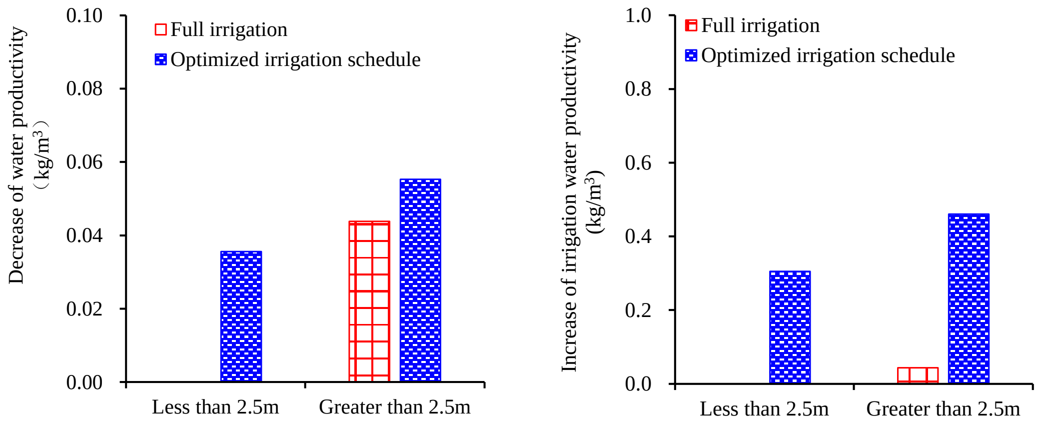


Figure 11. Water saving performance of optimized irrigation schedule for spring wheat in each zone.

4.2. Water Consumption Characteristics

Figure 12 shows the daily water consumption and cumulative water consumption of spring wheat at each growth stage in each zone under the optimized irrigation schedule. It could be seen that the average daily water consumption increased rapidly from 1.87–1.89 mm at the sowing–tillering stage to a maximum of 5.82–5.89 mm at the tillering–heading stage, and then gradually fell to 4.95–5.16 mm at the heading–filling stage and further to 2.66–3.08 mm at the filling–ripening stage. The difference in daily water consumption at different growth stages did not vary much between the two groundwater depths. When the groundwater depth was less than 2.5 m, the cumulative water consumption at the sowing–tillering, tillering–shooting, shooting–heading, heading–filling, and filling–ripening stages was 80 mm, 220 mm, 349 mm, 424 mm, and 474 mm respectively. When the groundwater depth was greater than 2.5 m, the cumulative water consumption at these stages was 81 mm, 221 mm, 350 mm, 428 mm, and 486 mm respectively. It could be seen that, irrespective of the groundwater depths, the water consumption characteristics of the optimized irrigation schedule were basically the same—the average daily water consumption peaked at the tillering–heading stage, with a combined water consumption accounting for 55.4%–56.7% of the total water consumption during the whole growth period.

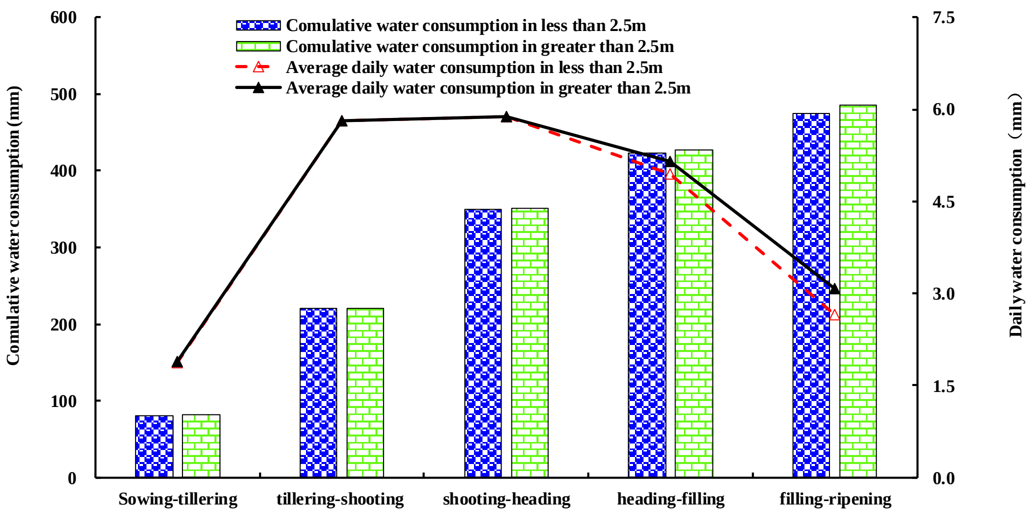


Figure 12. Spring wheat water consumption characteristics under optimized irrigation schedule.

