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Remote Sensing Derived Crop Coefficient for Estimating Crop Water Requirements for Irrigated Sorghum in the Gezira Scheme, Sudan

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ABSTRACT. Improved management of crop water requires accurate scheduling of irrigation which, in turn, requires accurate calculation of actual daily evapotranspiration (ET_a). This study was carried out to examine seasonal changes in crop coefficients and evapotranspiration values for sorghum irrigated in the Gezira scheme, with the use of remote sensing data and field measurements. Three methods, namely remote sensing-derived k_c, Farbrother k_c (experimental) and FAO k_c, revealed that the crop coefficient for sorghum reached growing season peaks of approximately 1.15, 1.21, and 1.17, respectively, at the beginning of October. The crop coefficient, derived from remote sensing data, varied over the growing season from 0.62 in the initial growth stage, 1.15 in the mid-season stage to 0.58 at harvest. The total ET_c over the growing season of irrigated sorghum estimated by remote sensing-derived k_c, experimental k_c and FAO k_c was 674, 704, and 642 mm, respectively. The ET_c by the three methods, combined with the Penman-Monteith reference ET_0, was also compared with the actual ET measured by the water balance approach. Statistical analysis showed that the remote sensing-derived k_c was superior to the others in all regression parameters. This study demonstrates that remote sensing data are a very useful tool for estimating water requirements for field crops, hence providing irrigation decision makers with information not available before.

Keywords: Crop coefficient, evapotranspiration, Gezira scheme, remote sensing, SEBAL, sorghum

1. Introduction

Evapotranspiration (ET), together with precipitation and irrigation, determines soil moisture in semi-arid zones; moreover**,** vegetation productivity is closely related to the ET rate. To develop more efficient and sustainable water management techniques for arable regions and to better predict actual or potential crop production, it is necessary to evaluate ET. Crop water requirement (CWR) for irrigating sorghum in the Gezira scheme is**,** however**,** estimated by using the experimental crop coefficient established by Farbrother during the early 1970s (Farbrother, 1973). Because of dynamic weather conditions, newly released varieties and new recommended cultural practices, crop coefficients need to be updated in order to predict correct ET. Allen et al. (1990) suggested that crop coefficients (k_c) need to be derived empirically for each crop on the basis of lysimetric data and local climatic conditions. Crop coefficients (commonly used in places where local data are not available) for a number of crops grown under different climatic conditions were suggested by Doorenbos and Pruitt (1977), emphasizing the strong need to develop k_c under given climatic conditions (Allen et al., 1990).

Remote sensing (RS) data offer a means for quickly determining ET over large vegetation areas. Particularly SEBAL, (Surface Energy Balance Algorithm for Land) an algorithm used to calculate ET from satellite images, was tested and validated across different climates and for different vegetation surfaces over the past two decades (Bastiaanssen et al., 1998b; Allen et al., 2005; Gieske and Meijninger, 2005).

Tasumi et al. (2005) used ET maps predicted by SEBAL to determine actual k_c for a large number of agricultural fields in southern Idaho; the energy balance-determined k_c curves agree relatively well with some other widely used k_c (i.e. Allen and Brockway curves) for sugar beet and grain crops (Tasumi et al., 2005).

The approach normally used to quantify the consumptive use of water by irrigated crops is the crop coefficient-reference crop ET procedure. The reference evapotranspiration represents the non-stressed ET based on the weather data taken from a grassed weather surface (Allen, 2000a). Allen (2000a) mentioned that, during the growing season, there are good opportunities to update or correct the k_c determined by the Food and Agricutlure Organization of the United Nations (FAO) or other methods with the use of remotely sensed ET.

The lack of actual measurements of k_c values causes uncertainty about appropriate coefficients for sorghum grown in the Gezira scheme. The above fact provides an opportunity to compare the existing k_c with remote sensing-derived k_c values. The objectives of this study are (i) to use remote sensing data to derive crop coefficients for irrigated sorghum in the Gezira scheme and (ii) to estimate crop water requirements of sorghum based on the remote sensing-derived k_c ($ET_c = k_c \times ET_0$) and to compare the results with other methods (i.e. experimental and FAO).

