ORIGINAL ARTICLE

The effects of drought and salinity on KS and RAW managerial coefficients in the efficient water management in maize farms

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Abstract

This study aimed to investigate the simultaneous effects of drought and salinity on irrigation management coefficients in maize farms. A three-year field research was conducted in the form of a 3×3 factorial experiment with a randomized complete block design and three replications from 2020 to 2022 in a maize farm, in Aliabad Fashafoye, Qom province, Iran. The applied treatments included three levels of salinity ($S_0 = 1.8$, $S_1 = 5.2$, and $S_2 = 8.6$ dS/m) and three levels of irrigation ($W_0 = 100\%$, $W_1 = 75\%$, and $W_2 = 50\%$ of field capacity). Evapotranspiration stress coefficient (K_S) due to $W_0 S_1$ and $W_0 S_2$ treatments was (0.975 and 0.934), (0.974 and 0.932), and (0.962 and 0.935) in 2020, 2021, and 2022, respectively. According to the results, K_S decreased by increasing the salinity level of irrigation water, so a 1-unit increase in salinity level above the tolerance threshold of the crop to salinity decreased K_S by 0.78 and 1.76% for S_1 and S_2, respectively. Moreover, each percent of volumetric moisture decrease from field capacity decreased K_S by 5.9 and 13.3% in W_1 and W_2, respectively. Also, with the increase in the intensity of the stresses, the readily available water (RAW) of treatments decreased. The sole application of salinity stress decreased the decreasing slope of RAW by 3.2%, while the application of both stresses resulted in the decreasing slopes of 4.9, 5.7, and 7.8% at the salinity levels of S_0, S_1, and S_2, respectively, compared to the control. The findings of this study show that the accurate estimation of crop evapotranspiration and RAW can help to improve the irrigation schedule, and the amount of irrigation water used is less than in non-stress conditions due to the reduction of total evapotranspiration and less water uptake in environmental stresses in maize farms.

Keywords Evapotranspiration stress coefficient · Fodder maize · Readily available water · Abiotic stresses

Introduction

Drought and salinity are among the most critical abiotic environmental stresses in most semi-arid regions worldwide. The access of the agricultural sector to high-quality water resources is becoming more and more limited every moment due to the high population growth and the development of urban and industrial areas. Therefore, the use of low-quality water, such as saline and brackish water–water with salinity levels between fresh water and seawater (between 1000 and 10,000 ppm)-, has become essential to overcome the problem of water shortage in many regions.

The response of plants to stresses is complex and is influenced by factors such as plant variety and physiology (Moles et al. 2016). The reduction of water potential in the soil due to salinity and water stresses reduces the plant's ability to uptake water, resulting in a decrease in the growth rate of cells in the tissue and vascular systems of plants. This affects the intensity of photosynthesis, the construction of organic matter in the plant, and, finally, the yield (Munns 2011). In such challenging conditions, the stomata are closed to reduce transpiration, and the gas exchanges between the plant and the environment are minimized (Umar and Siddiqui 2018). Xin et al. (2016) investigated the effects of irrigation water deficiency (80 and 60% of field capacity) and the electrical conductivity of irrigation water (1.7, 4, 6, and 8 dS/m) on sunflower plants. They showed that the stresses undesirably

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increased the resistance of stomata, reduced leaf growth, and reduced yield.

In another research on cherry tomatoes, two levels of irrigation water salinity (4 and 7 dS/m) and three levels of water stress (40, 50, and 65% of field capacity) had significant effects on yield, total evapotranspiration, and water use efficiency (WUE). The salinity stress of 7 dS/m caused a 27% decrease in yield and a 19.2% decrease in WUE compared to the control (Abdoli et al. 2018). When the amount of soil water decreases, if it is not compensated, the concentration of salt in the rhizosphere region increases, resulting in increased osmotic pressure and limited plant growth.

Investigating the effects of abiotic stresses in fodder maize farms is important since fodder maize is an essential source of supplying human food and animal fodder. The findings of the two-year study of fodder maize cultivars in the Bajgah area, Fars province, Iran, showed that by reducing the amount of irrigation water by 25% (I_2) and 50% (I_3) compared to the control (I_1), the evapotranspiration, transpiration, and evaporation in treatments I_2 and I_3 decreased significantly by (19 and 42%), (25 and 43%), and (3 and 39%), respectively. Also, with increasing salinity from 0.6 (S_1 as the control) to 2 (S_2) and 4 dS/m (S_3), no significant differences were observed in the evapotranspiration values. However, transpiration decreased by 5 and 12%, respectively, in S_2 and S_3 compared to S_1. Also, evaporation increased by 16 and 33% compared to the control (S_1), showing the effects of salinity on the reduction of growth, the size of plant canopy and roots, and the consequent decrease of evapotranspiration and transpiration. In other words, the reduction in the size of the canopy results in higher evaporation from the bare soil surface exposed to sunlight (Azizian and Sepaskhah 2014).

In another study on maize, water stress with a severity of 50% of field capacity in the vegetative growth stage caused irreparable damage to crop yield. Besides, the reproductive growth stage (flowering) and early seed filling were the most sensitive stages to water stress. In addition to the yield, applying a fixed amount of water stress in the four-leaf, twelve-leaf, flowering, and seed pulping stages had various effects on the amount of plant evapotranspiration. The lowest amount of evapotranspiration was related to the flowering stage because of the greater sensitivity of maize toward drought at this stage (Saeidi et al. 2022; Saeidi and Sotoudehnia 2021; Hoffman et al. 1983). Lacerda et al. (2016) showed that with the increase of salinity in the maize rhizosphere region, soil water potential decreased and root water uptake decreased. Therefore, with the decrease in the quality of irrigation water (increasing the electrical conductivity from 0.5 to 7.5 dS/m), the amount of evapotranspiration and crop yield decreased by 31 and 60%, respectively. Another research showed that eliminating an irrigation stage during vegetative growth, flowering, and seeding of maize led to the yield of 68.0, 62.2, and 66.5 tons/ha, respectively, indicating

the maximum effect of water stress on the reduction of crop yield in the flowering stage (Mohammadi Behmadi and Armin, 2016). In another two-year study, increasing irrigation water salinity and soil nitrogen deficiency increased the stomatal resistance of maize, which reduced transpiration (Saeidi et al. 2021).

Estimating the actual amount of evapotranspiration in crops is of great importance in determining their water requirements (Ippolito et al. 2023). Usually, climatic factors, plant type (genotype), cultivation managerial conditions, soil quality, and changes in environmental conditions during the growing season are effective on the amount of crop evapotranspiration and differentiate its amount from the area's potential evapotranspiration. If the above conditions are not favorable for evapotranspiration, the crop will face stress, and the yield of the product will decrease.

