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Estimating crop yield under conditions of soil water deficit and salinity stress with crop water productivity model

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Abstract
The aim of this study was to simulate grain yield, biomass production, canopy cover and water productivity of winter wheat grown under soil water deficit and salinity stress by AquaCrop model. Five different irrigation strategies (S_{100} - S_{75} - S_{50} – S_{25} and S_0) and 5 different irrigation water salinity levels (T_1 = 0.3 dS m^{-1}, T_2 =5 dS m^{-1}, T_3 = 7.5 dS m^{-1}, T_4 = 10 dS m^{-1}, T_5 = 15 dS m^{-1}) were used with the model to estimate deficit irrigation and salinity stress scenarios. According to estimation of the model the grain and biomass yields were fluctuated in the range of 5.43-8.00 t ha^{-1} and 12.84-17.67 t ha^{-1} at irrigation treatments. The application of 25%, 50% and 75% level of deficit irrigation, grain yield reduction was obtained 5%, 13% and 26% respectively. It was compared to the T_1 (control) treatment, a low value of 3% was obtained for the T_2 treatment. Yield loss of T_3 and T_4 salinity treatments were found to be 19% and 43% respectively. The crop yield reduction was dramatically (86%) at 15 dS m salinity level of irrigation water. The lowest yield was obtained at all salinity levels in I_{25} treatment, where 75% water saved. The highest and lowest water productivity was 1.28 kg m^{-3} and 1.20 kg m^{-3} respectively. It is possible to irrigate much more areas saving water with deficit irrigation and also the yields obtained from these areas were 2.17, 6.17 and 17.2 tons more than the yields obtained from areas irrigated with full irrigation. For, sustainable water management in agriculture area, using simulation model such as AquaCrop is useful tolls to estimate effect of applied water depth and quality of irrigation water on crop yield.

Keywords
Deficit irrigation, Salinity stress, Wheat yield, AquaCrop

Introduction

The population of the world is estimated to reach 9.8 billion people in the next 30 years, according to the United Nations, and global water and food demands can also be foreseen to increase accordingly. The agricultural sector uses 70% of the world's fresh water. Water is a limited resource and climate change has accelerated the depletion of the natural resource. The growing population has also increased per capita water use, compounding the global situation of freshwater scarcity (Maysoun et al., 2021). In order to manage over this problem, field management strategies such as using marginal water resources for irrigation, choosing convenient planting techniques, planting salt resistance genotypes are suggested (Dastranj and Sepaskhah, 2021).

The global wheat production came to about 778.6 million tons in 2021-22 growing season (Shahbandeh, 2022). Wheat is one of the strategic crops in Turkiye where wheat cultivation area has a value of 2.4% in the world as of 2020/21 production season (USDA, 2021). According to 2020 United States Department of Agriculture data, Turkey ranks 9th in world wheat exports and its self-sufficiency level is between 95-100% over the years about wheat production. Wheat being the winter season crop (vegetation period; 270 days) needs about 350 to 500 mm irrigation water throughout the growing period in Central Anatolia Region of Turkey.

The decrease in freshwater resources and winter precipitation due to the effect of climate change makes it even more necessary to determine irrigation strategies in wheat. In determining the effects of irrigation strategies and irrigation water qualities on crop yield, computer models are a very useful tool to see the results that may arise in the future.

The FAO's AquaCrop water productivity model is well known simulation model to estimate the effects of different irrigation applications and irrigation water quality parameters on crop yields (Steduto et al., 2012). The model has been tested to simulate yield response to water for most of the major field crops cultivated worldwide (Steduto et al., 2009). This model was used to simulate to effects of deficit irrigation and irrigation water salinity level on winter wheat yield and biomass in this study.

Material and Methods

Experimental field

A field research project was conducted in Ankara/Turkiye (40º 04'N and 32º 36'E) to calibrate and validate the AquaCrop (Ver. 6.1) model for semi-arid climate conditions between 2008 and 2012 (Kale Çelik et al., 2018). According to the results of the project, the prediction accuracy of the model for arid and semi-arid regions was found to be statistically acceptable. In this study, the field data of this project was used as input in the AquaCrop model and the model was run for different irrigation and salinity scenarios.