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2. Methodology

2.1. Study Area

The Gezira scheme (Figure 1) is characterized by a semi-arid climate. The annual mean air temperature is 28.0 °C and the monthly mean solar radiation ranges between approximately 20 and 26 $\mathrm{MJ{\cdot}m^{-2}}$, with the minimum occurring in July and December. Total precipitation is 280 mm (20-year average), almost all in the rainy season (July-October). Dry spells occur during the rainy season, resulting in delayed crop growth. The most important crops in the scheme include cotton, sorghum, groundnut, wheat and vegetables. Sorghum considered the most important cereal in Sudan is usually planted during July with supplementary irrigation provided throughout the growing season from the Blue Nile. Farah et al. (1997) reported that the area annually planted with sorghum is about 2.1 million ha, of which 80% is completely rain fed with the remainder given supplementary irrigation throughout growing seasons.

2.2. Data and Image Processing

Multidate remote sensing-derived data of Enhanced Thematic Mapper Plus (ETM+) on board the Landsat 7 satellite were used for the estimation of actual evapotranspiration ($\mathrm{ET_a}$) and the computation of the crop coefficient. Landsat 7 has 30 m spatial resolution and 7 spectral bands in red, near-infrared and thermal infrared; the sensor possesses a panchromatic band with a 15 m resolution. The dates of the satellite images used were 28 July, 29 August, 16 October and 17 November of 2004.

Since the satellite data were of different dates, the images were geographically registered to each other and to the map projection of Universal Transfer Mercator (UTM). The $\mathrm{ET_a}$ was estimated on the basis of the energy balance approach. The energy responsible for evapotranspiration is estimated as the residual part of the energy balance equation. This energy ultimately comes from solar radiation and can be determined from satellite spectral data with few ground observations. Morse et al. (2000) stated that remote sensing-based ET estimations using the surface energy budget are proving to be the most recently accepted technique for the estimation of areal ET. The SEBAL model utilizes Landsat data and other sensors with thermal measurements to solve the energy balance equation and hence generate an areal map of ET (Bastiaanssen et al., 1998a, b; Tasumi et al., 2000). The model uses the spatial modeler function of Earth Resources and Data Analysis System (ERDAS) Imagine, image-processing software to solve the different components of the energy balance equation. The simplified form of such an equation is:

$$R_n = H + G + \lambda E \tag{1}$$

where R_n is the net radiation at the surface, H is the sensible heat flux to the air, G is the soil heat flux, and λE is the latent heat flux (the energy required to convert water to vapor).

SEBAL uses seven spectral bands of ETM+ to compute the net radiation based on the following equation:

$$R_n = (1-\alpha)k^{\downarrow} + \varepsilon\sigma T_a^{\ 4} - \sigma\varepsilon_0 T_0^{\ 4} - (1-\varepsilon_0)\varepsilon\sigma T_a^{\ 4} \tag{2}$$

where α is the surface albedo derived from bands 1, 2, 3, 4, 5, and 7, $k^{\downarrow}$ is the incoming shortwave radiation ($\mathrm{W{\cdot}m^{-2}}$), ε is the atomspheric emissivity, σ is the Stefan-Bolzmann's constant ($5.67 \times 10^{-8}\ \mathrm{W{\cdot}m^{-2}{\cdot}k^{-2}}$), T_a is the air temperature in Kelvin, ε_0 is the emissivity of the surface, and T_0 is the surface temperature.

The soil heat flux (G) is estimated as a function of net radiation, surface albedo, surface temperature and NDVI, using the empirical equation developed by Bastiaanssen (1995):

$$G = \left[\frac{T_0 - 273.1}{\alpha}\left(0.0032\alpha + 0.0074\alpha^2\right)\left(1 - 0.98 NDVI^4\right)\right] R_n \tag{3}$$

The sensible heat flux (H) is estimated from wind speed

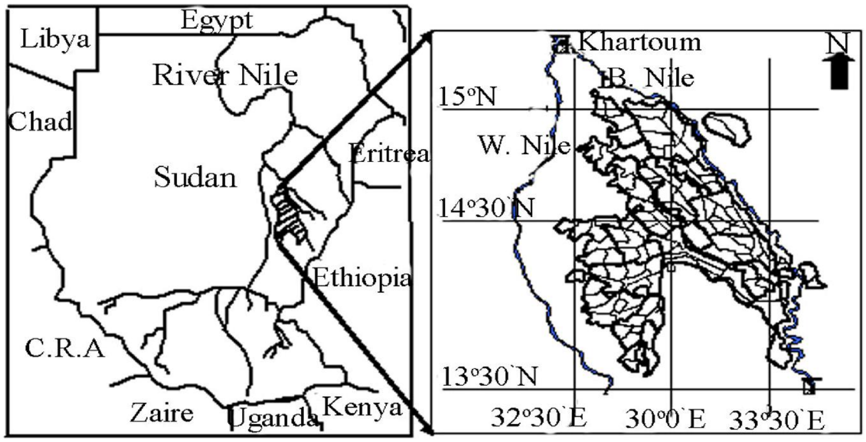

Figure 1. Location of the study area.

