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Crop Water Productivity and Crop Coefficients of Lentil (*Lens Culinaris* M.) Under Different Irrigation Regimes

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Abstract: This study was conducted for two consecutive winter seasons (2014/15 and 2015/16) at Hudeiba Research Station Farm to determine the effects of deficit irrigation imposed at different developmental stages and throughout the growing season on water use and water productivity of lentil (*L. culinaris* M.) and to derive the crop coefficient. Lentil Aribo cultivar was grown under six irrigation treatments in which one-irrigation was skipped at some of the growth stages, *i.e.* vegetative (W3), flowering (W4), pod setting (W5) and ripening stage (W6) and irrigation without skipping with intervals of 10 days (full irrigation) (W1) and irrigation every 15 days (W2) (moderate water stress throughout the growing season). The experimental design was randomized complete block design with three replications. The average estimated values of crop coefficients during the initial, mid -season and late -season stages were 0.28, 1.06 and 0.48, respectively. The results revealed that the highest grain yield was recorded in full irrigation (1003 kg ha^{-1}) and significantly ($p < 0.001$) decreased by 13, 28 and 31% when deficit irrigation was applied throughout the growing season, at flowering and at pod setting stages, respectively. The highest and lowest values of crop water productivity resulted from deficit irrigation imposed at vegetative stage and at flowering stages, respectively. The most sensitive stages of lentil to water deficit were the flowering and pod setting. Therefore, under water shortage and/or high cost of irrigation water conditions, if only one irrigation is to be saved, the vegetative and ripening stages could be a safe option.

Key words: *Lens culinaris* M.; deficit irrigation; growth stages; grain yield; Water Productivity.

INTRODUCTION

Lentil (*Lens culinaris* M.) is one of the most important pulse crops of the world consumed for its high protein and mineral content. Lentil seeds contain 1-2% fat, 24–32% proteins and minerals (iron, cobalt and iodine) and amino acids (lysine and arginine) ((Raghuvanshi and Singh 2009). In addition to human consumption, high-quality lentil hay is extensively used as animal feed (Lardy and Anderson 2009). It also supports crop rotation due to its potential to sustain soil productivity by nitrogen fixation (Abi-Ghanem *et al*. 2011). The major lentil-growing countries of the world are Canada, India, Turkey, Australia, USA, Nepal, China, Bangladesh, Iran, Ethiopia and Syria (Ahlawat 2012). The crop is cultivated under rainfed conditions in these countries. The total lentil cultivated area in the world is estimated around 4.5 million hectares, producing 4.9 million tons of seeds with an average productivity of 1080 kg ha^{-1} (FAOSTAT 2015). In Sudan, Lentil is traditionally grown in northern Sudan under pump irrigation in Rubatab area (Salih *et al*. 1996).

The River Nile State (16°-22°N, 32°-36°E) is one of the most important regions for agricultural production in northern Sudan, especially for winter crops such as wheat, pulses, vegetables, fruits and spices. Two-thirds of the State area is desert and semi-desert with rainfall less than 100 mm/year (Ahmed 2008). The agricultural production is mainly dependent on irrigation. The River Nile and Atbara River and groundwater are the main water sources of the State. Many studies showed that pumping irrigation water from the Nile and underground water is the main cost item leading to the high total cost of agricultural production (Faki 1999). There is an urgent need to use available water resources efficiently and enhancing crop water productivity (CWP). Improving water productivity by producing more food with less water is essential for future food production and sustainable agriculture. Among the water management practices for increasing water productivity, deficit irrigation (DI) was considered. DI increased water productivity by either withholding or skipping irrigation event or reducing the amount of water applied per irrigation at some growth stages of the crop (Kirda 2002). Jalota *et al*. (2006) reported that at field level, reducing evapotranspiration through deficit irrigation and identifying the most sensitive crop growth stage to water stress is one of the ways to enhance crop productivity with less water. In areas where water is the limiting factor for crop production, maximizing WP by DI is often economically more profitable for the farmer than maximizing yield (English 1990). For instance, water saved by DI can be used to irrigate more land which may largely compensate for the economic loss due to yield reduction (Kipkorir *et al*. 2001). Research results indicate that higher water productivity for various crops is recorded with deficit irrigation practice if the moisture stress resulting from the deficit is not so severe (Sammis *et al*. 2000). Igbadun *et al*. (2006) found that the status of crop water productivity was dictated by the amount of water applied, the growth stages at which irrigation was reduced and the frequency of withholding irrigation.

