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ORIGINAL PAPER

Soil Salt Accumulation, Physiological Responses, and Yield Simulation of Winter Wheat to Alternate Saline and Fresh Water Irrigation in the North China Plain

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Abstract

Large amounts of shallow underground water typically with salt content at around 4.7 dS m^{-1} are available in the North Chain Plain (NCP), which requires managing and thus can be properly used in irrigated agriculture to relieve the increasing pressure on fresh water in this region for supplementary irrigation. Field experiments were conducted to investigate the soil salt accumulation, responses, and yield simulation of winter wheat to the alternate irrigation strategies during 2017–2019. Five irrigation strategies included rain-fed cultivation (NI), fresh and saline water irrigation (FS), fresh water irrigation (FF), saline water irrigation (SS), and saline and fresh water irrigation (SF) during the growth stages. Irrigation with saline water increased soil salinity level and could be balanced annually; however, the leaf gas exchange of winter wheat was almost not significantly affected. The salinity caused by saline water irrigation negatively influenced the vegetative growth. The grain yield was increased by 24% and 32% under the FS and SF treatments compared to NI, while a minor reduction by 12% and 5% in yield under these treatments was recorded compared with the FF treatment. The SALTMED model was calibrated and validated to predict yield, and the high value of the R^2 reflected a good agreement between modeled and observed values, indicating that the SALTMED model was able to simulate grain yield under the alternate irrigation strategies in the regional climate condition. Supplementary irrigation using saline water at the stem elongation stage and fresh water at the flowering stage is a practical solution to achieve comparable yields with low risk of salt accumulation for winter wheat particularly in the NCP.

Keywords Rain-fed · Brackish water · Growth · Model · Salinity · Yield

1 Introduction

The potentiality for sustainable agricultural development in arid and semi-arid regions is limited by scarce water resources for irrigation (Acosta-Motos et al. 2017), and this is prominent in the North China Plain (NCP) (Yang et al. 2010; Soothar et al. 2019a). It is reported that the NCP is greatly susceptible to fresh water shortage, whereas the underground water has a capacity to fulfill the supplementary water requirements preserving limited fresh water resources (Yang et al. 2010). The excess amount of saline water in the upper aquifer of NCP is characterized by brackish water at around 4.7 dS m^{-1}, and thus, utilization of brackish water for winter wheat seems feasible to cope with the current tight water situation (Liu et al. 2016; Xue and Ren 2017; Pang et al. 2018). However, previous studies have shown that the continuous use of saline water for irrigation can lead to long-term soil and environmental problems, such as soil salinization (Hussain et al. 2020). Increasing adoption of saline water irrigation also damages

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plants in addition to the degradation of agricultural lands (Feng et al. 2015; Wang et al. 2016). Salinity drastically increases osmotic stress and soil water suction, causes effective shift in soil moisture, and decreases root water potential and plant water uptake, resulting in partial stomata closure and reduction in transpiration rate (Feizi et al. 2010). In addition, saline water also decreased fertile tillers and root penetration (Plaut et al. 2013).

Winter wheat (WW) is a foremost important staple crop. China is one of the significant WW-producing countries, and more than 75% of WW is produced in the NCP (Lv et al. 2013). The NCP is situated in typical continental monsoon climate areas, where the annual precipitation is between 400 and 600 mm and mostly occurs during summer season (Sun et al. 2010). However, it was noted that the large amount of rainfall occurred after WW harvest (Soothar et al. 2019a). Hence, the growth stages of WW cannot be completely developed, as enough fresh water storage may not be available for irrigation during peak dry period (Sun et al. 2010; Chen et al. 2014). Hu et al. (2005) reported that 50% of the cultivated area of NCP already relied on underground saline water for irrigation of WW. Some studies have been conducted on saline water irrigation or supplementary irrigation with saline and fresh water in this region (Jiang et al. 2012; Wang et al. 2016). Liu et al. (2016) concluded that irrigation with saline water at the jointing stage could be used for WW in order to minimize risk of salt accumulation and enhance yield and water productivity. However, the appropriate alternate irrigation water supplies at different growth cycles have not been well defined vaguely, and the long-term soil salt distribution, growth, and physiological responses of *Triticum aestivum* L. to supplementary saline water irrigation have not been fully explored.

The continuous and over-pumping of groundwater for irrigation is not only the direct cause for the decline in water table and seawater intrusion in the aquifers of the NCP, but is also substantially affecting the regional climate. In recent decades, accumulated studies have worked on model development and validations for yield simulation under rapidly changing climate conditions. Plant water and soil modeling is considered as an effective tool to manage limited water resources. Models can offer quantitative and qualitative predictions for crop responses to environmental and non-environmental abiotic stresses (Soothar et al. 2019b). The SALTMED model has been adopted for various field crops under different water qualities and irrigation modes. This model has successfully been calibrated and validated for tomato, chickpea, sugarcane, wheat, and quinoa crops under different irrigation management scenarios (Ragab et al. 2005; Montenegro et al. 2010). The abovementioned studies indicated that the numerical SALTMED model can simulate growth and grain yield of field crops reasonably in dry conditions with saline irrigation.

It was hypothesized that the irrigation with alternate saline and fresh water during the growth stages could sustain the yield of WW and the SALTMED model could simulate the yield of WW under the alternate saline and fresh water irrigation mode. The aim of the present study was to investigate the effect of supplementary irrigation alternately with saline and fresh water at different growth stages on plant growth, physiological responses, and yield simulation of WW as well as soil salt accumulation in the rootzone.