and surface temperature, using the concept of dry and wet pixels:

$$H = \rho_{air} C_p (dT) / r_{ah} \tag{4}$$

where ρ_{air} is the air density (kg·m^{-3}), C_p is the specific heat capacity of air (≈ 1004 J·kg^{-1}·k^{-1}), dT is the near surface to air temperature difference, and r_{ah} is the aerodynamic resistance to heat transport (s·m^{-1}). Once the three components above are estimated, the latent heat flux is estimated as the remaining term using Equation 1. To extrapolate the instantaneous ET into daily values, the evaporative fraction Λ (defined as the ratio of latent heat flux to the net available energy at the surface) was used; experimental evidence indicates that the Λ has a constant value during cloud-free days (Nichols and Cuenca, 1993). The calculation of the ET$_a$ includes the transformation of the 24 h integrated net radiation ($Rn_{24\,h}$) from W·m^{-2} to mm per day using the surface temperature-dependent latent heat of vaporization as follows:

$$ET_a = \frac{8.64 \times 10^7}{\lambda} \Lambda \times Rn_{24\mathrm{h}} \tag{5}$$

where λ is the energy required to evaporate the water. The detailed description of the SEBAL model and the computation of its parameters can be found in Bastiaanssen (1995), Bastiaanssen et al. (1998a, b) and Bastiaanssen (2000).

2.3. Calculation of Reference and Actual Evapotranspiration

Several methods are available for estimating reference evapotranspiration (ET$_0$). FAO-56 (Allen et al., 1998) mentioned that Penman derived an equation for computing evaporation from an open water surface with the use of standard climatiological records of sunshine, temperature, humidity and wind speed. The climatic conditions of the original Penman equation are the same as the local climatic conditions in this study (Table 1); additional daily weather data were gathered from the weather stations. According to Smith et al. (1992), FAO-PM provides more consistent ET$_0$ estimates and functions better than other ET$_0$ methods. Therefore in the present study, the PM method recommended by FAO 56 was used to estimate ET$_0$. Furthermore, REF-ET software version 2.0 developed by Allen (2000b) was used to estimate ET$_0$.

Table 1. Climatic Conditions in the Gezira Scheme during 2004/05 Season (GMS)

Month	T$_{min}$ (°C)	T$_{max}$ (°C)	RH (%)	Sunshine (hrs)	Rainfall (mm)
Jul	24.1	38.5	60.9	8.3	00.7
Aug	23.4	36.4	70.1	7.7	86.8
Sep	23.1	37.6	67.0	8.1	07.6
Oct	22.4	39.0	50.5	9.8	11.3
Nov	20.1	38.0	39.8	10.4	00.0

Two methods were used to compute the ET$_a$ In the first method, the ET$_a$ was measured by the water balance approach. Because of the negligible values of runoff, deep percolation and capillary rise in the Gezira clay soil, the simplified water balance equation reads as follows:

$$\Delta S = I + P - ET_a \tag{6}$$

where ΔS is the change in soil moisture storage (mm), I is the irrigation applied (mm), P is the precipitation (mm), and ET_a is the actual evapotranspiration (mm).

During field studies, soil moisture content was monitored by gravimetric methods before and after each irrigation cycle at depths of 10 cm down to one meter. The relevant weather data were collected on a daily basis from the Gezira meteorological station. The irrigation water applied each time was calculated from Equation (6) because the soil moisture storage was monitored before each irrigation and 2 to 3 days after irrigation. The ET$_a$ during each irrigation cycle was calculated from soil moisture depletion between each post- and pre-irrigation moisture sampling, according to the following equation:

$$ET_a = \left[\frac{p + \sum_{i=1}^{n} (\theta_{1i} - \theta_{2i}) \Delta z_i}{\Delta t} \right] \tag{7}$$

where ET_a is the actual crop evapotranspiration during the irrigation cycle (mm/d), P is the precipitation (mm) between the post- and pre-irrigation gravimetric soil sampling, n is the number of soil layers from which the soil moisture samples were taken, θ_{1i} and θ_{2i} are the volumetric soil moisture content during post- and pre-irrigation cycles, respectively, for the soil layer i, Δt is the time elapsed between θ_{1i} and θ_{2i} (days), and, Δz_i is the thickness of each soil layer sampled (mm).