The precise value of the seasonal ET is a basic prerequisite for calculating the water use efficiency. ETc is a function of reference crop evapotranspiration and crop coefficient. The approach of using the product of reference ET (ETo) and a crop coefficient (kc) as proposed by FAO (Doorenbos and Pruitt 1977; Allen *et al*. 1998) is commonly used to calculate ET worldwide. Of the many approaches used to calculate ETo, the FAO Penman–Monteith equation, based on meteorological data and a hypothetical reference crop, is now considered the standard reference (Allen *et al*. 1998). The kc varies with crop characteristics and only to a limited extent with climate. The objectives of this study are: (i) to evaluate the effect of deficit irrigation imposed at different developmental stages and throughout the growing season on water use and crop water productivity of the lentil crop, (ii) derive the crop coefficient of lentil under semi-desert climatic conditions of northern Sudan

MATERIALS AND METHODS

A field experiment was conducted for two consecutive seasons (2014/2015 and 2015/2016), at Hudeiba Research Station Farm, Ed-Damer, Sudan, latitude 17° 34′ N, Longitude 33° 56′ E, and altitude 350 m above sea level. The local climate is semi-desert (Adam 2005), very hot and dry in summer and relatively cool in winter. Data of maximum, minimum temperature, relative humidity, sunshine hours and wind speed at 2 m height, were obtained from Hudeiba Meteorological Station to calculate ETo using Penman-Monteith Equation. The daily weather data were averaged for each 10 days along the growing season as presented in Table 1. The soil is clay in texture and is classified as Vertic Torrifluvent, fine Smectitic, Calcareous, hyperthermic, Bergieg series (USA, Soil Taxonomy); with very low permeability, field capacity of 46% by volume and a permanent wilting point of 25% by volume. In general, the soil is non-saline and non-sodic, with alkaline reaction and is low in organic carbon and nitrogen content (Table 2). Lentil Aribo cultivar was grown under six irrigation treatments at different developmental growth stages, in which one-irrigation was skipped at some of the growth stages as follows:

W1 = Irrigation every 10 days throughout the season (full irrigation, the control).
W2 = Irrigation every 15 days throughout the season (moderate water stress).
W3 = Skipped from (21 – 30 days) at (vegetative stage).
W4 = Skipped from (41 – 50 days) at (flowering stage).
W5 = Skipped from (61 – 70 days) at (pod setting stage).
W6 = Skipped from (above 80 days) at (ripening stage).

The experiment was laid out in a randomized complete block design (RCBD) with 3 replications. Plot consisted of five ridges, 10 m long and 75 cm apart (37.5 m^2). The crop was sown manually during the third week of November in both seasons. Seeds were drilled in one row on top of the ridges at the rate of 60 kg per hectare. Nitrogen at the rate of 43 kg N per ha (in form of urea) was applied uniformly, to all experimental plots before the second irrigation. Hand weeding of the experimental area was performed as required. At harvest, six meters out of the three central ridges (13.5 m^2) of each plot were harvested for final yield assessment during both seasons. A sub sample of ten plants was taken for determining the yield components (number of pods per plant, number of seeds per pod and the 1000 seeds weight).