2 Materials and Methods

2.1 Site Description

The field trials were initiated from 2015 during the WW growing season at the experimental station of the Institute of Dryland Farming, Hebei Academy of Agriculture and Forestry Sciences (latitude, 37° 54′ N; longitude, 115° 42′ E), which is situated in the NCP. The experimental site falls in a typical continental monsoon climate. The monthly mean rainfall and average temperature during the growing seasons are shown in Fig. 1. The soil was classified as silt loam having the particle size distribution of sand, silt, and clay at 11.2%, 61.5%, and 12.3%, respectively, and the field condition at the experimental site was well-drained soil and the water table remained always below 40 m (Soothar et al. 2019a).

2.2 Treatments and Growing Conditions

The treatments included (1) rain-fed cultivation (NI); (2) irrigation water applied at the stem elongation stage with fresh water and the flowering stage with saline water (FS); (3) irrigation water applied at the stem elongation and flowering stage both with fresh water (FF); (4) irrigation water applied at the stem elongation and flowering growth stage both with

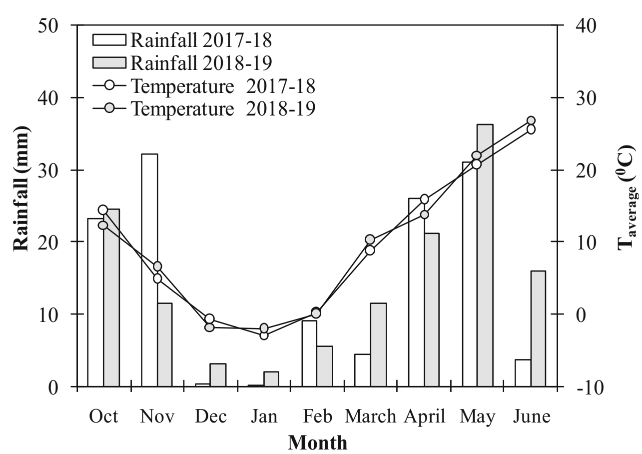

Fig. 1 Monthly average rainfall and temperature ($T_{average}$) during the cropping seasons of winter wheat

saline water (SS); and (5) irrigation water applied at the stem elongation stage with saline water and the flowering stage with fresh water (SF). The same amount of irrigation water was applied in the FS, FF, SS, and SF treatments with fresh or saline water in each irrigation event. The treatments in the field were set in a completely randomized design with three replicates. The plot size for each replicate was 10 m by 7.5 m. A separate 20-m-wide buffer zone was provided around the irrigated plots with the non-irrigated WW to protect from reciprocal effects of adjacent plots.

Wheat was sown in the middle of October and harvested on around the 10th of June in 2017 and 2018. The seedling rates and row spacing were according to local guidelines. Apart from the irrigation practice, other cultural fertilizers and management practices were the same for all the treatments in accordance with farm's guidelines. For irrigation management, basin irrigation method was used in the field. The plots in the FS, FF, SS, and SF treatments were irrigated twice on 178 days after sowing (DAS) and 221 DAS in 2018, and 165 DAS and 215 DAS in 2019 at the beginning of stem elongation and flowering growth stage in accordance with the experimental treatments. For each irrigation event, the water quantity for all the supplementary irrigation treatment plots was 900 m^3/ha according to the locally recommended amount of irrigation water for WW in the NCP. For land preparation, the amount of 970 m^3/ha fresh water was applied to the entire field plots before sowing. The fresh water used for irrigation was from deep underground having electrical conductivity of 0.39 dS m^{-1}. The saline water for irrigation at 4.7 dS m^{-1} representing the average saline water concentration in the shallow groundwater of the NCP was used (Soothar et al. 2019a). The ion composition of the fresh and saline water is shown in Table 1. At the time of irrigation, the required depth of water was calculated by empirical equation (Memon et al. 2021) and the installed flow meter was used to measure the water flow.

2.3 Data Collection, Measurements, and Analyses

The leaf gas exchange including photosynthetic rate (A_n), stomatal conductance (g_s), and transpiration rate (T_r) were recorded between 9:00 and 11:00 on 206 (heading stage), 221(flowering stage), 241 (milky stage), and 242 days (milky stage) after sowing (DAS) during 2017–2018, and on 207 (heading stage), 220 (flowering stage), 221 (flowering stage), and 236 DAS (milky stage) during 2018–2019 on sunny days with atmospheric CO_2 concentration by a portable photosynthesis system (Li-6400, Li-Cor Biosciences, NE, USA). Leaf area index (LAI) and chlorophyll content were determined on 176, 186, 206, 221, and 242 DAS during 2017–2018, and on 165, 183, 207, 221, and 238 DAS during 2018–2019 by a leaf area meter (model 3050A, Li-Cor Biosciences, NE, USA) and chlorophyll meter (SPAD 502Plus, Konica Minolta, INC. Japan), respectively. Plant height was measured regularly during the experimental period. At physiological maturity, plants in 2 by 2 m were harvested from each replicate plot and were threshed separately. The above-ground dry biomass and grain yield were recorded and the relative yield (%) was calculated with the FF treatment considered as the control treatment. Crop harvest index (CHI) was computed by the grain yield divided by the biomass.

Soil samples were collected at a 20-cm interval down to 100-cm soil depth during the different growth stages and also before sowing and after harvest of WW. In each replicate plot, the soil sample was taken from the mixed soils collected from five different locations in each replicate plot. Soil water contents were measured using the gravimetric method. The collected samples were air-dried, ground, and then sieved passing through a 2-mm sieve. Soil salinity of all the replicated soil samples was assessed in terms of EC with soil and water solution mixed ratio at 1:5 by an EC meter (model LE703, Mettler Toledo International Inc., Shanghai, China).