Experimental field soils are non-saline and mostly silty clay loam and clay loam textures. Average field capacity on the volume basis of soil is 36%, wilting point 21% and bulk density 1.22 gr cm^{-3}. *Bayraktar-2000* wheat variety was cultivated during the experimental studies.

The research area has typical continental climate which summers are dry and hot, winters are rainy and cold. The daily temperature differences are quite high. The lowest temperature measured in the region is -4.7 °C, the highest temperature is 34.3 °C, and the annual average temperature is 9.1 °C. The average annual total precipitation is 398.6 mm, most of which falls during the winter months.

Model description

AquaCrop version 6.1 was used in this study and it was obtained from the official website of FAO via https://www.fao.org/aquacrop/software/aquacropstandardwindowsprogramme/en/ link. AquaCrop is a crop simulation model which describes the interactions between the plant and the soil. From the root zone, the plant extract water and nutrients. Field and irrigation management are considered since it affects the interaction. The described system is linked to the atmosphere through the upper boundary which determines the evaporative demand (ET_o) and supplies CO_2 and energy for crop growth. Water drains from the system to the subsoil and the ground water table through the lower boundary. If the groundwater table is shallow water can move upward to the system by capillary rise (Raes et al., 2012).

Method

In order to simulate grain and biomass yield of wheat under drought and salinity stress with AquaCrop model, five irrigation strategies and five different irrigation water salinities scenarios were created. For irrigation scenarios; Fixed irrigation dose (90 mm) was applied in the stem elongation, heading and milk stages for full irrigation treatment (I_{100}). In deficient irrigation treatments (I_{75} - I_{50} – I_{25}) 75%, 50% and 25% of the full irrigation amount was applied on the same day as I_{100} treatment. No irrigation water applied for rainfed treatment (I_0). Initial soil moisture contents during model run were taken from the project carried out between 2011-2012. For salinity scenarios; five irrigation water salinity levels (S) were used as 0.3, 5, 7.5, 10 and 15 dS m^{-1}.

Input data for AquaCrop (Ver. 6.1) was *i)* climate file; daily rainfall, minimum and maximum air temperature, CO_2 amount and ET_o, *ii)* crop file; emergence, start of flowering time, duration of flowering, canopy senescence, maximum canopy cover and maturity time, *iii)* soil file; saturated hydraulic conductivity, wilting point and field capacity, *iv)* management file; field management practices, irrigation schedule, irrigation water quality, *v)* initial condition; initial soil water content, initial soil salinity. Crop inputs includes conservative and user-specific parameters (Table 1).

Experimental field soil parameters which were given in Table 2 were used as soil inputs in the model. Total applied irrigation water amount according to irrigation treatments were 270 mm, 203 mm, 135 mm and 68 mm for S_{100} - S_{75} - S_{50} – S_{25} respectively.

Result and Discussion

Effect of deficit irrigation treatments on yield and biomass of wheat

The lowest average grain yield and biomass amounts were found at the rainfed treatment, which did not apply irrigation water during the growing period, with a value of 5.13 t ha^{-1} and 12.84 t ha^{-1}. The highest average grain yield and biomass values of 8.43 t ha^{-1} and 17.67 t ha^{-1} were obtained respectively at the control (S_{100}) treatment which was fully irrigated during the stem elongation, heading and milk stages. The grain yields and biomass were fluctuated in the range of 8.00 t ha^{-1} – 6.28 t ha^{-1} and 17.00 t ha^{-1} - 14.53 t ha^{-1} at the deficit irrigation treatments. According to variance analysis there is significant negative relationship ($P<0.05$) between treatments (Figure 1). The application of 25%, 50% and 75% level of deficit irrigation, grain yield reduction was obtained 26%, 13% and 5% respectively. According to the study was conducted by Tari (2016) that deficit water application in the stem elongation and heading stages of winter wheat crucially diminish the yield. However other studies have indicated that the application of 40-60% deficit irrigation causes only in average 15% reduction in wheat yield (Pereira et al. 2002; Memon et al. 2021). There is a positive and significant relationship between grain yield and biomass with the determination coefficient (R^2) 0.98 (Figure 2).