5. Conclusions

(1) The Aquacrop model after verification can satisfactorily simulate the dynamic process of the soil moisture content during the growth period of spring wheat and its yield under different

irrigation schedules respectively, which can be used to investigate the water-yield response mechanism of spring wheat.

(2) The average groundwater table during the spring wheat growing season makes a critical precondition for the simulation of the zoned irrigation schedule, which gives the regional representativeness and feasibility for the optimized irrigation schedules, and importantly provides a solution to the disruption between the spatial variability and the optimization of the irrigation schedule in shallow groundwater areas.

(3) For an irrigation quota within 360 mm, as the irrigation quota increases, the water consumption, seepage, and yield all increase, while the groundwater utilization presents a decreasing trend. In order to get the greater yields, the choice of irrigation schedule is especially important.

(4) Where the groundwater depth is greater than 2.5 m, two rounds of irrigation are made at both the tillering–shooting stage and the shooting–heading stage. Where the groundwater depth is less than 2.5 m, two rounds of irrigation are made at the tillering–shooting stage and one round of irrigation is made at the shooting–heading stage.

(5) The main water-saving effect of the optimized irrigation schedule is that the spring wheat yield, the soil moisture availability, and the irrigation water productivity increase while, the irrigation amount and the ineffective seepage decrease, from which the additional water consumption can be fully used for crop transpiration, being a kind of effective water consumption.

Author Contributions: All authors read and approved the manuscript. Z.P. put up with the main idea of this research. conceptualization, Z.P.; methodology, Z.P., B.Z., Y.L. and Z.W.; software, Z.P.; validation, Z.P., B.Z., and J.C.; formal analysis, Z.P. and H.C.; writing—original draft preparation, Z.P.; writing—review and editing, Z.P., B.Z., Z.W., and H.C.; project administration, Z.P. and Y.L.; funding acquisition, B.Z.

Funding: This study was supported by the National Key R&D Program of China (2018YFC0407703), the IWHR Research & Development Support Program (ID0145B082017, ID0145B742017, ID0145B102019 and ID01881910), The Key R&D projects of Ningxia Hui Autonomous Region (2018BBF02022), the Chinese National Natural Science Fund (51822907 and 51979287), 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 (SKL2018CG03).

Acknowledgments: The authors greatly appreciate the anonymous reviewers and the academic editor for their careful comments and valuable suggestions to improve the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Wang, P.; Yu, J.J.; Pozdniakov, S.P.; Grinevsky, S.O. Shallow groundwater dynamics and its driving forces in extremely arid areas: A case study of the lower Heihe River in northwestern China. *Hydrol. Process.* **2014**, *28*, 1539–1553. [CrossRef]
2. Satchithanantham, S.; Krahn, V.; Ranjan, R.S.; Sager, S. Shallow groundwater uptake and irrigation water redistribution within the potato root zone. *Agric. Water Manag.* **2014**, *132*, 101–110. [CrossRef]
3. Ghamarnia, H.; Golamian, M.; Sepehri, S.; Arji, I. Shallow groundwater use by Safflower (*Carthamus tinctorius* L.) in a semi-arid region. *Irrig. Sci.* **2011**, *29*, 147–156. [CrossRef]
4. Gao, X.Y.; Huo, Z.L.; Qu, Z.Y. Modeling contribution of shallow groundwater to evapotranspiration and yield of maize in an arid area. *Sci. Rep.* **2017**, *7*, 1–13. [CrossRef] [PubMed]
5. Kong, F.R.; Qu, Z.Y.; Liu, Y.J.; Ma, Y.X. Experimental research on the effect of different kinds of groundwater buried depth on soil water, salinity and crop growth. *China Rural Water Hydropower* **2009**, *5*, 44–48. (In Chinese)
6. Kruse, E.G.; Champion, D.F.; Cuevas, D.L.; Yoder, R.E.; Young, D. Crop water use from shallow, saline water tables. *Trans. Asae* **1993**, *36*, 697–707. [CrossRef]
7. Wang, X.H.; Hou, H.B. The influence of shallow groundwater on crops growth laws. *J. Irrig. Drain.* **2006**, *25*, 13–16. (In Chinese)
8. Zhang, C.X. Study on groundwater utilization by dry crops. *J. Irrig. Drain.* **1989**, *8*, 20–24. (In Chinese)