The crop water use (actual crop evapotranspiration) was estimated from the change in soil moisture using the gravimetric method. Soil samples were augured from a profile of 60 cm depth at 20 cm intervals, 2-3 days after irrigation and immediately before each irrigation event. This was done from planting to harvest. Soil samples were oven-dried at 105°C for 24 hours. The estimated gravimetric moisture contents were converted into volumetric values by multiplication by the soil bulk density.

$$ET = \Delta S = \frac{\sum_{i=1}^{n} (\theta 1 - \theta 2) d}{\Delta t} \quad \text{........................ Equation 1}$$

Where: ET = Crop Evapotranspiration

n = number of soil layers sampled in the effective root zone which is = 3 (0-20, 20-40, 40- 60)

θ1 volumetric moisture content within 2-3 days after irrigation

θ2 = volumetric moisture content before the next irrigation in the i-th layer

d = the thickness of i-th layer (mm), which is = 200 mm

Δt = the time interval between two consecutive measurements (days).

The kc values were calculated at ten-day intervals as the ratio between ETc and ETo values (Allen *et al*. 1998):

$$kc = \frac{ETc}{ETo} \quad \text{........................ Equation 2}$$

Crop water productivity (CWP) was calculated as

$$CWP = \frac{Y}{ETc} \quad \text{.. Equation 3}$$

Where, Y= yield (kg ha^{-1})

ETc = seasonal crop evapotranspiration (m^3 ha^{-1}).

Analysis of variance (ANOVA) was carried out using MSTAT statistical package (1984). The data obtained were analyzed for each season separately and then combined analysis was run for the two growing seasons because the homogeneity test was positive. Differences among treatment means were tested for statistical significance using Duncan's Multiple Range Test at P≤ 0.05

Table 1.Mean decade values of weather data during 2014/2015 and 2015/2016 seasons

Month	RH (%)	Max Temp (^oC)	Min Temp (^oC)	Wind speed (m/s)	Sunshine (hr)	ETo (mm)
			2014/2015			
15-Nov	38	35.4	21.7	1.8	10.2	5.3
25-Nov	40	30.6	15.4	1.9	10.3	4.7
5-Dec	50	34.3	18.3	1.1	10.0	4.1
15-Dec	51	32.9	17.8	1.6	9.7	4.3
25-Dec	48	31.7	16.0	1.6	10.0	4.3
5-Jan	45	26.8	12.1	2.9	9.5	4.7
15-Jan	52	26.3	10.2	2.0	9.9	3.9
25-Jan	62	34.0	16.9	1.2	9.8	4.2
5-Feb	48	36.2	17.6	1.3	9.9	4.8
15-Feb	34	33.7	14.8	2.1	9.5	5.7
25-Feb	42	36.1	16.9	2.0	9.4	5.9
			2015/2016			
15-Nov	46	33.4	19.6	2.3	9.5	5.3
25-Nov	48	35.3	19.6	1.4	10.3	4.7
5-Dec	45	29.6	17.3	2.3	8.7	4.7
15-Dec	46	26.9	12.5	2.4	10.2	4.4
25-Dec	49	27.2	12.8	2.2	9.0	4.1
5-Jan	47	27.5	12.3	2.0	10.0	4.2
15-Jan	40	30.4	15.2	1.8	10.1	4.6
25-Jan	44	26.1	11.5	2.5	10.2	4.7
5-Feb	42	29.5	13.7	2.3	9.8	5.1
15-Feb	52	33.7	17.2	2.0	9.9	5.3
25-Feb	36	33.5	16.3	2.1	9.0	5.4

(Source: Hudeiba Meteorological Station, 2016)

Table 2. Selected physical and chemical properties of the soil at the experimental site in Hudeiba Research Station