Model simulates water productivity (WP) as a function of evapotranspiration (ET). WP expresses the yield which was produced per cubic meter of water loss by ET at field level. WP=Grain yield / ΣET where GY is the grain yield in kg ha^{-1}, and ET is the crop evapotranspiration (mm). Table 3 showed WP values under deficit irrigation treatments.

The results indicated that, there was not significant differences between water productivity values of full irrigation and 25% and 50% deficit irrigation treatments. However applied irrigation amount was half of the full irrigation treatment at 50% deficit irrigation treatment. The relationship water productivity and grain yield for different water deficit irrigation strategies were presented in Figure 3.

Table 1. Crop inputs for winter wheat

Conservative Crop parameters	*Values*
Temperature - base and upper ˚C (LE)	0 -27
Canopy cover (CC_o; per seedling at 90% emergence) % (M)	6.46
Maximum canopy cover (CC_x) % (C)	90
Canopy growth coefficient (CGC;incease in CC relative to existing CC per GDD*) %(C)	2.7
Canopy decline coefficient (CDC) % (C)	0.35
Growth threshold of leaf (p_{upper}) (D)	0.21
Growth threshold of leaf (p_{lower}) (D)	0.64
Curve shape of leaf growth stress coefficient (D)	5.0
threshold of stomatal conductance (p-upper) (D)	0.64
Curve shape of stomata stress coefficient (D)	2.46
Senescence stress coefficient (D)	0.71
Curve shape of senescence stress coefficient (D)	2.49
Harvest index %(M)	36
Water productivity $g_{(biomass)}$ m^{-2} (D)	15.1
User-Specific Crop Parameters	*Values*
Sowing rate, kg seed ha^{-1} (M)	170
1000 seed mass, g (M)	33.50
Germination rate, % (M)	85
Cover per seeding, cm^2 $plant^{-1}$ (M)	1.5
Plant density, plants m^{-2} (M)	431.3
Sowing date (M)	October 20
Plant emergence date and as a GDD (M)	123 (October 31)
Day of Max canopy cover and as a GDD (M)	1276 (May 12)
Day of maximum root depth and as a GDD (M)	775 (March 16)
Day of start senescence and as a GDD (M)	1768 (June 10)
Day of maturity and as a GDD (M)	2605 (July 20)
Time to reach flowering and as a GDD(M)	1320 (May 15)
Duration of flowering stage and as a GDD (M)	179 (May 25)
Effective root depth (minimum and maximum), m (M)	0.3 and 1.5
Saturated hydraulic conductivity for 0-30 and 30-150 cm soil depth, mm day^{-1} (M)	125-230

LE; local experience, M; measured, C; calibrated (Kale Celik et al. 2018), *GDD; growing degree days, D; default (Steduto et al., 2012)

Table 2. Soil inputs used in AquaCrop model

Soil depth (m)	Soil moisture contents (%)			Soil texture	Soil salinity (dS m^{-1})	Bulk density (g cm^{-3})	K_{sat} (mm day^{-1})
	Field capacity	Wilting point	Saturation				
0.0 – 0.30	33.78	16.67	44.60	SiCL	1.02	1.26	230
0.30 – 0.60	35.56	22.01	46.52	CL	0.72	1.27	175
0.60 – 0.90	36.24	21.94	47.19	CL	0.68	1.20	125
0.90 – 1.20	37.12	22.71	48.85	CL	0.65	1.21	125

