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Evaluation and Application of the AquaCrop Model in Simulating Soil Salinity and Winter Wheat Yield under Saline Water Irrigation

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Abstract: Saline water irrigation has been considered a useful practice to overcome the freshwater shortage in arid and semi-arid regions. Assessing and scheduling the appropriate irrigation water amount, salinity, and timing is essential to maintaining crop yield and soil sustainability when using saline water in agriculture. A field experiment that included two irrigation levels (traditional and deficit irrigation) and three water salinities (0, 5, and 10 dS/m) was carried out in the North China Plain during the 2017/18 and 2018/19 winter wheat growing seasons. AquaCrop was used to simulate and optimize the saline water irrigation for winter wheat. The model displayed satisfactory performance when simulating the volumetric soil water content ($R^2 \geq 0.85$, RMSE $\leq$ 2.59%, and NRMSE $\leq$ 12.95%), soil salt content ($R^2 \geq 0.71$, RMSE $\leq$ 0.62 dS/m, and NRMSE $\leq$ 26.82%), in-season biomass ($R^2 \geq 0.89$, RMSE $\leq$ 1.03 t/ha, and NRMSE $\leq$ 18.92%), and grain yield ($R^2 \geq 0.92$, RMSE $\leq$ 0.35 t/ha, and NRMSE $\leq$ 7.11%). The proper saline water irrigation strategies were three irrigations of 60 mm with a salinity up to 4 dS/m each at the jointing, flowering, and grain-filling stage for the dry year; two irrigations of 60 mm with a salinity up to 6 dS/m each at the jointing and flowering stage for the normal year; and one irrigation of 60 mm with a salinity up to 8 dS/m at the jointing stage for the wet year, which could achieve over 80% of the potential yield while mitigating soil secondary salinization. Nonetheless, the model tended to overestimate the soil moisture and wheat production but underestimate the soil salinity, particularly under water and salt stress. Further improvements in soil solute movement and crop salt stress are desired to facilitate model performance. Future validation studies using long-term field data are also recommended to obtain a more reliable use of AquaCrop and to better identify the influence of long-term saline water irrigation. Finally, AquaCrop maintained a good balance between simplicity, preciseness, and user-friendliness, and could be a feasible tool to guide saline water irrigation for winter wheat.

Keywords: saline water irrigation; winter wheat; AquaCrop; simulation; optimization

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1. Introduction

Winter wheat (*Triticum aestivum* L.) is one of the most critical crops to ensure global food security, providing over 20% of the calories consumed by the world's population [1,2]. The North China Plain (NCP) is the major cereal-producing area in China, which accounts for approximately 60% of the national wheat production [3,4]. Under the monsoon climate, annual rainfall in the NCP is mainly concentrated in the summer season, while only 20% to 30% falls in the winter wheat growing period, which provides approximately 25% to 40% of the total wheat water requirement [3,5]. Additional irrigation during the winter wheat growing season becomes essential to uphold high grain yield in the NCP [6]. However, excessive use of groundwater for winter wheat irrigation has significantly reduced the groundwater table in recent decades and is seriously restricting sustainable crop production in the NCP. On the other hand, many regions in the NCP possess plentiful saline and brackish water resources [7]. Applying these marginal water resources for irrigation

could not only maintain crop production compared with skipping irrigation but also facilitate groundwater renewal and freshwater storage, and prevent ecological environmental degradation if accurate management of poor-quality water is achieved [8,9]. Therefore, saline water irrigation has been considered a practical solution to overcome the freshwater shortage during the winter wheat season and is gaining increasing attention in the arid and semi-arid areas of the NCP [10,11].

Crop production and land sustainability are two factors of substantial interest when applying saline water irrigation in agriculture [12]. Increased soil salinity under saline water irrigation can reduce the soil osmotic potential, inhibiting crop growth and water uptake [13]. Gradually, salt ions accumulate to a toxic level in plants, inducing nutritional imbalance, early senescence, and notable yield loss [14]. Winter wheat is classified as a moderately salt-tolerant crop with a soil salinity threshold of 6 dS/m and an irrigation water salinity threshold of 4 dS/m [9]. Beyond the tolerance threshold, wheat grain yield reduces by approximately 1.8% for each 1 dS/m increase in the irrigation water salinity [15]. Furthermore, saline water irrigation may aggravate the risk of soil secondary salinization, causing soil degradation problems, such as a surface crust, aggregate destabilization, and permeability reduction, which seriously limit soil sustainability [9]. To cope with soil salinization under saline water irrigation, excessive irrigation is usually adopted for salt leaching in the root zone [7]. Nonetheless, excessive irrigation may not only reduce water use efficiency but also result in nutrient loss and groundwater pollution [16]. Contrarily, deficit irrigation with saline water could mitigate soil salinization by decreasing the salt input while satisfying the crop water requirement at the critical growth stages, which appears to be a more reliable practice for saline water irrigation [17,18]. In addition, rainfall plays a major role in soil salt accumulation and leaching. The crop yield and soil salinity under saline water irrigation could be significantly affected by rainfall conditions [8,19]. Therefore, assessing and scheduling the proper irrigation water amount, salinity, and timing under different hydrological years to stabilize yield and minimize soil salinization is essential when using saline water for wheat irrigation.

Mathematical models for simulating soil water and solute transport, as well as predicting crop responses to soil moisture and salinity, can be useful tools to assess the effects of saline water irrigation strategies on soil quality and crop yield [20,21]. Modeling tools also have the capability to integrate saline water management and long-term histrionic climate data, developing optimal irrigation scenarios for different rainfall years [8,19,22]. In recent years, numerical models, such as SWAP, HYDRUS, SALTMED, and UNSATCHEM, were successfully applied to evaluate saline water irrigation for numerous crops and regimes [8,11,19,20]. However, these models usually require substantial input parameters and complex calibration and validation processes. Recently, the AquaCrop model has been increasingly selected to assess crop responses and field management for saline conditions [23–26]. AquaCrop is a water-driven model and was extensively tested for various soils, crops, and climates to identify crop growth and production under different soil moisture and irrigation strategies [4,27,28]. The current version of AquaCrop is implemented with a solute transport calculation routine based on the Richards equation to predict soil salinity dynamics. Pourgholam-Amiji et al. [26] evaluated the performance of AquaCrop to simulate soil salinity dynamics in a coastal paddy field. The results indicated that AquaCrop could be a feasible tool to predict the soil salinity change trend. AquaCrop is also capable of simulating salt stress effects on canopy development, stomatal closure, and biomass production using a salt stress–response curve. The model provides accurate crop simulations under saline conditions for barley, wheat, rice, bitter gourd, and cotton [20,23–25,29]. Furthermore, Mohammadi et al. [30] verified the good performance of AquaCrop for the wheat grain yield prediction response to water and salt stress simultaneously. Compared with other sophisticated models, AquaCrop requires fewer input data while being able to obtain a similar or higher accuracy, exhibiting a better balance of simplicity, robustness, preciseness, and user-friendliness [31–33]. Nonetheless, site-specific and careful calibration and validation are essential to achieve reliable use of AquaCrop for

simulating crop responses under saline conditions and developing effective saline water irrigation strategies. Hassanli et al. [34] reported that the AquaCrop model using default parameters predicted maize yield under salinity stress with a greater error compared with SALTMED and SWAP. So far, AquaCrop has not been tested with saline water irrigation for winter wheat in the NCP. Thus, our objectives were to (1) calibrate and validate AquaCrop for winter wheat under various irrigation levels and water salinities based on a two-yield field experiment in the NCP; (2) evaluate the performance of AquaCrop in estimating the effects of saline water irrigation on volumetric soil water content, soil salt content, in-season biomass, and grain yield; and (3) develop proper saline water irrigation strategies for winter wheat in different hydrological years using modelling and simulation.