Depth (cm)	0-23	23-44	44-87	87-120	120-157	157-203	Mean
Sand (%)	4	3	3	3	4	3	4
Silt (%)	47	42	39	37	40	37	40
Clay (%)	49	55	58	60	56	60	56
Hydraulic conductivity (cm/hr)	0.32	0.1	0.1	0.11	0.07	0.07	0.13
Moisture content at wilting point (m^3/m^3)	21	23	26	24	27	29	25
Moisture content at field capacity (m^3/m^3)	38	43	47	44	50	54	46
Soil bulk density (g/cm^3)	1.77	1.66	1.85	1.74	1.71	1.83	1.76
pH	7.8	8	7.9	7.7	8	7.9	7.9
Electrical conductivity (dS/m)	0.3	2.4	3.6	3.5	3.6	4.9	3.1
Calcium carbonate (%)	6	4.6	5.4	6	5.2	5.4	5.4
Total nitrogen (%)	0.045	0.04	0.045	0.03	0.035	0.035	0.038
Organic carbon (%)	0.499	0.312	0.203	0.265	0.187	0.218	0.281
Cation exchange capacity (meq/100g soil)	48	54	53	52	53	58	53
Sodium absorption ratio	1	7	10	12	7	7	7

(Source: Land and Water Research Centre Laboratory, 2015)

RESULTS AND DISCUSSION

Grain Yield

The effect of deficit irrigation on grain yield of lentil is presented in Table 3. The combined analysis carried out on grain yield in response to deficit irrigation applied during different crop stages revealed a highly significant difference ($p < 0.001$). The highest grain yield was recorded in W1 (full irrigation) treatment with 1003 kg ha^{-1}. Applying deficit irrigation throughout the growing season (W2), during flowering (W3) and pod setting stage (W6) led to reduction in grain yield by 13, 28 and 31 %, respectively, compared to full irrigation. The results also showed that there were no significant differences between full irrigation treatment and deficit irrigation applied at vegetative and ripening stages. Deficit irrigation applied throughout the growing season, at vegetative and ripening stages produced statistically similar yields, but significantly higher than the yields for deficit irrigation applied at flowering and pod setting stages (Table 3). In this study, yield results indicated that imposing deficit irrigation during the vegetative stage had no significant effect on economic yield of lentil. On the other hand, imposing deficit irrigation during flowering and pod setting stages had adverse effect and must be avoided. This result is supported by the findings of Ahmed and Nourai (1993) who stated that irrigation every 10 or 20 days during the vegetative stage had no significant effect on seed yield of lentil. However, a significant ($P = 0.01$) reduction in seed yield in response to longer irrigation intervals during the reproductive phase was detected. Taha *et al*. (1986) reported that the best yields of lentil were obtained with the 21-day interval during the vegetative stage and more frequent irrigation during the reproductive stage.

Table 3. Seed yield of lentil as affected by deficit irrigation for the seasons 2014/2015- 2015/2016 and combined analysis at Hudeiba, northern Sudan

Irrigation treatments	Grain yield (kg/ha)		
	2014/2015	2015/2016	combined
W_1	1137.5a	867.7a	1002.6a
W_2	1006.4a	732.6ab	869.5b
W_3	1058.8a	785.8a	922.3ab
W_4	820.2b	615.1bc	717.6c
W_5	809.2b	569.9c	689.5 c
W_6	1053.3a	779.8a	916.6ab
Mean	980.9	725.1	853
Sig. level	**	**	***
SE±	57.8	49.5	38.1
C.V. (%)	10.2	11.8	10.9

*, **, *** Significant at $p \leq 0.05$, 0.01 and 0.001, respectively.
Means followed by the same letter(s) within a column are not significantly different at $p \leq 0.05$ according to Duncan's Multiple Range Test

Seasonal Water Use

The seasonal water used by the crop as evapotranspiration (ETc) is summarized in Table 4.

In 2014/15 the greatest amount of seasonal water used (3352 m^3 ha^{-1}) was observed in the full irrigation treatment (W1). The amount of seasonal water used by other treatments varied between 3098 and 2945 m^3 ha^{-1} depending on the growth stage in which water deficit was applied. The least seasonal water used (2945 m^3 ha^{-1}) was observed in W5, when deficit irrigation was imposed at pod setting stage.