Allen et al. (1998) reported that the resistance of leaf stomata varies based on plant species and farm management. The stomatal resistance is influenced by the climate and irrigation, and as the plant's access to the soil water is limited, the stomata are closed, stomatal resistance increases, and transpiration decreases. Therefore, the proper management of water consumption in the stressful conditions of maize cultivation is essential. The evapotranspiration stress coefficient (K_S) can be used to calculate the actual amount of crop evapotranspiration to prevent unnecessary water consumption. K_S is equal to 1 in ideal and non-stress conditions and decreases in stress conditions. Rudnick et al. (2017) studied the effects of three regimes of full irrigation, limited (75% of full irrigation), and rainfed with five levels of nitrogen fertilization (0, 84, 140, 196, and 252 kg/ha) on maize. They showed a significant decrease in K_S in rainfed conditions and limited irrigation compared to full irrigation and less nitrogen consumption compared to its full consumption. In addition to K_S, when the amount of water flowing toward the plant roots is not enough to provide the required water for transpiration, the soil moisture at that point is known as the limit of readily available water (RAW). At this point, the plant reduces its transpiration by increasing stomatal resistance (Allen et al. 1998).

RAW is a moisture level between field capacity (FC) and wilting point (WP), which changes during the plant growth period. Based on research in Colorado, America, the amount of RAW for maize in the stages of four-leaf, sixteen-leaf growth, seed pulping, and ripening was 50, 70–60, 50, and 60–70% (Al-Kaisi and Broner 2009). In stressful conditions, the amount of RAW decreased, the effect of which can be observed by increasing the stomatal resistance of the leaves using a porometer (Saeidi et al. 2021). In the report of Allen et al. (1998), the amount of RAW was considered constant, and salinity only affected the K_S.

It is assumed that the quality and quantity of irrigation water can have a direct and vital effect on the yield of fodder

maize, so changing the quality of irrigation water, including mineral content, salinity level, pH, TDS, etc., possibly leads to significant changes in the growth and development of stems and leaves and the production of fodder and seeds. This assumption may be because irrigation with a suitable quality facilitates factors such as the optimal absorption of nutrients by the plant and prevents the negative effects of high water salinities. This also shows the importance of irrigation quality in improving the yield and quality of fodder for animal nutrition.

This study aimed to investigate the values of RAW and K_S of maize under drought and salinity stress conditions. By knowing the range of fluctuations of these variables, it is possible to achieve proper irrigation management and increase the WUE. In this situation, it will be possible to determine the crop water requirements only through total evapotranspiration and avoid excessive water consumption. One-year field studies cannot reliably evaluate the long-term effects of drought and salinity stresses because the results are highly dependent on soil conditions at the beginning of the growing season (Feng et al. 2003). Therefore, cultivation was carried out for three consecutive crop years in the present study.

Material and methods

Study area, treatments, and research methodology

Field studies were conducted in the form of a 3×3 factorial experiment with a randomized complete block design and three replications in three consecutive crop years from 2020 to 2022 in a maize farm with an area of 1500 m^2 in Aliabad Fashafoye Qom province, Iran (51°40′ E, 35°17″ N). The altitude of the area is 1191 m above sea level, and its climate is arid and semi-arid, with negligible precipitation and relatively hot summers and cold winters. The area is exposed to unseasonal winds due to its flatness. The maximum temperature in summer is 42 °C, while the minimum temperature is − 4 °C in winter (Table 1). The closest synoptic stations to the region are Varamin and Imam Khomeini Airport stations. The conventional cultivation pattern in the region is autumn wheat and barley, alfalfa, and maize.

The fodder maize (Sc.704) was planted in stacks and 3×3-m plots at a distance of 3 m from each other at the beginning of July every year. The seeds had a minimum viability of 95% and a purity of 98% and were planted on 25 cm rows and 5 cm deep using pneumatic planting equipment. The distance between the stacks (rows) was 60 cm. The treatments included three levels of irrigation (to induce water stress) and three levels of electrical conductivity, so a total of 27 plots were considered in this study (Fig. 1).

Tillage operations included plowing to a depth of about 30 cm and disking to crush the clods. The soil surface was leveled before planting to make the surface uniform. Irrigation levels included W_0, W_1, and W_2 by providing 100, 75, and 50% of crop water requirements, respectively, which were controlled by a TDR-150 device (Spectrum America) during the experiment. The salinity levels included S_0, S_1, and S_2, defined as irrigation by water with electrical conductivity of 1.8, 5.2, and 8.6 dS/m, respectively, which was obtained through the mixing of well saline water (Wilcox class C_5S_4—Table 2) with fresh (drinking) water. The salinity levels selected were based on the experimental equation of Maas and Hoffman according to the relative performance of the product (Maas 1990). In order to examine the soil, three samples were taken from the depths of 20, 40, and 60 cm, the physicochemical properties of which are described in Table 3.

Chemical fertilization was conducted using N-urea (350 kg/ha), triple superphosphate (180 kg/ha), and potassium sulfate (200 kg/ha) based on soil fertility tests. The triple superphosphate and potassium sulfate fertilizers were spread in one step before planting. Urea was added to the rows in three stages, one-third at the same time as planting, and the rest in two stages, equally during thinning and the stage of the emergence of crown flowers.

According to the purpose of harvesting maize fodder, the planting and harvesting dates in the first to third crop years were (7/6/2020 and 10/24/2020), (7/9/2021 and 10/29/2021), and (7/5/2022 and 11/2/2022), respectively. Therefore, the growth period was considered between 120 and 130 days. The periods related to the time of planting to harvesting were adapted according to the FAO report no. 56, which divides the growth period of the plant into four stages: initial, development, middle, and final.

Table 1 Average meteorological parameters during the period under cultivation in the study area

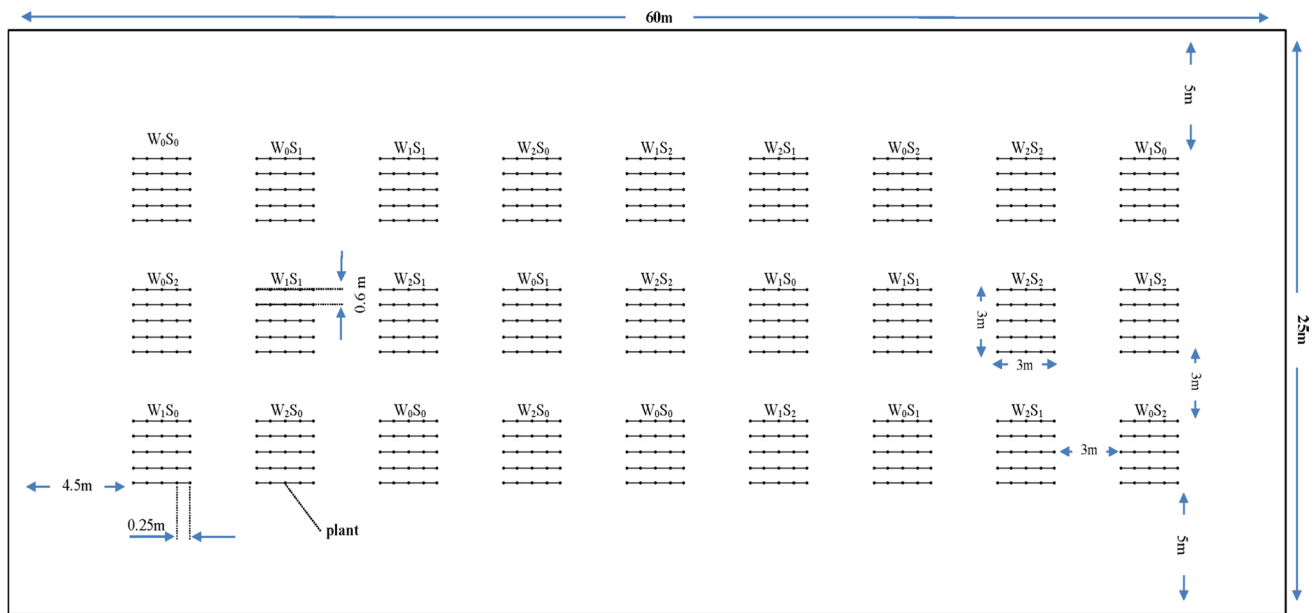| Month	Temperature (°C)			Relative humidity (%)			Maximum wind (m/s)	Precipitation (mm)
	Min	Max	Ave	Min	Max	Ave		
July	18.4	44.0	32.6	12.8	42.2	27.3	14.1	0.0
August	17.1	43.1	31.8	12.1	47.5	30.7	13.2	0.0
September	13.6	40.3	27.8	16.2	59.6	37.1	13.5	0.0
October	7.5	34.8	21.0	17.2	64.9	40.1	13.6	0.0
November	1.2	28.3	13.4	45.7	94.1	70.2	11.3	0.0