2. Materials and Methods

2.1. Study Site

The field experiment took place on an experimental farm at Fengxian county (34°73′ N, 116°45′ E, altitude: approximately 50 m) during the 2017/18 and 2018/19 winter wheat seasons. This study site is located in the central NCP and is characterized by a temperate semi-humid monsoon climate. The monthly temperature (°C), rainfall (mm), and reference evapotranspiration (mm) during the two growing seasons are shown in Figure 1. The other detailed meteorological data for the experiment duration are presented in Huang et al. [4]. The soil texture and hydraulic parameters of the research site are presented in Table 1. The topsoil has a soil organic matter content of 10.2 g/kg, a total N content of 0.38 g/kg, an available P content of 11.2 mg/kg, and an available K content of 62.4 mg/kg.

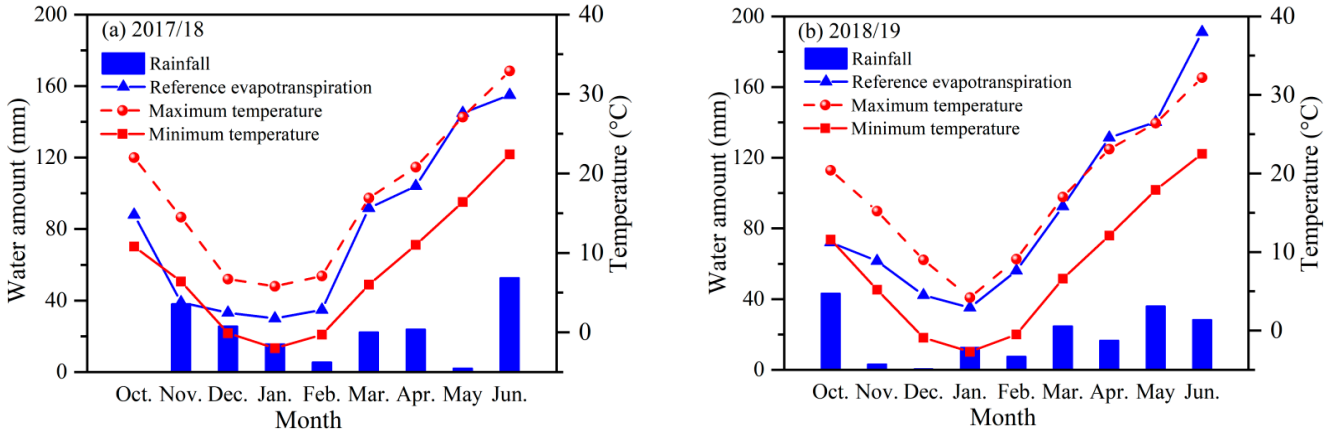


Figure 1. Monthly average maximum and minimum temperature (°C), rainfall (mm), and reference evapotranspiration (mm) in the 2017/18 season and 2018/19 season.

Table 1. Selected soil properties of the research site.

Soil Layer (cm)	Texture	Bulk Density (g/cm^3)	Saturated Hydraulic Conductivity (cm/h)	Saturated Water Content (*v*/*v*, %)	Field Capacity (*v*/*v*, %)	Permanent Wilting Point (*v*/*v*, %)
0 to 60	Sandy loam	1.43	3.23	40.2	21.4	9.8
60 to 120	Loam	1.45	1.67	45.5	27.6	11.3

2.2. Field Experiments

Winter wheat (*Triticum aestivum* L.), a local cultivar of Sumai-10, was sown with a row spacing of 15 cm and a density of approximately 300 plants/m^2 in 4 m × 5 m field plots on 20 October in 2017 and 2018. The N, P, and K in the form of urea, super-phosphate, and potassium chloride were applied at 200, 100, and 100 kg/ha as basal fertilizer, respectively. After sowing, all plots were well irrigated to promote seed emergence and seedling growth.

Based on the traditional irrigation practices for high wheat yield, supplemental irrigation was set at the critical water requirement stages, namely, before winter, jointing, booting, flowering, and grain-filling [35–37]. The corresponding dates for applying the irrigation were 20 December, 25 March, 15 April, 1 May, and 15 May, respectively, according to the growth stages of winter wheat in the study region. Due to the limited rainfall and its unreliability, the water volume applied for each irrigation was set to 60 mm (a common value for wheat irrigation in the NCP), regardless of the rainfall events before irrigation. The deficit irrigation was performed by applying irrigation at the jointing and flowering stages only. The basin irrigation was conducted with the surface flood method through a plastic tube and a low-pressure pump. A flow meter was connected with the tube to measure the irrigation water amount. The irrigation water salinity ranged from 0 dS/m to 10 dS/m. The freshwater was the groundwater from the research farm. The saline water was prepared by adding sodium sulfate, calcium chloride, sodium chloride, and magnesium chloride (2:2:1:1) into the groundwater to the salinities of 5 and 10 dS/m. Therefore, the experiment treatments consisted of two irrigation levels and three water salinities, as follows: T0, T5, and T10—traditional irrigation with 0, 5, and 10 dS/m; D0, D5, and D10—deficit irrigation with 0, 5, and 10 dS/m. Each treatment was replicated 3 times. Before the sowing in 2018/19, additional irrigation of 80 mm was applied in the saline water irrigation treatments to leach the accumulated salts of the topsoil layer.

2.3. Observations

Soil samples were collected from the 0–60 cm layer with an interval of 10 cm on the day before and after irrigation. The gravimetric soil water content was determined by drying samples at 105 °C in a fan-forced oven (DHG-9070G, Shanghai Jinlan Instrument Company, Shanghai, China) until obtaining a constant weight. The volumetric soil water content was determined by multiplying the gravimetric soil water content by the bulk density. Wheat biomass accumulations were monitored on 20 December, 25 March, 15 April, 1 May, and 15 May. At each stage, wheat plants of 0.25 m^2 area (0.5 m × 0.5 m) were sampled. Plant samples were oven-dried at 105 °C for half an hour and then oven-dried at 60 °C until achieving a constant weight. The in-season aboveground biomass was observed. The canopy cover (CC) was calculated through the leaf area index method using a Li-3200 (Li-Cor Inc, Lincoln, NE, USA). At harvest, wheat samples of 1 m^2 area (1 m × 1 m) were collected from the middle plot. The harvest samples were oven-dried at 105 °C for half an hour and then oven-dried at 60 °C to a constant weight. The dried samples were threshed using a thresher to obtain the grain yield. After the harvest, soil samples from the 0–60 cm layer were used to prepare a saturated extract with distilled water (1:1). Then, the soil salt content was measured using an electrical conductivity meter (DDBJ-350, INEAS Scientific Instrument Company, Shanghai, China).