During 2015/2016 statistical analysis revealed that the highest seasonal crop water used was recorded under full irrigation and was significantly

($p \leq 0.001$) reduced through the imposition of deficit irrigation. There were no statistical differences among the seasonal water use of treatments W3, W4, W5 and W6.

The total numbers of irrigations given in each irrigation regime in both seasons of lentil for W1, W2, W3, W4, W5 and W6 were 9, 7, 8, 8, 7 and 8, respectively. The higher water used values at full irrigation (W1) could be related to higher soil evaporation resulting from more frequent wetting of the soil surface (Allen *et al*. 1998)

Deficit irrigation throughout the growing season decreased seasonal water use by 15%, while deficit irrigation at vegetative, flowering, pod setting and ripening stages decreased seasonal water use by 10, 13, 14 and 11%, respectively, in comparison with the full irrigation.

Yield-ETc Relationship

The relationship between lentil grain yield and ETc is presented in Fig. 1. Grain yield varied from 690 to 1003 kg ha^{-1} and ETc values from 2910 to 3351 m^3 ha^{-1}. The linear regression between grain yield and ETc showed that about 60% of the variation in grain yield could be attributed to variations in ETc. Within the range of observed ETc values, the regression slope predicts a yield increase of 177.3 kg ha^{-1} for each 100 m^3 ha^{-1} increase in ETc. The negative value of the intercept indicates that a certain ETc threshold value must be reached before any grain yield is obtained, which was 2509 m^3 ha^{-1} in this study. The regression of Fig. 1 shows that about 40% of the grain yield variation is not explained by ETc. Other factors could explain that additional variation *e.g*. in this study virus diseases were major constraint to lentil production, especially in the second season Several previous studies have also shown a linear relationship between grain yield and ETc for durum and bread wheat in Syria (Zhang and Oweis 1999) and onion in Northern Nigeria (Igbadun *et al*. 2012)

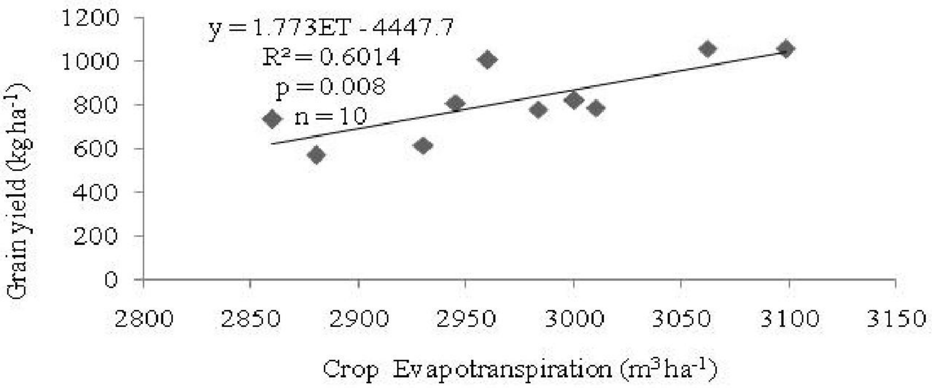

Fig. 1. The relationship between grain yield of lentil and crop evapotranspiration (ETc).

Water Productivity

CWP data are summarized in Table 4. During 2015/2016, deficit irrigation did not result in significant differences in CWP between the full irrigation and deficit irrigated treatments, except for deficit irrigation applied during pod setting stage, where a significant decrease in CWP was observed. The highest CWP value was observed in the W3 treatment in which deficit irrigation was applied at vegetative stage, whereas the lowest value was observed in the W5 treatment in which deficit irrigation was applied at pod setting stage. Although water productivity increased with water shortage, its maximum value did not correspond to irrigation treatment receiving minimum water supply (W5), since water stress at pod setting induced high production losses. Similar findings were reported by Chen *et al*. (2010) who reported that increase of irrigation water amount resulted in more crop yields, but the water amount required to gain maximum WP was much less than that required for obtaining the maximum crop yield.