A total of 16 ground truth points were acquired, and the root-mean-square error (RMSE) between the estimated and measured ET values was found to be around 0.2.

The second method the surface energy balance algorithm for land (SEBAL) (Bastiaanssen 1995) was used to calculate the ET$_a$ from Landsat ETM+ satellite images (Figure 2). The SEBAL method recently modified by Tasumi et al. (2000) is less user- and ground- data dependent. Actual ET maps were used to compute the crop coefficient for sorghum based on k_c = ET$_a$/ET$_0$, where ET$_a$ is the actual ET estimated, using the SEBAL model, from four Landsat images in 2004, and ET$_0$ the PM reference evapotranspiration.

2.4. Crop Coefficient

Crop coefficients (k$_c$) used for estimating ET for specific crops by measuring potential or reference ET must be derived empirically for each crop based on local climatic conditions (Doorenbos and Pruitt, 1977). Allen et al. (1998) stated that the k$_c$ for any period of the season can be derived by assuming that, during the initial and mid-season stages, k_c is constant and equal to the k_c value of the growth stage under consideration. During the crop development and late season stages, k_c varies linearly between k_c at the end of the previous stage and k_c at the beginning of the next stage. The following equation was used in a spreadsheet program to compute the k_c value on each day of the entire season:

$$k_{\mathrm{c\,i}} = k_{\mathrm{c\,prev}} + \left[\frac{i - \sum\left(L_{\mathrm{prev}}\right)}{L_{\mathrm{stage}}}\right]\left(k_{\mathrm{c\,next}} - k_{\mathrm{c\,prev}}\right) \tag{8}$$

where i is the day number within the growing season, k_{ci} is the crop coefficient on day i, L_{stage} is the length of the stage under consideration (days), and $\sum(L_{prev})$ is the sum of the length of all previous stages (days).

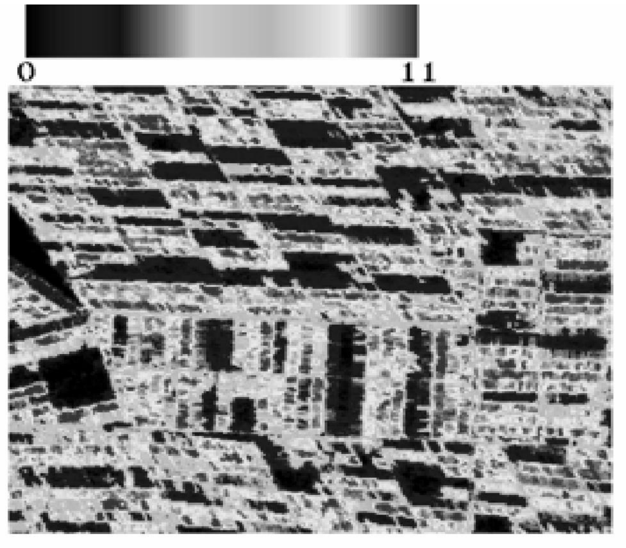

Figure 2. Daily ET in mm/day derived from ETM+ data.

2.4.1. Crop Coefficient Derived from Remote Sensing Data

The k_c for sorghum was calculated by the relation $k_c = \mathrm{ET_a}/\mathrm{ET_0}$, where $\mathrm{ET_a}$ is the actual evapotranspiration estimated from four Landsat images with the use of SEBAL, and $\mathrm{ET_0}$ the PM reference ET (mm/d) calculated on the basis of the following equation (Allen et al., 1998):

$$ET_o = \frac{0.408(Rn - G_o) + \gamma \dfrac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \tag{9}$$