Fig. 1 Schematics of plots in the first year of planting

Table 2 The chemical properties of salt water samples

EC dS/m	pH	CO_3^{-2} meq/l	HCO_3^{-1} meq/l	Cl^- meq/l	SO_4^{-2} meq/l	Anions	Ca^{+2} meq/l	Mg^{+2} meq/l	Na^+ /l	Cations	SSP %	SAR	TDS mg/l	Class
10.42	7.06	0	5.73	61.75	36.6	104.15	29.57	13.68	60.86	104.11	59.97	13.09	6425.6	C5S4

Table 3 Some physicochemical properties of the soil at the experiment site

Depth (cm)	EC (dS/m)	pH	TNV (%)	OC (%)	Total N (mg/kg)	P (mean) (mg/kg	K (mean) (mg/kg)	FC (%)	PWP (%)	Texture
0–20	8.67	7.86	14.18	0.61	627.8	5.65	197.30	29.8	14.7	Loam
20–40	7.96	7.88	12.35	0.58	582.0	5.38	181.37	28.5	15.1	Loam
40–60	8.42	7.94	13.11	0.53	561.2	4.93	168.02	35.6	18.4	Clay loam

For all treatments, during the initial period of growth (from the time of planting to the stage of 5 to 8 leaves), 100% of the crop water requirement was provided in each plot. Water and salinity stresses were applied after the initial stage. Salinity treatments were carried out based on mixing the saline water and freshwater using Eq. (1)

$$EC_f = \frac{EC_w \times V_w + EC_s \times V_s}{V_w + V_s} \tag{1}$$

$$V_t = V_w + V_s \tag{2}$$

where EC_f is the final electrical conductivity (dS/m), EC_s is the electrical conductivity of saline water (dS/m), EC_w is the electrical conductivity of fresh water (dS/m), V_s is the volume of saline water (l), V_w is the volume of freshwater (l), and V_t is the total volume of water (l) with the desired electrical conductivity for irrigation. After determining the volume of saline water and fresh water to be mixed, they were provided in PVC plastic tanks, and the electrical conductivity of the irrigation water produced was controlled using a portable EC meter.

The research data for each study year included periodic evapotranspiration values (for four growth stages: initial, development, middle, and final) and crop yield (tons/ha) of each treatment. The analysis of variance (ANOVA) and means comparison were performed by Tukey's HSD method at a 95% confidence level using the SAS software ver. 5.4.

Measurement of crop evapotranspiration (ET$_c$)

The soil moisture content of the root zone was measured daily with a time domain reflectometry (TDR) device at five depths of 7.5, 12, 20, 40, and 60 cm according to the growth and development of plants by a pair of stainless steel probes. To eliminate the undesirable effects, soil moisture data were collected around the center of the plots three times, the arithmetic mean of which was recorded during the experiments. At first, before planting the seeds, the TDR device was calibrated by the soil of the cultivation place. To do this, data were recorded by the device for each sample of the actual soil moisture from saturated to dry, and then the samples were determined in the laboratory, and finally, a linear fit between the values read by the device (X-axis) and the real moisture value (Y-axis) with high correlation ($R^2 = 0.96$) was obtained to convert the device data to real volumetric soil moisture data. Since there was no atmospheric precipitation in the area during the growing seasons of the plants (summers), and assuming that the plots were small (9 m^2) and there were no seams and cracks in the deep soil or preferential flows in it, it was ensured that the process of reducing soil moisture in the days after irrigation was only due to the evapotranspiration. Therefore, it was possible to estimate the amount of crop evapotranspiration using Eq. (3)

$$\sum_{i=1}^{n} \left[(\theta_{FC} - \theta_i)/100 \right] \times D_i \times C_{ws} = ET = d_{H_2O} \qquad (3)$$

where $d_{(H2O)}$ is the depth of irrigation water (cm), θ_{FC} is the volumetric moisture content of the FC of the soil (%), θ_i is the volumetric moisture content of the ith soil layer (%), D_i is the depth of the ith soil layer (cm), and C_{ws} is the water stress coefficient of the plot. The value of C_{ws} is 1, 0.75, or 0.5 according to the water stress levels.

Timing and volume of irrigation water

The irrigation was applied according to the daily measurement of soil moisture to achieve water stress levels. No water stress was applied to W_0 plants, while W_1 and W_2 plants were irrigated each time the soil moisture decreased by 25 and 50% of total available water (TAW), respectively. As demonstrated before, the stresses were applied in the last three stages of the plant growth period. The hypothesis proposed for TAW is a level of moisture between the FC and soil WP, in which the crop enters the stress phase with the consumption of water and the reduction of soil moisture. Due to the simultaneous application of water stress and salinity, the number of irrigation times was not the same in the treatments, and the volume of irrigation water of the plots was determined using Eq. (4)

$$V_{H_2O} = d_{H_2O} \times A \qquad (4)$$

where $V_{(H2O)}$ is the volume of water required for the treatments in different plots (m^3), $d_{(H2O)}$ is the required depth of irrigation water (m), and A is the area of the plot (m^2).

Flood irrigation with a slow flow was used to irrigate the plots in the form of stack irrigation. Irrigation water was distributed uniformly on the surface of the plots. Due to the smallness of the plots (9 m^2), their distance, being enclosed by stacks, and the lack of runoff, the irrigation application efficiency was considered 100%. However, to increase the reliability of moisture transfer between the plots, the distances between them (sidewalks) were heavily irrigated and transparent plastic was immediately stretched over them in the first days of planting and simultaneously with the irrigation of the plots. This not only prevented the sunlight from shining on the soil of the sidewalks but also prevented the suction and transfer of moisture between the plots. The average depth of maize root development was considered to be 60 cm. This was verified after the harvest and digging of a pit in the soil of the plots, where root remains were not observed at a depth of more than 60 cm.