9. Yang, P.Y.; Wu, B.; Wang, S.X.; Dong, X.G.; Liu, L. Research on irrigation schedule of cotton drip irrigation under plastic film based on the different ground water table in arid areas. *Agric. Res. Arid Areas* **2014**, *32*, 76–82. (In Chinese)
10. Zhuang, Y.; Lu, J.; Jiao, X. Effect of groundwater table on cotton irrigation regulation. *Water Sav. Irrig.* **2015**, *3*, 15–17. (In Chinese)
11. Wang, B.L. Experimental study on the utilization of shallow groundwater for spring wheat. *Agric. Sci. Technol.* **2011**, *12*, 108–132.
12. Liu, Z.D.; Liu, Z.G.; Yu, J.H.; Nan, J.Q.; Qin, A.Z.; Xiao, J.F. Effects of groundwater depth on maize growth and water use efficiency. *J. Drain. Irrig. Mach. Eng.* **2014**, *32*, 617–624. (In Chinese)
13. Xue, J.Y.; Guan, H.; Huo, Z.L.; Wang, F.X.; Huang, G.H.; Boll, J. Water saving practices enhance regional efficiency of water consumption and water productivity in an arid agricultural area with shallow groundwater. *Agric. Water Manag.* **2017**, *194*, 78–89. [CrossRef]
14. Ghamarnia, H.; Farmanifard, M. Yield production and water-use efficiency of wheat (*Triticum aestivum* L.) cultivars under shallow groundwater use in semi-arid region. *Arch. Agron. Soil Sci.* **2014**, *60*, 1677–1700. [CrossRef]
15. Ren, D.Y.; Xu, X.; Huang, Q.Z.; Huo, Z.L. Analyzing the Role of Shallow Groundwater Systems in the Water Use of Different Land-Use Types in Arid Irrigated Regions. *Water* **2018**, *10*, 634. [CrossRef]
16. Wang, X.W.; Huo, Z.L.; Guan, H.; Guo, P. Drip irrigation enhances shallow groundwater contribution to crop water consumption in an arid area. *Hydrol. Process.* **2018**, *32*, 747–758. [CrossRef]
17. Chen, H.; Liu, Z.Y.; Huo, Z.L.; Qu, Z.Y.; Xia, Y.H.; Fernald, A. Impacts of agricultural water saving practice on regional groundwater and water consumption in an arid region with shallow groundwater. *Environ. Earth Sci.* **2016**, *75*, 1204. [CrossRef]
18. Ebrahimi, H.; Ghazavi, R.; Karimi, H. Estimation of Groundwater Recharge from the Rainfall and Irrigation in an Arid Environment Using Inverse Modeling Approach and RS. *Water Resour. Manag.* **2016**, *30*, 1939–1951. [CrossRef]
19. Gao, X.Y.; Bai, Y.N.; Huo, Z.L.; Xu, X.; Huang, G.H.; Xia, Y.H.; Steenhuisc, T.S. Deficit irrigation enhances contribution of shallow groundwater to crop water consumption in arid area. *Agric. Water Manag.* **2017**, *185*, 116–125. [CrossRef]
20. Xue, J.Y.; Huo, Z.L.; Wang, F.X.; Kang, S.Z.; Huang, G.H. Untangling the effects of shallow groundwater and deficit irrigation on irrigation water productivity in arid region: New conceptual model. *Sci. Total Environ.* **2018**, *619*, 1170–1182. [CrossRef]
21. Gao, X.Y.; Huo, Z.L.; Xu, X.; Qu, Z.Y. Shallow groundwater plays an important role in enhancing irrigation water productivity in an arid area: The perspective from a regional agricultural hydrology simulation. *Agric. Water Manag.* **2018**, *208*, 43–58. [CrossRef]
22. Karimov, A.K.; Šimůnek, J.; Hanjra, M.A.; Avliyakulov, M.; Forkutsa, I. Effects of the shallow water table on water use of winter wheat and ecosystem health: Implications for unlocking the potential of groundwater in the Fergana Valley (Central Asia). *Agric. Water Manag.* **2014**, *131*, 57–69. [CrossRef]
23. Liu, J.; Sun, S.K.; Wang, Y.B.; Zhao, X.N. Evaluation of crop production, trade, and consumption from the perspective of water resources: A case study of the Hetao irrigation district, China, for 1960–2010. *Sci. Total Environ.* **2015**, *505*, 1174–1181. [CrossRef] [PubMed]
24. Bai, L.L.; Cai, J.B.; Liu, Y.; Chen, H.; Zhang, B.Z.; Huang, L.X. Responses of field evapotranspiration to the changes of cropping pattern and groundwater depth in large irrigation district of Yellow River basin. *Agric. Water Manag.* **2017**, *166*, 17–32. [CrossRef]
25. Du, J.; Yang, P.L.; Ren, S.M.; Li, Y.K.; Wang, Y.Z.; Yuan, X.Q.; Li, X.Y.; Du, J. The canal-lining project on groundwater and ecological environment in Hetao irrigation District of Inner Mongolia. *Chin. J. Appl. Ecol.* **2011**, *22*, 144–150. (In Chinese)
26. Li, Z.Z.; Fu, X.J.; Tian, Y.; Zhen, Q. Study on the Change of Soil Moisture and Groundwater by Jiefangzha Region in Hetao Irrigation District. *Inn. Mong. Water Resour.* **2018**, *5*, 16–17. (In Chinese)
27. Allen, R.; Periera, L.; Raes, D.; Smith, M. *Crop Evapotranspriation: Guidelines for Computing Crop Water Requirement*; FAO Irrigation and Drainage Paper No.56; FAO: Rome, Italy, 1998.
28. Hsiao, T.; Heng, L.; Steduto, P.; Rojas-Lara, B.; Raes, D.; Fereres, E. AquaCrop—The FAO Crop Model to Simulate Yield Response to Water: III. Parameterization and Testing for Maize. *Agron. J.* **2009**, *101*, 448–459. [CrossRef]