SiCL; Silty Clay loam, CL; Clay Loam, K_{sat}; Saturated hydraulic conductivity

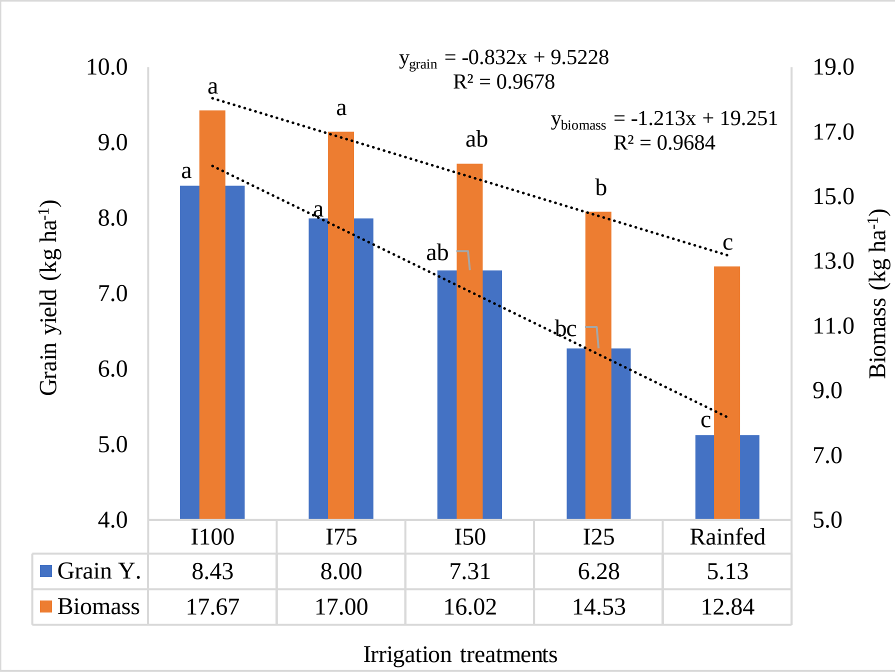

Figure 1. Estimated grain yield and biomass for irrigation treatments

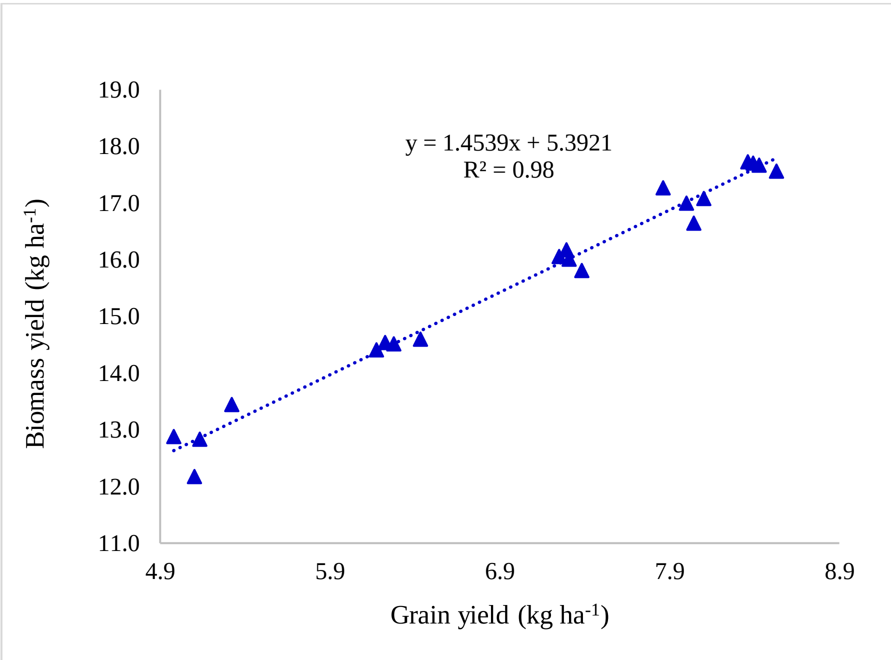

Figure 2. Grain yield and biomass relationship

Table 3. Water productivity of irrigation treatments

Treatment	Irrigation amount (mm)	Yield (kg ha^{-1})	ET (mm)	WP (kg m^{-3})
I_{100}	270	843	659	1.28
I_{75}	204	800	630	1.27
I_{50}	135	731	585	1.25
I_{25}	66	628	523	1.20