Calculating evapotranspiration stress coefficient (KS) and readily available water (RAW)

Since the tolerance of water stress by plants depends on the total water potential and not the soil moisture content, and the soil texture, directly and indirectly, affects the matric (Ψ_m) and osmotic (Ψ_s) potential of the soil, the contribution of salinity of the RAW and the plant depletion coefficient ($P \leq 1$), which is a function of the atmospheric evaporation intensity, should be taken into account. Allen et al. (1998) have referred to K_S as a dimensionless coefficient of reducing the evapotranspiration of available plant water, which is the relative evapotranspiration (Eq. 5)

$$\frac{ET_s}{ET_c} = K_s \qquad (5)$$

where ET_s and ET_c are the crop evapotranspiration under stressed and non-stressed conditions (mm), respectively. K_S has always a value between 0 and 1, and its value decreases during severe stress conditions.

When the soil is subjected to heavy irrigation (i.e., irrigation that allows the soil to be soaked to a depth of about 7–10 cm to the point of saturation), after 24–48 h depending on the type of soil texture and gravity water infiltration, the soil suction will be in the FC status where a suction of -0.33 bar is achieved. In this situation, the crop can absorb water without any water stress. Over time and crop evapotranspiration, another moisture range is formed in the soil where the suction is around 15 bar and the crop is no longer

able to absorb water from the soil, which is called WP. FC and WP are important soil moisture points, and their difference, regardless of the type of soil texture, is called TAW. The values of these two moisture points are determined by the laboratory analysis. Theoretically, the plant should be able to use water up to WP, but the water uptake before reaching this point is greatly reduced. Depending on the type of soil texture, total porosity, distribution of soil porosity, and the stress conditions created in the water-soil–plant system, most plants can absorb water up to about 2/3 of TAW without any water stress. A fraction of TAW that plants are able to absorb water without causing water stress is known as RAW, which is calculated by dividing the difference of water drained to the FC by the amount of TAW in the root development zone (Eq. 6)

$$RAW_T = \frac{1}{100} \sum_{i=1}^{n} \left(\frac{\theta_{FC_i} - \theta_{TDR_i}}{TAW_i} \right) \Delta z_i \qquad (6)$$

where θ_{FC}, θ_{TDR}, Δz, i, and $\sum$ are volumetric moisture (%) of FC, TDR reading, the thickness of soil layer (mm), the number of studied layers, and the summation operator to include the total depth of the plant root development zone in the entire growing season, respectively. RAW_T is the total amount of readily available water for each treatment (mm). If the soil moisture is higher than the RAW value in non-stressed conditions, the irrigation water salinity that increases the osmotic pressure can affect the usable amount of plant water by reducing the soil water potential.

Apart from the environmental abiotic stresses applied to the plant, finding the moisture point for irrigation is essential in the effective management of irrigation. This moisture point is known as the maximum allowable depletion (MAD) (Farahbakhsh et al. 2023), P coefficient (Allen et al. 1998), and root water uptake point (Babazadeh et al. 2017). In the current research, the variation of this moisture point due to environmental abiotic stresses has been discussed. The effect of stresses on K_S and RAW in two conditions of sole salinity stress (without applying the water stress) and the simultaneous application of water stress and salinity are investigated on soil water depletion from the root zone. The analysis is performed in a Cartesian coordinate system along with the decreasing slope percentage of the treatments, up to a crop yield reduction of 35% compared to the potential yield of the area.

Results and discussion

Effects on the biological performance of maize

According to the purpose of harvesting maize fodder, maize bushes were cut from the lowest part of their stems.

The number of plants placed in each random throw of a 1.5×1.5-m wooden frame with an area of 25.2 m^2 was used as the criterion for measuring the performance of the plots. The collected plant samples were weighed with a digital weighing scale with an accuracy of ± 10 g, and the crop yield was calculated into tons/ha according to the surface of the wooden frame used and plant weight.

The results of the three-crop year research showed that the simultaneous water stress and salinity caused a decrease in crop yield compared to the control (W_0S_0). The average yield in the most severe stress condition (W_2S_2) in 2020, 2021, and 2022 has decreased by 34, 34.7, and 32.5%, respectively, compared to the control of the same year. Table 2 shows the range of changes in yield during three crop years and the average yield each year for different treatments. Figure 2 depicts the effects of various levels of water stress (W_0, W_1, and W_2) and salinity (S_0, S_1, and S_2) on the relative yield of maize during the crop years under study. The results showed that, on average, with the application of salinity stress, the relative yield value in the treatments W_0, W_1, and W_2 changed in the ranges of 88.88–100, 80.1–82.6, and 66.3–76.2%, respectively (Table 4).

The three-year average results showed that in the treatment W_0, with the increase in salinity from S_0 to S_1 and S_2, the biological performance decreased by 6.2 and 11.2%, respectively. In the same way, in treatment W_1, it decreases by 1.4 and 3%, and in treatment W_2, a 6.3 and 13% reduction in yield occurs. Also, in treatment S_0, with the increase of water stress from W_0 to W_1 and W_2, a decrease in yield by 17.4 and 23.8%, respectively, was observed. In treatment S_1, 13.3 and 23.9%, and in S_2, 9.8 and 25.4% reduction in yield was achieved compared to the maximum performance, which belonged to treatment W_0S_0. As a result, the effect of water stress on yield reduction was greater than the effect of salinity. Therefore, the quantitative effects of water stress and salinity on yield are not the same. This is consistent with the results of recent studies on the maize Sc.704 cultivar (Saeidi 2021).

The results also showed an increase in the slope of the decrease in the relative crop yield with the increase in water stress and salinity. In treatments W_0, W_1, and W_2, respectively, an average decrease of 3, 5.3, and 8.9% of the crop yield was observed per 1-unit increase in the EC from the tolerance threshold level of maize in the region.