Table 4. Crop water use (ETc) and crop water productivity of lentil as affected by deficit irrigation at seasons 2014/2015 and 2015/2016 at Hudeiba Research Farm.

Irrigation Treatments	Seasonal ETc (m^3ha^{-1})			CWP (kgm^{-3})		
	2014/15	*2015/16*	*Mean*	*2014/15*	*2015/16*	*Mean*
W1	3352	3350a	3351	0.339	0.259a	0.299
W2	2960	2860c	2910	0.340	0.256a	0.298
W3	3062	3010b	3036	0.346	0.261a	0.304
W4	3000	2930bc	2965	0.274	0.210ab	0.242
W5	2945	2880bc	2913	0.276	0.198b	0.237
W6	3098	2983bc	3041	0.340	0.261a	0.301
Mean	3069	3002	3036	0.319	0.241	0.280
significance		***			ns	
SE±		42.9909			0.0172	
C.V. (%)		2.48			12.37	

ns: Not significant. *, **, *** Significant at $p \leq 0.05$, 0.01 and 0.001, respectively.
Means followed by the same letter(s) within a column are not significantly different at $p \leq 0.05$ according to Duncan's Multiple Range Test

Determination of Crop Coefficients (kc)

Doorenbos and Pruitt (1977) divided the kc curve into four stages: initial, crop development, mid and late-season stages. The Initial growth stage occurs from sowing to about 10% ground cover. Crop development stage occurs from about 10% to70% ground cover. The Mid-season stage including flowering and yield formation, while the Late-season including ripening and harvesting. Lengths of initial, development, mid-season and late-season stages for lentil crop were determined as 17, 24, 35 and 25 days, respectively. In this study, crop coefficients kc of lentil were calculated on ten-day intervals then the data were plotted in a graph to obtain smooth kc values for each growth stage. Fig. 2 shows the changes of kc for lentil.

The kc values increased from initial stage to mid- season stage then decreased during the late- season stage. The average estimated values of crop coefficients were 0.28, 1.06 and 0.48 for initial, mid -season and late -season stages, respectively. Knowing only the average weather data, these values of crop coefficients could be used in calculation of crop water requirements for lentil crop in the Northern region of the Sudan under similar soil, climatic and crop management conditions.

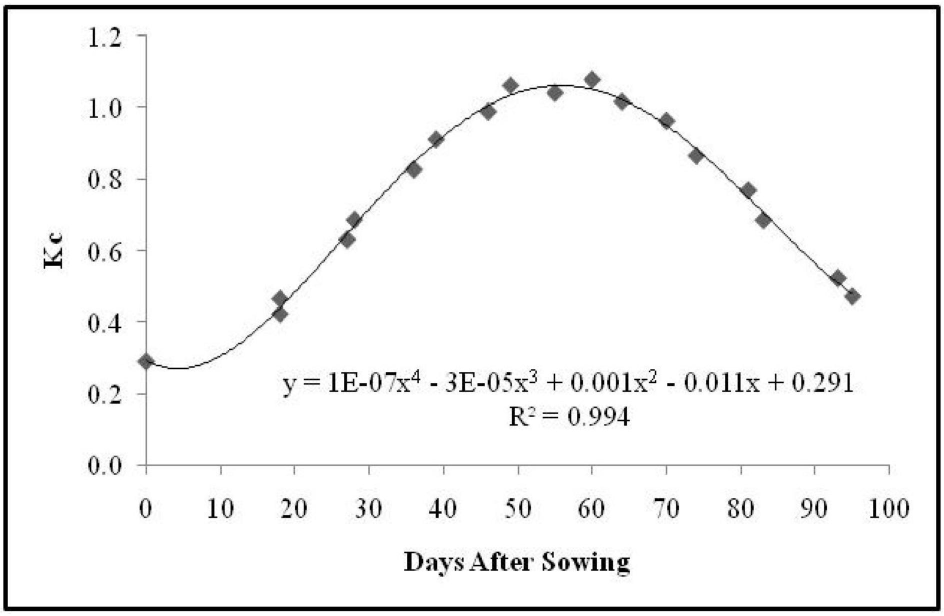

Fig. 2. Lentil crop coefficients (kc) during crop growth stages.