29. Raes, D.; Steduto, P.; Hsiao, T.; Fereres, E. AquaCropThe FAO Crop Model to Simulate Yield Response to Water: II. Main Algorithms and Software Description. *Agron. J.* **2009**, *101*, 438–447. [CrossRef]
30. Steduto, P.; Hsiao, T.; Raes, D.; Fereres, E. AquaCrop—The FAO Crop Model to Simulate Yield Response to Water: I. Concepts and Underlying Principles. *Agron. J.* **2009**, *101*, 426–437. [CrossRef]
31. Andarzian, B.; Bannayan, M.; Steduto, P.; Mazraeh, H.; Barati, M.E.; Barati, M.A.; Rahnama, A. validation and testing of the Aquacrop model under full and deficit irrigated wheat production in Iran. *Agric. Water Manag.* **2011**, *100*, 1–8. [CrossRef]
32. Kahimba, F.C.; Bullock, P.R.; Sri-Ranjan, R.; Cutforth, H.W. Evaluation of the SolarCalc model for simulating hourly and daily incoming solar radiation in the Northern Great Plains of Canada. *Can. Biosyst. Eng.* **2009**, *51*, 1–11.
33. Willmott, C.J. Some comments on the evaluation of model performance. *Bull. Am. Meteorol. Soc.* **1982**, *63*, 1309–1313. [CrossRef]
34. Willmott, C.J.; Maasuura, K. Advantages of the meanabsolute error (MAE) over the root mean square error (RMSE) in assessing average model performance. *Clim. Res.* **2005**, *30*, 79–82. [CrossRef]
35. Zhao, S.Z.; Kong, F.J.; Wang, X.K.; Li, S.B.; Meng, K.W. Confirming of critical depth of groundwater level and discussion on it's significance-take Hetao Irrigation Area for example. *J. Inn. Mong. Agric. Univ.* **2008**, *29*, 164–167. (In Chinese)
36. Ruan, B.Q.; Han, Y.P.; Jiang, R.F.; Xu, F.R. Appropriate water saving extent for ecological vulnerable area. *J. Hydraul. Eng.* **2008**, *39*, 809–814. (In Chinese)