The results of the ANOVA of the biological yield and total evapotranspiration of maize are brought in Table 3. The ANOVA of the three-year study of the water stress, salinity, as well as their interaction (W_S), showed that hypothesis H_0 on the equal average of the performance in three levels of water stress (W_0, W_1, and W_2) is rejected ($P \leq 0.01$). So, there was a significant difference between the average of the three groups of water stress, and as a result, water stress had significant effects on crop yield. Similar results
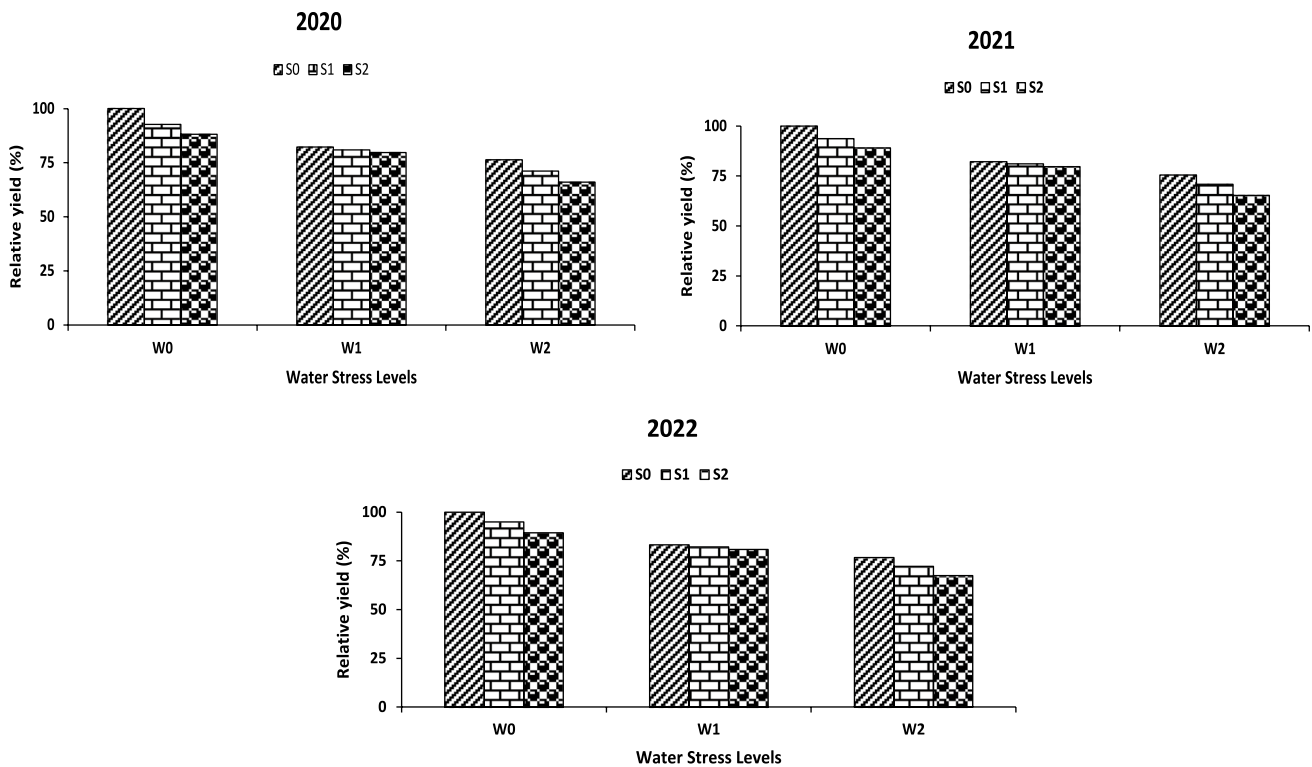
2020

☑ S0 ☰ S1 ■ S2

2021

☑ S0 ☐ S1 ☑ S2

2022

☑ S0 ☐ S1 ☐ S2

Fig. 2 The effects of simultaneous water stress and salinity on the average yield in the study crop years

Treatments	Range of yield changes during three consecutive crop years	Yield$_{ave.}$ (tons/ha)			Average yield during three consecutive crop years
		2020	2021	2022	
W_0S_0	49.83–50.71	50.39[a]	50.36[a]	50.16[a]	50.30
W_0S_1	46.00–48.65	46.71[b]	47.23[b]	47.68[b]	47.21
W_0S_2	43.83–45.62	44.36[c]	44.84[c]	44.84[c]	44.68
W_1S_0	41.31–41.86	41.41[d]	41.39[d]	41.80[d]	41.54
W_1S_1	40.65–41.38	40.75[d]	40.85[d]	41.24[d]	40.94
W_1S_2	39.90–40.75	40.16[d]	40.17[d]	40.60[d]	40.31
W_2S_0	37.47–38.73	38.44[e]	38.06[e]	38.51[e]	38.34
W_2S_1	35.19–36.63	35.81[f]	35.71[f]	36.26[f]	35.93
W_2S_2	32.84–34.05	33.23[g]	32.91[g]	33.87[g]	33.34

Table 4 The annual yield in the study treatments during three consecutive crop years

were observed for the three groups of salinity stress (S_0, S_1, and S_2), and therefore, salinity had a significant effect on crop yield. Also, the interaction effects of water stress and salinity were significant ($P \leq 0.01$) on the crop yield of the treatments. This means that individual water stress and salinity factors alone and their interaction have significant effects on crop yield. These results are consistent with Reis et al. (2015) for Stevia (a natural sweetener source 150 times sweeter than sucrose) who reported lower yields in higher salinity levels. Table 3 also shows the effects of the

treatments on total evapotranspiration, which were similar to the biological yield in the study crop years.

Regarding the similar results obtained for the treatments W_1S_0, W_1S_1, and W_1S_2, it should be noted that the comparisons were made using the Tukey's test (HSD) with $\alpha = 0.05$, and the results indicated that there was no significant difference between these three treatments, where a common letter (d) is used for them (Table 5). Based on this, the nine treatment groups under research were divided into seven categories from a to g.

Table 5 The analysis of variance of the biological yield and total evapotranspiration of maize

Sources of variation	Degrees of freedom	Mean of squares					
		Biological yield			Total evapotranspiration		
		2020	2021	2022	2020	2021	2022
Block	2	0.473*	0.287 ns	0.691*	19.705**	27.721**	77.343**
W_S	2	290.206**	321.11**	291.154**	216,001.896**	216,923.303**	213,188.505**
S_S	2	39.112**	35.385**	31.182**	3792.977**	3885.173**	4011.223**
$S_S \times W_S$	4	5.013**	4.353**	3.679**	41.222**	44.603**	91.098**
Error	16	0.117	0.281	0.156	0.249	0.16	0.116
CV	_	0.829	1.283	0.947	0.097	0.077	0.661

ns, ** and * indicate non-significant, significant at $P \leq 0.01$ and $P \leq 0.05$, respectively. W_S and S_S are water stress and salinity, respectively

The increase in water stress and salinity from W_0S_0 to W_2S_2 caused an increase in the osmotic pressure of the soil solution and a decrease in the water potential in the soil, resulting in a decrease in water absorption and transpiration and a decrease in crop yield. Also, the application of stresses during critical growth periods, such as the appearance of the crown (male) and female flowers, causes a disruption in pollination, plant sterility, and an obstacle in the formation of maize seeds. Results in Qazvin with a cold semi-arid climate on the effects of irrigation water salinity (2.1, 3.5, and 5.7 dS/m) on the dry yield of fodder maize showed a decrease of 6, 14, and 26% compared to the control (0.5 dS/m) (Saeidi 2021).