Table 1 Ion composition of fresh and saline water used for irrigation during the experimental period. The values are means ± SE ($n = 3$). SAR was calculated as $Na^+/[(Ca^{2+} + Mg^{2+})/2]^{1/2}$

Ions	Fresh water (meq. L^{-1})	Saline water
Ca^{2+}	0.76 ± 0.03	1.29 ± 0.13
Mg^{2+}	0.55 ± 0.04	1.78 ± 0.15
K^+	0.39 ± 0.03	6.32 ± 0.52
Na^+	7.24 ± 0.40	43.28 ± 5.03
SAR	8.95 ± 0.29	34.93 ± 3.40

2.4 Model Calibration and Validation

The SALTMED model was used for this field study, as it was designed to be generic, physically based, and friendly to be used for simulation (Ragab et al. 2005). It includes a number of physical processes that simulate under various field conditions. The calibration and validation procedures were described in Soothar et al. (2019b). Data requirement for model calibration, such as plant parameters including crop growth stages, crop coefficient, and fractions cover, was noted from literatures. The shoot height, root length, and leaf area and its index were recorded from the experiments. The required daily climatic data including maximum and minimum temperature, relative humidity, solar radiation, wind flow, rainfall, and net radiation were collected from the metrological station located about 80 m from the experimental plots and were used as input data. Irrigation management practices for each treatment in terms of irrigation date, amount of irrigation water, and water quality parameters were used in the model for model calibration and validation. The required soil physico-chemical properties were taken from field observations. For calibration processes, the FF treatment (control) was adjusted for validation of the other designed treatments. The model validation was made for both cropping seasons by comparing simulated data against observed grain yield data. The validation between simulated and observed data was computed by statistical and graphical procedures, and the data were plotted against time in order to visually assess SALTMED model's performance. Different statistical indices including relative error (%), root mean square error (RMSE), normalized root mean square error (NRMSE), D-index, R^2, and coefficient of efficiency were used for comparison of simulated against observed data. The index of agreement (D-index) proposed by Willmott (1981) was given in relationships. According to the d-statistic, the closer the index value is to one, the better the agreement between the two variables that are being compared and vice versa.

$$RMSE = \left[\sum_{i=1}^{n} \frac{(Pi-Oi)^2}{n}\right]^{0.5}$$

$$NRMSE = \left[\sum_{i=1}^{n} \frac{(Pi-Oi)^2}{n}\right]^{0.5} x\frac{100}{M}$$

$$R^2\left\{\frac{\sum_{i=1}^{n}\left(O_i-\overline{O}\right)\left(P_i-\overline{P}\right)}{\left[\sum_{i=1}^{n}\left(O_i-\overline{O}\right)\right]^{0.5}\left[\sum_{i=1}^{N}\left(P_i-\overline{P}\right)\right]^{0.5}}\right\}^2$$

$$d = 1-\left[\frac{\sum_{i=1}^{n}(P_i-O_i)^2}{\sum_{i=1}^{n}\left(\left|P_i^{/}\right|+\left|O_i^{/}\right|\right)^2}\right]$$

where n is the number of observations, P_i is the predicted observation, and O_i is the measured observation.

2.5 Statistical Analysis

The data were statistically analyzed using SPSS software version 22.0 (IBM Corporation, New York, USA). The means were compared by Duncan's multiple range test at $P \leq 0.05$.

3 Results

3.1 Soil Water Content Under Irrigated and Rain-Fed Modes

The average soil water contents before sowing were around 25% and 21% in 2017–2018 and 2018–2019, respectively (Fig. 2). After the harvest of WW in both seasons, soil water content in the NI treatment was significantly lower in 0–60-cm soil layer compared to the irrigated treatments. In the treatment plots irrigated with saline and fresh water, soil water contents varied in the soil profile (Fig. 2). During the growth period, soil water contents increased in the irrigated treatments after the irrigation events (Fig. 3). In 0–60-cm soil layer, the lowest average soil water contents were observed in the NI treatment throughout most of the cropping seasons.

3.2 Morphological Responses of Winter Wheat Under Irrigated and Rain-Fed Modes

Significant differences in plant height under the irrigation modes were observed after 186 and 183 DAS in the 2017–2018 and 2018–2019 cropping seasons, respectively (Fig. 4).

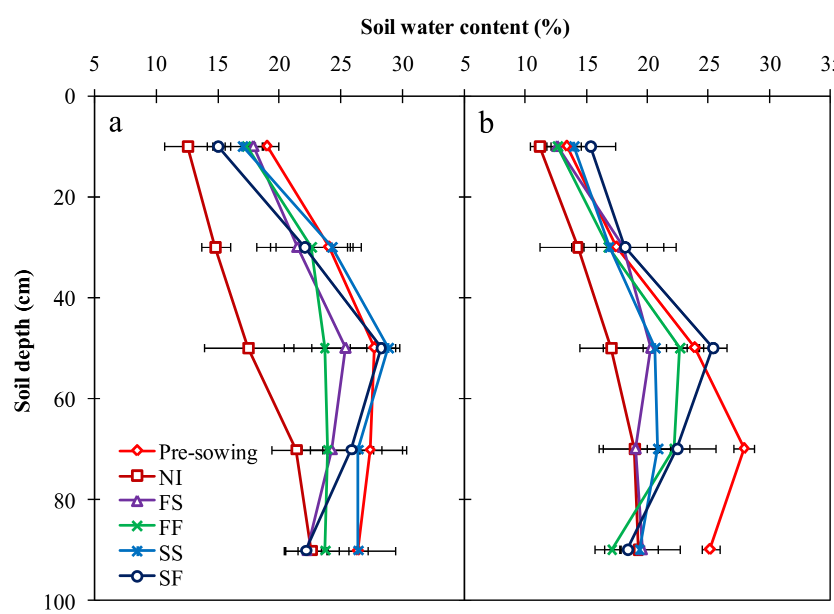

Fig. 2 The soil water contents under the treatments before sowing and after harvest in **a** 2017–2018 and **b** 2018–2019. The NI, FS, FF, SS, and SF indicate rain-fed cultivation, irrigation with fresh water at the stem elongation stage and saline water at the flowering stage, irrigation with fresh water at the stem elongation and flowering stage, irrigation with saline water at the stem elongation and flowering stage, and irrigation with saline water at the stem elongation stage and fresh water at the flowering stage, respectively. The values are means ± SE ($n = 3$)