2.4. AquaCrop 6.1

AquaCrop is a daily water-driven model consisting of a soil module, crop module, atmosphere module, and field management module. It relates the soil–crop–atmosphere structure through the soil water balance. The canopy cover curve determined by the initial CC (CC0), canopy growth coefficient (CGC), maximum CC (CCx), and canopy decline coefficient (CDC) is used to separate the reference evapotranspiration into soil evaporation and crop transpiration according to Equation (1). Then, the model calculates the biomass (B, t/ha) by multiplying the normalized water productivity (WP*, g/m^2) and the accumulative crop transpiration according to Equation (2). The crop grain yield (Y, t/ha) is estimated by multiplying the final aboveground biomass and the harvest index (HI, %) according to Equation (3). AquaCrop simulates crop water stress by adjusting the canopy expansion, stomatal closure, canopy senescence, and harvest index. Water stress coefficients are determined by their sensitivity to the available water depletion in the root zone. Moreover, the model assesses the salt movement and retention in the soil profile using the BUDGET calculator based on the convection and diffusion processes of

solute transports. The effect of soil salinity on crop production is described through a salt stress–response curve with an upper and lower threshold. Additional detailed concepts and principles of AquaCrop are described in Raes et al. [27] and Van Gaelen et al. [38].

$$T_c = CC^* \times K_{cTr,x} \times ET_0 \quad (1)$$

$$B = WP^* \times \sum T_c \quad (2)$$

$$Y = f_{HI} \times HI_0 \times B \quad (3)$$

where T_c is the crop transpiration (mm/d), CC* is the actual canopy cover (%), $K_{cTr,x}$ is the maximum standard transpiration coefficient, f_{HI} is the harvest index coefficient, and HI_0 is the reference harvest index (%).

2.5. Calibration, Validation, and Evaluation

The essential model input consisted of meteorological data, crop characteristics, irrigation management, and soil profile properties, which were determined using field observations. The initial conditions adopted were 80% of the field capacity and 1 dS/m according to the measurement after sowing. Table 2 presents the main winter wheat characteristics used in AquaCrop. Some of them were carefully calibrated and validated in a previous study and were applicable in the present study, such as the threshold temperatures, canopy development parameters, root development parameters, crop phenology, crop production parameters, and water stress coefficients [4]. The salt stress responses were parameterized using the field observations of the traditional irrigation treatment with saline water (i.e., T5 and T10). The lower and upper thresholds for salt stress were adjusted to 5 dS/m and 18 dS/m, respectively. The salt stress coefficients of canopy cover and stomatal closure were repeatedly calibrated for the F5 and F10 treatment until the biomass and grain yield estimations were close to the observations.

Model evaluation was carried out for the volumetric soil water content, soil salt content, biomass, and grain yield using the coefficient of determination (R^2), root mean squared error (RMSE), normalized root mean square error (NRMSE), and prediction error (Pe) according to Equations (4)–(7).

$$R^2 = \left\{ \frac{\sum_{i=1}^{n} (O_i - \overline{O})(S_i - \overline{S})}{\left[\sum_{i=1}^{n} (O_i - \overline{O})^2\right]^{0.5} \left[\sum_{i=1}^{n} (S_i - \overline{S})^2\right]^{0.5}} \right\}^2 \quad (4)$$

$$RMSE = \left[\frac{\sum_{i=1}^{n} (O_i - S_i)^2}{n} \right]^{0.5} \quad (5)$$

$$NRMSE = \frac{100}{\overline{O}} \left[\frac{\sum_{i=1}^{n} (O_i - S_i)^2}{n} \right]^{0.5} \quad (6)$$

$$Pe = \frac{(S_i - O_i)}{O_i} \times 100\% \quad (7)$$

where S_i is the simulated value, O_i is the observed value, $\overline{S}$ is the average simulated value, $\overline{O}$ is the average observed value, and n is the number of observations. An R^2 value close to 1 indicates a better fit. RMSE is the variance of the simulation error. NRMSE is the normalized mean of the model deviation. The simulation performance is considered excellent, good, acceptable, or poor if the NRMSE value is <10%, 10% to 20%, 20% to 30%, or >30%, respectively. Pe is used to indicate the under- or overestimation of the model.

Table 2. Crop parameters of the AquaCrop model used in this study.

Parameter	Value
Base temperature, °C	0
Upper temperature, °C	26
Initial canopy cover (CC_0), %	4.5
Canopy growth coefficient (CGC), %/d	3.5
Maximum canopy cover (CC_x), %	97
Canopy decline coefficient (CDC), %/°C d	0.4
Time from sowing to emergence, °C d	266
Time from sowing to maximum canopy cover, °C d	1606
Time from sowing to the start of senescence, °C d	1850
Time from sowing to maturity, °C d	2375
Time from sowing to flowering, °C d	1606
Duration of flowering, °C d	272
Length building up harvest index, °C d	723
Maximum effective rooting depth, m	1.2
Average root zone expansion, cm/d	0.5
Minimum effective rooting depth, m	0.3
Crop transpiration coefficient ($K_{cTr,x}$)	1.10
Normalized crop water productivity (WP*), g/m^2	17
Reference harvest index (HI_0), %	45
Upper threshold for canopy expansion ($P_{exp,\ upper}$)	0.20
Lower threshold for canopy expansion ($P_{exp,\ lower}$)	0.65
Upper threshold for stomatal closure ($P_{sto,\ upper}$)	0.65
Upper threshold for canopy senescence ($P_{sen,\ upper}$)	0.70
Lower threshold for salinity stress, dS/m	5
Upper threshold for salinity stress, dS/m	18
Distortion of canopy cover response to salinity, %	25
Stomatal closure response to salinity, %	115

2.6. Scenario Analysis

After the calibration and validation, the model was used to predict winter wheat production and soil salt accumulation under different saline water irrigation conditions and typical rainfall years. Using the weather data of the research region from 1989 to 2019, rainfall category years were classified depending on the empirical frequency analysis method. Annual 25%, 50%, and 75% occurrence rainfalls were used to represent a wet year (2016/17, rainfall = 277.4 mm), normal year (1994/95, rainfall = 211.6 mm), and dry year (1998/99, rainfall = 178.2 mm), respectively. In terms of irrigation scheduling, the irrigation frequency ranged from non-irrigation (rainfed) to five irrigations based on the traditional irrigation practices in the study region [35–37]. The irrigation timings were set to the before winter, jointing, booting, flowering, and grain-filling stages, respectively. Therefore, six different stage-based irrigation scenarios were assessed, namely, rainfed: non-irrigation; A: one irrigation of 60 mm at the jointing stage; B: two irrigations of 60 mm each at the jointing and flowering stages; C: three irrigations of 60 mm each at the jointing, flowering, and grain-filling stages; D: four irrigations of 60 mm each at the jointing, booting, flowering, and grain-filling stages; and E: five irrigations of 60 mm each at the before winter, jointing, booting, flowering, and grain-filling stages. The irrigation and rainfall distribution during the scenario analysis is presented in Table 3. Furthermore, nine irrigation water salinity levels were evaluated for the A to E scenarios, namely, 0, 2, 4, 6, 8, 10, 12, 14, and 16 dS/m. Saline water irrigation was assessed by considering high grain yield and low soil salinity after harvest. The relative grain yield was determined using the ratio of the simulated grain yield and the potential grain yield (E scenario with 0 dS/m). As the soil salt content approached 4 dS/m, secondary salinization was induced by the saline water irrigation.

Table 3. Irrigation scenarios applied by the AquaCrop model in the dry, normal, and wet years.