Effects on periodic evapotranspiration and the relationship between ETT and crop yield

The results showed that water stress and salinity decreased the amount of plant evapotranspiration in maize compared to the ideal conditions of the region (W_0S_0) so that the three-year average values of evapotranspiration from W_0S_0 to W_2S_2 decreased by 50.1%. This confirms the reduction of water absorption by the crop and the effect of increasing the salinity of irrigation water, which increases the osmotic

pressure of water, on reducing crop evapotranspiration. Table 6 shows the number of irrigations, the average evapotranspiration, and its changes during three consecutive crop years.

The results revealed that in W_0, W_1, and W_2, with the increase of salinity from S_0 to S_2, the three-year average value of evapotranspiration decreased by (3.0–7.0%), (3.5–8.5%), and (4.5–9%), respectively. On the other hand, in S_0, S_1, and S_2, with the increase of water stress from W_0 to W_2, the three-year average value of evapotranspiration decreased by (22.2–45.4%), (23.0–46.3%), and (24.0–47.0%), respectively. These results are due to the reduction of water potential caused by salinity stress, which reduces plants' ability to absorb water and also reduces transpiration. The results of this research are consistent with the results of Heidarinia (2016), who states that increasing the irrigation water salinity from 2 to 7 dS/m decreased the amount of maize evapotranspiration by 8.24%. Since the application of water and salinity stresses was during the development, middle, and final stages of the plant's growth period, and no stress was taken into account in the initial stage of growth, Fig. 3 shows the effects of water stress and salinity on average evapotranspiration of maize during the three development, middle, and final stages.

Table 6 The number of irrigations and total ET during the study crop years

| Treatment	Number of irrigations	ETT (mm)	ETT			ETTave. (mm)
			2020	2021	2022	
W_0S_0	19	691.9–697.0	692.7	695.7	693.3	693.9
W_0S_1	19	665.2–679.1	675.3	677.8	666.9	673.3
W_0S_2	19	645.8–651.1	646.7	648.2	648.5	647.8
W_1S_0	23	536.2–542.0	538.1	540.2	541.1	539.8
W_1S_1	23	514.0–530.0	517.4	519.3	521.5	519.4
W_1S_2	23	486.7–498.9	494.7	497.3	491.1	494.4
W_2S_0	24	376.6–382.1	378.4	380.2	378.7	379.1
W_2S_1	24	357.0–365.7	361.8	363.8	359.8	361.8
W_2S_2	24	343.0–352.9	344.9	346.2	346.8	346.0
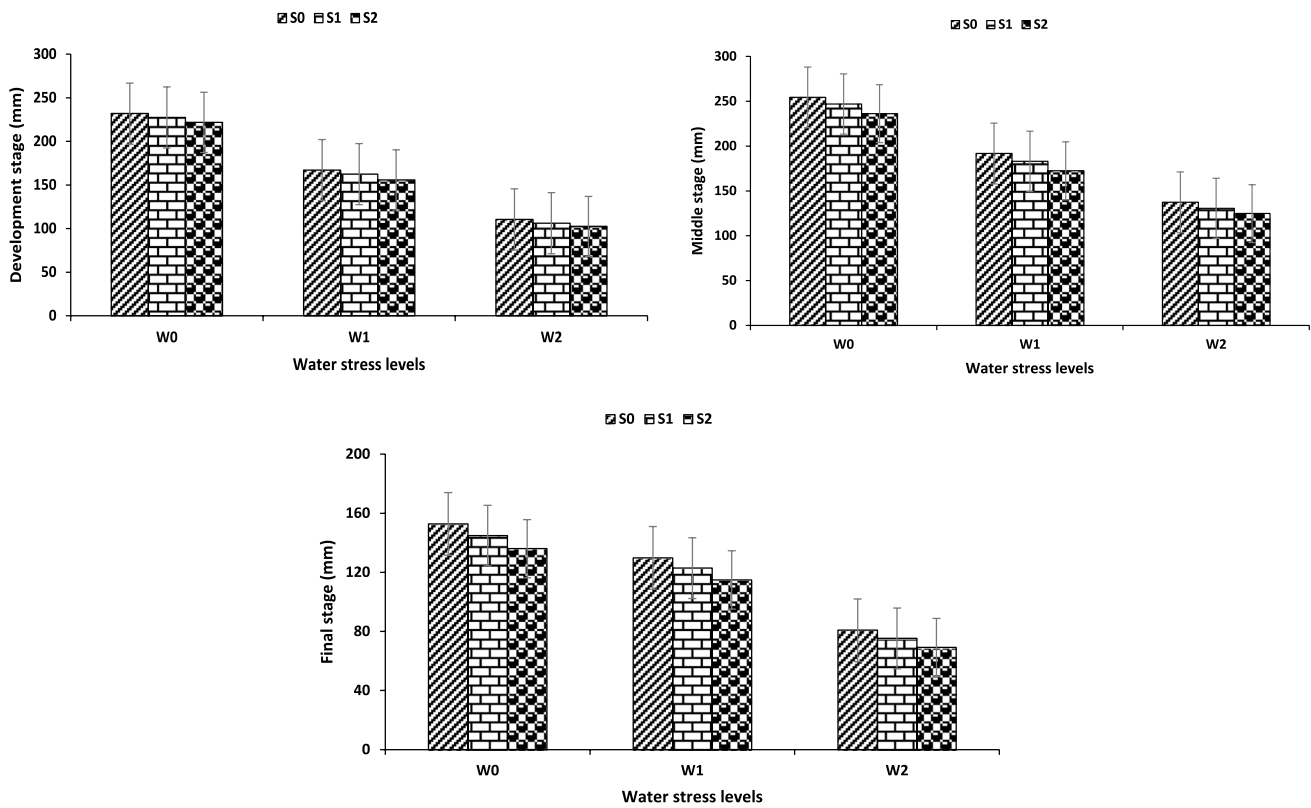
Fig. 3 Effects of water stress and salinity on average evapotranspiration of maize during plant growth

Periodic evapotranspiration values varied due to the increase in stresses compared to the control in the range of 102.5–231.8 mm (in the development stage), 124.7–254.4 mm (in the middle stage), and 69.1–152.7 mm (in the final stage). The percentage of these values in different treatments was between 44.2 to 100% (in the development stage), 49 to 100% (in the middle stage), and 45.3 and 100% (in the final stage) compared to the control (W_0S_0). These results show that the highest percentage of evapotranspiration reduction occurred in the development stage with an average of 55.8%, showing the high impact of simultaneous water stress and salinity in this stage.

The results of ANOVA showed that the effects of water stress, salinity, and their interaction in different plant growth stages were significant on evapotranspiration (Table 7). Also, the mean comparisons indicate the remarkable effects of various stress levels in all three growth stages, revealing the priority of increasing water stress on the reduction of periodic evapotranspiration rather than increasing the irrigation water salinity. These results are closely related to the matric and osmotic potential of water, and soil–plant systems. In stressful environmental conditions, plants secrete a series of compatible osmolyte compounds to make the water potential of their internal cell environment (protoplast) more negative than outside it, which increases the plant's tolerance to stress conditions and the entry of water into plant cells. The above findings confirm the results of Shalheret and Hsiao (1986) and Meiri (1984), who stated that the linear regression coefficient for reducing the yield of agronomical plants as a function of moisture deficiency is two to three times higher than the osmotic coefficient.

