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Determination of crop coefficients, water requirements and water productivity for summer maize (*Zea mays* L.) under central Gezira clay soil conditions, Sudan

Hisham M. Mohammed[I], Hussien, S. Adam[1] , Siddig. E. Idris[I] and Osama A.Muhieldeen[I]

1. Faculty of Agricultural Sciences, University of Gezira, Wad Medani, Sudan.
Corresponding Author: E-mail: Talib.Doka1971@gmail.com
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Abstract
Understanding crop water needs is essential for irrigation scheduling and water saving in an arid region because of its limited water supply. This research was, therefore, conducted to determine growth stage specific K_c and crop water use for maize (*Zea mays* L.) cultivar Hudaiba2 at the Experimental Farm, University of Gezira, during summer seasons 2015/16 (first season) and 2016/17 (second season) to estimate crop coefficients (K_c), crop water requirements (CWR) and water productivity (WP) of maize cultivar Hudaiba2. The reference evapotranspiration (ET_o) was calculated using the FAO computer program (CROPWAT). Actual crop evapotranspiration (ET_c) was estimated by the gravimetric method. Crop coefficients were derived from the relationship between reference evapotranspiration and actual crop evapotranspiration. The results showed that crop coefficients values for maize were 0.49 and 0.46 for initial stages, 1.30, and 1.32 for the mid stages and then decreased gradually to 0.47 and 0.40 for the late stages, in the first and second season; respectively. The peak K_c occurred during the period 60 to 70 days after sowing (DAS), coinciding with the maximum ET_c of 7.24 and 8.22 mm/day at the mid-season stage for maize. The crop consumptive water uses of maize were 547 and 505.1 mm (5470 and 5051 m^3/ha) for the total growing period in the first and second season; respectively. The mean yield of maize was 4238.5 kg/ha and the crop water productivity was 0.72 kg/m^3. For this reason K_c value must be used to calculate the applied water to increase the yield and water productivity.
Keywords: crop coefficients, water requirements, water productivity, maize

Introduction
Maize or corn is a cereal crop that is grown widely throughout the world in a range of agro-ecological environments. Maize was introduced into Africa in the 1500s and has since become one of Africa's dominant food crops (IITA, 2009). Maize is the most important cereal crop in sub-Saharan Africa (SSA) and an important staple food for more than 1.2 billion people in SSA and Latin America. Most maize production in Africa is rain fed. Irregular rainfall can trigger famines during occasional droughts. The crop is grown in climates ranging from temperate to tropic during the period when mean daily temperatures are above 15°C and frost-free. Adaptability of varieties in different climates varies widely (FAO, 2002). It is grown as a rain-fed crop in Kordofan, Darfor and

Southern States and in small holdings in the Northern States, with average production of about 0.697 ton/ha (FAO, 2005). There has been an increasing interest in maize production in Sudan (Nour, *et al.* 1997) as the crop is also suitable for irrigated schemes, especially in the Gezira and Rahad. It can play an important role in the economy of the country, for export as well as for food. The design of irrigation scheme, in terms of areas to be cropped, the cropping pattern, canal capacities, depends to a large extent on accurate figures of crop water requirements (Adam, 2005).