Scenario	Irrigation Amount/Rainfall (mm)					
	Before Winter	Jointing	Booting	Flowering	Grain-Filling	Total
	Dry year (1998/99, rainfall = 178.2 mm)					
Rainfed	0/40.2	0/9.3	0/6.5	0/7.9	0/114.3	178.2
A	0/40.2	60/9.3	0/6.5	0/7.9	0/114.3	238.2
B	0/40.2	60/9.3	0/6.5	60/7.9	0/114.3	298.2
C	0/40.2	60/9.3	0/6.5	60/7.9	60/114.3	358.2
D	0/40.2	60/9.3	60/6.5	60/7.9	60/114.3	418.2
E	60/40.2	60/9.3	60/6.5	60/7.9	60/114.3	478.2
	Normal year (1994/95, rainfall = 211.6 mm)					
Rainfed	0/49.2	0/28.1	0/10.6	0/12.4	0/111.3	211.6
A	0/49.2	60/28.1	0/10.6	0/12.4	0/111.3	271.6
B	0/49.2	60/28.1	0/10.6	60/12.4	0/111.3	331.6
C	0/49.2	60/28.1	0/10.6	60/12.4	60/111.3	391.6
D	0/49.2	60/28.1	60/10.6	60/12.4	60/111.3	451.6
E	60/49.2	60/28.1	60/10.6	60/12.4	60/111.3	511.6
	Wet year (2016/17, rainfall = 277.4 mm)					
Rainfed	0/58.3	0/73.8	0/24.8	0/29.3	0/91.2	277.4
A	0/58.3	60/73.8	0/24.8	0/29.3	0/91.2	337.4
B	0/58.3	60/73.8	0/24.8	60/29.3	0/91.2	397.4
C	0/58.3	60/73.8	0/24.8	60/29.3	60/91.2	457.4
D	0/58.3	60/73.8	60/24.8	60/29.3	60/91.2	517.4
E	60/58.3	60/73.8	60/24.8	60/29.3	60/91.2	577.4

The corresponding dates when applying the irrigation at the before winter, jointing, booting, flowering, and grain-filling stages were 20 December, 25 March, 15 April, 1 May, and 15 May, respectively.

3. Results

3.1. Volumetric Soil Water Content

The simulated and observed volumetric soil water contents (SWCs) at the 0 to 60 cm soil profile during the experiment are presented in Figure 2. The soil moisture generally increased with the irrigation water amount and salinity. During the experiment period, the soil water content generally ranged from approximately 40% to 100% of the field capacity under the two irrigation strategies. Slight over-irrigation occurred at the before winter stage in 2017/18 due to the rainfall in November and December. The traditional irrigation with saline water also resulted in slightly higher soil water content above the field capacity due to reduced evapotranspiration. At the same irrigation water salinity, the measured SWC was 1.36% to 45.68% higher in traditional irrigation than in deficit irrigation across the two growing seasons. The observed SWCs of the F5 and F10 treatments were increased by 1.81% to 23.08% and 1.65% to 39.56% compared with F0, respectively. The D5 and D10 treatments were increased by 1.02% to 23.08% and 0.85% to 31.33% compared with D0, respectively. The AquaCrop model gave good simulation results for the SWC under different irrigation levels and water salinities. The model evaluation indicators (i.e., R^2, RMSE, NRMSE) ranged from 0.87 to 0.95, 1.22% to 2.59%, and 8.09% to 12.95% in the calibration and 0.88 to 0.96, 1.52% to 2.75%, 10.32% to 18.12% in the validation, respectively. Nonetheless, the simulation accuracy of the SWC decreased under deficit irrigation with saline water. The simulated SWC tended to be higher than the observed ones, with a Pe value of −12.71% to 24.21% in the 2017/18 season and −3.75% to 45.75% in the 2018/19 season, respectively.

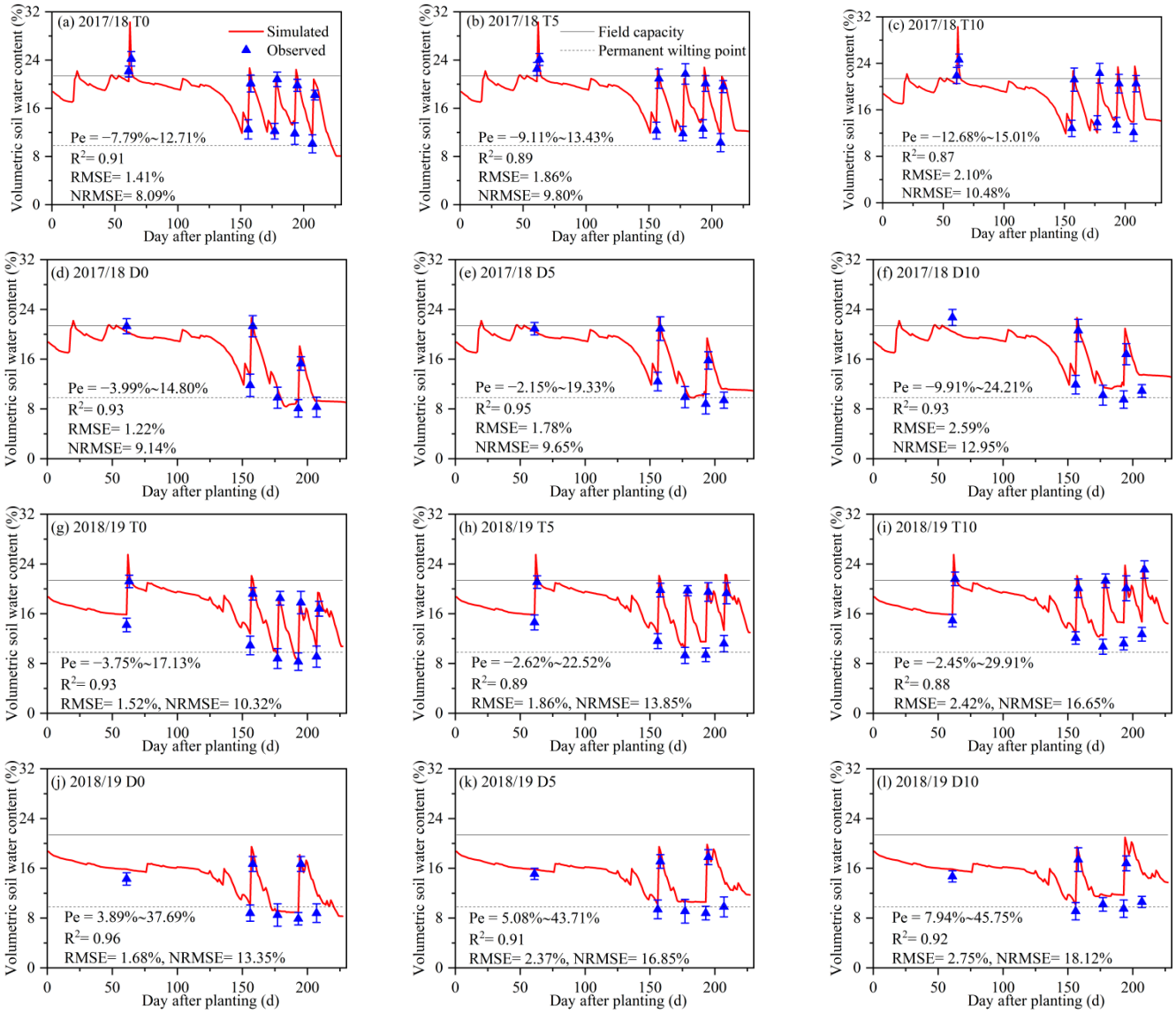


Figure 2. Simulated and observed volumetric soil water content of the 0–60 cm soil profile in the 2017/18 season and 2018/19 season.