where ET_o denotes the crop reference evapotranspiration (mm /d), Rn is the net radiation at crop surface (MJ/m^2/d), G_o is the soil heat flux density (MJ/m^2/d), T is the mean daily air temperature at 2 m height ($^\circ$C), u_2 is the wind speed at 2 m height (m·s^{-1}), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), $e_s - e_a$ is the saturation vapor pressure deficit (kPa), γ is the psychometric constant (kPa·$^\circ$C^{-1}), and Δ is the slope vapor pressure curve (kPa·$^\circ$C^{-1}). The average values of $\mathrm{k_c}$ from several sorghum fields (the k_c values during the initial (0.62), mid-season (1.15) and late-season (0.58) stages) were used to construct the sorghum crop coefficient according to the procedure described by Doorenbos and Pruitt (1977). It is worth mentioning here that the length of sorghum growing stages (days) during the initial, crop development, mid-season and late-season was 20, 30, 40 and 30 days, respectively.

2.4.2. Adjustment of FAO Crop Coefficient

The standard k_c of every growing stage (initial, mid, and end) for sorghum was taken from the FAO-33 documentation, Table 18, and adjusted to local field information. The k_c for the mid- and end-growing stages of the crops was adjusted to the local climatic conditions by using the climatological data (wind speed at 2 m and minimum relative humidity) from the Gezira Meteorological Station (GMS) located almost inside the command area. The maximum mean height of the crop was taken from the FAO-56 document (Table 12). By using Equations 10 and 11 suggested by Allen et al. (1998), the adjusted k_c values of the mid- and end-growing stages for the sorghum crop were computed as follows:

$$k_{c\,mid} = k_{c\ \mathrm{mid(tab)}} + \left[0.04\left(u_2 - 2\right) - 0.004\left(RH_{\mathrm{min}} - 45\right)\right]\left(\frac{1}{3}h\right)^{0.3} \tag{10}$$

$$k_{c\ \mathrm{end}} = k_{c\ \mathrm{end(tab)}} + \left[0.04\left(u_2 - 2\right) - 0.004\left(RH_{\mathrm{min}} - 45\right)\right]\left(\frac{1}{3}h\right)^{0.3} \tag{11}$$

where $k_{c\ \mathrm{mid(tab)}}$ and $k_{c\ \mathrm{end(tab)}}$ are the suggested k_c values, u_2 is the mean value for the daily wind speed at 2 m height over grass, RH_{min} is the mean value for daily minimum relative humidity, and h is the mean plant height. Daily climatological data used for this purpose were taken from GMS. The justification for the correction in the above equations is explained by Allen et al. (1998).

3. Results and Discussions

3.1. Crop Evapotranspiration ($\mathrm{ET_c}$)

Figure 3 shows the changes in crop water requirements based on 10-day intervals by the three methods (remotely sensed k_c, experimental k_c and FAO k_c). Maximum rates occurred in the middle of October and minimum rates in the middle of November at the end of the season. The ET rates for sorghum estimated by remote sensing, experimental and FAO methods ranged between 3.5 and 7.0, 3.5 and 7.6, as well as 2.0 and 7.1 mm/d, respectively.

The minimum ET occurred during the first 20 days, when only few leaves contributed to the evapotranspiration (initial crop stage), and the bulk of the water evaporated from the soil. Water consumption increased after one month, mainly attributed to water used by the plants during the vegetation stage. As with other cereals crops, the maximum quantity of water was required during the mid-season stage (flowering and ripening) when the net radiation was intercepted mostly by the crop canopy that promotes transpiration. The Sorghum water requirements started to decrease at the end of October toward the harvesting stage.

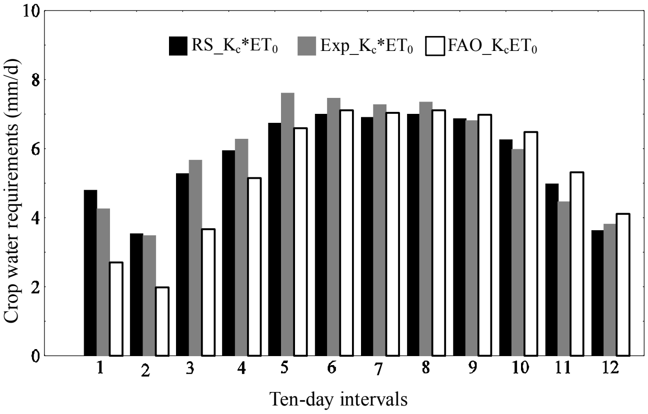

Figure 3. Evolution of crop water requirements for irrigated sorghum during the season.