Crop coefficients vary for the different crops, as well as for the crops grown in the same location. In addition, crop coefficient change based on the growing stage of the crop. Values of K_c vary with the crop; the main factors affecting its values are crop characteristics, crop planting or sowing date, rate of crop development and length of growing season (Sertoli, 2015). Allen, *et al*. (1998), determined the K_c of maize as 0.3, 0.5, 1.2 and 0.5 for the K_c ini, K_c dev, K_c mid and K_c end, respectively. Abedinpour (2015) found that the K_c values for the initial, crop development, mid-season, and late stages were 0.40 – 0.60, 0.70 –0.80, 1.1–1.21, and 0.50 – 0.65, respectively, while the values reported for maize by FAO are 0.3, 1.2, 0.3 – 0.6 for the initial, mid-season and late stage, respectively. FAO, 2002 reported that the crop factor (K_c) relating water requirements (ET_c) to reference evapotranspiration (ET_o) for different crop growth stages of grain maize is for the initial stage 0.3-0.5, the development stage 0.7- 0.85, the mid-season stage 1.05 -1.2, during the late season stage 0.8-0.9, and at harvest 0.55-0.6. In Tanzania, Igbaduna *et al.,* (2007) reported that the estimated values of K_c for maize at initial crop development, mid-season, late season and maturity were 0.53, 0.82, 1.10 and 0.1.06, respectively. Also Popova, *et al*., (2006) in Bulgaria found that the K_c values at initial crop development, mid-season and late season were 0.28, 1.28 and 0.23, respectively. Atta, *et al.*, (2015) reported that the estimated values of K_c for maize at initial, mid-season and late season were 0.55 to 0.86, 1.11 and 0.85, respectively.

Reference evapotranspiration (ET_o) depends on the climate and varies with location. Meteorogical stations are used to collect the climatic data for calculating ET_o, including temperature (maximum and minimum), dew relative humidity, wind speed, sunshine hours and solar radiation. Crop water requirement (CWR) is the quantity of water utilized by a crop, irrespective of its source, for obtaining maximum yield in a particular area without adverse effects on soil properties. According to the FAO, 2002 Maize is an efficient user of water in terms of total dry matter production and among cereals it is potentially the highest yielding grain crop. The total ET_c of maize were 273 - 470 mm (Abdul Salam and Suad, 2006), 414.0 - 417.6 mm (Diakhate, 2014) and 611.5 mm (Zhao and Nan, 2004) while it exceeded 500 mm as reported by Tariq and Usman (2009). For maximum production, a medium maturity grain crop requires between 500 and 800 mm of water depending on climate. Yield of maize under irrigation is 6 to 9 ton/ha FAO (2002). The water productivity for grain yield was 0.8 to 1.6 kg/m^3. The present work was undertaken to estimate crop coefficients (K_c), water requirements and water productivity of maize.

Materials and Methods

Experiments were carried out during the winter seasons of 2015/16 (first season) and 2016/17 (second season) at the Experimental Farm, University of Gezira. It lies north of Wad Medani town, Lat. 14.4° N, Long. 33.5° E and altitude of 405 masl. The soil in the farm is Vertisol, with a high CEC, and a pH of 7.5 (Alhilo, 1996). It is characterized by its alkaline reaction with low permeability. The land was prepared by disc plow followed by harrowing and leveling. Maize (Hudaiba2) cultivar was sown on ridges 80 cm apart by placing 2-3seeds per hole and 25 cm between holes. The plot area was 64 m^2, each plot was separated from the other by 2 m. Three weeks later, plants were thinned to one plant per hole. Urea was applied at the rate of 86 kg N ha^{-1} as recommended by the Agricultural Research Corporation.

Reference evapotranspiration (ET_o)

The climatic data for reference evapotranspiration were collected from Wad Medani Meteorological Station during the period from 20th July to 10th November for the two seasons (2015/16 and 2016/17). The CROPWAT software was used to estimate reference evapotranspiration.

Effective Rainfall

Effective rainfall is that fraction of the total rainfall that forms part of the consumptive use of the crop. Rainfall period extent from May to November, the most rain falls in the period of July to September with a peak in August. Rainfall during July and August in Gezira area provides a part or the whole of the requirement. The effective rainfall was taken as 75% from the total rainfall according to Mohamed *et al.,* (2015).

Crop evapotranspiration (ET_c)

Crop evapotranspiration (ET_c) was calculated from soil moisture depletion measured by the gravimetric method. Three soil samples were taken from each plot using an auger every 20 cm down to 100 cm depth. The gravimetric moisture samples were collected one to two days after each irrigation and one hour before the next irrigation throughout the growing season and samples were taken eleven times every season. The samples were labeled and weighed immediately and the wet weight (W_w) was determined and then oven dried at 105 ºC for 24 hours and re- weighed for the dry weight (D_w).