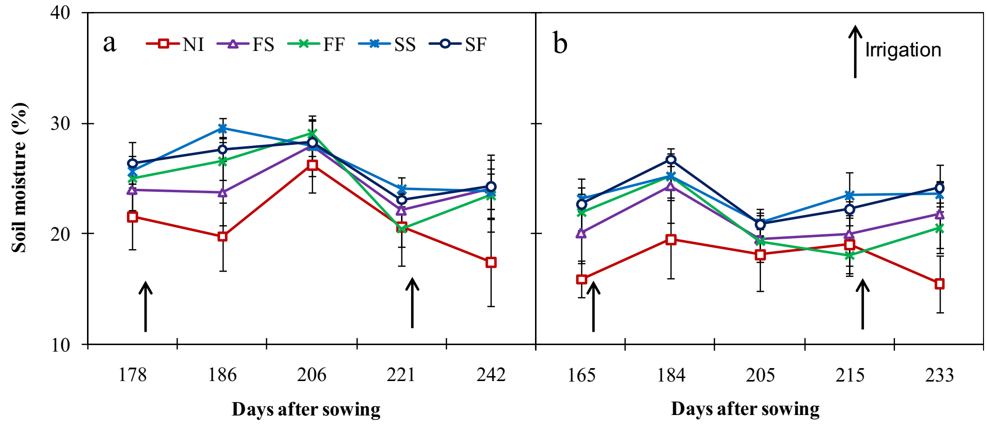

Fig. 3 The soil water contents at the depth of 0–60 cm at different growth stages of winter wheat in **a** 2017–2018 and **b** 2018–2019. The NI, FS, FF, SS, and SF indicate rain-fed cultivation, irrigation with fresh water at the stem elongation stage and saline water at the flowering stage, irrigation with fresh water at the stem elongation and flowering stage, irrigation with saline water at the stem elongation and flowering stage, and irrigation with saline water at the stem elongation stage and fresh water at the flowering stage, respectively. The values are means ± SE ($n = 3$)

The treatments receiving fresh water at the stem elongation stage under the FF and FS treatments had the highest plant height, whereas the lowest plant height was observed in the NI treatment. The LAI peaked at the grain filling stage of WW (Fig. 4). When the LAI reached the maximum, the LAI was significantly different among the treatments. The highest LAI was observed in the FF treatment followed by the FS and SF treatments, and the lowest LAI was observed in the NI treatment in both growing seasons.

3.3 Physiological Responses of Winter Wheat Under Irrigated and Rain-Fed Modes

In both seasons, the average A_n was not significantly affected by the supplementary alternate irrigation using saline and fresh water except the NI treatment in the growing season of 2018–2019 (Fig. 5a). The NI treatment featured a decreased A_n by 14% and 21% compared to the FF treatment during 2017–2018 and 2018–2019,

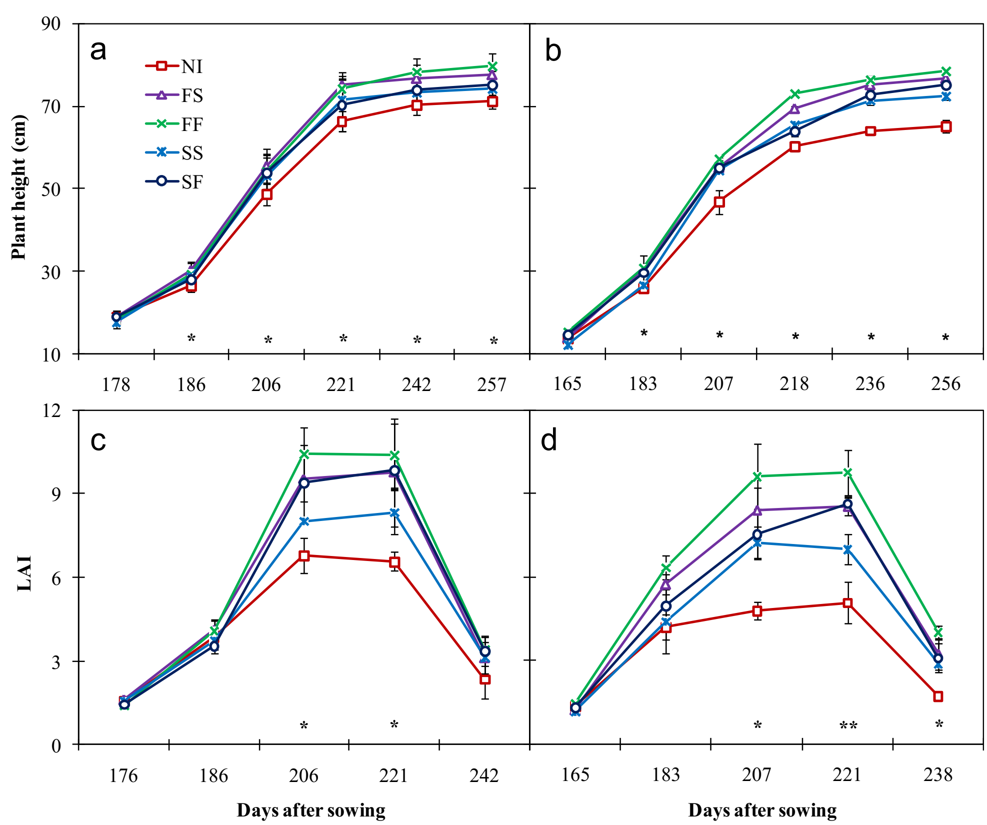

Fig. 4 Plant height **a** 2017–2018 and **b** 2018–2019 and LAI **c** 2017–2018 and **d** 2018–2019 of winter wheat. The NI, FS, FF, SS, and SF indicate rain-fed cultivation, irrigation with fresh water at the stem elongation stage and saline water at the flowering stage, irrigation with fresh water at the stem elongation and flowering stage, irrigation with saline water at the stem elongation and flowering stage, and irrigation with saline water at the stem elongation stage and fresh water at the flowering stage, respectively. The values are means ± SE ($n = 3$). * and ** indicate significant differences among the treatments at $P \leq 0.05$ and $P \leq 0.01$, respectively