The monthly water requirements (Figure 4) of sorghum by the three methods clearly illustrate that the FAO value underestimates the actual water requirement during August (initial stage), while in September the experimental method demonstrates a higher water requirement than do the other two methods. During October and November, the values by the three methods are fairly similar.

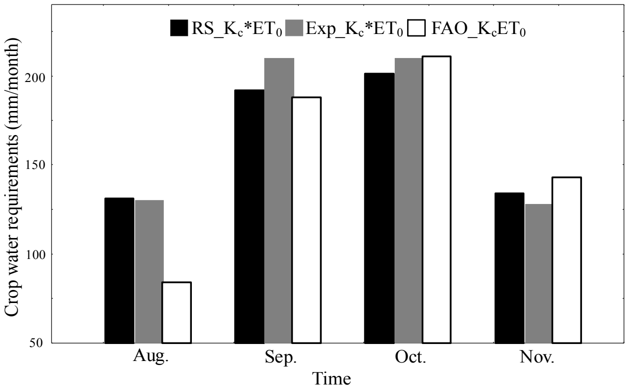

Figure 4. Monthly crop water requirements.

The seasonal water requirements for sorghum estimated by the above methods and by SEBAL are shown in Figure 5. Seasonal values of ET by remotely sensed k_c, experiment k_c, and FAO k_c were 674, 704, and 642 mm, respectively, while the value by SEBAL was around 596 mm. The difference between the SEBAL value and the values of the other three methods lies in that SEBAL takes all factors into consideration (e.g. water deficit, land preparation, diseases, weather conditions, etc.); however, the merit of the SEBAL estimate lies in the spatial information.

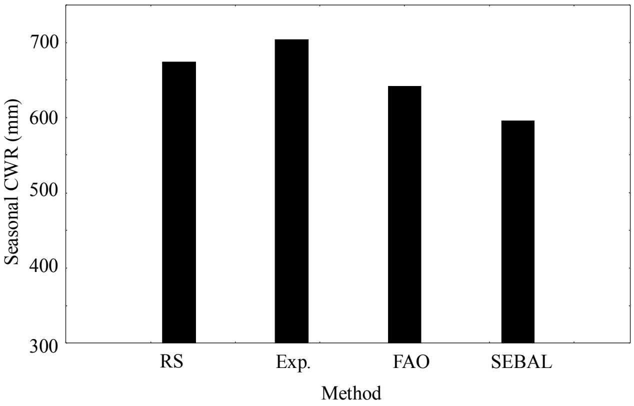

Figure 5. Seasonal water requirements for irrigated sorghum as estimated by different methods.

3.2. Crop Coefficient for Irrigated Sorghum

To examine the changes in the k_c for sorghum throughout the growing season the data were divided into 10-day intervals (Figure 6). The k_c for sorghum reached its maximum value of approximately 1.15, 1.21, and 1.17 as estimated by remote sensing, experimental and FAO methods, respectively, in the middle of October. The values then decreased gradually from mid-October to mid-November. The k_c derived from remote sensing data was higher than that from FAO during the initial and crop development stages, but lower during the mid-season and late season stages. The experimental k_c value was higher during the crop development and mid-season stages, while the derived k_c was higher than the experimental k_c during the late season stage.

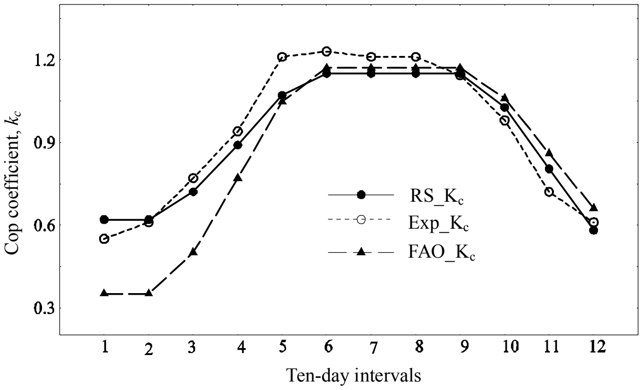

Figure 6. Crop coefficient of irrigated sorghum.

The experimental k_c curve developed during the early 1970s (Farbrother, 1973) is expressed in 10-day intervals and has been used by the Gezira Sudan Board (GSB) to compute water demand for sorghum in the scheme.