$\theta_g = 100\ (W_w - D_w)/\ D_w$……………...(1)

The values of gravimetric moisture content (θ_g) were converted to volumetric values (θ_v) by multiplying by dry soil bulk density of the profile (ρ), using the following formula.

$\theta_v = \theta_g\ \rho$……………..(2) The change in soil moisture (ω) was obtained from:

$\omega = (\theta_2 - \theta_1)\ R$ …………….... (3) Where:

R = Sampling depth (cm),
θ_1 = Initial moisture content,
θ_2 = Final moisture content.

Determination of crop coefficients (K_c)

Crop coefficients (K_c) for maize were estimated according to the method described by Doorenbos and Pruitt (1975), where the ratios of actual crop evapotranspiration (ET_c) measured gravimeter-ically to the reference evapotranspiration (ET_o) calculated as averages from the Penman-Monteith on decadal basis:

$K_c = ET_c/\ ET_o$ ……………......................(4)

Measurement of applied water

Water flow into each plot was measured from a small calibrated diesel water pump (Honda GX160, 1100 L/minute).

Irrigation requirement (IR)

The IR basically represents the difference between the crop water requirement and effective precipitation. The irrigation requirements (IR) were estimated as difference between crop water requirement and effective rainfall. The irrigation requirement was obtained as follow:

$IR = ET_c - ER$ ……………………(5)

Water productivity (kg/m^3)

Water requirement (consumptive water use) and crop water productivity (WP) of crops are two important factors that are normally considered when assessing the feasibility of growing crops in any region.

CWP (kg/m^3) = Yield (kg) / applied water (m^3) …………....(6)

Results and Discussion

Reference evapotranspiration (ET_o)

The average climatic data and the calculated ET_o in mm/day are presented in Table (1). The average ET_o during the growing season ranged between 5.51 to 7.04 mm/day. The lowest value of ET_o coincided with the lowest average relative humidity (44.5 %) and lowest wind speed (1.27 m/s), while the highest value of ET_o was associated with the highest maximum air temperature (42.1 C^o) and wind speed (3.82 m/s). Allen *et al.*, (1998) reported that under arid conditions, small variations in wind speed might result in larger variations in the evapotrans-piration rate.

Effective rainfall

Fig. (1) shows the variation of the total amount of effective rainfall for maize growth period during the two seasons from July to November with the peak on August and July. First season 2015/16 shows the lowest monthly average distribution of the effective rainfall from July to October compared to the second season (2016/17). The total amount of effective rainfall was equal to 49 and 161.3 mm for seasons 2015/16 and 2016/17, respectively.

Crop evapotranspiration (ET_c)

As observed from Table (2) for seasons (2015/16 and 2016/17) the actual measured values of crop evapotranspiration (ET_c) started with a low value of 3.62 and 4.01 mm/day during the initial stage and then increased to a peak of consumptive water use of 7.24 and 8.22 mm/day during the mid-stage and thereafter the ET_c decreased during the late stage to a value of 2.80 and 2.05 mm/day for the first and second seasons, respectively. In both seasons the highest water requirements were recorded at the mid-season stage, while the lowest values were observed at the initial growth stage. The low crop water requirement at the initial stage was mainly due to the low crop leaf area development. On the other hand, the rapid reduction in ET_c in the late season stage was due to the physiological senescence of leaves. The period of maturity coincides with the period of less water demand because of drying of leaves and minimum leaf area available for transpiration. The average seasonal measured value of ET_c was 5.21 and 4.81 mm/day for the first and second seasons, respectively. The calculated total crop water requirement used was 547 and 505.1mm (mean 526 mm). This finding matches closely with that of Atta *et al.*, (2015) who found that the crop evapotranspiration of maize was 524.5 mm. Also Salih and Falih (2012) reported that the total water consumption was 610 mm. This finding is higher than that obtained by Doornbos and Pruitt (1983) which stated that to obtain high yields water requirements are 430 to 490 mm depending on climate and length of growing period. It is below the finding of Tariq and Usman (2009) who reported that the total crop water requirement was 450 mm. The measured data of crop evapotranspiration (ET_c) for the two seasons were plotted versus days after sowing (DAS) in Fig. (2). ET_c gravimetric regression curve were constructed with the regression equation and R^2 are presented.