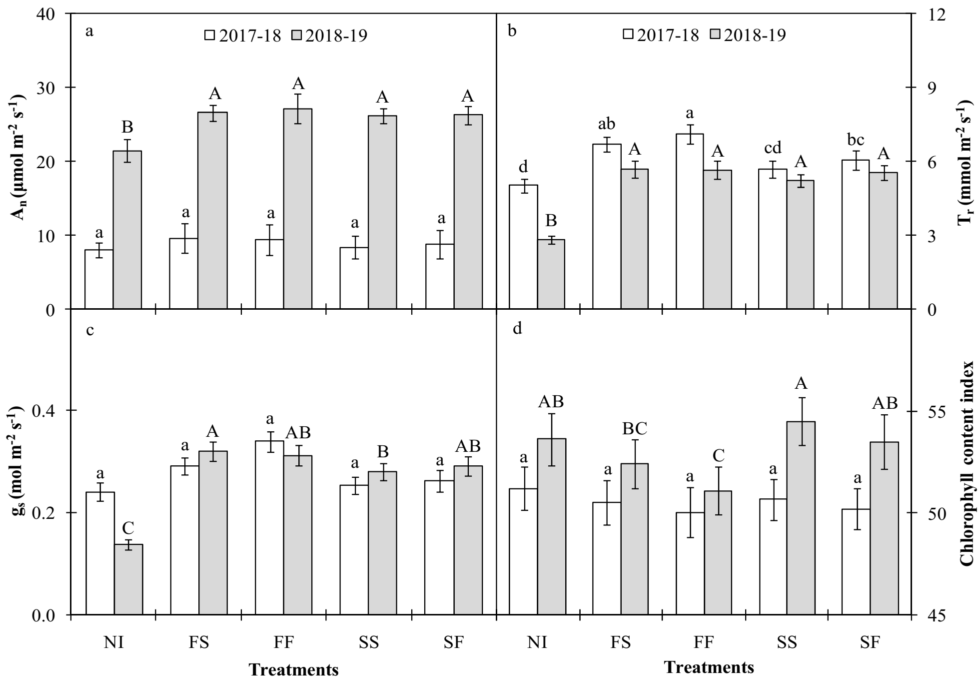

Fig. 5 **a** Averaged photosynthetic rate (A_n), **b** transpiration rate (T_r), **c** stomatal conductance (g_s), and **d** chlorophyll content index of winter wheat. The values are means ± SE ($n = 3$). The NI, FS, FF, SS, and SF indicate rain-fed cultivation, irrigation with fresh water at the stem elongation stage and saline water at the flowering stage, irrigation with fresh water at the stem elongation and flowering stage, irrigation with saline water at the stem elongation and flowering stage, and irrigation with saline water at the stem elongation stage and fresh water at the flowering stage, respectively. The lowercase and capital letters above bars indicate significant differences among the treatments during 2017–2018 and 2018–2019, respectively, according to Duncan's multiple range test at $P \leq 0.05$

respectively. The g_s and T_r were significantly affected by the treatments during both growing seasons (Fig. 5b, c). The FF and FS treatments had the highest g_s and T_r, while the NI treatment showed the lowest g_s and T_r. The chlorophyll content was not significantly affected by the treatments during 2017–2018. However, the significantly lowest chlorophyll content was observed in the FF treatment during the cropping season of 2018–2019 (Fig. 5d).

3.4 Soil Salinity Development Within the Rootzone

In the soil profile, increased soil $EC_{1:5}$ under the FS, SS, and SF treatment was found compared with the NI and FF treatment, and the soil $EC_{1:5}$ was the highest under the SS treatment (Table 2). The variations of soil $EC_{1:5}$ were mainly observed in the soil depth of 0–60 cm. During the growing period, the soil $EC_{1:5}$ in the rootzone increased from the stem

Table 2 Soil salinity in terms of $EC_{1:5}$ (μS cm^{-1}) under the treatments after harvest of winter wheat in the two growing seasons

Season	Treatment	Soil layer (cm)				
		0–20	20–40	40–60	60–80	80–100
2017–18	NI	174 ± 5^c	205 ± 24^c	217 ± 48^d	245 ± 51^c	271 ± 47^a
	FS	294 ± 25^b	310 ± 44^b	333 ± 45^c	308 ± 41^{bc}	275 ± 26^a
	FF	195 ± 19^c	226 ± 28^c	276 ± 50^{cd}	273 ± 49^c	272 ± 18^a
	SS	438 ± 97^a	483 ± 36^a	485 ± 21^a	410 ± 49^a	361 ± 86^a
	SF	259 ± 29^{bc}	371 ± 51^b	408 ± 17^b	371 ± 41^{ab}	310 ± 7^a
2018–19	NI	310 ± 70^d	262 ± 34^d	294 ± 5^b	331 ± 26^a	317 ± 30^a
	FS	447 ± 53^c	417 ± 51^c	532 ± 80^{ab}	395 ± 43^a	368 ± 41^a
	FF	330 ± 10^d	290 ± 51^d	376 ± 32^{ab}	389 ± 59^a	360 ± 80^a
	SS	931 ± 27^a	699 ± 90^a	634 ± 160^a	495 ± 150^a	410 ± 94^a
	SF	583 ± 90^b	533 ± 98^b	490 ± 39^{ab}	400 ± 21^a	371 ± 54^a