3.2. Soil Salt Content

Figure 3 shows the simulated and observed soil salt contents (SSCs) in the 0 to 60 cm soil profile at harvest in 2017/18 and 2018/19. Saline water resulted in notable soil salt accumulation, especially under traditional irrigation. The observed SSCs of the F5 and F10 treatments were 1.65 dS/m to 7.00 dS/m and 4.35 dS/m to 6.82 dS/m higher than F0, respectively. The D5 and D10 treatments were increased by 1.57 dS/m to 2.55 dS/m and 3.72 dS/m to 5.50 dS/m compared with D0, respectively. The SSCs of F5 and F10 were 0.80 dS/m to 3.90 dS/m and 0.40 dS/m to 2.30 dS/m higher than D5 and D10, respectively. In general, AquaCrop predicted the SSC with satisfactory accuracy under different saline water irrigation conditions. The R^2, RMSE, and NRMSE values ranged from 0.81 to 0.94, 0.12 dS/m to 0.42 dS/m, and 7.49% to 18.75% in 2017/18 and 0.71 to 0.98, 0.18 dS/m to 0.62 dS/m, and 12.15% to 26.82% in 2018/19, respectively. However, the model tended to underestimate the soil salinity, particularly under high water salinity. The Pe values ranged from −77.78% to 14.29% in the calibration and −73.33% to 14.81% in the validation, respectively.

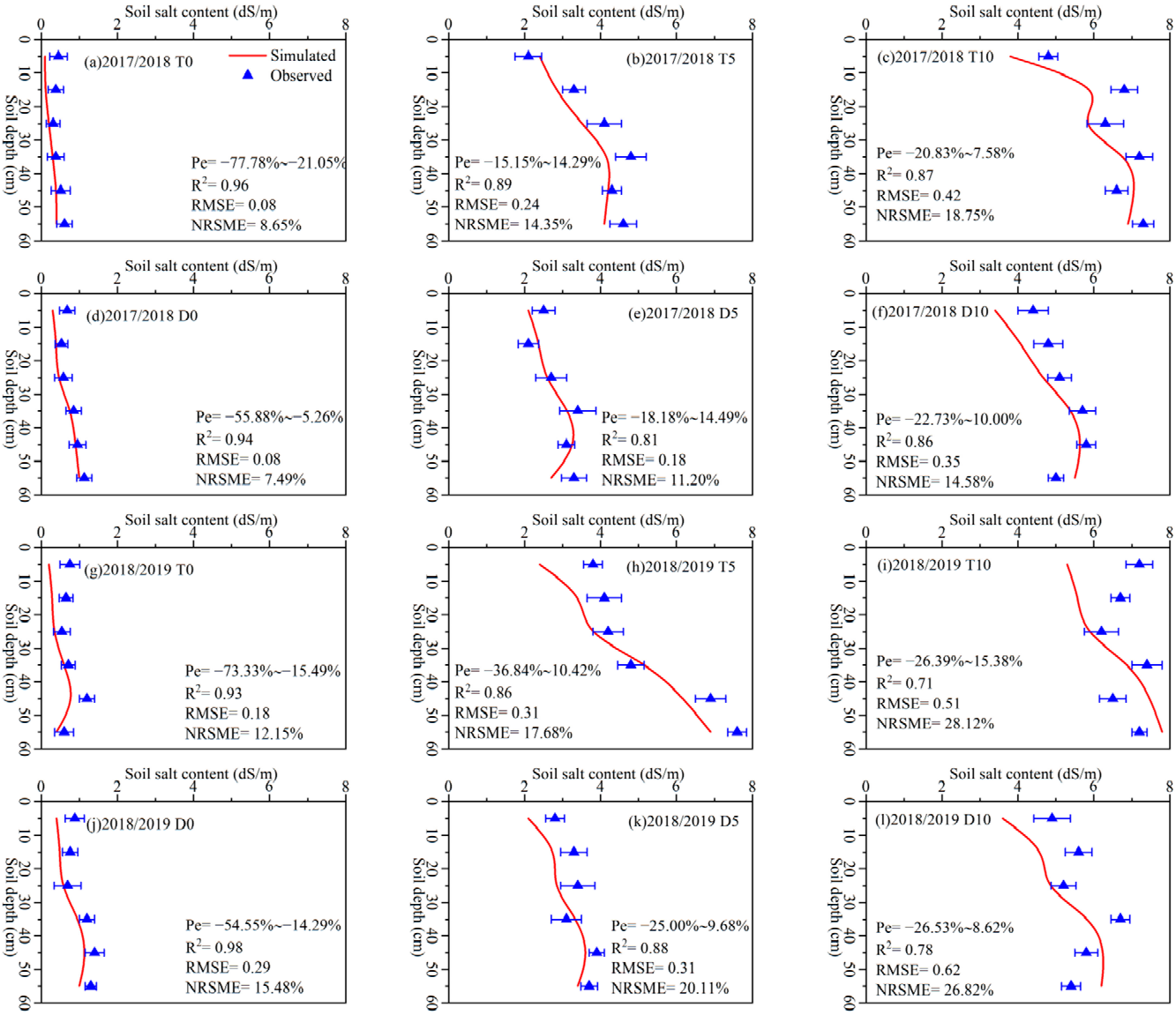


Figure 3. Simulated and observed soil salt content of 0–60 cm soil profile at harvest in the 2017/18 season and 2018/19 season.

3.3. In-Season Biomass

The simulated in-season biomass is compared with the observed values in Figure 4. The in-season biomass reduced as the water deficit and irrigation water salinity increased. The observed in-season biomasses of the traditional irrigation treatments were 3.23% to 23.28% higher than the deficit irrigation treatments across the irrigation water salinity. The traditional irrigations with 5 dS/m and 10 dS/m saline water reduced the in-season biomasses by 4.41% to 10.65% and 4.48% to 16.78% compared with freshwater irrigation, respectively. The in-season biomasses of D5 and D10 were 1.36% to 13.80% and 3.79% to 20.20% lower than the D0 treatment, respectively. The AquaCrop model accurately estimated the in-season biomass under various freshwater and saline water irrigation, with R^2, RMSE, and NRMSE varying from 0.91 to 0.98, 0.62 t/ha to 0.88 t/ha, and 8.12% to 12.85% in 2017/18 and 0.89 to 0.98, 0.80 t/ha to 1.03 t/ha, and 9.84% to 18.92% in 2018/19, respectively. Nonetheless, the in-season biomass was generally overestimated during the mid and late stages. The Pe values ranged from −3.24% to 95.43% in the calibration and −1.46% to 35.87% in the validation.