CONCLUSIONS

- Deficit irrigation significantly reduced grain yield; the greatest reduction occurred when water stress was imposed at flowering and pod setting (sensitive stages) while the least reduction occurred when water stress was imposed during the vegetative and ripening stages.

- The highest and lowest values of CWP resulted from deficit irrigation imposed at vegetative stage and at flowering stage, respectively.
- Consequently, water supply should be assured at these stages for high yield; however, To save irrigation water and increase water productivity, irrigation can be limited at vegetative and ripening stages with a slight yield decrease.
- The average estimated values of crop coefficients during the initial, mid -season and late -season stages were 0.28, 1.06 and 0.48, respectively

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[2]هيئة البحوث الزراعية محطة بحوث الحديبة

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المستخلص: اجريت هذه التجارب بمزرعة محطة بحوث الحديبة للموسمين الشتويين (15/2014و16/2015) لدراسة تاثير الاجهاد المائى خلال مراحل نمو مختلفة وخلال كل الموسم على معدل الاستهلاك المائى وانتاجية الماء المحصولية لمحصول العدس وكذلك حساب معامل المحصول. تم استخدام تصميم القطع العشوائية الكاملة فى ثلاثة مكررات. تمت زراعة صنف العدس "اريبو" فى فى ست معاملات رى (W1 = الرى كل عشرة ايام (رى كامل)، W2 = الرى كل 15 يوما (اجهاد متوسط خلال كل الموسم)، W3 = اجهاد فى مرحلة النمو الخضرى ، W4 = اجهاد فى مرحلة الازهار ، W5 = اجهاد فى مرحلة عقد القرون ، W6 = اجهاد فى مرحلة النضج. بلغت قيمة الاستهلاك المائى السنوى تحت ظروف الرى الكامل حوالى 3351 متر مكعب للهكتار وإنّ قيم معامل المحصول للمراحل الابتدائية و المتوسطة و النهائية بلغت حوالى 0.28، 1.06 و0.48، على التوالى. اظهرت النتائج ان اعلى انتاجية غلة ($1003\ kg\ ha^{-1}$) قد سجلت تحت ظروف الرى الكامل ولقد نقصت معنويا ($P \leq 0.001$) ب 13؛ 28 ؛ 31% فى الاجهاد المتوسط خلال كل الموسم، الاجهاد فى مرحلة الازهار والاجهاد فى مرحلة عقد القرون، على التوالى. كما اظهرت النتائج عدم وجود فروق معنوية بين الرى الكامل والاجهاد المائى فى مرحلة النمو الخضرى والاجهاد المائى فى مرحلة النضج. اظهرت النتائج ايضا ان اعلى استهلاك مائى لوحظ عند الرى الكامل وانخفضت كميات الاستهلاك المائى بصورة معنوية($P \leq 0.001$) خلال تطبيق الاجهاد المائى وانه لا توجد اى فروق معنوية بين المعاملات W3، W4 ، W5 وW6. اعلى قيمة لانتاجية

الرى المحصولية قد سجلت عند الاجهاد المائى فى مرحلة النمو الخضرى بينما سجلت اقل قيمه عند الاجهاد المائى فى مرحلة الازهار. اكثر مرحلة حساسة للاجهاد المائى هى مرحلة الازهار ومرحلة عقد القرون، لذا تحت ظروف قلة المياه او ارتفاع تكاليف الرى يمكن توفير ريه واحدة في أي من مرحلتي النموء الخضري والنضج.