The NI, FS, FF, SS, and SF indicate rain-fed cultivation, irrigation with fresh water at the stem elongation stage and saline water at the flowering stage, irrigation with fresh water at the stem elongation and flowering stage, irrigation with saline water at the stem elongation and flowering stage, and irrigation with saline water at the stem elongation stage and fresh water at the flowering stage, respectively. The values are means ± SE ($n = 3$). Within the same column, different letters indicate significant differences among the treatments according to Duncan's multiple range test at $P \leq 0.05$

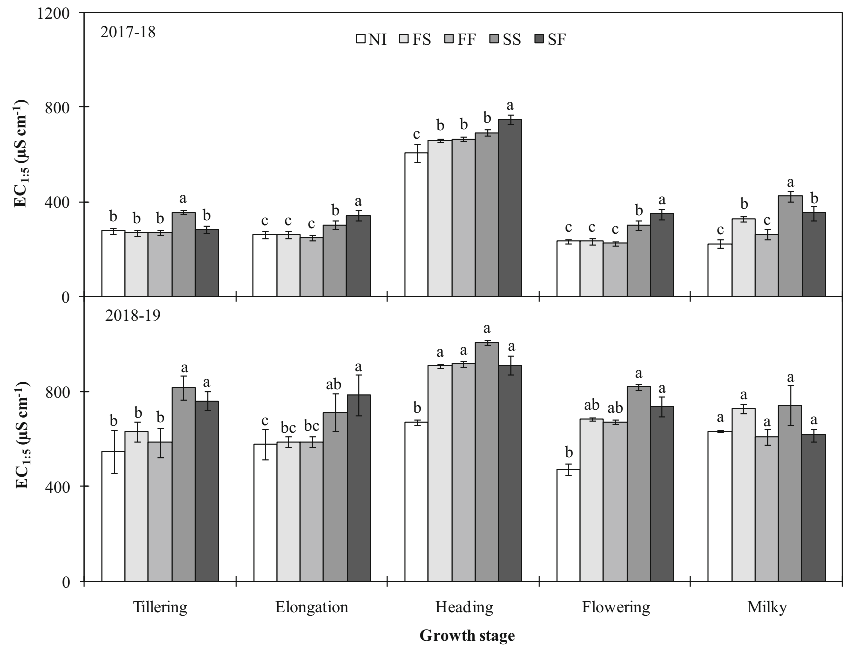

Fig. 6 Soil $EC_{1:5}$ in the rootzone during different growth stages of winter wheat. The values are means ± SE ($n = 15$). The NI, FS, FF, SS, and SF indicate rain-fed cultivation, irrigation with fresh water at the stem elongation stage and saline water at the flowering stage, irrigation with fresh water at the stem elongation and flowering stage, irrigation with saline water at the stem elongation and flowering stage, and irrigation with saline water at the stem elongation stage and fresh water at the flowering stage, respectively. The different letters indicate significant differences among the treatments according to Duncan's multiple range test at $P \leq 0.05$

elongation stage and then decreased from the heading stage to milky stage in both seasons (Fig. 6).

3.5 Biomass, Yield, and Harvest Index Under Irrigated and Rain-Fed Modes

The dry biomass was the highest in the FF treatment; intermediate in the FS, SF, and SS treatments; and the lowest in the NI treatment (Table 3). The grain yield was increased in the FF, FS, and SF treatments compared with the SS and NI treatments. However, decreased grain yield by 12%, 20%, and 5% was observed in the FS, SS, and SF treatments, respectively, compared to the FF treatment across the two growing seasons (Table 3). There was a significant negative relationship between relative grain yield and mean soil $EC_{1:5}$ (Fig. 7). The crop harvest index (CHI) was significantly different among the treatments in 2017–2018, while similar CHI was observed in the cropping season of 2018–2019 (Table 3). The average CHI across the two seasons was different significantly among the treatments.

3.6 Performance of SALTMED Model Under Irrigated and Rain-Fed Modes

The grain yields of WW were simulated under all the treatments with a maximum of 25.6% difference under the NI treatment (Table 4). The mean relative error, RMSE,

Table 3 Effect of rain-fed, fresh irrigation, saline irrigation, and their alternation treatments on dry biomass, grain yield, and CHI of winter wheat

Season	Treatment	Dry biomass (t ha^{-1})	Grain yield (t ha^{-1})	CHI
2017–18	NI	9.26 ± 0.5^{b}	6.14 ± 0.2^{c}	0.64 ± 0.04^{b}
	FS	9.38 ± 0.3^{b}	7.17 ± 0.1^{b}	0.77 ± 0.03^{a}
	FF	12.01 ± 0.1^{a}	8.08 ± 0.1^{a}	0.67 ± 0.00^{ab}
	SS	9.51 ± 0.4^{b}	6.31 ± 0.2^{c}	0.67 ± 0.02^{ab}
	SF	10.21 ± 0.2^{b}	7.83 ± 0.0^{a}	0.77 ± 0.02^{a}
2018–19	NI	6.23 ± 0.1^{b}	6.03 ± 0.1^{c}	0.97 ± 0.02^{a}
	FS	8.41 ± 0.3^{a}	7.89 ± 0.1^{ab}	0.94 ± 002^{a}
	FF	10.11 ± 0.6^{a}	8.98 ± 0.5^{a}	0.90 ± 0.04^{a}
	SS	8.35 ± 0.5^{a}	7.32 ± 0.1^{b}	0.88 ± 0.07^{a}
	SF	8.77 ± 0.9^{a}	8.28 ± 0.2^{a}	0.97 ± 0.12^{a}