Similar studies in this field, which consider the yield as a linear function of two variables, i.e., salinity and irrigation water amount, have also been presented by Parra and Romero (1980) on beans and Jensen (1982) on barley, who prioritized the effects of water stress in reducing the plant growth compared to salinity. The coefficients of the above equations were reported as 07.0 and 02.0 for the salinity factor and 83.0 and 14.0 for the water amount factor, respectively, indicating the greater effect of the amount of water compared to the salinity of the irrigation water. Therefore, similar consideration of the effects of water and salinity stresses on yield is not compatible with reality. Of course, it should be noted that these effects are separate from the effects of ion toxicity and ionic imbalance of the soil solution. Similar to this research, Ors and Suars (2017), who studied six levels of salinity and three levels of water stress on spinach, confirmed the heterogeneity of the effects of water stress, salinity, and their interaction on plant yield. Therefore, by managing the reduction of the above stresses

Table 7 The analysis variance of growth stages in three consecutive years

SV	d_f	Mean squares								
		Development stage			Middle stage			Final stage		
		2020	2021	2022	2020	2021	2022	2020	2021	2022
Block	2	1.063 ns	3.077 ns	13.077*	19.610**	7.521 ns	15.734**	2.203 ns	25.524*	29.694**
Ws	2	32,508.983**	33,685.256**	32,316.903**	30,087.483**	30,500.111**	28,948.621**	11,506.964**	10,785.898**	11,719.285**
Ss	2	176.651**	271.185**	212.233**	567.758**	717.788**	612.583**	563.453**	343.821**	521.067**
Ss×Ws	4	4.796 ns	1.549 ns	3.665 ns	7.316**	17.347 ns	29.748**	8.128 ns	14.414*	7.125 ns
Error	16	1.921	1.786	2.219	1.38	9.507	2.4	5.026	4.627	3.679
CV	–	0.839	0.809	0.905	0.629	1.65	0.836	1.972	1.863	1.699

ns, ** and * indicate non-significant, significant at $P \leq 0.01$ and $P \leq 0.05$, respectively. W_S and S_S are water stress and salinity, respectively
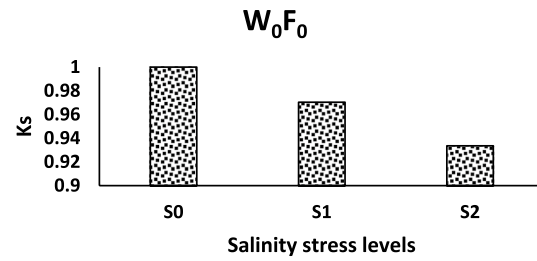
Fig. 4 Three-year average K_S at different salinity levels

in the critical stages of plant growth, it is possible to increase evapotranspiration and consequently, crop yield (Yagoubi et al. 2023). As a result, understanding the sensitivity of plant growth stages and reducing environmental stresses, especially water stress in sensitive stages of growth through irrigation, will help in improving the effectiveness of irrigation management, increasing transpiration, and ultimately crop production.

The evapotranspiration stress coefficient (KS) of maize

Figure 4 shows the three-year average values of K_S in the entire growing season of the plant at different levels of irrigation water salinity. The letter F_0 indicates the complete fertilization level.

K_S varied according to the growth stage and amount and type of stress. With the increase of stress severities and due to the decrease of water potential in the soil, transpiration and K_S have decreased. The reduction of K_S from the value 1 indicates the reduction of evapotranspiration. In the comparison of the effectiveness of the two water and salinity stresses on the reduction of K_S, the effect of water stress is greater than that of the applied water salinity stress. The reduction of K_S leads to a decrease in the crop yield compared to the ideal conditions of the region (W_0S_0).

Results showed that with the increase of salinity from S_0 to S_1 and S_2, per 1 unit increase of salinity (1 dS/m) above the tolerance threshold of the plant, K_S decreased by 78.0 and 76.1%, respectively. Nonetheless, by increasing water stress from W_0 to W_1 and W_2, this coefficient decreased by 5.9 and 13.3%, respectively, per 1 unit of reduction in soil volumetric moisture content. Similar research on four salinity levels (4, 6, 8, and 10 dS/m) for autumn wheat showed that with the increase of irrigation water salinity, K_S varied from 1 to 0.82 (Abedinpour 2017).

Using K_S makes it possible to calculate the actual evapotranspiration and the crop water requirement under stress. Therefore, in environmental stress conditions, crop evapotranspiration (ET_c) is lower than the ideal conditions, and the plant receives less water from the soil. If irrigation is more than the plant's evapotranspiration requirement, it will

cause water loss and soil salinity. Therefore, the existence of environmental stresses has a significant effect on the estimation of the actual ET_c, and the lack of attention to it causes increased water consumption and water shortage.

Effects on the available water (RAW) of maize

Using two parameters K_S and RAW in a Cartesian coordinate system (Fig. 5), the condition of soil water content was investigated in the entire period of the growing season under drought and salinity stress conditions. By calculating the amount of RAW for the plots under stress and without stress (W_0S_0), it was concluded that the amount of RAW in the plots (treatments) was different and its value decreased by increasing the intensity of stress. By measuring the amount of soil water at the place of root-zone activity, the amount of root water depletion from each plot was estimated, and by comparing it to the control plot on the X-axis, the K_S diagram was drawn in terms of RAW in an X–Y coordinate system. The results showed that the soil water content of treatment W_0S_1 was higher than that of treatment W_0S_2,

indicating the reduction of water absorption capacity for the crop due to the increase of soil solution salts and the decrease of the total potential energy of the soil solution.

The three-year average graph showed that with the increase of salinity from W_0S_0 to W_0S_1 and W_0S_2, the relative RAW level decreased from 1 to 0.96 and 0.91, respectively. Based on Fig. 5, the amount of water content of the treatment $\overline{w}(1\&2)_{S_0}$ was more than $\overline{w}(1\&2)_{S_1}$, and $\overline{w}(1\&2)_{S_1}$ more than $\overline{w}(1\&2)_{S_2}$. Therefore, by increasing the intensity of stress, the diagonal lines of the graph will intersect the X-axis near the RAW in the control, and the crop will receive less usable water. The reason that these treatments did not completely cut the X-axis and reached the X-axis with dashed lines is that the crop never reached the permanent wilting point (PWP) during the cultivation.