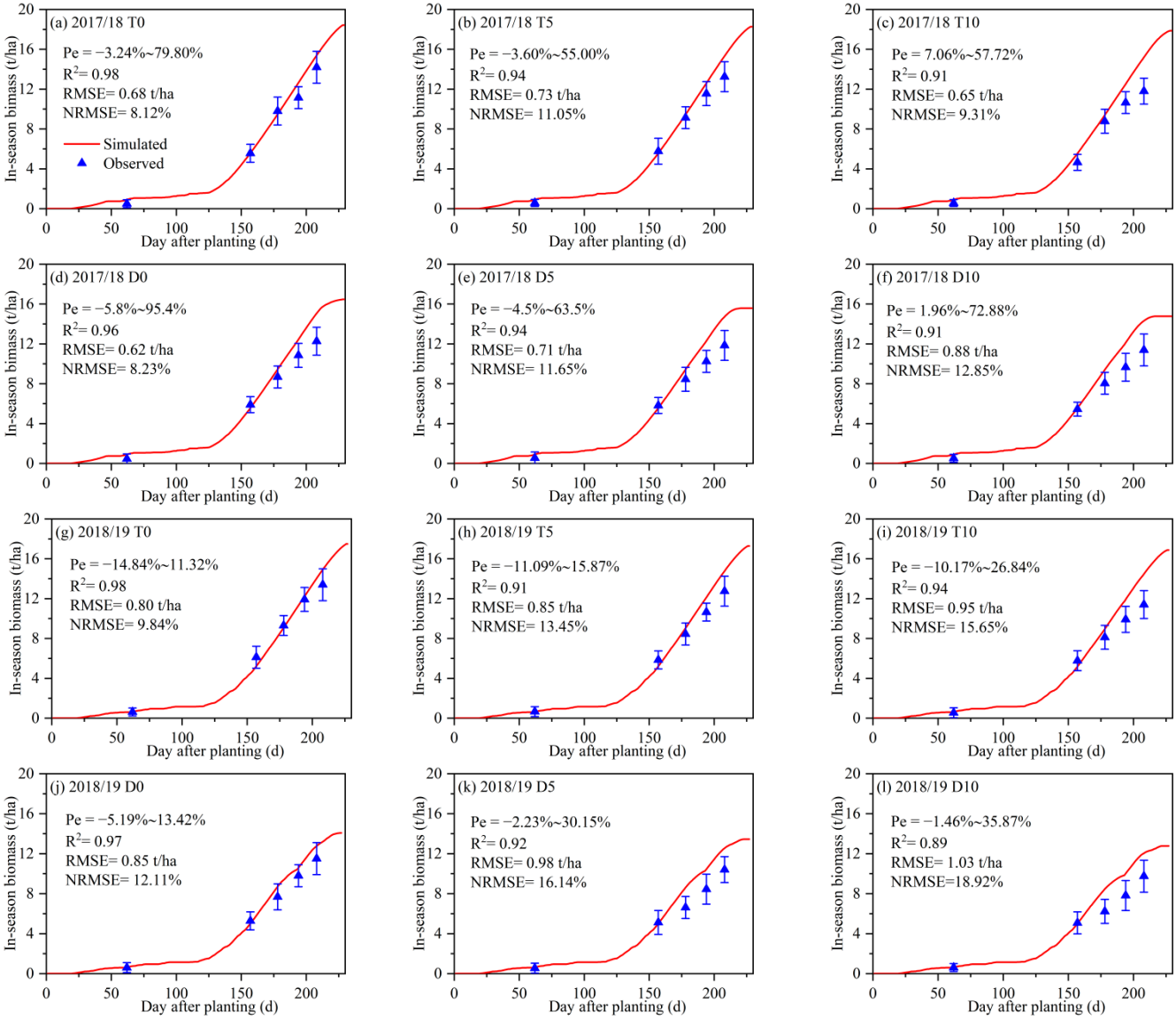


Figure 4. Simulated and observed in-season biomass in the 2017/18 season and 2018/19 season.

3.4. Grain Yield

The simulated and observed final grain yields from different treatments in the 2017/18 and 2018/19 seasons are shown in Figure 5. Compared with the freshwater treatments, the water salinities of 5 dS/m and 10 dS/m decreased the grain yield by 2.45% to 5.10% and 8.83% to 10.10% under traditional irrigation, and 4.88% to 5.9% and 9.74% to 14.10% under deficit irrigation, respectively. At the same water salinity, the observed grain yield of the traditional irrigation treatments was 16.81% to 23.30% higher than the deficit irrigation ones. There was a good agreement between the simulated and observed grain yield values. In the calibration, the values of R^2, RMSE, and NRSME were 0.96, 0.21 t/ha, and 4.65%, respectively. In the validation, the corresponding values were 0.92, 0.35 t/ha, and 7.11%, respectively. Nevertheless, the simulations of grain yield tended to be higher than the observed ones, especially under high irrigation water salinity. AquaCrop overestimated the grain yield by 1.84% to 11.11% and 3.27% to 12.35% in the calibration and validation, respectively.

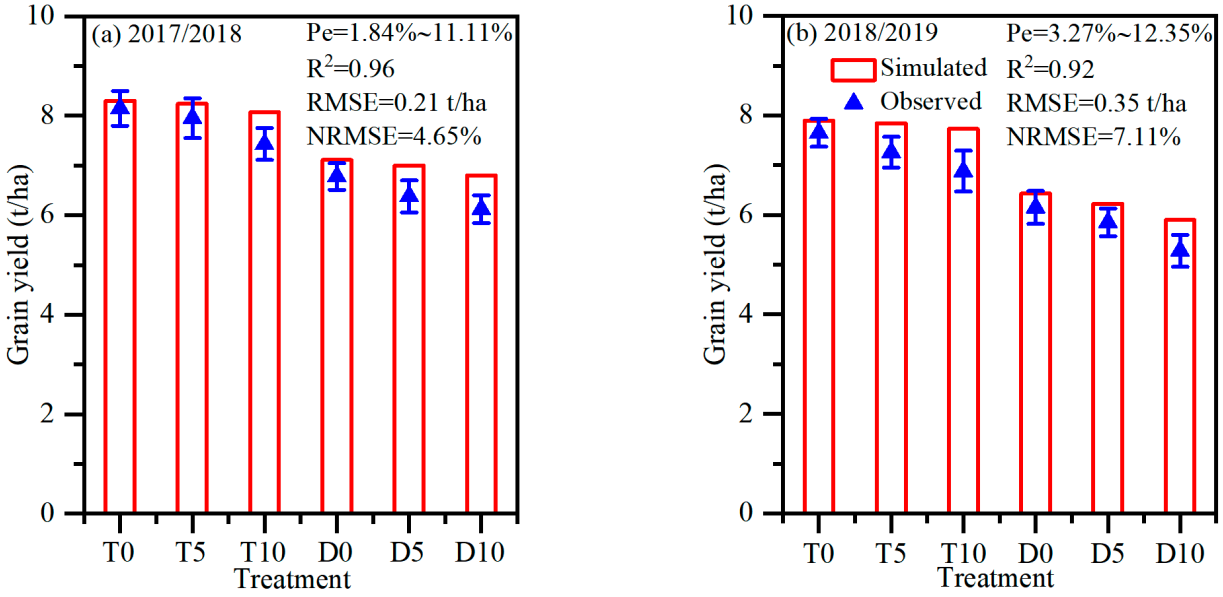


Figure 5. Simulated and observed grain yield in the 2017/18 season and 2018/19 season.

3.5. Scenario Analysis

The grain yield and soil salt content of different saline water irrigations in the dry, normal, and wet years were simulated using the validated model, as presented in Tables 4 and 5, respectively. In general, the grain yield increased with irrigation amount and rainfall while decreasing with water salinity. Deficit irrigation with saline water could be an alternate irrigation strategy to stabilize the wheat yield. In the dry year, the grain yields of C, D, and E with 2 dS/m to 16 dS/m water salinities ranged from 6.34 t/ha to 8.00 t/ha, which were equal to 78.27% to 98.77% of the potential yield. In the normal year, the grain yields of these saline water irrigation strategies ranged from 6.06 t/ha to 7.54 t/ha, which were 79.74% to 99.21% of the potential yield. In the wet year, the grain yields of B, C, D, and E with 2 dS/m to 16 dS/m water salinities were in the range of 6.48 t/ha to 8.34 t/ha, achieving 77.42% to 99.64% of the potential yield. On the other hand, saline water irrigation induced a secondary salinization risk (SSC > 4 dS/m). The soil salt content at harvest generally increased with saline water amount and salinity. Considering the sustainable land use, saline water irrigation with salinities below 4 dS/m, 6 dS/m, and 6 dS/m can be applied in dry, normal, and wet years, respectively. Furthermore, appropriate deficit irrigation strategies and in-season rainfall were conducive to mitigating soil salt accumulation. The C, B, and A irrigation scenarios were the proper deficit irrigation strategies when using saline water in dry, normal, and wet years, respectively. In the dry year, three irrigations of 60 mm (C) using 0 dS/m to 4 dS/m water salinities each at the jointing, anthesis, and grain-filling stages achieved grain yields of 93.33% to 94.69% of the potential yield and soil salinities of 0.78 dS/m to 3.55 dS/m. In the normal year, two irrigations of 60 mm (B) using 0 dS/m to 6 dS/m water salinities each at the jointing and anthesis stage obtained grain yields of 85.92% to 87.11% of the potential yield and soil salinities of 0.77 dS/m to 3.45 dS/m. In the wet year, one irrigation of 60 mm (A) using 0 dS/m to 8 dS/m water salinities at the jointing stage achieved grain yields of 80.17% to 81.72% of the potential yield and soil salinities of 0.22 dS/m to 2.18 dS/m.