$$ET_{c\ gravi} = 0.6841 + 0.2137x - 0.0019x^2 \quad \text{………………………………} (7)$$

$$R^2 = 0.8829$$

The regression equation can be used to calculate the crop evapotranspiration (ET_c) for any period within the growing season.

Crop coefficients (K_c)

The K_c values which were calculated using equation (4) are shown in Table (3). There was a gradual increase in K_c as plant development continued until the K_c reached its maximum values of 1.30 and 1.32 at the full growth period and the K_c decreased to 0.44 and 0.47 at the end of the growing season for the first and second season, respectively.

The peak K_c values of 1.30 and 1.32 were obtained at 70 DAS and coincided with the maximum ET_c of 7.24 and 8.22 mm/day for the first and second season, respectively. The K_c values for the initial, mid-season, and late stages were 0.49 – 0.45, 1.30 –1.32, and 0.47 – 0.40, in the first and second season, respectively. The measured K_c values were different from FAO (2002) reported values; this different is due to FAO K_c values were generalized and recommended for a wide range of climatic conditions. This finding of K_c values was within the range of Piccinni *et al*., (2009), who reported that maize K_c varied from 0.1 to 1.3 in India. The K_c was within the range of previous reports of Shankar *et al.* (2012) who reported that K_c values for the initial, development, mid and late stages were 0.55, 1.08, 1.25 and 0.75, respectively. Abedinpour (2015) reported that K_c values for the initial, crop development, mid-season, and late stages were 0.40 – 0.60, 0.70 – 0.80, 1.1–1.21, and 0.50 – 0.65, respectively. The K_c value was larger than that measured by Attarod *et al*., (2009) who reported that daily average K_c for the winter season was between 0.2 and 1.20. Also, K_c value was larger than that measured by Ayotamuno *et al.*, (1997), Abdul Salam and Suad (2006), Popova *et al*., (2006), Rong (2012) and Atta *et al*., (2015) in the start stage, where the differences were most likely to be caused by the climatic conditions.

Regression analysis of K_c gravimetric

The measured data of crop coefficients (K_c) were plotted versus days after sowing (DAS) in Fig. (3). Crop coefficients (K_c) regression curve were constructed with the regression equation and R^2 are presented.

$$K_{c\ gravi} = 0.0373x - 0.0003x^2 + 0.0708 \qquad (8)$$

$$R^2 = 0.8874$$

The regression equation can be used to calculate the K_c for any period within the growing season.

Measurement of applied water (m^3/ha)

Total water applied by irrigation (6081 m^3/ha) was more than the estimated consumptive water use (4593.5 m^3/ha). Also, the amount of irrigation water applied during the first irrigation was high (811 m^3/ha) which was due to the heavy cracking clay soils. The variation in water amount applied in each irrigation was attributed to the variations of the climatic conditions of the month.

Irrigation requirement (IR)

The irrigation requirements (IR) were estimated as difference between crop water requirement and effective rainfall (Table 4). The irrigation requirement was obtained by equation 5. Results showed that the irrigation requirements were 498 and 420.7 mm for the first and second seasons, respectively.