The NI, FS, FF, SS, and SF indicate rain-fed cultivation, irrigation with fresh water at the stem elongation stage and saline water at the flowering stage, irrigation with fresh water at the stem elongation and flowering stage, irrigation with saline water at the stem elongation and flowering stage, and irrigation with saline water at the stem elongation stage and fresh water at the flowering stage, respectively. The values are means ± SE ($n = 3$). Within the same column, different letters indicate significant differences among the treatments according to Duncan's multiple range test at $P \leq 0.05$

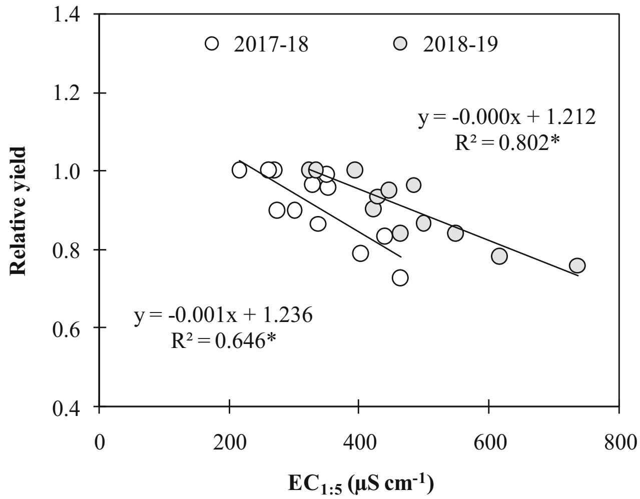

Fig. 7 Correlations between the relative grain yield and soil $EC_{1:5}$ at 0–100 cm in the crop rootzone during the experimental seasons. * indicates the significance of the regression lines at $P \leq 0.05$

NRMSE, and index of agreement for grain yield of WW were 5.71%, 0.64, 8.70, and 0.92, respectively. A significant linear relationship was observed between recorded and simulated grain yield of WW (Fig. 8).

4 Discussion

Supplementary irrigation is imperative to cope with less precipitation and high evapotranspiration (ET) during peak dry months for WW (Liu et al. 2016; Xue and Ren 2017). Thus, underground saline water is considered as a vibrant source of irrigation for sustainable agriculture development in the NCP (Soothar et al. 2019a). Previous studies reported that the abiotic stress resulting from saline irrigation decreased root water and nutrient uptake and consequently affected crop response and increased the risk of salt accumulation (Kutuk et al. 2004; Katerji et al. 2009; Feng et al. 2015; Acosta-Motos et al. 2017; Li et al. 2019). Using conventional water management protocols, irrigation water with different qualities applied at the key growth stages needs to be further understood. Moreover, crop water models having the capability to predict crop development and yield as influenced by supplementary irrigation with different water qualities needs further investigation. Therefore, the main focus of this study was to examine how supplementary irrigation using saline and fresh water alternately affected the development and yield simulation of WW as well as salt accumulation in the rootzone.

Saline irrigation increased soil salinity level. The soil $EC_{1:5}$ under the SS treatment was the highest in the soil profile, intermediate in the FS and SF treatment, and lowest in the FF and NI treatment (Table 2). In addition, the different soil salinity levels under the treatments were mainly observed in the soil profile of 0–60 cm. The soil salinity also changed depending on the water quality applied and the growing seasons. The average $EC_{1:5}$ in the root zone increased from the stem elongation stage to heading stage and then decreased and could be balanced annually (Fig. 6). Soothar et al. (2019a) reported that the heavy amount of rainfall mainly occurred after WW harvest, and thus, the soluble salts got leached from effective rootzone. Ma et al. (2008) found that soluble salts were found leached from soil profile up to the depth of 150 cm during heavy rainy season. Likewise, Liu et al. (2016) reported that the additional alternate saline and fresh irrigation reduced salt accumulation especially in the upper soil layers up to 30-cm depth and the risk of long-term soil salinity was considered as low due to deep leaching of soluble salt during wet years. Similarly, Sharma et al. (1994) observed that the monsoon climate areas with a mean annual rainfall of 500 mm

Table 4 Statistical output on validation between simulated and observed grain yield of winter wheat during the two growing seasons

Treatment	Season	Simulated yield	Relative error (%)	RMSE	NRMSE	d-Index	BIAS
NI	2017–18	4.9	24.5	0.64	8.70	0.92	− 0.27
	2018–19	4.8	25.6				
FS	2017–18	7.7	− 7.1				
	2018–19	8.1	− 2.6				
FF	2017–18	8.0	− 2.5				
	2018–19	8.8	0.9				
SS	2017–18	6.0	5.3				
	2018–19	6.5	12.6				
SF	2017–18	8.0	0.5				
	2018–19	8.3	− 0.2				

The NI, FS, FF, SS, and SF indicate rain-fed cultivation, irrigation with fresh water at the stem elongation stage and saline water at the flowering stage, irrigation with fresh water at the stem elongation and flowering stage, irrigation with saline water at the stem elongation and flowering stage, and irrigation with saline water at the stem elongation stage and fresh water at the flowering stage, respectively

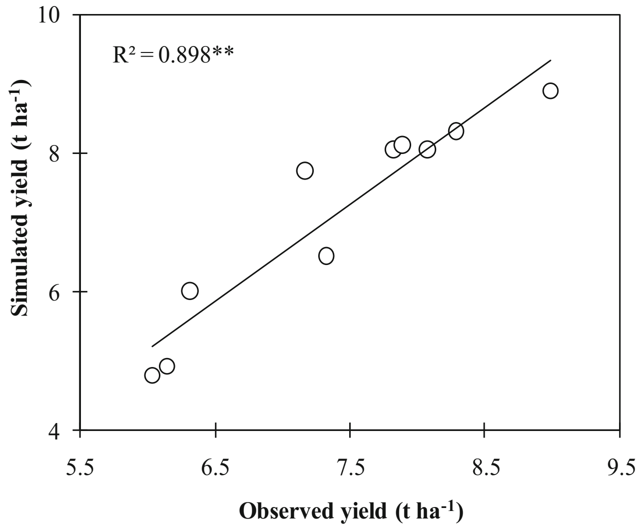

Fig. 8 Relationship between the simulated and observed grain yield of WW during the two cropping seasons in the NCP. ** indicates the significance of the regression line at $P \leq 0.01$

or more, about 80% of the salts accumulated by irrigation application during WW season, were leached without any irrigation practices.