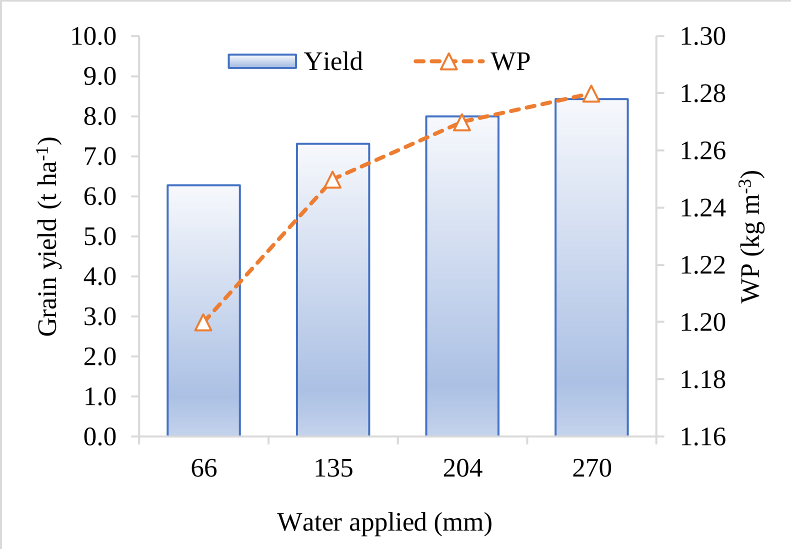

Figure 3. Water productivity and grain yield relations for deficit irrigation strategies

It is possible to irrigate much more areas saving water with deficit irrigation. As an example; the yields were calculated that the areas will be irrigated with saved water for every 2700 m^3 of available irrigation water (Table 4). According to calculation results; since larger areas are irrigated when 25, 50 and 75 percent irrigation savings are made, the yields obtained from these areas were 2.17, 6.17 and 17.2 tons more than the yields obtained from areas irrigated with full irrigation.

Table 4. Additional irrigated areas and grain yield with saved water

Treatments	100% full irrigation	25% saved water	50% saved water	75% saved water
Irrigated area (ha)	1.00	1.32 (=2700/2040)	2.00 (=2700/1350)	4.09 (=2700/660)
Grain yield (t)	8.43	10.56 (=8.00 x 1.32)	14.62 (=7.31 x 2.00)	25.68 (=6.28 x 4.09)

A research study was carried out by Mustafa et al. (2017) to determine the effects of deficit irrigation applications on wheat yield and water productivity. According to results of this study the highest yields were obtained at yield formation and ripening stages and water saved about 35% compared to full irrigation application.

Effect of irrigation water salinity on grain and biomass yield of wheat

Obtained the grain and biomass yields under different irrigation water salinity levels and statistical classifications on related treatments were given in Figure 4. The increase in irrigation water salinity caused a significant decrease in grain yield and biomass value. It was compared to the yield of T_1 (control) treatment, 3% lower yield was obtained at the T_2 treatment. Yield loss of T_3 and T_4 salinity treatments were found to be 19% and 43% respectively. The crop yield reduction was dramatically (86%) at 15 dS m^{-1} salinity level of irrigation water. The similar results were also presented regarding the decrease in yield as a result of the increase in the salinity of the applied irrigation water (Tekin et al. 2014; Mostafazadeh-Fard et al. 2009; Gowing et al. 2009; Kumar, 2020; and Hammami et al. 2020).