Crop water productivity (CWP)

Crop water productivity was calculated according to equation 6. There were significant differences in seed yield between the two seasons. Seed yield was 4105 and 4372 kg/ha in the first and second season, respectively. It was within the range of previous reports of Radma and Dagash (2013) who reported that seed yield ranged between 3870 and 4180 kg/ha. Results in Table (5) showed that the average water productivity was 0.58 and 0.88 kg/m^3 in the first and second season, respectively, which was in line with those of Elzubeir and Elamin (2011) who reported that maize water productivity in the Sudan varied from 0.60 to 0.78. Also, Tariq and Usman (2009) reported that the average water productivity of maize ranged from 0.7 to 1.8 kg/m^3. On the other hand, this finding was low compared to that reported by FAO (2002) who showed that water productivity varied between 0.8 and 1.6 kg/m^3. Al-Kaisi and Broner (2009) reported that crop water use was influenced by prevailing weather conditions, available water in the soil, crop species and growth stage.

Conclusion

The crop coefficients for the two seasons showed similar trend and very close values were observed at different growth stages, which make them consistent with season of cultivation, and thus reliable. Crop coefficients increased from early stage to its maximum measured value at the middle of the growth period and thereafter k_c decreased to the lower value at the end of the growing season. The total average water consumptive use of maize was 526 mm (5260 m^3/ha) for the growing period. Across the seasons, the daily average of ET_c values were 5 mm/day and the maximum ET_c reached 7.73 mm/day which was recorded for mid-season stage. Development of site specific K_c helps tremendously in irrigation management and furthermore provides precise water application in the region.

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حساب معامل المحصول والاحتياج المائى وكفاءة استخدام مياه الرى لمحصول الذرة الشامى فى التربة الطينية – بولاية الجزيرة ، السودان

هشام موسى محمد احمد[1] و حسين سليمان ادم[2] و صديق عيسى ادريس[1] و اسامة عباس محى الدين[1]

1. كلية العلوم الزراعية ، جامعة الجزيرة ، ودمدنى السودان.

المستخلص

إنّ فهم الاحتياجات المائية ضرورى جدا لجدولة الرى وحفظ المياه فى المناطق الجافة وذلك نسبة لمحدودية الامداد المائى. أجريت هذه الدراسة بمزرعة جامعة الجزيرة – كلية العلوم الزراعية بولاية الجزيرة في موسمين 2016/2015م و2017/2016م. بهدف حساب معامل المحصول (K_c) والاحتياج المائي (CWR) وكفاءة استخدام المياه (WP) لمحصول الذرة الشامي (صنف حديبة 2). تم حساب البخرنتح المرجعي (ET_o) باستخدام برنامج CROPWAT كما تم حساب البخر نتح للمحصول(ET_c) باستخدام الطريقة الوزنية ومن ثم تم تقدير معامل المحصول (K_c) من العلاقة بين البخرنتح المرجعى والبخرنتح للمحصول. أوضحت النتائج أن معامل المحصول يبدأ من 0.49 و 0.45 فى المراحل الأولية من عمر المحصول حتى يصل إلى أعلى قيمة له 1.30 و 1.32 ومن ثم يتناقص تدريجيا إلى أن يصل أدنى قيمة له 0,44 و 0,47 فى الطور النهائي لمحصول الذرة الشامى للموسم الاول والثانى على التوالي. أعلى قيمة لمعامل محصول الذرة الشامى كانت بعد مرور 60 و 70 يوم من تاريخ الزراعة وهى 1.30 و 1.32 ملم/يوم. الاستهلاك المائي خلال الموسم بلغ 547 و 505.1 ملم و كانت الإنتاجية 4238.5 كجم/هكتار أما متوسط كفاءة استخدام المحصول لمياه الري فكانت 0.72 كجم/م^3. لهذا فان قيم معامل المحصول يجب أنّ تستخدم لحساب كمية الماء المضاف لزيادة الانتاجية وكفاءة استخدام المياه.

Table (1): Climatic data and reference evapotranspiration (ET_o) for maize during the first and second seasons.