Table 4. Estimates of grain yield (t/ha) under different saline water irrigation scenarios in the dry, normal, and wet years.

Scenario	Irrigation Water Salinity (dS/m)								
	0	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**
	Dry year (1998/99, rainfall = 178.2 mm)								
Rainfed	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81
A	5.94	5.96	5.97	5.97	5.94	5.90	5.84	5.76	5.71
B	7.14	7.10	7.00	6.90	6.81	6.71	6.62	6.48	6.34
C	7.67	7.63	7.56	7.46	7.36	7.26	7.12	7.00	6.88
D	8.02	8.00	7.97	7.94	7.88	7.82	7.76	7.66	7.57
E	8.10	8.10	8.09	8.08	8.06	8.03	8.01	7.98	7.94
	Normal year (1994/95, rainfall = 211.6 mm)								
Rainfed	3.96	3.96	3.96	3.96	3.96	3.96	3.96	3.96	3.96
A	5.55	5.57	5.59	5.61	5.58	5.55	5.49	5.43	5.37
B	6.62	6.64	6.59	6.53	6.48	6.37	6.27	6.18	6.06
C	7.46	7.41	7.33	7.22	7.12	6.98	6.88	6.76	6.58
D	7.55	7.54	7.52	7.49	7.46	7.41	7.36	7.31	7.26
E	7.60	7.59	7.57	7.55	7.52	7.49	7.44	7.39	7.35
	Wet year (2016/17, rainfall = 277.4 mm)								
Rainfed	4.32	4.32	4.32	4.32	4.32	4.32	4.32	4.32	4.32
A	6.84	6.82	6.79	6.75	6.71	6.57	6.50	6.49	6.48
B	7.14	7.15	7.16	7.16	7.14	7.14	7.14	7.10	7.07
C	7.68	7.68	7.68	7.63	7.54	7.48	7.46	7.37	7.25
D	8.36	8.34	8.29	8.20	8.09	7.95	7.88	7.78	7.57
E	8.37	8.34	8.27	8.16	8.03	7.86	7.80	7.63	7.56

Table 5. Estimates of soil salt content (dS/m) under different saline water irrigation scenarios in the dry, normal, and wet years.

Scenario	Irrigation Water Salinity (dS/m)								
	0	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**
	Dry year (1998/99, rainfall = 178.2 mm)								
Rainfed	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
A	0.80	1.25	1.72	2.17	2.63	3.12	3.58	4.07	4.50
B	0.78	1.73	2.68	3.58	4.52	5.43	6.37	7.32	7.75
C	0.78	2.17	3.55	4.33	5.42	6.18	6.23	7.30	8.03
D	0.80	2.60	3.85	5.03	5.43	6.07	6.57	7.10	7.75
E	0.42	1.80	3.13	4.20	5.02	5.70	6.20	6.70	7.45
	Normal year (1994/95, rainfall = 211.6 mm)								
Rainfed	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
A	0.78	1.28	1.62	2.05	2.52	2.97	3.40	3.83	4.28
B	0.77	1.75	2.55	3.45	4.38	5.28	6.18	7.05	7.63
C	0.80	2.17	2.97	3.87	4.82	5.95	6.75	7.57	7.62
D	0.55	1.60	2.55	3.55	4.48	5.43	6.15	6.88	7.58
E	0.27	1.38	2.37	3.43	4.48	5.38	6.12	6.93	7.57
	Wet year (2016/17, rainfall = 277.4 mm)								
Rainfed	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
A	0.22	0.70	1.20	1.70	2.18	2.70	3.22	3.68	4.17
B	0.20	1.23	2.18	3.07	4.00	4.93	5.87	6.82	7.78
C	0.22	1.68	2.57	3.97	4.80	5.68	6.65	7.38	7.88
D	0.18	1.62	2.47	3.75	4.73	5.70	6.42	7.35	7.38
E	0.13	1.17	2.30	3.55	4.68	5.15	6.43	6.67	7.37

4. Discussion

4.1. Model Performance

In general, the AquaCrop model accurately predicted the soil moisture in the 0 cm to 60 cm layer under various irrigation levels and water salinities. The robust capability

of AquaCrop to simulate volumetric soil water content was also identified by several studies that tested AquaCrop for wheat, maize, and cotton applied with different irrigation strategies and saline conditions [23,38,39]. In the study, saline water irrigation increased the volumetric soil water content during the winter wheat growing seasons, which could be mainly attributed to the reduced evapotranspiration under salt stress [12]. After calibrating the salt stress parameters (e.g., salinity thresholds, stomatal responses), AquaCrop adequately captured the increased soil moisture under saline water irrigation. Nonetheless, the model tended to overestimate the volumetric soil water content, in particular under water deficit and high salinity. The overestimation could have been due to the deviation in evapotranspiration calculation using the non-adjusted or low evaporation and transpiration coefficients [33,40]. Furthermore, the model cannot simulate the preferential flows caused by soil cracks and macropores, resulting in the underestimation of the drainage, and thus, a higher soil water content [4]. Another possible reason is the oversimplification of the root module in AquaCrop [23]. With the increasing soil salinity in the root zone, the reduced osmotic potential of a soil solution can immediately inhibit root growth and water uptake [12]. The model is not able to consider the effects of salt stress on root development and extraction, causing simulation errors in soil water balance.

Additionally, AquaCrop could be a useful tool to predict soil salt accumulation under saline water irrigation. In line with our results, other studies also reported the satisfactory performance of AquaCrop in simulating soil salinity for different saline environments [23,25,26]. Although the prediction accuracy of soil salinity in our study was acceptable, the simulated SSC values tended to be lower than the observations, especially under high salinity water irrigation. One reason could be the simplification in the solute transport module of AquaCrop, which only considers convection and diffusion processes [34]. The solute transport of the root zone is complex and can be affected by several factors, such as meteorological conditions, soil dispersion, adsorption, and root extraction [23,34]. Moreover, the overestimated volumetric soil water content in the root zone might indicate reduced upward salt movement through the capillary rise, thus leading to lower soil salinity during simulation [39].