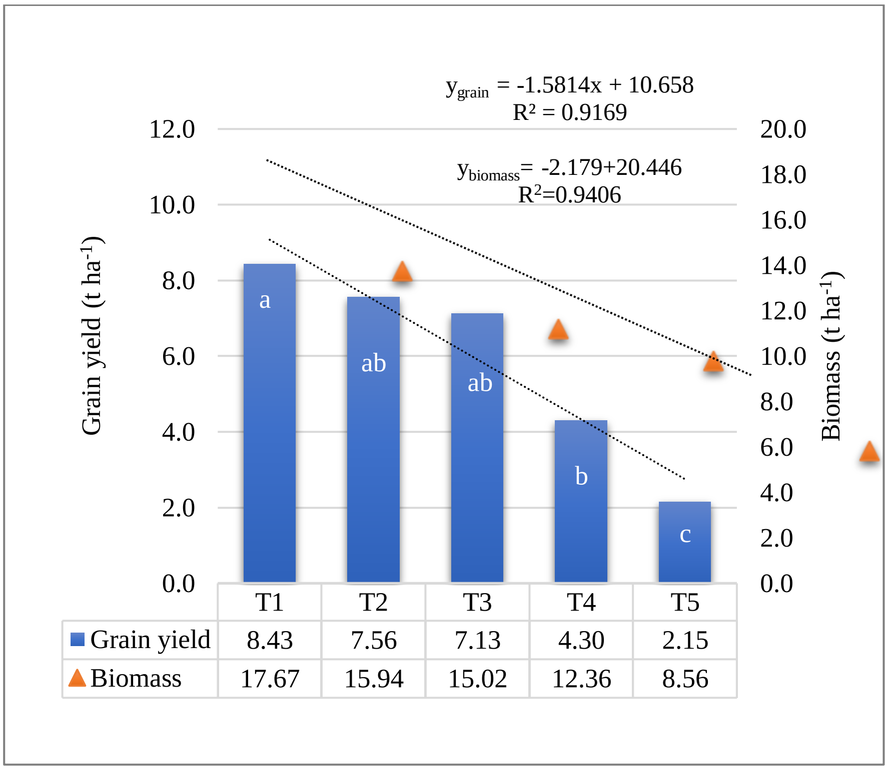

Figure 4. The grain yields and biomass values for different irrigation water

Canopy cover (CC) of wheat

Hammani et al. (2020) was reported that the maximum 85% and minimum 30% CC were obtained in the sub-humid areas. The canopy cover values of all treatments showed the same trend until early spring.

The highest CC value was obtained as 82.5% on S_{100} treatment. Figure 5 shows that water deficit stress effects on canopy cover of winter wheat.

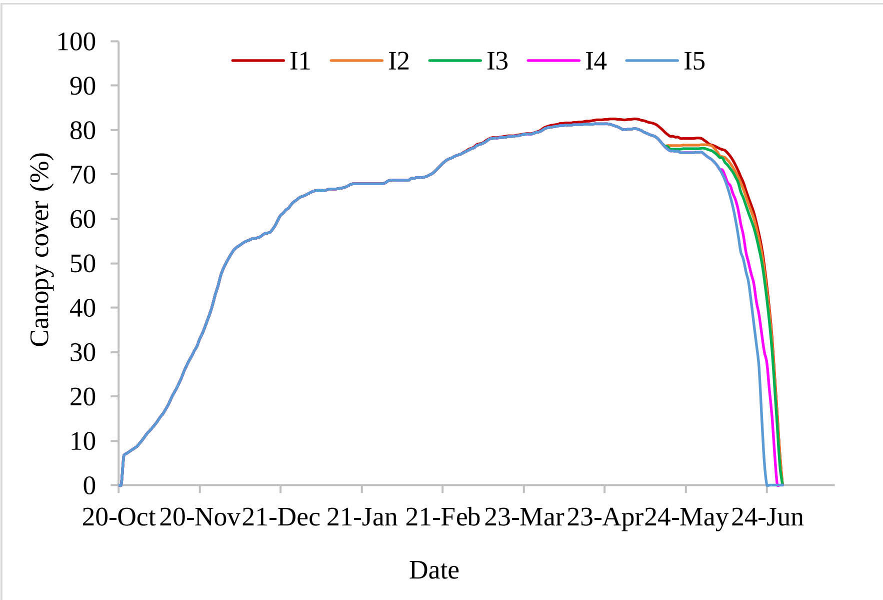

Figure 5. Canopy cover of wheat under different irrigation water amount

The simulation results showed that the application of saline irrigation water in semi-arid conditions such as the Central Anatolia region caused a decrease in CC of 18.8% (Figure 6). Similar result was obtained by Hammani et al. (2020) such as the salinity induces a 10% reduction in the CC in the sub-humid environment and 5–30% in the dry climate condition.