DAS	Min. temp. (Cº)	Max. temp. (Cº)	R.H %	Wind speed (m/s)	Sunshine (hours)	Rainfall (mm)	Rad Mj/m^2/day	ET_o mm/d
10	23.66	42.12	70.65	3.82	7.26	49.20	20.45	7.04
20	23.05	35.84	75.40	3.14	7.50	5.95	20.80	5.60
30	23.30	36.79	72.50	2.76	7.25	16.95	20.55	5.69
40	23.07	36.73	71.92	2.64	9.15	19.20	23.40	6.12
50	23.49	36.01	69.20	2.65	9.00	19.75	23.05	6.19
60	22.86	36.21	74.95	1.81	9.10	21.10	22.90	5.72
70	22.90	37.28	65.40	1.89	10.40	5.90	24.50	6.01
80	23.26	38.85	56.55	1.87	9.15	0.10	22.15	6.06
90	23.39	39.46	57.55	1.52	9.72	2.40	22.45	5.86
100	22.94	38.71	44.47	1.27	10.31	0	22.65	5.51
110	19.47	38.55	44.60	2.08	10.25	0	22.25	6.01
Mean	22.85	37.87	63.60	2.31	9.01	12.78	22.29	5.98

Table (2): Crop evapotranspiration (ET_c) in mm /day of maize for summer seasons 2015/16 and 2016/17

Irrigation number	DAS		Intervals (day)		ETc (mm/day)		Effect. Rainfall (mm)	
	season		season		season		season	
	2015/16	2016/17	2015/16	2016/17	2015/16	2016/17	2015/16	2016/17
1st	10	25	10	27	3.62	4.01	4.2	88.05
2nd	20	10	10	10	4.37	5.54	4.8	0
3rd	31	27	11	28	5.22	8.22	11.1	69.67
4th	42	10	11	10	5.30	7.18	9	0
5th	52	10	10	10	6.54	4.55	0.3	0
6th	65	10	13	11	7.24	3.10	18.6	3.6
7th	75	12	10	10	6.71	2.05	1.33	0
8th	85	*	10	*	5.37	*	0.15	*
9th	95	*	10	*	4.30	*	0	*
10th	105	104	10	*	2.80	*	0	*
Mean					**5.21**	**4.81**	**4.95**	**16.13**

Table (3): Reference evapotranspiration (ET_o), actual evapotranspiration (ET_c), and crop coefficients (K_c), for maize for summer seasons 2015/16 and 2016/17

Irrigation number	DAS		ET_c (mm/day)		ETo (mm/day)		K_c	
	season		season		season		season	
	2015/16	2016/17	2015/16	2016/17	2015/16	2016/17	2015/16	2016/17
1st	10	25	3.62	4.01	7.39	4.94	0.49	0.81
2nd	20	10	4.37	5.54	6.42	6.02	0.68	0.92
3rd	31	27	5.22	8.22	6.22	6.23	0.84	1.32
4th	42	10	5.30	7.18	5.76	6.90	0.92	1.04
5th	52	10	6.54	4.55	6.54	5.55	1.00	0.82
6th	65	10	7.24	3.10	5.57	5.53	1.30	0.56
7th	75	12	6.71	2.05	6.18	5.12	1.08	0.40
8th	85	*	5.37	*	6.05	*	0.89	*
9th	95	*	4.30	*	5.97	*	0.72	*
10th	105	104	2.80	*	5.89	*	0.47	*
Mean			**5.21**	**4.95**	**6.24**	**5.76**	**0.88**	**0.84**

Table (4): Irrigation requirement (IR) for maize seasons 2015/15 and 2016/17

Season	ET_c	ER	IR (mm/season)
2015	547.0	49.0	498.0
2016	526.1	105.4	420.7
Mean	**536.6**	**77.2**	**459.35**

Table (5): Water productivity (kg/ m^3) for maize seasons 2015/15 and 2016/17

Season	**Yield (kg/ha)**	**AW (m^3/ha)**	**WP (kg/ m^3)**
2015/16	4105.0	7474	0.55
2016/17	4372.0	4958	0.88
Mean	**4238.5**	**6081**	**0.72**