The estimation of in-season biomass fitted well with the observations under different irrigation strategies and water salinities while tending to overestimate at the middle and late growth stages. Consistent with this, several studies indicated that AquaCrop can give good estimates of biomass at the vegetative establishment stage but overestimate it during the late growth stage [28,33]. This could be because the model uses the same value of the normalized water productivity (WP*) across the growing season, which was supposed to be smaller at the senescence period [4]. Another possible reason is that AquaCrop cannot assess the impacts of ionic stress on crop development and production under saline conditions. As the salt stress is prolonged, salt ions in plant tissues may accumulate to a toxicity level that accelerates the senescence and death of mature leaves [9]. As for the grain yield, saline water irrigation with salinities of 5 dS/m and 10 dS/m reduced the wheat yield by 2.45% to 14.10%, compared with freshwater irrigation. Similarly, a previous field study reported that saline water irrigation with salinities of 6.0 dS/m to 12.0 dS/m resulted in yield reductions of 4.30% to 16.30% for winter wheat [15]. The AquaCrop model performed well in predicting the grain yield under saline water irrigation, though it tended toward overestimation. Consistent with our results, Soomro et al. [24] reported that the simulated values of AquaCrop were slightly higher than the measured yield for bitter gourd under saline water irrigation. In the study, this discrepancy could have been caused by the overestimation of soil moisture, biomass, and the underestimation of soil salinity. Overall, the effects of saline water irrigation on soil water content, salinity, and wheat production could be satisfactorily simulated using AquaCrop.

4.2. Model Application

Compared with rainfed irrigation, saline water irrigation with salinities of 0 dS/m to 16 dS/m achieved over 75% of the potential grain yield under different rainfall years,

implying that saline water irrigation could be an alternative practice to overcome irrigation water shortage while maintaining wheat yield. This is supported by several experimental and numerical studies. For example, Chauhan et al. [41] found that saline water irrigation with a salinity of up to 12 dS/m achieved a wheat yield as high as 90% of the optimal grain yield. Wang et al. [7] also reported that 96% of the maximum wheat yield can be obtained under the optimized irrigation strategies for water salinities of 3.3 dS/m to 6.8 dS/m. Furthermore, simulated results applying the SWAP model for wheat crops indicated that a yield potential of over 80% could be maintained by using saline water up to 8 dS/m after sowing [42]. Nonetheless, the increasing water salinity could induce soil secondary salinization (soil salinity > 4 dS/m), inhibiting the sustainability of agricultural land. The soil salinity also increased with the number of irrigation events using saline water. Therefore, proper deficit irrigation was a promising strategy for the safe utilization of saline water that not only upheld the wheat yield but also mitigated salt accumulation. Moreover, in-season rainfall played a crucial role in soil desalinization, facilitating the sustainable use of saline water. Considering a high grain yield and low soil salinity, three irrigations of 60 mm with a salinity up to 4 dS/m each at the jointing, flowering, and grain-filling stages for the dry year; two irrigations of 60 mm with a salinity up to 6 dS/m each at the jointing and flowering stages for the normal year; and one irrigation of 60 mm with a salinity up to 8 dS/m at the jointing stage for the wet year could obtain optimal results. Similarly, a simulation study for winter wheat in the North China Plain suggested that one brackish water (3 g/L) irrigation of 60 mm at the jointing stage and two brackish water (3 g/L) irrigations of 60 mm each at the jointing and flowering-filling stages could be the suitable practices to achieve high grain yield and to maintain low salt accumulation [8]. Another modeling study for wheat crops in the arid and semiarid regions of Iran also showed that saline water with a salinity of up to 8.31 dS/m could be applied without any risks during above-average rainfall years [19]. Winter wheat is sensitive to soil water deficit at the jointing to grain-filling stages but is relatively tolerant to salt stress during these periods [8,9]. In our model results, deficit irrigation based on these stages using saline water achieved over 80% of the potential yield while minimizing the soil salinity for different rainfall years, which could be a reliable water-saving strategy in the research region.

Nonetheless, the above suggestions based on the model application have some limitations that must be noted. First, although the AquaCrop model performed well in simulating the soil water and salt transport, as well as the winter wheat growth and production, the prediction errors notably increased with increasing drought and salinity. Soil water deficit and salinity can significantly impact the model accuracy. Substantial deviations of AquaCrop under severe water and salt stress were reported in several previous studies [32–34]. The discrepancies could be related to the oversimplification in its soil water balance calculation, solute transport processes, root development component, and salt stress responses, as discussed earlier [4,32,40]. For optimizing saline water irrigation, further developments in the modules of soil salt transport and crop salt stress were desired to improve the estimation of soil salinity and crop production under saline conditions. Second, the present model study was conducted based on two traditional irrigation practices and three salinity levels. Specific irrigation management might influence the model performance and scenario analysis. Therefore, it is desired that the model could be validated by the field data using precise irrigation threshold limits (i.e., field capacity) in future studies. Third, model performance and application could also be influenced by climate change [43]. In the study, AquaCrop was only calibrated and validated based on a two-year field experiment. It is suggested that long-term field data with higher climate variability can be used during the calibration and validation to obtain a more reliable application of AquaCrop [44]. Moreover, the study only assessed the soil salinity after the saline water irrigation of a single wheat season. It is necessary to predict the effects of long-term saline water irrigation on salt accumulation in future studies. Furthermore, the conjunctive use of saline and fresh water for irrigation can alleviate the negative effects of sole saline water irrigation on crops and land sustainability [45]. The optimization of the saline water irrigation strategy could be

further improved by considering cyclic irrigation with saline and fresh water. Overall, the AquaCrop model maintained a good balance between user-friendliness, simplicity, and preciseness and could be a feasible tool to guide the saline water irrigation for winter wheat.

5. Conclusions

AquaCrop was calibrated and validated for winter wheat under various saline water irrigation conditions based on a two-year field experiment in the NCP. The model performed well at simulating the volumetric soil water content with $0.85 \leq R^2 \leq 0.95$, $1.22\% \leq RMSE \leq 2.59\%$, and $8.09\% \leq NRMSE \leq 12.95\%$. AquaCrop also gave acceptable predictions of the soil salt content with $0.71 \leq R^2 \leq 0.98$, 0.12 dS/m $\leq RMSE \leq 0.62$ dS/m, and $7.49\% \leq NRMSE \leq 26.82\%$. The in-season biomass values were accurately simulated with $0.89 \leq R^2 \leq 0.98$, 0.62 t/ha $\leq RMSE \leq 1.03$ t/ha, and $8.12\% \leq NRMSE \leq 18.92\%$. The estimates of the grain yield were close to the measurements with $0.92 \leq R^2 \leq 0.96$, 0.21 t/ha $\leq RMSE \leq 0.35$ t/ha, and $4.65\% \leq NRMSE \leq 7.11\%$. These results indicated that AquaCrop could be an effective tool to evaluate the effects of saline water irrigation on soil salinity and winter wheat production. The model application suggested that three irrigations of 60 mm with a salinity up to 4 dS/m each at the jointing, flowering, and grain-filling stages for the dry year; two irrigations of 60 mm with a salinity up to 6 dS/m each at the jointing and flowering stages for the normal year; and one irrigation of 60 mm with a salinity up to 8 dS/m at the jointing stage for the wet year were the proper saline water irrigation strategies in the study region, which obtained over 80% of the potential grain yield while mitigating soil secondary salinization. Nonetheless, AquaCrop overestimated the soil water content, in-season biomass, and grain yield but underestimated the soil salt content, especially under deficit irrigation and high irrigation water salinity. Further improvements in modules of soil solute transport and crop salt stress were desired to obtain better model performance. Moreover, the model was only calibrated and validated using two years' worth of experimental data. Future validation studies based on a long-term field experiment are necessary to improve the reliable use of AquaCrop and to identify the sustainability of long-term saline water irrigation.

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