The k_c was determined for the initial, mid- season and late season growth periods and used to construct the k_c curve (Figure 6). The different k_c values during the four growth stages and the corresponding values of leaf area index (LAI) are shown in Table 2.

The k_c derived from remote sensing data, together with the experimental and FAO crop coefficient are plotted in Figure 6. From the curves, the k_c values can easily be classified into four stages as suggested by Doorenbos and Pruitt (1986) and Allen et al. (1998): initial, crop development, mid-season and late season stages. The derived k_c of about 0.62 at the beginning of the season was probably due to the effect of the frequency of irrigation and to atmospheric demand (ET_0). The value of 0.62 corresponded well with the ET_0 value (7.7 mm/day) and with LAI less than 0.65 during this period. The stage of vegetation growth was a dynamic growth period with a k_c value ranging between 0.72 and 1.15. At the beginning of the mid-season stage (flowering and seed filling period), the value was relatively constant. During the late season, the k_c deceased and reached 0.58 at harvesting stage. The value of the derived k_c during the mid-season (1.15) corresponded to the maximum LAI of more than 3 (Table 2), then LAI decreased to around 0.95 at the end-season stage. Sin (1989) reported that k_c values are curvilinearly related to LAI. It is important to mention that LAI values in this study were derived from the Landsat images that were acquired at different stages of crop growth. The derived k_c during the mid-season was lower than the experimental and FAO k_c by 2 and 5%, respectively. The average remote sensing-derived k_c during the initial stage was 44% higher than the FAO k_c. This could be attributed to the arid climatic conditions in the Gezira area, which contributed to high physiologic activity and a high evaporation rate from the soil surface as a result of frequent rainfall and irrigation. On the other hand, the drop in k_c during the late-season following the typical pattern of the k_c of annual crops (Doorenbos and Pruitt, 1977) was associated with leaf senescence and loss of photosynthetic capacity.

Table 2. Crop Coefficient and LAI Values for Four Crop Growth Stages of Irrigated Sorghum in the Gezira Scheme

Method	Crop coefficient values			
	Initial Stage	Crop-develop stage	Mid-season stage	End-season stage
Experimental	0.55	0.94	1.21	0.61
Remote sensing	0.62	0.89	1.15	0.58
FAO	0.35	0.77	1.17	0.66
LAI	0.64	2.24	3.20	0.95

3.3. Evaluation of Crop Water Requirements Methods

Table 3 shows the seasonal evolution of ET_c for irrigated sorghum estimated from the remote sensing-derived k_c. The ET_c increased from 35 mm to 67 mm per 10-day intervals in the initial and development stages. The mid-season stage was characterized by a maximum ET_c, reaching 70 mm then declining to 32 mm per 10-day interval in the late season stage. These results explain the statement by Doorenbos and Pruitt (1977) that the water requirements of crops vary markedly during the growing period mainly because of variations in crop canopies and climatic conditions.

The total seasonal ET_c of sorghum was estimated at 674 mm, with an average daily ET_c of 5.76 mm. The water from effective rainfall during the season was estimated at 103 mm, representing 15% of ET_c, with an additional amount of 571 mm provided by irrigation.

The actual ET measured in the field by the water balance approach was compared with each of the remotely sensed k_c, the experimental k_c and the FAO k_c combined with the PM reference ET, by the statistical analysis introduced by Hussein (1999). The following linear relationship was assumed:

$$y = ax \tag{12}$$

where y is the average 10-day ET measured by the water balance approach, x the corresponding ET_c by one of the other three methods, and a the dimensionless regression coefficient. In the comparison, the standard error of estimate (*SEE*), and the coefficient of determination r^2 were calculated for the regression model given in equation (12) because *SEE* and r^2 denote the mean deviation of the regression from ET values measured by the water balance approach and the degree of the correlation between ET values by the water balance approach and each of the other three methods. The regression parameters (a, *SEE*, and r^2) were computed by the following equations:

$$a = \sum xy \Big/ \sum x^2 \tag{13}$$

$$SEE = \left[\frac{\sum (y - ax)}{n - 2} \right]^{0.5} \tag{14}$$

$$r^2 = 1 - \frac{(SEE)^2 (n-2)}{S_y^2 (n-1)} \tag{15}$$

where n is the number of data points, and S_y the standard deviation of y. In equation 14, n - 2 was used instead of n because x and y were assumed to be responding to the same causative factors (Hussein, 1999).