AW= Applied water (m^3/ha), WP= Water productivity (kg/ m^3)

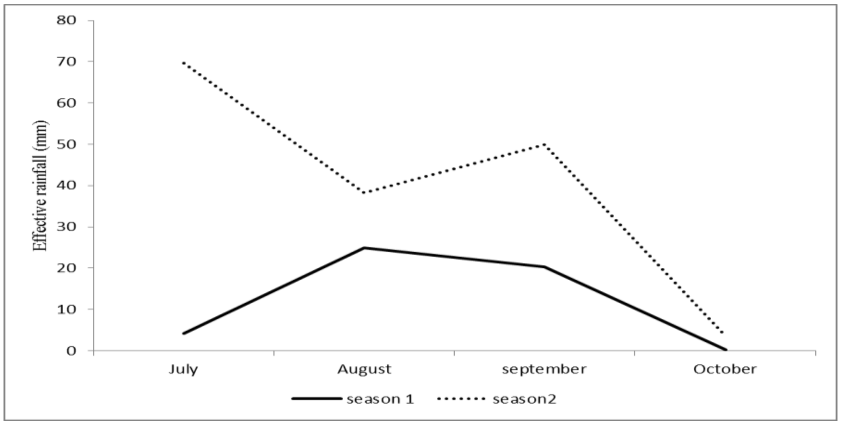

Fig. (1): Effective rainfall (mm) for maize growth period from July to October for the two seasons (2015/16 and 2016/17)

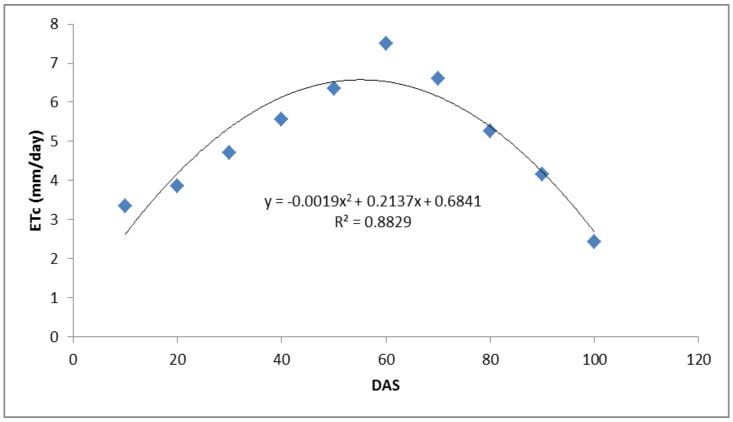

Fig. (2): Crop evapotranspiration (ET_c) from soil moisture content versus days after sowing for the two seasons (2015/16 and 2016/17)

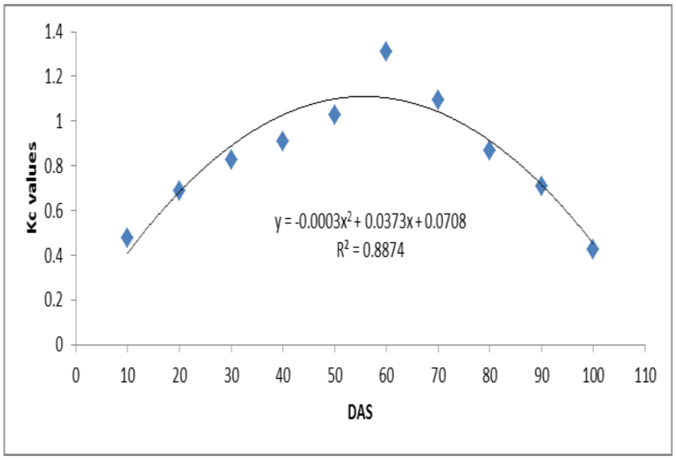

Fig. (3): Crop coefficient (K_c) as an average for 10 days periods versus days after sowing (mean for two seasons)