Also, in the interpretation of the graph, the average values of the decreasing slope are presented with a triangular symbol. With the increase in the intensity of stress, the decreasing slope has increased significantly, showing the effects of simultaneous water stress and salinity on the amount of soil water content. In other words, the different slopes show the
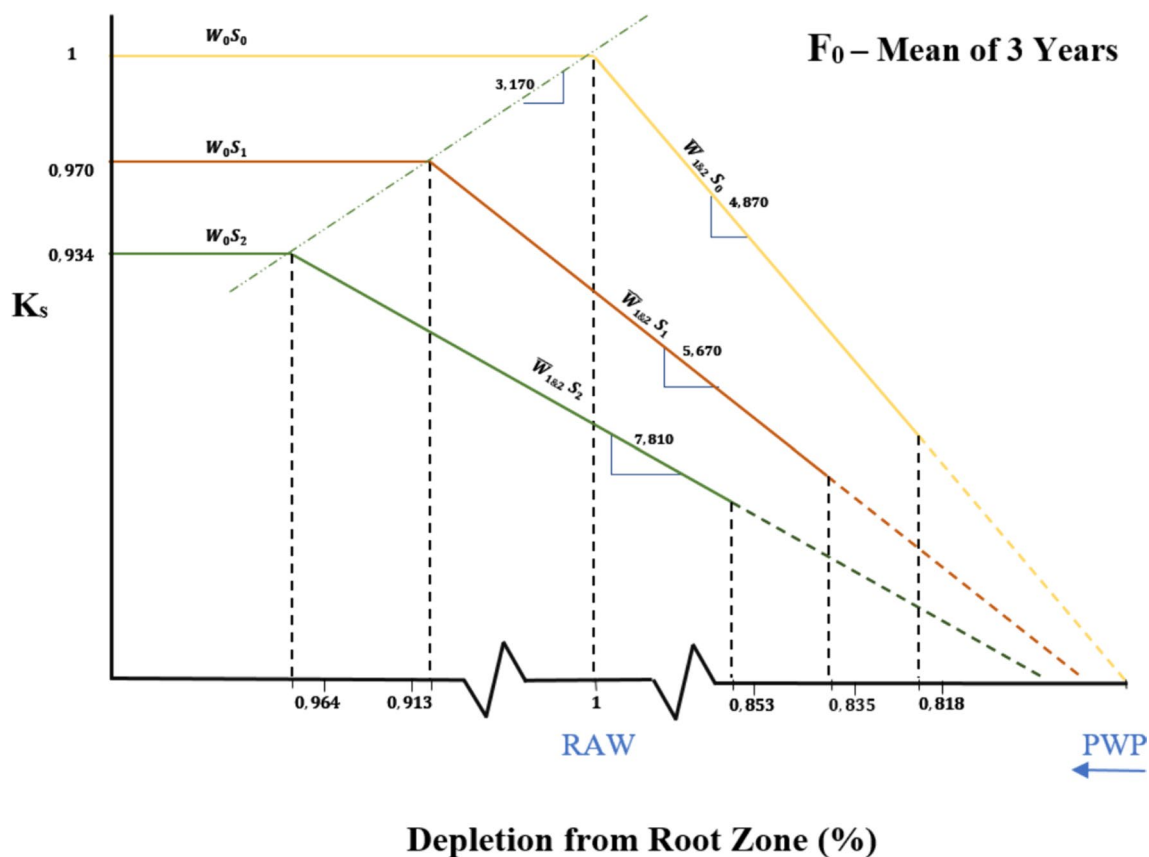

Fig. 5 The changes in RAW in the study years under the influence of simultaneous water stress and salinity. K_s: The coefficient of water, salinity, and simultaneous water stress and salinity. F_0: No fertility stress. W_0S_0: Control. W_0S_1: No water stress at the salinity level S_1.

W_0S_1: No water stress at the salinity level S_2. $\overline{W}_{1\&2}S_0$: Water stress at the salinity level S_0. $\overline{W}_{1\&2}S_1$: Water stress at the salinity level S_1. $\overline{W}_{1\&2}S_2$: Water stress at the salinity level S_2

effectiveness of the treatments on crop evapotranspiration, and there is a direct relationship between plant evapotranspiration and the amount of water that can be absorbed by the crop (Fig. 5). This confirms the results obtained from the effects of plant phenotypic and genotypic characteristics, environmental conditions, crop growth stages, and crop management, in estimating crop evapotranspiration.

According to Shi et al. (2020), flowering is the most sensitive stage to the application of environmental stresses in maize. Another factor that affects the ability of water uptake and its increase indirectly affects the water stress and the reduction of ET_c is the ambient temperature, which is not studied in this research. Finally, stresses reduce crop evapotranspiration and directly reduce the amount of available water compared to the ideal conditions of the region. Under these conditions, the irrigation amount based on the potential evapotranspiration of the region will be more than the actual crop water requirements. Therefore, the first action that farmers take in the conditions of environmental stress by observing the first signs of crop yield reduction is more irrigation to reach the region's potential yield, which is not necessary. It should be noted that with the reduction of water that can be absorbed by the plant, the crop yield will decrease and this will, directly and indirectly, have economic and social consequences for the farmers. Thus, understanding the exact amount of RAW in the conditions of environmental abiotic stress will be of great help in optimal water consumption to increase crop yield.

Conclusion

Due to the global water shortage crisis and increasing human needs, the importance of productivity and simultaneous improvement of the quantity and quality of water resources is considered a big challenge in the fields of economy, environment, and natural resources management. Drought and salinity, especially in arid and semi-arid regions, create limitations in the qualitative and quantitative growth of agricultural products, especially in the case of plants such as maize. The effects of these two stress factors on the processes of evapotranspiration and yield of maize were identified in this study. The results show that the simultaneous application of drought and salinity at different levels, by reducing the water potential in the soil and reducing the plant's energy to absorb water from the soil, leads to a decrease in evaporation and transpiration processes in the plant and increase challenges in maize plants in accessing usable water. These challenges can be seen directly in the reduction of plant yield.

In conditions of environmental stress, the ability to absorb water from the soil for the study plants decreased and their water requirements decreased. In such conditions,

the reduction of water consumption in irrigation is proven, because the plant needs less water due to the reduction of evaporation and transpiration. From another point of view, in the conditions of environmental stress, the physical properties of the soil are affected. These effects may lead to a decrease in the ease of water availability in the soil, which makes it challenging for water to be transferred to the plant. From the point of view of soil physics, this decrease in easy water availability can lead to a decrease in water absorption from the soil by the plant roots and, as a result, the water requirement of the plant. In this situation, the reduction of water consumption in irrigation is predictable as a physical result of the soil.

According to the results of this research for K_S, it is possible to obtain the actual evapotranspiration of maize plants under environmental stress conditions. These calculations can help to know more precisely the water requirement of the plant in various conditions and increase the effectiveness in the management of water resources and irrigation. The findings of this work show that in the situation where the irrigation water is unfavorable in terms of salinity, by calculating the evaporation and transpiration coefficient, it is possible to provide less water to the plant and receive the same favorable performance from the plant. This approach can be useful in optimizing water consumption and managing water resources in conditions of environmental stress. With the approach of reducing the amount of irrigation water in saline conditions, less accumulation of minerals will occur in the soil. This will help maintain soil quality and prevent soil salinization and its subsequent problems, such as reducing land productivity. In this way, this approach not only helps to optimize water consumption but also prevents problems caused by soil salinity and helps to maintain soil health. The accurate management of the amount of water consumed prevents more accumulation of salt in the soil, ensures the maintenance of its physical structure, and may lead to improved soil quality and increased land productivity.

Declarations

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