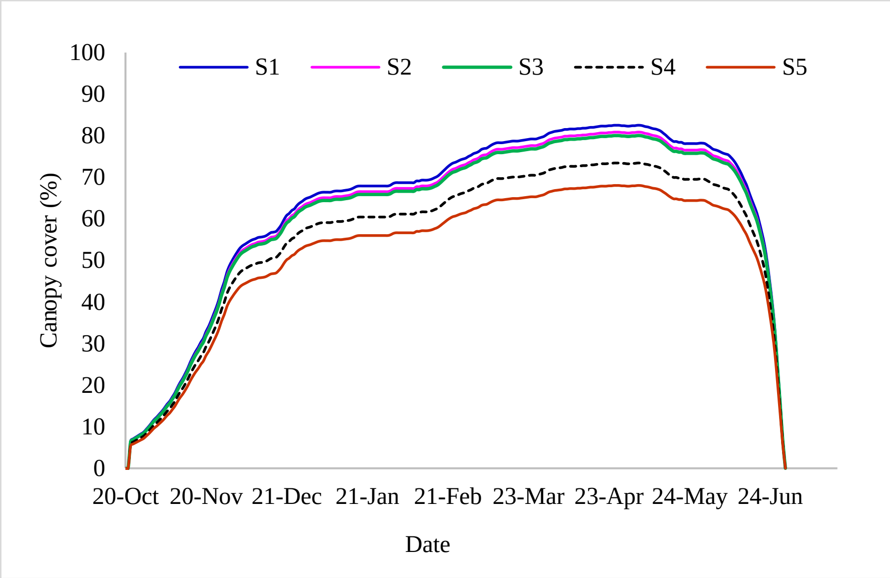

Figure 6. Canopy cover of wheat under different irrigation water salinity

Drought and salinity interactions

When all treatments were evaluated together, it was observed that the yield increased proportionally as the amount of irrigation water applied increased (Table 5). On the other hand, the lowest yield was obtained at all salinity levels in I_{25} treatment, where 75% water saved. When both the decrease in the amount of irrigation water and the increase in the salinity level come together, decline in yield were significant.

Table 5. Grain yield amount (t ha^{-1}) under drought and salinity stress

Treatments	**S_1**	**S_2**	**S_3**	**S_4**	**S_5**
I_{100}	8.43	7.56	7.13	4.30	2.15
I_{75}	8.00	6.65	5.67	3.89	1.91
I_{50}	7.31	5.93	4.62	3.30	1.85
I_{25}	6.28	4.91	3.62	2.66	1.19

Interaction between irrigation water salinity and irrigation water amount on wheat grain yield were found to be statistically significant at the level of 1%. The statistical evaluations were given in Table 6.

Table 6. Variance analysis table of grain yield

Sources	SD	SS	AS	F values	F Table	
					0.05	0.01
Salinity	4	204497904	215909047	155.40**	2.42	3.32
Irrigation	4	130111354	130111354	93.65**	1.56	2.40
Salinity * Irrigation	16	14.80	0.30	23.68**	1.32	2.34
Error	65					
Total	73					

**; Significant level of 0.01, SD; Standard deviation, SS; Sum of square, AS; Average of square

The change in the amount of irrigation water also changed the effects of irrigation water salinity on crop yield. The results are in agreement with previous studies which was conducted by Juis et al. (2003) and Mostafazadeh-Fard et al. 2009. Also, Gowing et al. (2009), reported that there were small but statistically significant effects of the interaction between the salinities of the irrigation and water use of wheat.

Conclusion

The deficit irrigation with water reduction of more than 75% of full irrigation was applied at growth stages of wheat, revealed the significant reduction in grain yield, biomass, water productivity and canopy cover as compared with full irrigation practice. Irrigation water salinity is one of the most important factors in limiting crop growth and reducing crop yield in arid and semiarid regions. In this study results showed that highest irrigation water salinity caused highest crop yield reduction. Also, increasing irrigation water depth in saline treatments resulted in increased grain and biomass yield. For sustainable water management in agriculture area, using simulation model such as AquaCrop is useful to estimate effect of applied water depth and quality of irrigation water on crop yield.

Compliance with Ethical Standards

Conflict of interest

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Author contribution

The author read and approved the final manuscript. The author verifies that the Text, Figures, and Tables are original and that they have not been published before.

Ethical approval

Ethics committee approval is not required.

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Data availability

Not applicable.

Consent for publication

Not applicable.

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