The results of the analysis for the different regression parameters are given in Table 4. It is clear that the *SEE* of the remotely sensed k_c method combined with PM reference ET was 0.31 mm/day, while the *SEE* values for the other two methods (experimental and FAO) were 0.38 and 0.35 mm/day, respectively. These results indicate that the remote sensing-derived k_c can estimate ET_c with minimum deviation from the actual values by the water balance approach. The values of coefficient a for the three methods ranged between 0.84 and 0.87 (Table 4). The coefficients of determination r^2 were similar by the three methods; however, remotely sensed k_c showed a slightly higher value (0.94) than did the other two methods.

We can tentatively conclude that the remote sensing-derived k_c can better improve the planning for irrigation water resources because k_c estimates based on satellite images represent real agricultural practices better than do those predicted

Table 3. Changes of Average 10-day ET_c for Sorghum during the Season Estimated Using the Crop Coefficient Derived from Remotely Sensed Data

Month	10-day intervals	Crop Stage	ET_c/10-days (mm)	RF_{eff}/10-days (mm)	CWR/10-days (mm)
Jul/Aug	1	Initial	48	12.4	35.6
Aug	2	Initial	35	59.9	00.0
Aug	3	Development	53	11.8	41.2
Sep	4	Development	59	5.0	54.0
Sep	5	Development	67	0.0	67.0
Sep	6	Mid-season	70	2.6	67.4
Oct	7	Mid-season	69	11.1	57.9
Oct	8	Mid-season	70	0.0	70.0
Oct	9	Mid-season	69	0.0	69.0
Nov	10	Late	57	0.0	57.0
Nov	11	Late	45	0.0	45.0
Nov	12	Late	32	0.0	32.0

by field data and tabulated k_c values published in the literature. The experimental and FAO methods are highly dependent on *in situ* data; therefore, a lack or a deficiency in these data is considered the main source of uncertainty. On the other hand, the uncertainty of satellite derived k_c occurs when cloud contaminated images are used in the calculations.

Table 4. Statistical Analysis between Sorghum Actual Measured ET_c and Estimated Values Using Other Three Methods during the Study Season

ET_c Method	$y = ax$		
	a	r^2	SEE (mm/day)
$RS\_k_c*ET_0$	0.87	0.94	0.31
$Exp\_k_c*ET_0$	0.84	0.91	0.38
$FAO\_k_c*ET_0$	0.86	0.92	0.35

4. Conclusions

In the Gezira scheme, evaporation from free water surfaces (Penman, 1948) was used in the calculation of crop factors by Farbrother in the early 1970s. Farbrother and his co-workers developed crop factors and CWR for many irrigated crops in the scheme (Farbrother, 1976). Recently however, new varieties of sorghum and other crops in the scheme have been adopted for cultivation. The local climatic changes, the seasonal differences in crop growth patterns, and the new released varieties with different cultural practices clearly reflect the difficulties not only in extrapolating k_c for large areas, but also in applying k_c to individual years with variable crop patterns. Therefore, derived crop coefficients from real-time remotely-sensed data are very useful when a specific location or variety, or both, are required in heterogeneous fields or in large irrigation schemes where conditions vary greatly. Furthermore, the actual estimation of k_c values relying on conventional ground based methods is costly, labor-intensive and time-consuming.

In this study, remote sensing images acquired at strategic periods of crop growth were used to derive k_c of irrigated sorghum in the Gezira scheme and to construct k_c curves according to the procedure described by Doorenbos and Pruitt (1977). The values of remote sensing-derived k_c during the initial, development, mid- and late-season stages were 0.62, 0.89, 1.15 and 0.58, respectively. The total seasonal ET_c for sorghum using the derived k_c was around 674 mm with an average daily ET_c of 5.76 mm. On the other hand, the average seasonal ET estimated by SEBAL was 596 mm. Regression analysis of actual ET measured by the water balance approach and the corresponding ET_c estimated by remote sensing-derived k_c, experimental k_c and FAO k_c, combined with the PM reference ET, demonstrated that the remotely sensed k_c method was superior to the others in all regression parameters. The methodology used here is applicable to any irrigated area, where remote sensing measurements and ground data are available.

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