The soil salinity caused by saline water irrigation negatively influenced the vegetative growth of WW. When saline water was applied during the stem elongation growth stage under the SF and SS treatment, the plant height was decreased from this growth stage to maturity, while the plant height was the highest under the FF treatment at the end of the experiment (Fig. 4a, b). This is consistent with the findings of Chauhan et al. (2008), Liu et al. (2016), Pang et al. (2018) and Soothar et al. (2019a). Similarly, the saline irrigation also significantly reduced the LAI, and the lowest LAI was observed under the SS and NI treatment (Fig. 4c, d). Nonetheless, the alternate saline and fresh water irrigation improved the LAI under the FS and SF treatments compared with the SS and NI treatments. Due to the unfavorable soil water contents in the soil profile (Figs. 2 and 3), the plant height and LAI were restricted under the NI treatment, resulting in the reduced light interception (Acosta-Motos et al. 2017) together with the lowest leaf gas exchange parameters (Fig. 5), leading to significantly deceased biomass and grain yield (Table 3).These results are in line with Jiang et al. (2012) and Gioia et al. (2018).

It has been reported that the irrigation using saline water reduced water uptake efficiency, T_r, and net CO_2 assimilation, and due to these reductions, plant growth in turn was affected (Kutuk et al. 2004; Hussain et al. 2016; Acosta-Motos et al. 2017). The decreasing leaf g_s represents the resistance mechanism to cope with excessive salt levels, reducing the salt accumulation in the leaf and helping increase longevity by maintaining salts at sub-toxic levels for longer times which not occurs if T_r does not decrease (Alvarez and Anchez-Blanco 2014). Nevertheless, Pang et al. (2018) observed that additional alternate irrigation with fresh and saline water did not affect leaf A_n at different growth stages. In good agreement with this, for the irrigated treatments, the leaf gas exchange was almost not affected significantly by water qualities (Fig. 5). However, it was found that the g_s and T_r were significantly decreased by the NI treatment, and the A_n was also significantly reduced under the NI treatment in the growing season of 2018–2019 compared with irrigated treatments. These results indicated that the low soil water content was the main cause for the reduction in leaf gas exchange of winter wheat under the NI treatment, contributing to reduced biomass and grain yield (Table 3).

The saline irrigation applied at both key growth stages significantly reduced the grain yield compared with the alternate irrigation with saline and fresh water (Table 3) due to high soil salt accumulation in this treatment. There was a negative relationship between relative grain yield and mean soil $EC_{1:5}$ under different water treatments except the rain-fed condition (Fig. 7), indicating further that increasing soil salinity by saline irrigation led to the reduction in grain yield. It is noteworthy that the alternate irrigation with saline and fresh water, particularly the SF treatment, sustained the yield with a minor reduction in 5% compared with the FF treatment. Saline water between 6 to 9 dS m^{-1} was previously suggested for irrigation by Maas and Grattan (1999), while water salinity ranging from 3 to 8 dS m^{-1} salt content has been rated within the permissible limit and it was not so high for WW (Chauhan et al. 2008; Jiang et al. 2012; Liu et al. 2016; Soothar et al. 2019a). Pang et al. (2018) worked on the alternate irrigation for WW cultivation and found that the grain yield decreased up to 3% by the fresh water irrigation applied at jointing stage and heading stage irrigated by saline water. Previous studies noted that the use of supplementary saline and fresh water for irrigation held greater assurance that produced more yield for the similar salt load to the fields (Chauhan et al. 2008; Soothar et al. 2019b).

Montenegro et al. (2010) reported that the performance of SALTMED model was better for some field crops under additional supplementary irrigation in the rain-fed cultivation region. In the present study, the ability of the SALTMED model was reasonably good to capture the grain yield response under the supplementary irrigation using saline and fresh water at different growth stages of WW (Table 4). All these statistical parameters revealed that the model simulated grain yield of WW at a reasonable level of accuracy, though slightly over or underestimation was observed. The measurement coefficient R^2 was equal to 89.8%, showing that there was a good relationship between observed and simulated crop yield (Fig. 8). The efficiency criterion (d) confirmed the closeness of the simulated grain yield to observed ones with the calculated value of 0.92 (Table 4). These results revealed that the SALTMED model was a useful tool in grain prediction of WW under the alternate irrigation with saline water and rain-fed conditions in line with previous findings (Ragab et al. 2005; Rameshwaran et al. 2014; Soothar et al. 2019b).

5 Conclusions

The growth, physiological responses, and yield simulation of winter wheat in the treatments of rain-fed cultivation, irrigation with fresh water at the stem elongation stage and saline water at the flowering stage, irrigation with fresh water at the stem elongation and flowering stage, irrigation with saline water at the stem elongation and flowering stage, and irrigation with saline water at the stem elongation stage and fresh water at the flowering stage were investigated. The results showed that the irrigation with saline water applied at the stem elongation stage and fresh water utilized at the flowering stage considerably reduced soil salinity level and thus improved the vegetative growth compared with the saline irrigation treatment; consequently, the grain yield of winter wheat in the treatment was sustained compared to the fresh water irrigation. Therefore, supplementary irrigation with saline water at the stem elongation stage and fresh water at the flowering stage of winter wheat is a promising solution to cope with the intensified fresh water pressure to achieve comparable yields with low risk of salt accumulation.

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Declarations

Conflict of Interest The authors declare that there is no conflict of interest.

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